5-2016

Additive Friction Stir Manufacturing of 7055 Aluminum Alloy

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Additive Friction Stir Manufacturing of 7055 Aluminum Alloy

An Honors Thesis Presented to

The Department of Mechanical Engineering

Of the University of New Orleans

In Partial Fulfillment

Of the Requirements for the Degree of

Bachelor of Science, with University Honors

And Honors in Mechanical Engineering

By

Shawn Michael Puleo

May 2016

Acknowledgement

I would like to thank my advisor, Michael Eller, for his continued help and time spent through the process of developing this research and knowledge on the subject. I also would like to thank Dr. Paul Schilling for his help with specimen preparation and testing along with allowing access to university equipment. Anne Marie Joyce also provided important support and knowledge with specimen polishing and etching. All help throughout the project is greatly appreciated and valuable.

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Abstract

The objective of the report is to investigate the feasibility and reliability of additive friction stir manufacturing of 7055 aluminum alloy. This is a technique in which multiple lap welds are performed to create a three-dimensional part out of relatively thin plate aluminum. To accomplish this, a four inch stack of 7055 aluminum alloy lap welds must be created. The solid weld nugget is then machined out of the center of the welded stack to create ASTM approved subsize tensile coupons. Rockwell hardness, yield strength, ultimate tensile strength, and percent elongation information is gathered from the tensile coupons to investigate the effectiveness of the additive friction stir manufacturing process. The data shows that the additive manufactured material experiences a significant reduction in strength and percent elongation while not showing any significant response to heat treatment. Suggestions are made regarding possible changes to the weld schedule that could improve the material properties of the additive manufactured aluminum.

Keywords: Friction Stir, 7055 Aluminum, Additive Manufacturing, Tensile Strength

Introduction

Friction Stir Welding Theory

Friction stir welding is classified as a solid-state welding process. This means the material is joined together without reaching its melting temperature, thereby remaining solid state. Figure 1 show a basic schematic of fixed pin friction stir weld. The tool consists of a rotating shoulder and pin, or probe.

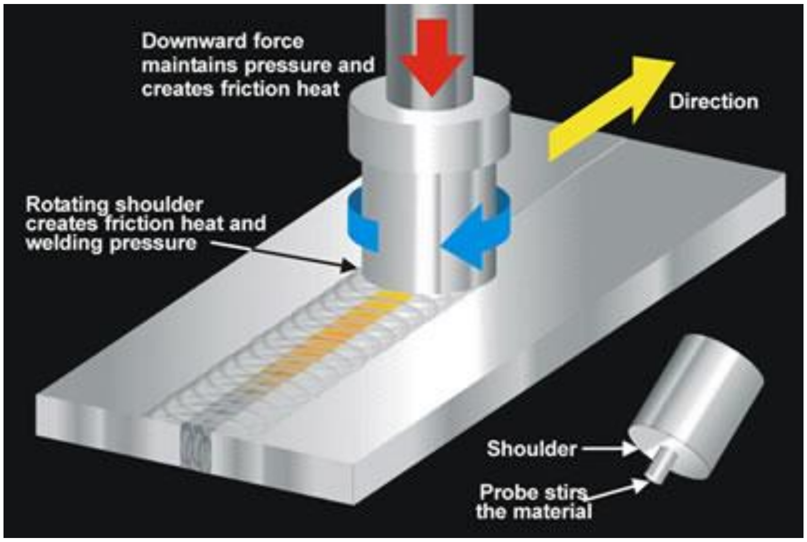

Figure 1: Basic Friction Stir Welding Schematic

The shoulder creates friction and generates enough heat to soften the material. The softening of the material being welded is called plasticization. A large downward force is also exerted by the shoulder on the material to create enough pressure to forge the plasticized material together. The pin at the center of the shoulder, protrudes into the material to create a stirring action within the plasticized material. The pin acts as a mechanism to break up the interface between the two pieces of material being joined and creates a well-mixed weld with fine grain microstructures.

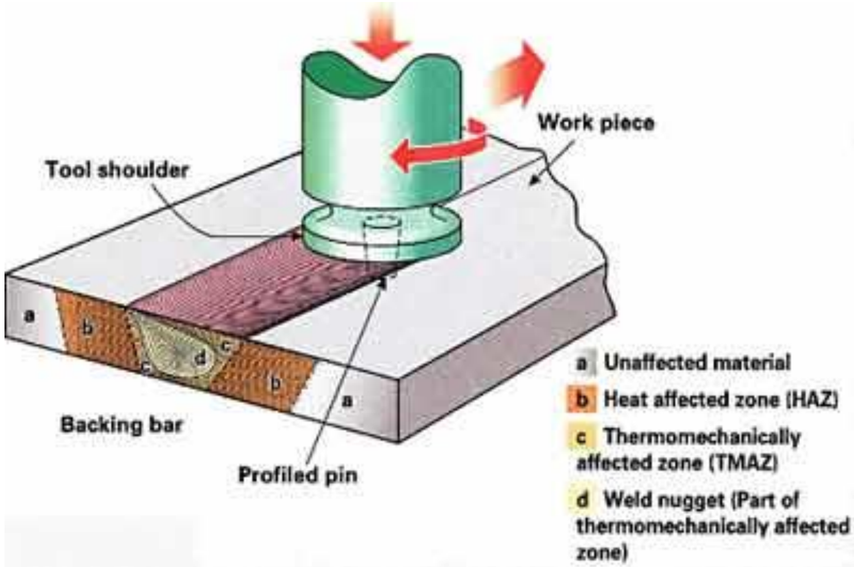

Figure 2: Friction Stir Weld Metallurgical Zones

Figure 2 shows the zones of a typical fix pin friction stir weld. The material furthest away from the center of the weld on both sides is called the parent material, or unaffected material. This is material that has not been changed in any way by either motion of the friction stir tool or the heat generated by the tool. The next zone in closer to the center of the weld is the heat affected zone (HAZ). This zone has not been disturbed by the motion of the tool; however, has been affected by the heat generated from the tool, in that the grains of the material could have grown or recrystallization could have occurred. The heat affected zone often contains the poorest mechanical properties. The next zone in is the thermomechanically affected zone (TMAZ). This zone generally begins at the point of contact between the material and the shoulder of the tool. The shoulder begins to rotate and mix the plasticized material along with changing the microstructure due to the heat input. Recrystallization could occur depending on the material alloy. The final zone of a friction stir weld is the weld nugget, which is part of the thermomechanically affected zone. This is primarily the region in which the pin passes during welding. The grain structure in the weld nugget

is often the most uniform and contains the best mechanical properties. Full recrystallization occurs in this region, along with nearly equiaxed grains, equal length.

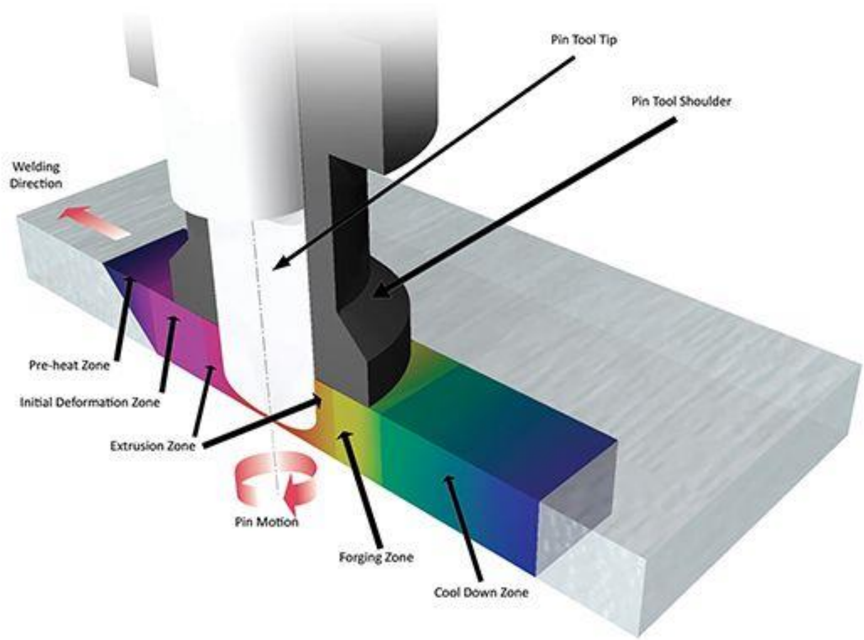

Figure 3: Friction Stir Welding Material Flow

Friction stir welding is often described as a joining, forming, forging, extrusion, and heat treatment process. Figure 3 shows the stages and material flow patterns during a typical friction stir weld. The first zone, at the leading edge of the friction stir tool, is the pre-heat zone. The material begins to heat up due to the friction heating from the rotating shoulder. The next zone is the initial deformation zone, in which the shoulder begins to mix the material by following the material in the flow path. The zone immediately around the pin is the extrusion zone. The material is forced around and through the various grooves in the pin. The material moves from front to back along with being pushed downwards towards the bottom of the weld. The zone after the pin is the forging zone. The material exiting the wake of the pin is forced into spaces between the pin and the

hardened material while also being compressed by the load being applied from the shoulder. The final flow zone is the cool down zone. Here, the material begins to harden and form the weld.

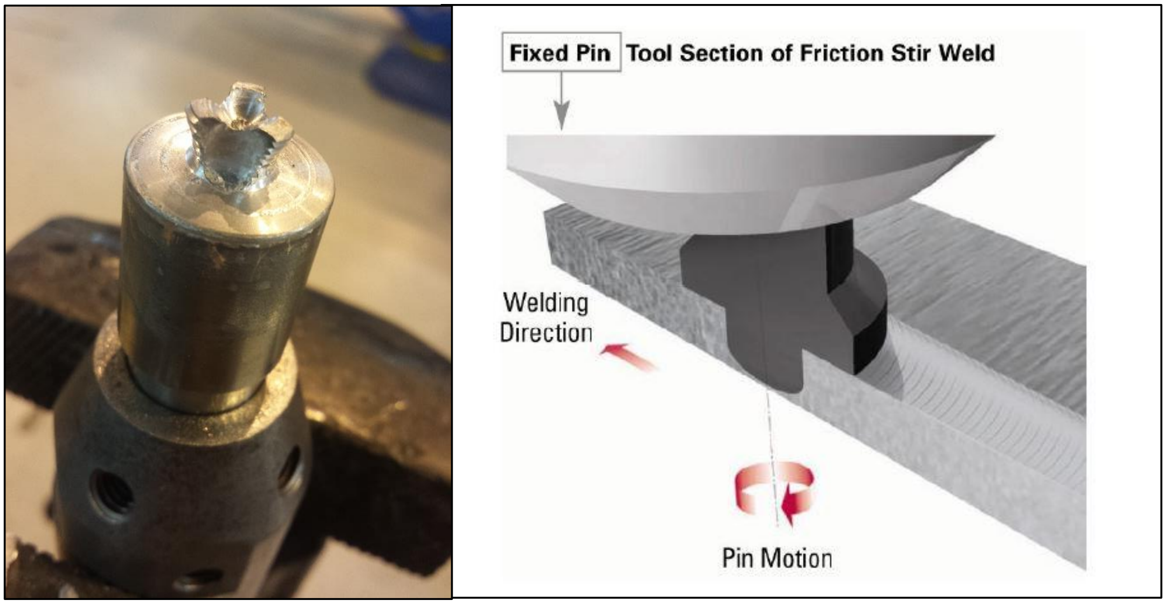

Figure 4: Fix Pin Friction Stir Weld Tool

Figure 4 show a general fixed pin friction stir welding tool. For this type of weld, the pin is attached to the shoulder of the tool and the length of the pin is not adjustable. Therfore, a fixed pin tool has to be designed for each specific weld performed. The length of the pin is determined by the thickness of the material. The fix pin tool shown on the left in Figure 4 is the pin used to conduct the research for this report.

Additive Friction Stir Manufacturing Process

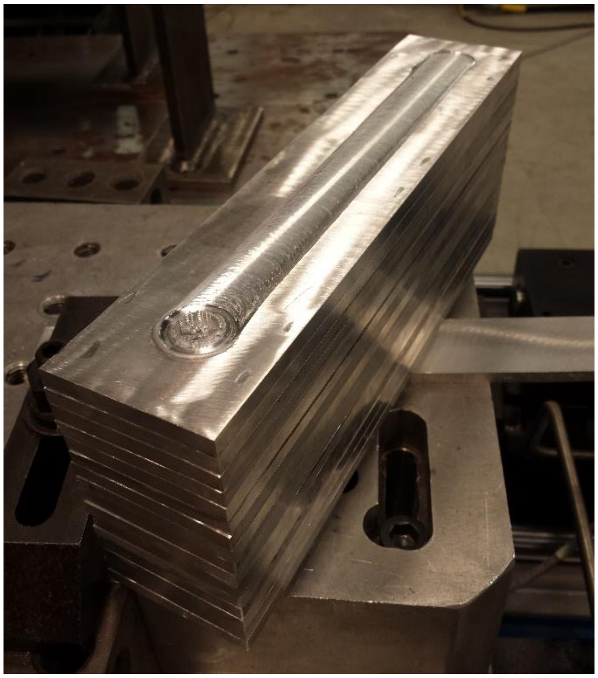

Figure 5: 4 Inch Additive Friction Stir Stack

The intent of this report is to document the viability of additive friction stir manufacturing. To do this, the general process will be described. Figure 5 shows a picture of the finished stack of 15 friction stir lap welds of 7055 aluminum alloy. As seen in Figure 6, plates are stacked on top of each other to create a stack of welded plates to the desired height. Figure 6 also shows the welding setup used to create the additive friction stir stack. To begin the process, two 7055 aluminum alloy plates are placed in the welding fixture and clamped to ensure no movement occurs during weld. These plates are stacked on anvil plates, as shown in Figure 6, to keep the welding surface at the same height for each consecutive weld. A lap weld is performed on the first two plates, with the pin penetrating about a tenth of an inch into the second plate.

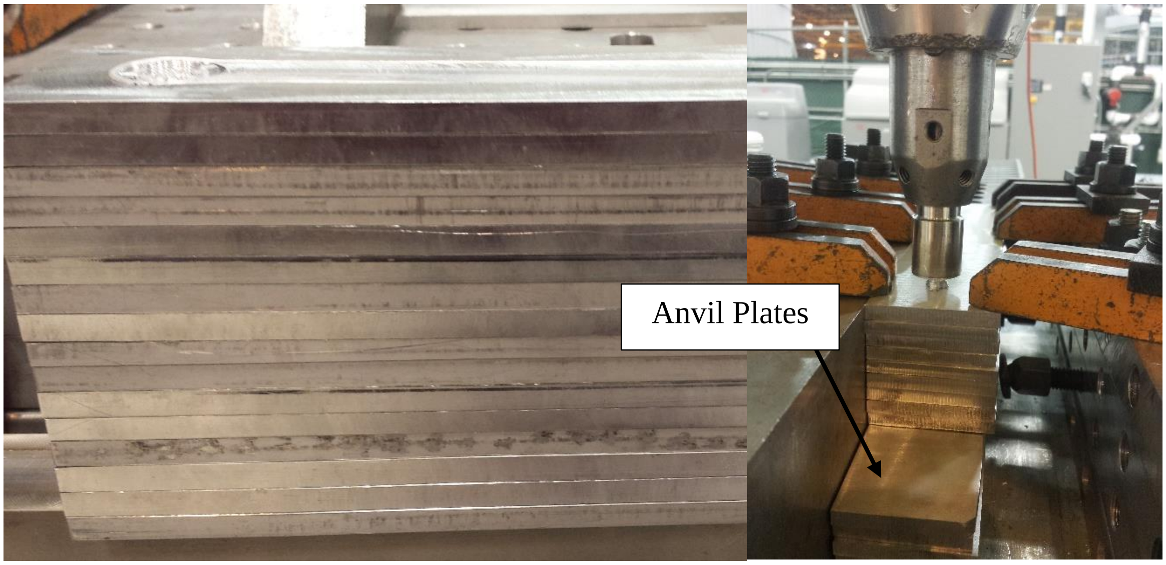

Figure 6: Layer View of Additive Friction Stir Stack (Left), Weld Setup (Right)

Once the weld is completed, it is taken out of the weld fixture and allowed to cool. The welded surface then needs to be sanded smooth to ensure the next plate will fit flush with the welded surface. A fix pin friction stir weld also leaves a small hole, the diameter of the pin, at the end of the weld. This hole needs to be filled in order for the next weld to be performed. If else, the pin tool would sink into the surface of the next weld near the hole. This would cause deep gouging by the shoulder, prohibit the further welds from being completed. Figure 7 shows a before and after sanding picture of one of the welds. As shown, the scroll marks and flashing on either side of the weld is removed with a belt sander and fine smoothed with scotch brite pads. The hole left at the end of the weld is plugged with a loose fitting aluminum cylinder. This fills the void and allows for the next weld to be performed as normal.

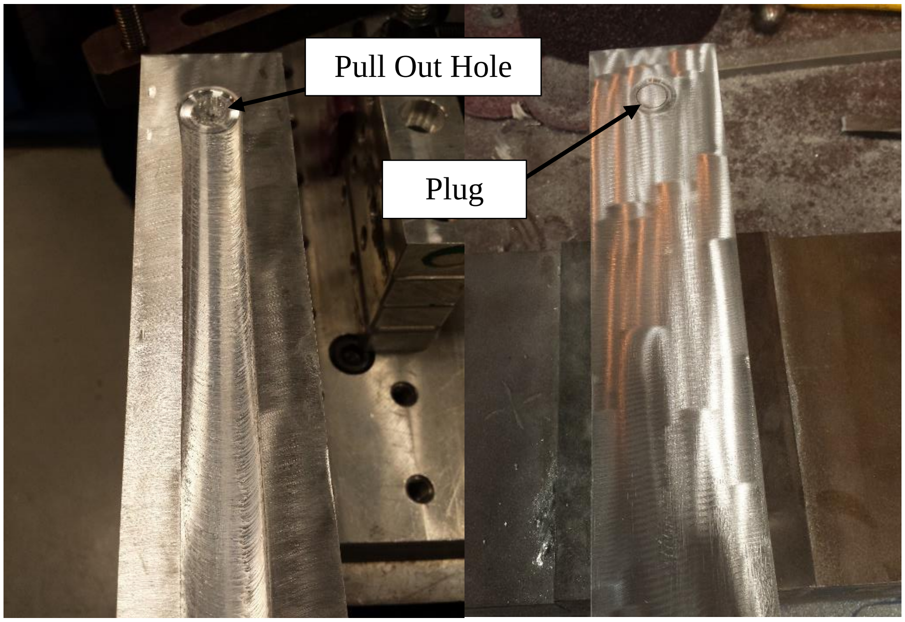

Figure 7: Friction Stir Weld Before Sanding (Left), After Sanding (Right)

Once the weld surface is sanded smooth, the weld stack is placed back into the weld fixture by removing one of the anvil plates then placing a new 7055 aluminum alloy plate on top of the weld stack. The next lap weld can then be performed as before and the process can be repeated until the weld stack reached the desired thickness.

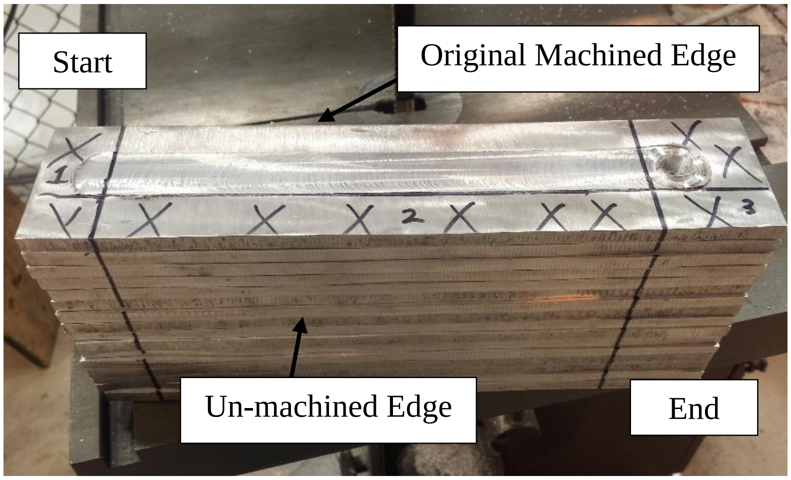

Figure 8: Weld Stack Band Saw Cut Away Sections

Figure 8 shows the completed weld stack and the sections to be cut away first using a bandsaw. The two end pieces are cut off to remove the start and finish of the friction stir welds. Then, the weld stack is bandsaw cut along the scroll line near the rough, un-machined edge of the weld stack.

The flat, machined edge of the weld stack is left to be used as a reference point to machine out the solid weld nugget in the center. Figure 9 shows the weld stack after the first series of bandsaw cuts have been made. The bandsaw cut side of the weld stack then needs to be machined flat until the face is 0.125 inches from the center of the weld nugget. This removes any non-welded material from this side and leaves only solid weld nugget. Next, the original machined edge, refer to Figure 8, is bandsaw cut along the weld scroll line to remove the bulk of the non-welded material. The welded stack is then clamped into a vise with the top welded surface facing up and machined flat. This process is repeated for the bottom surface of the welded stack. The weld stack can then be griped in a vise with the most recent bandsaw cut side facing up to be machined to a final thickness of 0.25 inches. The remaining plate, shown in Figure 10, is solid weld nugget and is to be machined into tensile samples. Figure 11 shows the individual tensile samples after the solid plate was rough cut with the bandsaw into

Figure 9: Bandsaw Cut Weld Stack

Figure 10: 0.25 Inch Thick Solid Weld Nugget Plate

the general shape of the tensile samples. The rough cut tensile samples were then machined into the final shape of the tensile samples with a reduced dogbone section in the center. The reduced cross-sectional area of the center portion focuses the stress in this region and avoids the tensile samples breaking in the grips of the tensile testing machine. The tensile samples shown in Figure 12 are machined to ASTM E8/E8M requirements for standard test methods for tension testing of metallic materials. From these tensile samples, the yield strength, ultimate tensile strength, percent elongation, and hardness of a solid 7055 aluminum alloy friction stir weld is determined.

Figure 11: Bandsaw Cut Tensile Samples

Before the tensile samples are tested, half of the tensile samples are heat treated to analyze the effect of a heat treatment process on each of the properties being determined. The hardness of each specimen is also tested before and after the heat treatment. This gives an indication what happened during the heat treatment process.

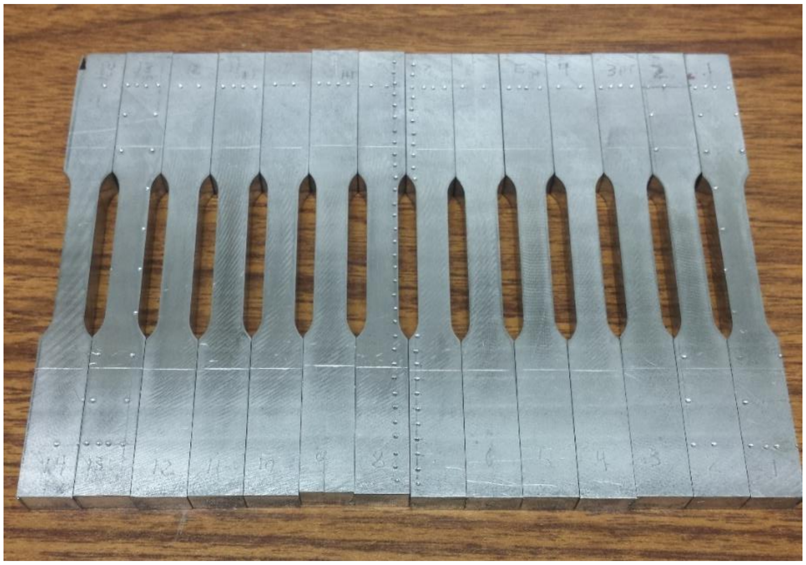

Figure 12: Tensile Samples, Dogbone Cut

Existing Additive Manufacturing Techniques

Additive manufacturing techniques have been developed that display promising and advantageous results; however, each process has its own drawbacks. NASA has demonstrated using electron beam freeform deposition to manufacture near net shape parts. As shown in Figure 13, the system utilizes a wire feed mechanize that introduces the metal wire into a focused electron beam. The electron beam melts the feed wire into a molten pool and builds up layers upon a substrate.

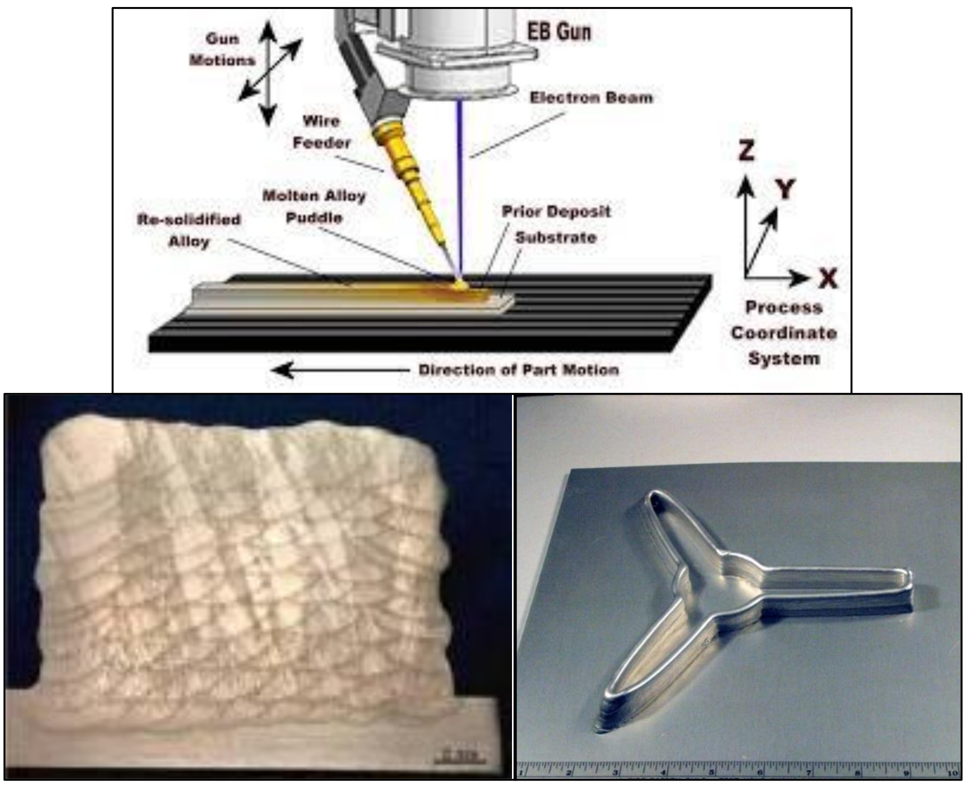

Figure 13: Electron Beam Free Form Fabrication

This process has been fairly well tested and proved; however, it has some drawbacks. The size of the part that can be produced is limited to the size of the vacuum chamber and the microstructure produced is anisotropic and contains large grains depending on the deposition rate. This often leads to poor mechanical properties.

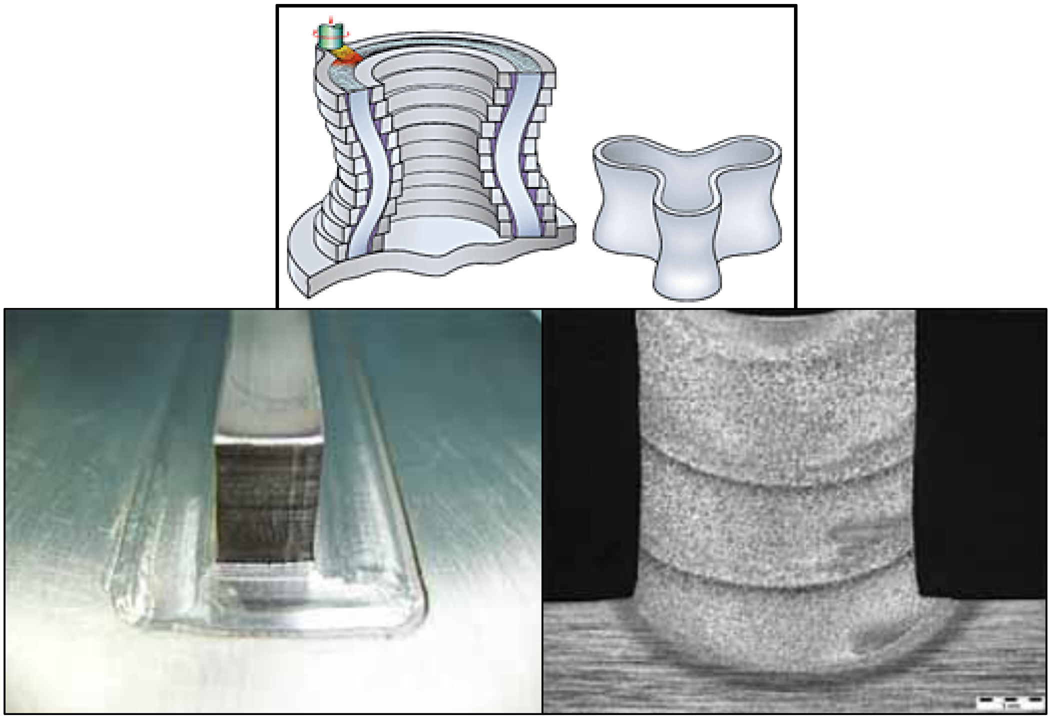

Figure 14: The Welding Institute Additive Friction Stir Process

The Welding Institute demonstrated an additive friction stir processing technique similar to the process of this report. Machined and preformed shapes are friction stir welded layer-by-layer to produce a near net shape part that requires little machining. Figure 14 shows a basic schematic of the process along with a macrograph of the microstructure. This produces a part with a fine grain microstructure that is equiaxed and isotopic; however, no data has been presented on the results of the process.

Aeroprobe uses a patented Additive Friction Stir process to build up near net shape parts layer by layer. Figure 15 shows a schematic of the general process. A rotating shoulder and spindle creates frictional heat while powdered material is forced down a hole in the center of the spindle. The heat plasticizes the powder and creates a substrate which can be built upon layer-by-layer.

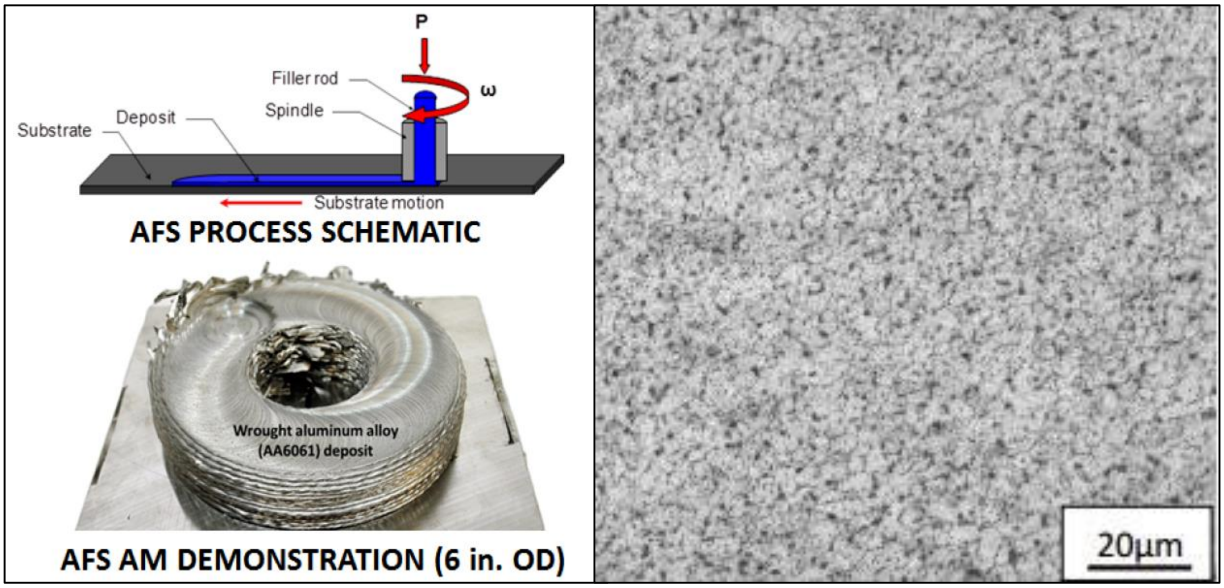

Figure 15: Aeroprobe Additive Friction Stir Process

Figure 15 also shows the microstructure produced from Aeroprobe's Additive Friction Stir process. It consists of a homogenous and equiaxed fine grain microstructure with no obvious layer interface.

Additive Friction Stir Manufacturing Applications

The additive friction stir process as described for the experiment of this report has practical applications that can be used to save time, costs, and materials in industrial settings. One potential application is to create strong stiffeners and stringer configurations for the aerospace industry.

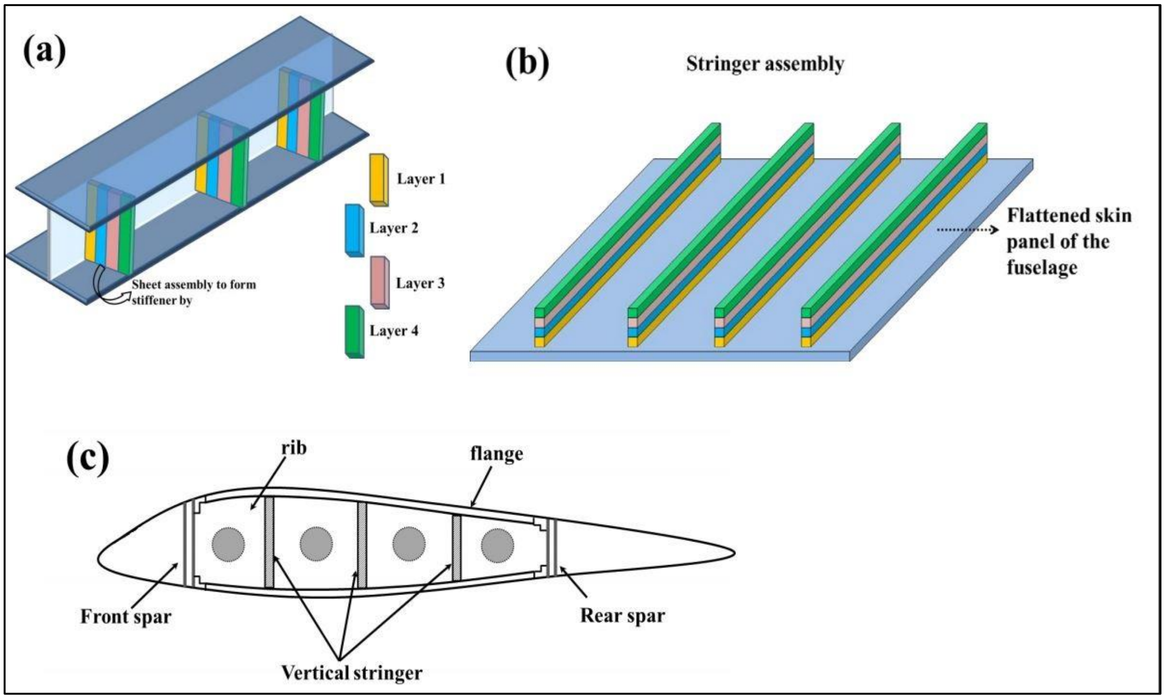

Figure 16: Additive Manufactured Stiffeners

In the aerospace industry, structures and pressure vessels often consist of a ribbed interior to increase the strength while also reducing the weight of the part. Currently, these parts are created using a subtractive manufacturing process. This consists of starting with plate metal with a thickness of the overall part thickness. The majority of the material is then machined away to create the desired shape or ribbed surface. Using this process, 90% of the starting martial could be machined away to create the final part. This leads to high machining costs and a large amount of wasted material.

An example of a possible use for this technique is the production of aluminum bulkheads as shown in Figure 17. These bulkheads are used as the main support structure in fighter jets. Currently they

are forged into the rough shape then machined into the final shape of the part. Using this process, about 90% of the material, by weight, is machined away from the structure. Also, the forging process creates a large amount of residual stress and distortion.

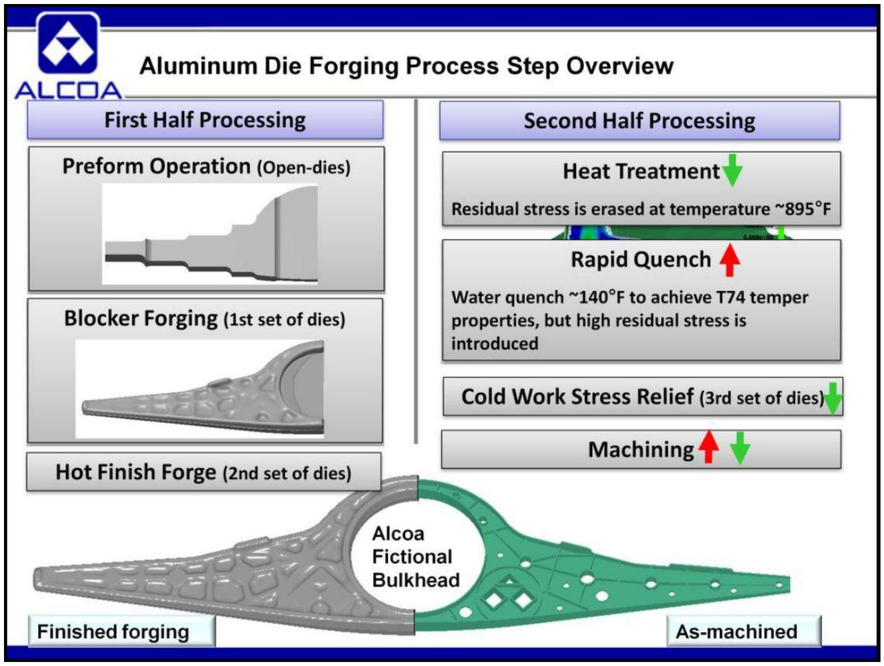

Figure 17: Forging of Alcoa Fictional Bulkhead

Figure 18 shows a picture of the Orion Crew Module. This structure also requires a large amount of machining and wasted material to get to the desired size and shape. Additive friction stir manufacturing could be used to produce these parts while saving machining time and material. These parts could be produced starting from a flat plate and built upon with additive friction stir. If stiffeners are needed or a section of the part requires a larger thickness, they could be additive friction stir manufactured.

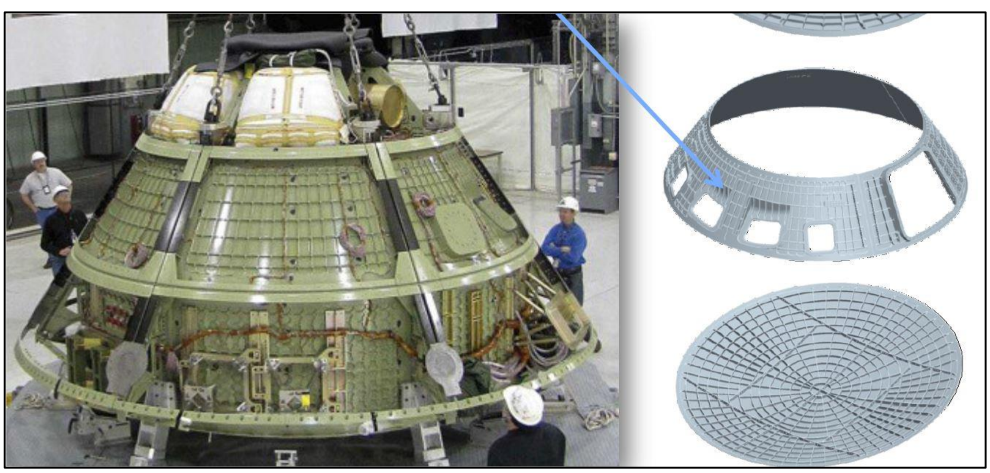

Figure 18: Orion Crew Module Window Frame Structure

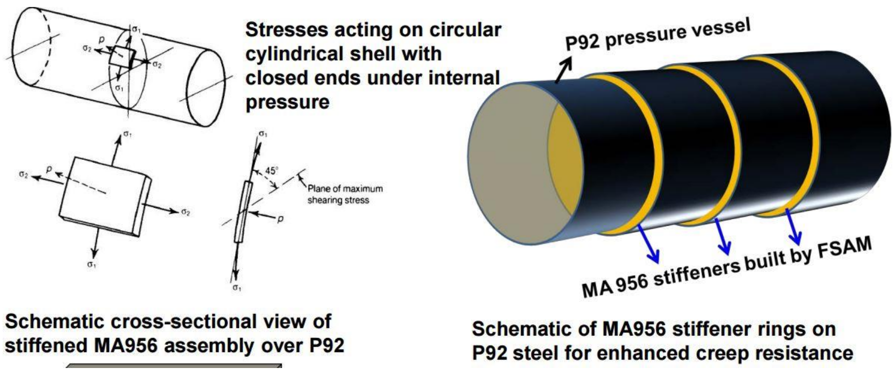

Figure 19: Creep Resistant Stiffeners

Additive friction stir manufacturing also has possible applications in the fossil and nuclear sectors. It can be used to enhance the creep resistance of pressure vessels and pipes under high pressures and temperatures. Figure 19 shows a technique that could help reduce creep failure in pressure vessels. Stiffener rings could be additively friction stir welded around tanks that are likely to experience creep. This process could be used on superheaters and reheaters due to the high operating temperature and pressures.

Results

Tensile Results

Four tensile samples were machined out of the base 7055 aluminum alloy. The tensile results are shown in Table 1. These results compare relatively well with tabulated material properties of 7055-T76511 aluminum alloy extrusions, as the base material for the welds is 7055 aluminum alloy extrusion.

Table 1: Base Material Tensile Results

	Yield Strength, σ_y, (psi)	Ultimate Strength, σ_{ult} (psi)	Percent Elongation, *e* (%)
Base Tensile 1	79800	93401	9.85
Base Tensile 2	80300	93755	9.80
Base Tensile 3	80300	93497	8.83
Base Tensile 4	80000	93299	9.75
Average	80100	93488	9.55

Table 2 shows tensile results for the additive friction stir manufacturing tensile samples. The odd numbered tensile samples were heat treated and the even number tensile samples were tested as welded. The tensile sample numbers increase from the start of the weld to the finish. As shown in Table 2, the heat treatment process did not have any significant effect on the mechanical properties except for percent elongation. The percent difference between the heat treated samples' and the non-heat treated samples' mechanical properties was less than four percent except for percent elongation. By heat treating the additive friction stir manufactured tensile samples, the percent elongation before failure increased by about 20 percent. Although the percent difference between the mechanical properties of heat treated and non-heat treated samples was small, that small increase was due to the heat treatment. This shows that possible a different heat treatment schedule could further increase mechanical properties.

Table 2: Additive Friction Stir Manufacturing Tensile Results

	Yield Strength, σ_y, (psi)	Ultimate Strength, σ_{ult} (psi)	Percent Elongation, *e* (%)	Joint Efficiency (%)
Weld Tensile 1	46600	53240	1.48	57.0
Weld Tensile 2	43700	55250	1.42	59.1
Weld Tensile 3	44650	60677	2.93	64.9
Weld Tensile 4	44200	55855	1.65	59.7
Weld Tensile 5	44400	62656	3.64	67.0
Weld Tensile 6	42200	53456	1.30	57.2
Weld Tensile 7	44450	57625	2.01	61.6
Weld Tensile 8	44300	56859	2.46	60.8
Weld Tensile 9	44300	59466	3.56	63.6
Weld Tensile 10	43800	59559	3.42	63.7
Weld Tensile 11	44400	57407	2.28	61.4
Weld Tensile 12	44000	58266	2.46	62.3
Weld Tensile 13	44400	50664	0.86	54.2
Weld Tensile 14	42800	48995	0.89	52.4
Average Heat Treated	44743	57391	2.39	61.4
Standard Deviation HT	825.85	4190.78	1.04	0.04
Average Non-Heat Treated	43571	55463	1.94	59.3
Standard Deviation NHT	780.42	3479.49	0.88	0.04
Percent Difference HT - NHT (%)	2.65	3.42	20.88	3.42

Figure 20 shows a bar plot of yield strength and ultimate tensile strength for each tensile sample. This plot shows that the yield strength of the additive friction stir manufactured material stayed relatively constant from the start of the weld to the finish. However, the ultimate tensile strength varied over the length of the weld. The general trend was that the beginning and end material experienced a lower ultimate tensile strength than the middle material.

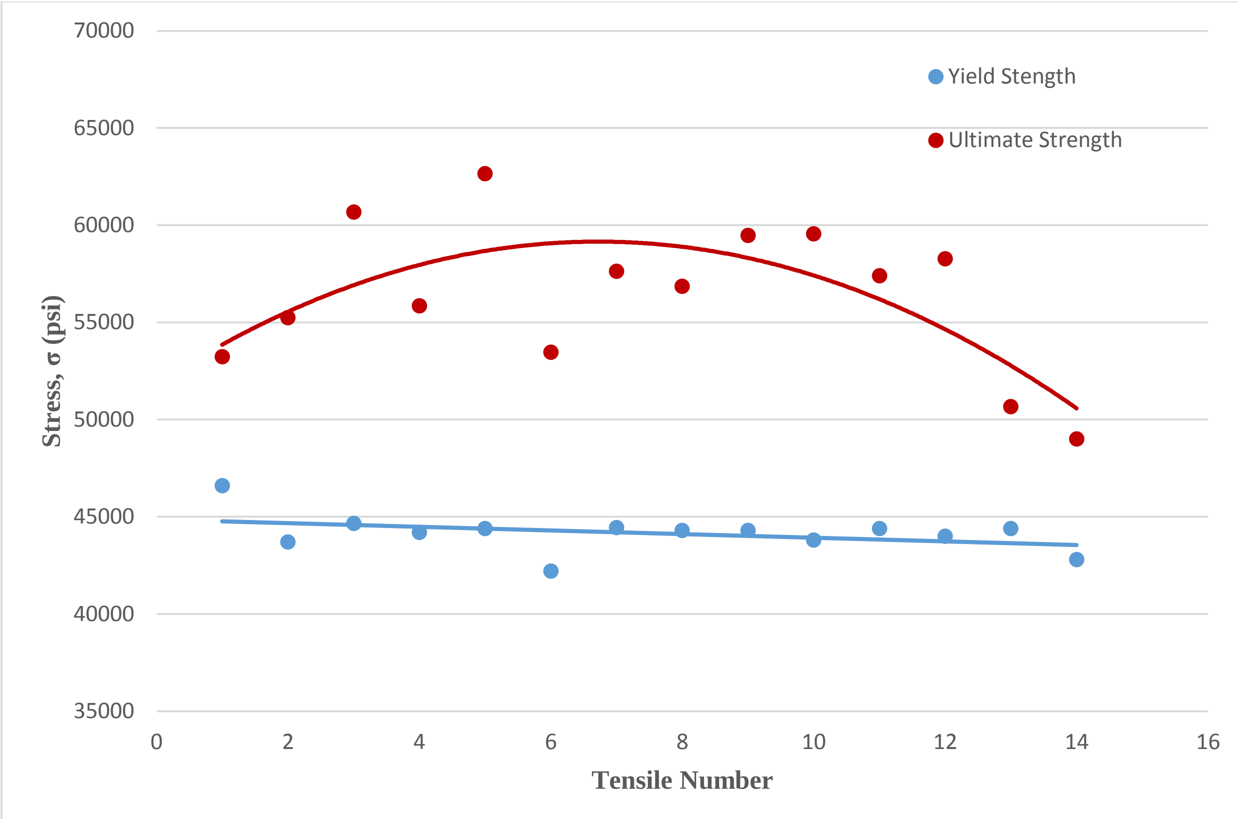

Figure 20: Yield versus Ultimate Strength

Rockwell Hardness

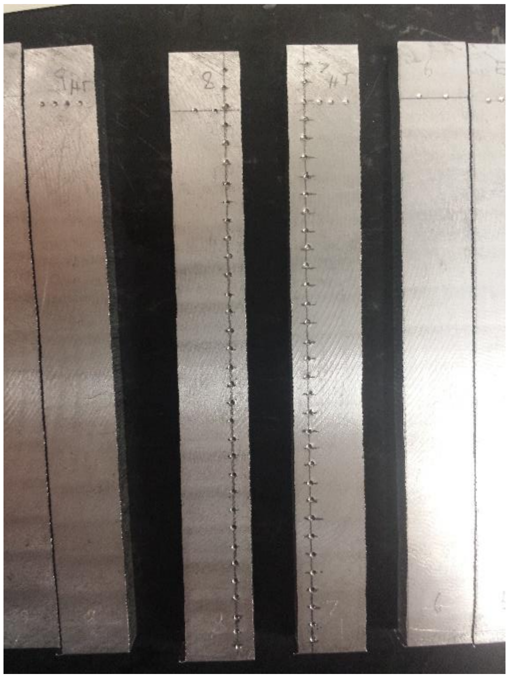

Figure 21: Rockwell Hardness Tests on Tensile Samples 7 and 8

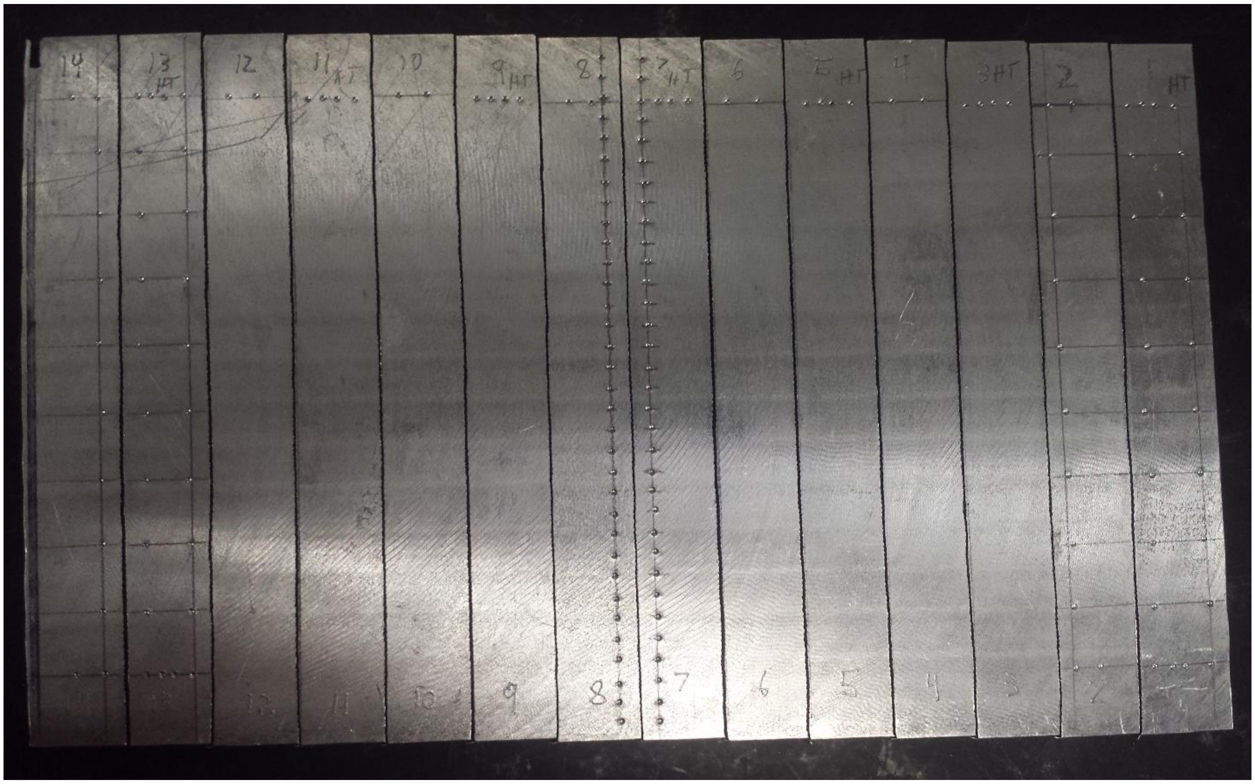

Figure 22: Layout of Rockwell Hardness Tests

The hardness of each additive friction stir manufactured tensile sample was measured using a Rockwell hardness tester set in HRB scale. The hardness of the tensile samples that were heat treaded was measure before and after the heat treatment to compare the effect on hardness. Figure 23 shows the hardness of the material before and after heat treatment from the start of the weld to the finish of the weld. As seen, there was a slight increase in hardness after the samples were heat treated. Also, the heat treatment seemed to have reduced the variation in hardness along the length of the weld.

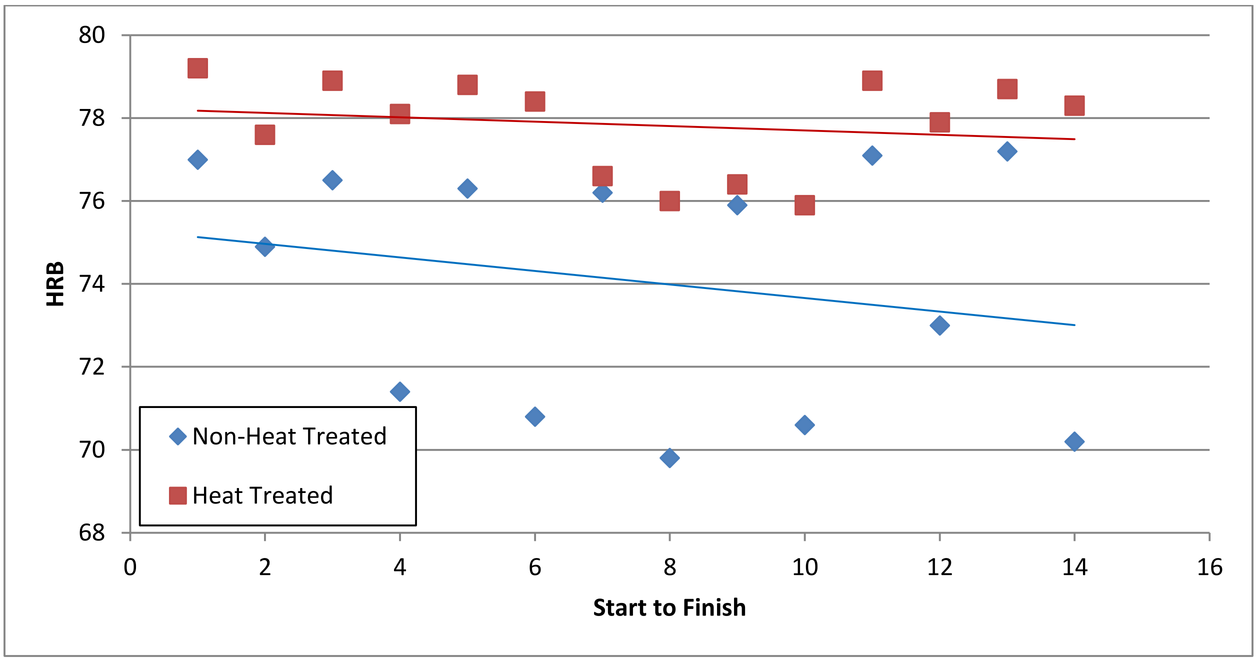

Figure 23: Rockwell Hardness from Weld Start to Finish

Rockwell hardness tests were also performed from the bottom to the top weld on tensile samples 7 and 8, as seen in Figure 21. Figure 24 shows the hardness measurements versus the distance from the bottom weld. The large variation from measurement to measurement could be due to the varying microstructure within each weld; however, a general trend of increasing hardness from the

bottom weld to the top weld can be seen by the trend line plotted on Figure 24. This is expected due to the bottom layers effectively being annealed during each successive lap weld. Figure 24 does not show any major effect of the heat treating process.

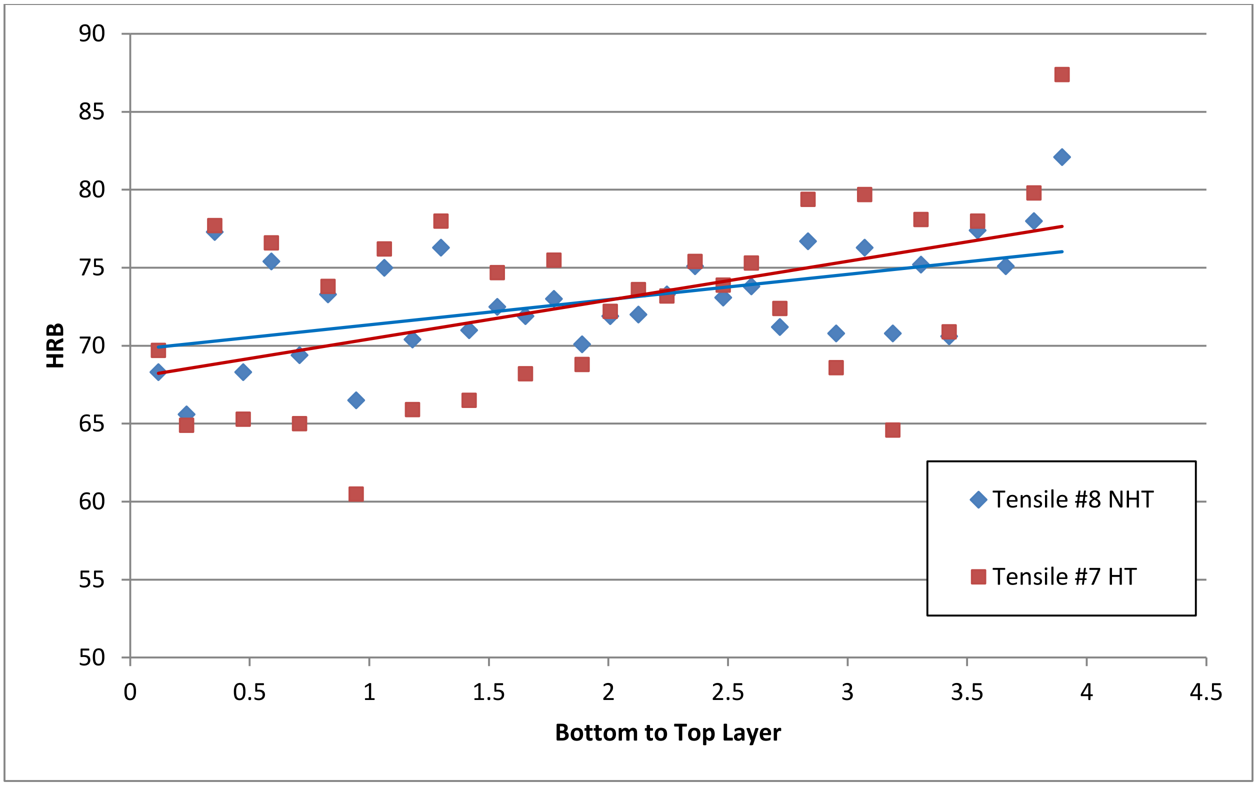

Figure 24: Rockwell Hardness from Bottom Weld to Top Weld

Microstructure

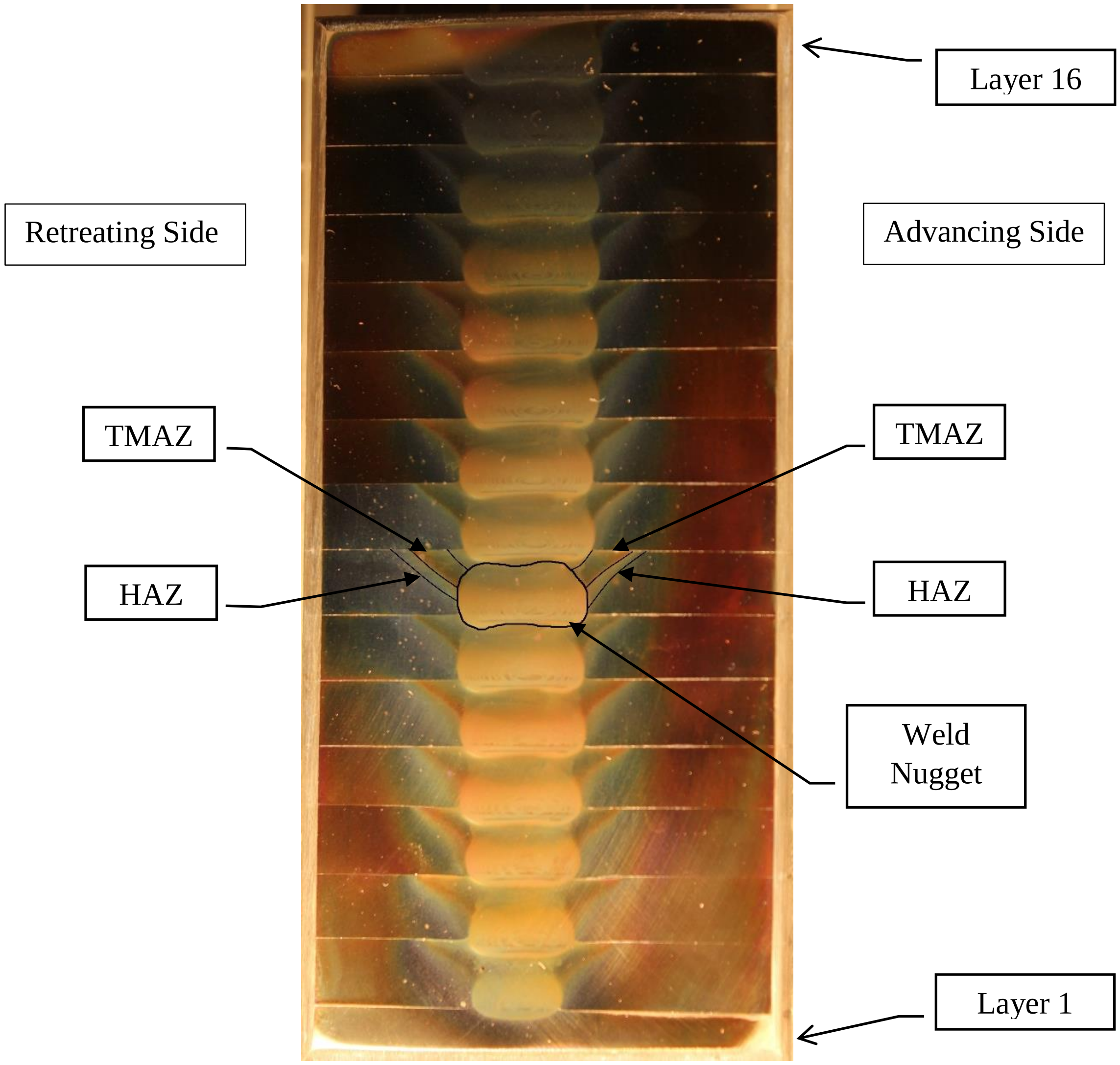

Figure 25: Macrograph from Start of Weld

Figure 25 shows a macrograph of the start of the additive friction stir manufactured stack shown in Figure 8. The heat affected shown, the thermomechanically affected zone, and the weld nugget are labeled, along with the advancing and retreating side of the weld.

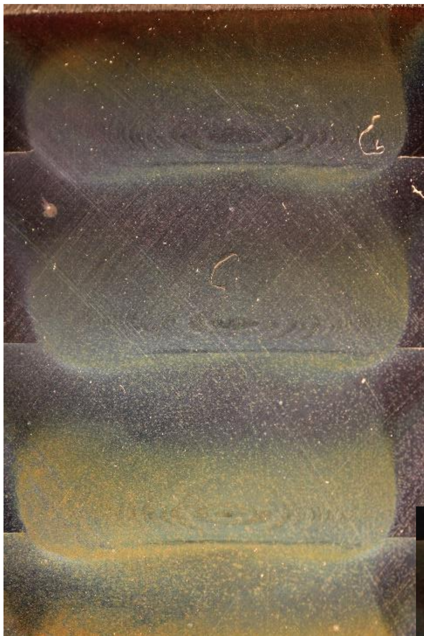

Figure 30: Macrograph Start, Layers 14-16

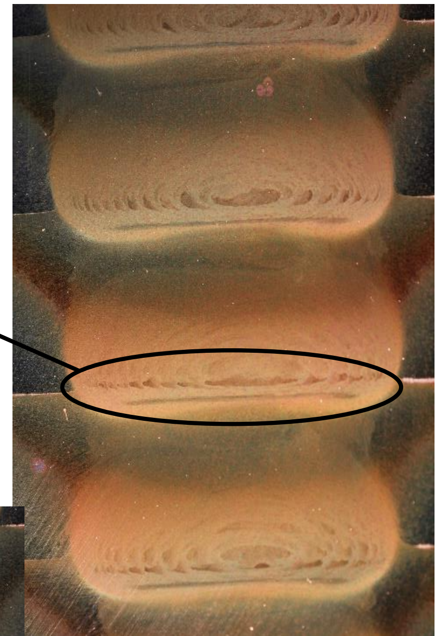

Figure 27: Macrograph Start, Layers 5-7

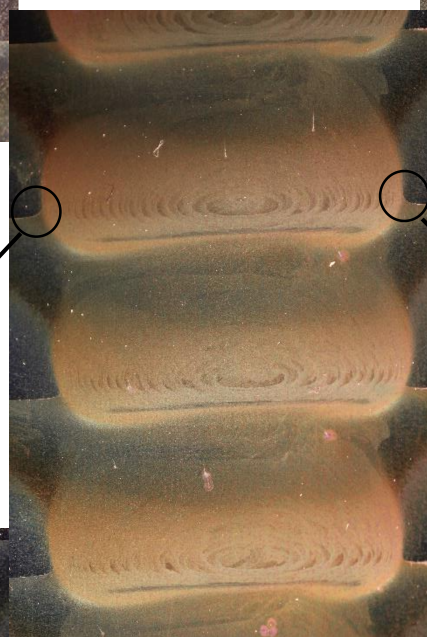

Figure 28: Macrograph Start, Layer 8-10

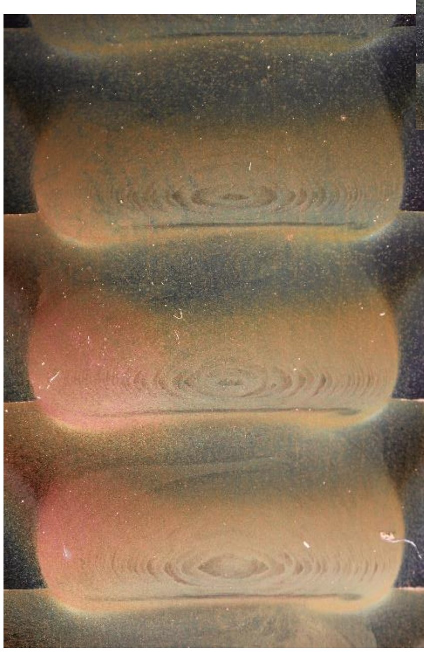

Figure 29: Macrograph Start, Layers 11-13

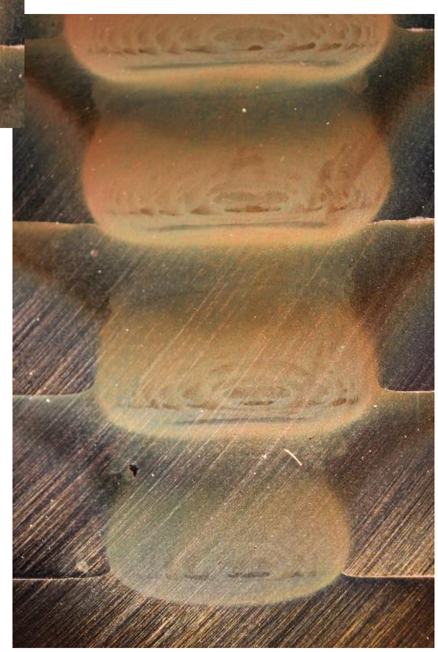

Figure 26: Macrograph Start, Layers 1-4

Figures 26 through 30 show a close up view of each weld. The welds are relatively defect free except for minor cold lapping and small signs of hooking.

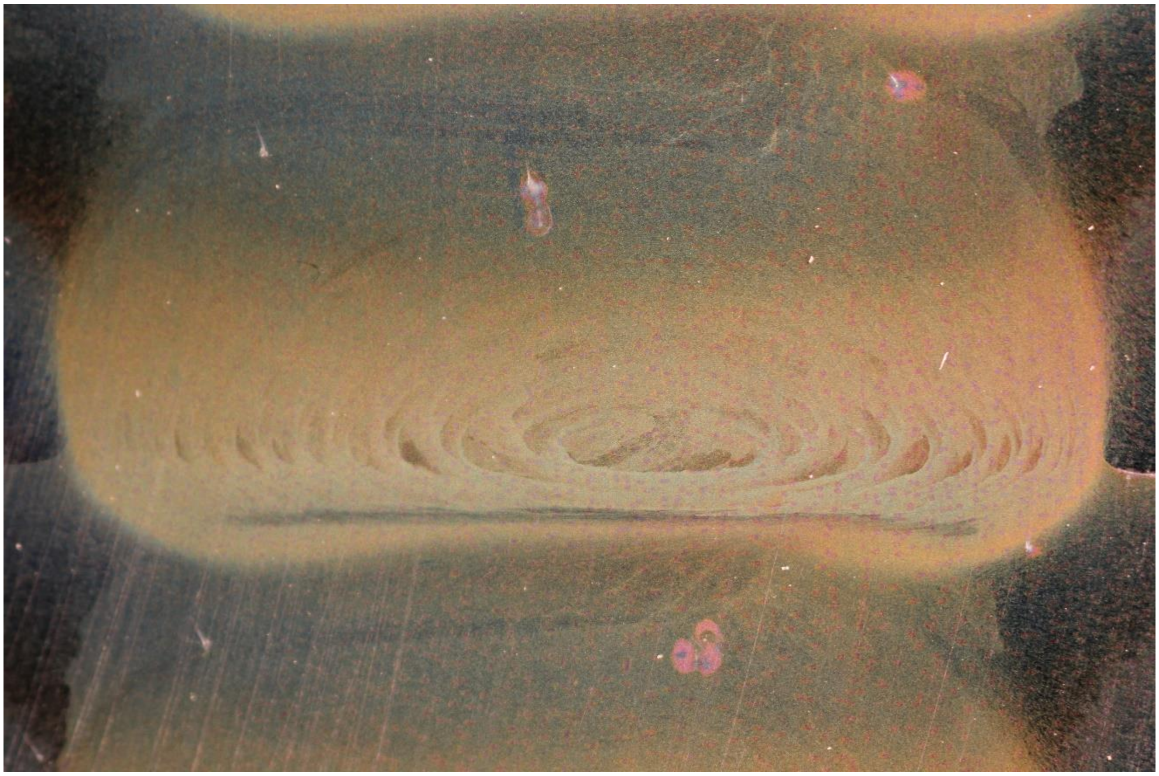

Figure 31: Weld Start Microstructure

As seen in Figures 26 through 30, the parent material has an equiaxed microstructure with a fine grain pattern. This is also the case in the weld nugget which is mostly equiaxed except for a few flow lines as seen in Figure 31.

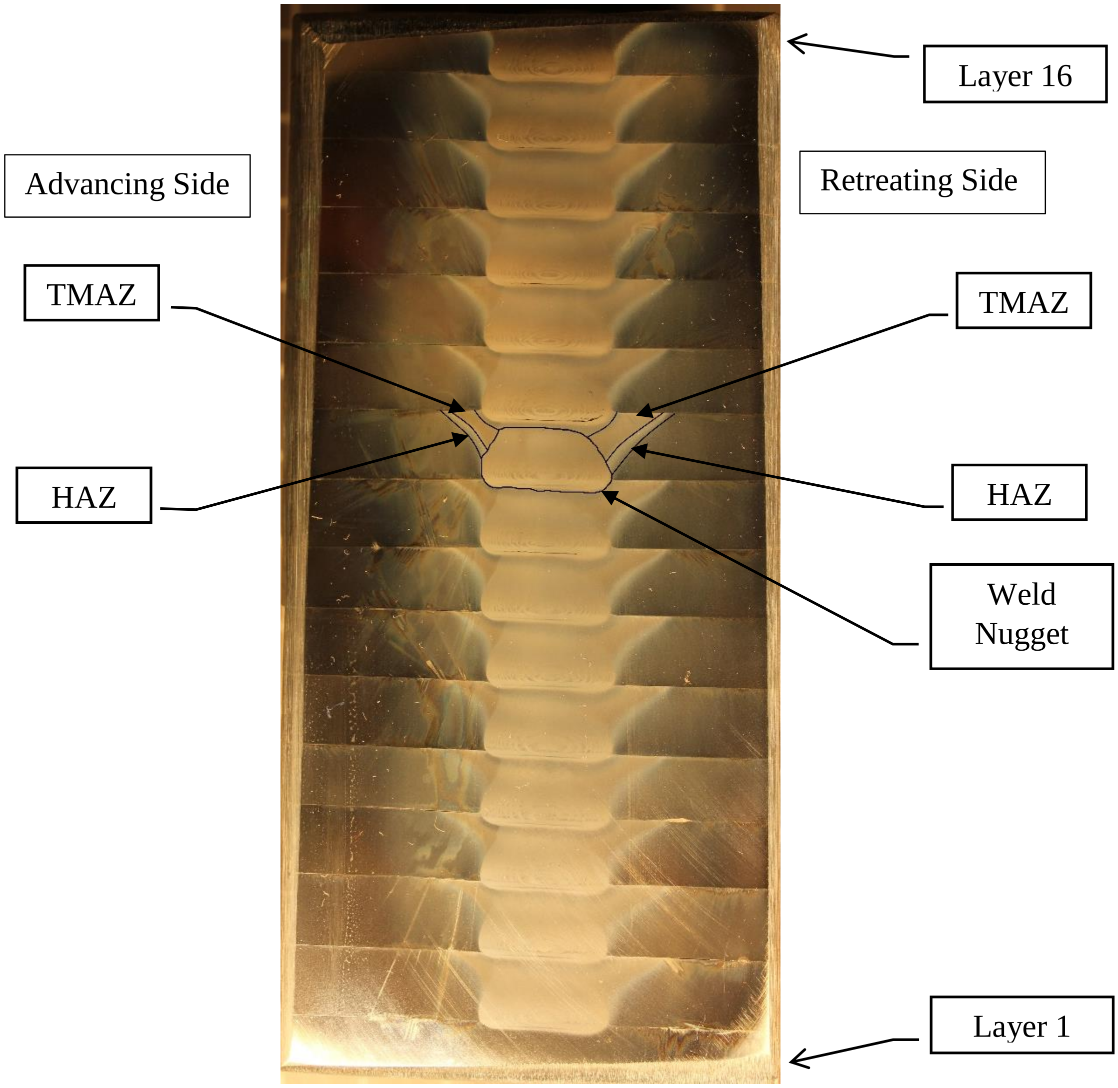

Figure 32: Macrograph from End of Weld

Figure 32 shows a macrograph of the end of the additive friction stir manufactured stack shown in Figure 8. The heat affected shown, the thermomechanically affected zone, and the weld nugget are labeled, along with the advancing and retreating side of the weld.

Figure 37: Macrograph End, Layers 14-16

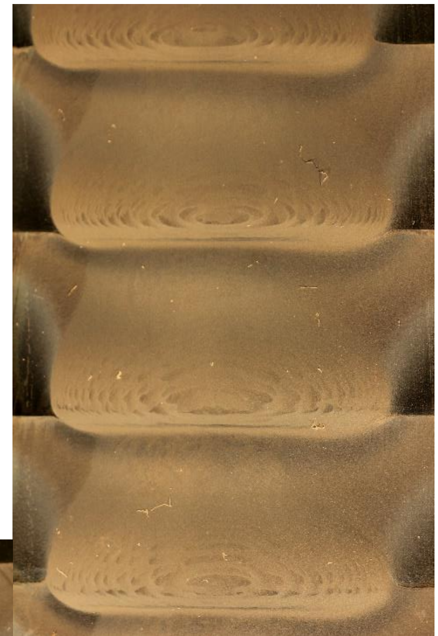

Figure 36: Macrograph End, Layers 5-7

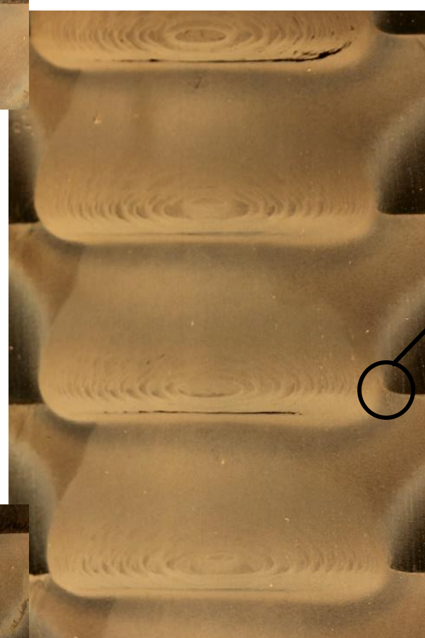

Figure 34: Macrograph End, Layers 8-10

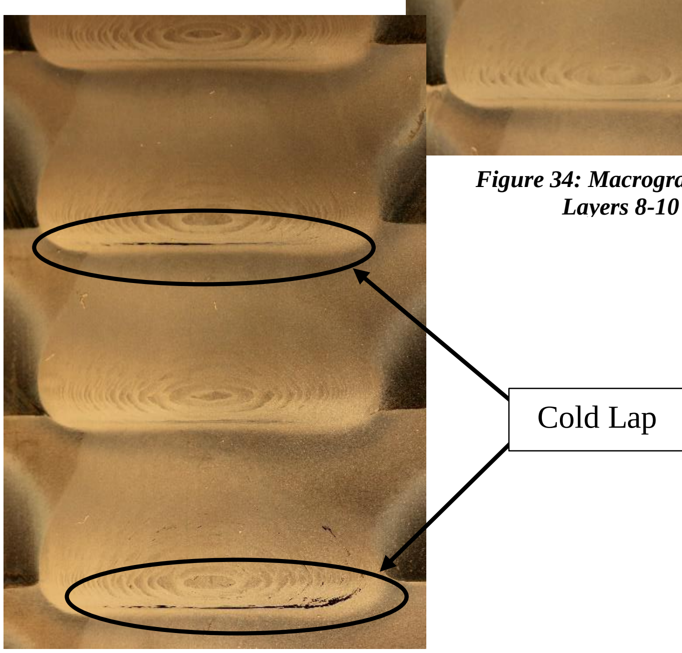

Figure 35: Macrograph End, Layers 11-13

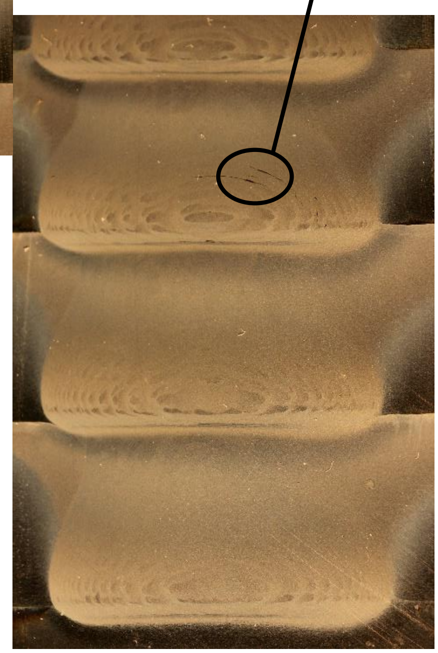

Figure 33: Macrograph End, Layers 1-4

As seen by Figures 32 through 36, near the end of the additive friction stir manufactured stack the microstructure as consists of fine equiaxed grains with only flow lines in the nugget of the welds. The end of the welds still contain very minimal hook; however, major cold lapping and worm holes developed, shown in Figure 33 and 36.

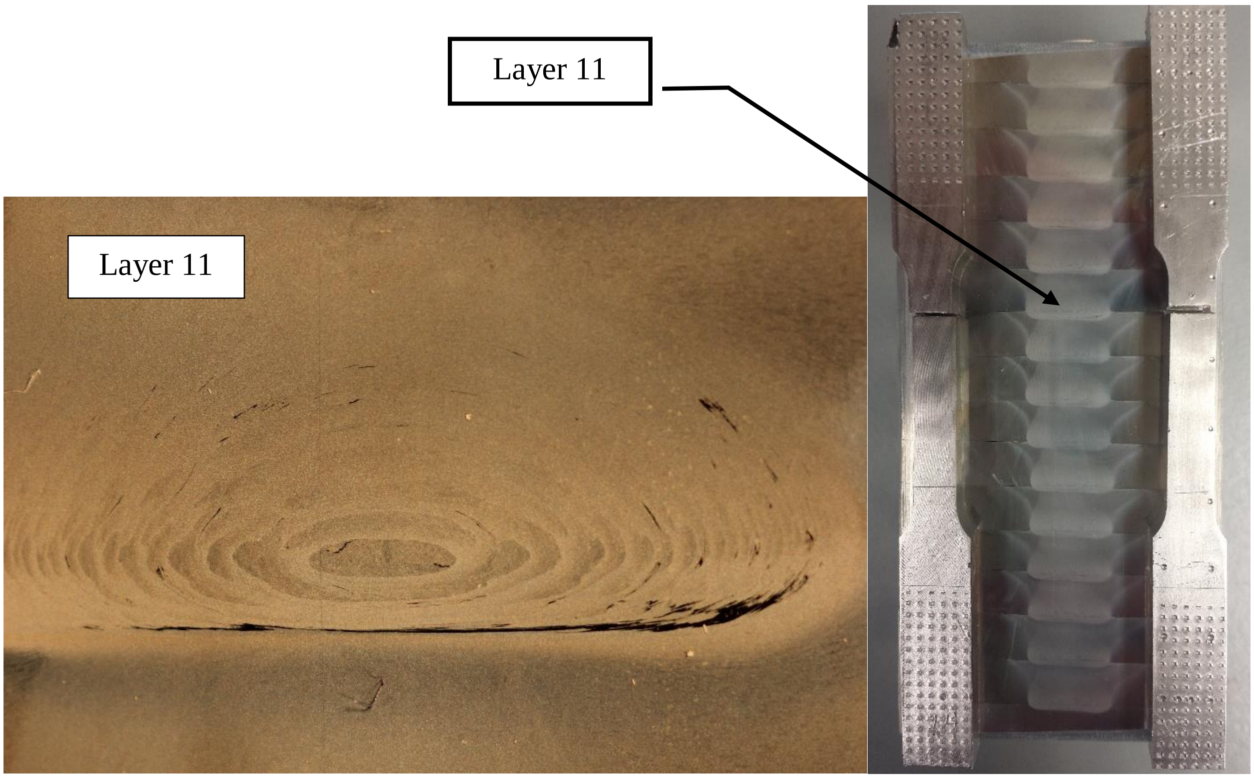

Figure 38: End Weld Major Cold Lapping in Layer 11

The macrographs show that near the end of the welds cold lapping developed between the two plates being joined. The left picture in Figure 38 shows a detailed view of the cold lapping in layer 11. The right picture shows layer 11 in relation to where the last four tensile samples broke, which was at that layer. This shows that the cold lapping caused a weak spot near the end of the weld. This could have led to the low ultimate tensile strength and percent elongation, shown in Table 2, for tensile samples 13 and 14.

Conclusion

In conclusion, the additively friction stir manufactured material experienced a significant reduction in strength of about 60 percent as shown in Table 2. The heat treating process did not show any significant effect on the material properties of the additively manufactured 7055 aluminum alloy. Only a slight increase in percent elongation was seen but not enough to justify the heat treatment process. As seen by the macrographs of the welds, the large reduction in mechanical properties could be due to cold lapping and worm holes in the weld. This could be caused by an insufficient weld schedule. The defects in the welds could have also caused the heat treatment to be non-effective. Worm holes and cold lapping would prevent the tensile samples from elongating before failure. This would make the effect of the heat treatment hard to distinguish. Although the welds contained many defects, the grain structure within the weld was acceptable and consisted of fine equiaxed grains.

To improve the mechanical properties of the additively manufactured material, many different modifications could be made. The major change in the process would be the weld parameters. Defects such as worm holes and cold lapping can generally be avoided with an appropriate weld schedule. To avoid creating worm holes and cold lapping, the forge force and spindle speed could be increased. This would apply more pressure to the weld to possible fill in any worm holes. An increase in spindle speed would break up the material interface more effectively, possible avoiding any cold lapping from developing. To improve the effect of the heat treatment process, a different heat treatment schedule could be used. Possibly a higher heat treatment temperature could be used with some type of moderate quenching rate. This may harden the microstructure and create stronger material properties.

In all, the additive manufacturing process described by this report shows promising results that could be further improved with small process modifications. This process could be an effective tool in an industrial applications to save time and production costs. With further research and development on this topic, additive friction stir manufacturing could be put into application.

Appendix

Appendix

Stress-Strain Curves

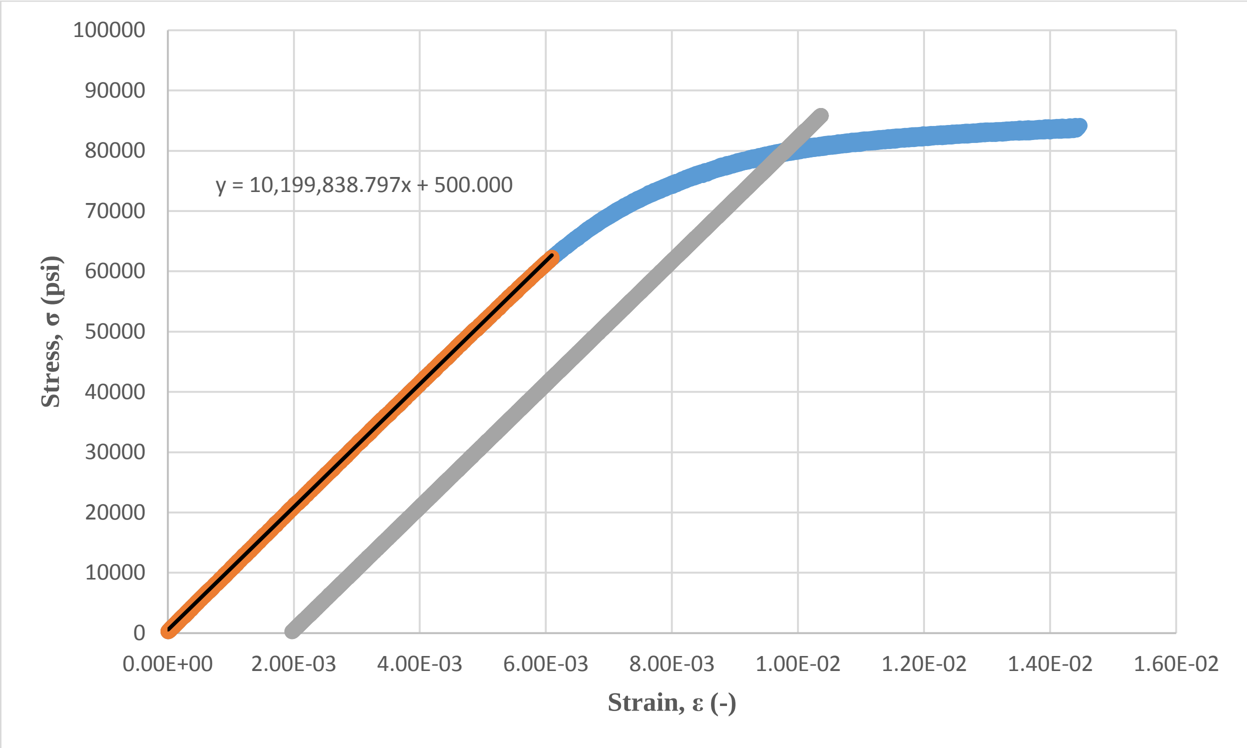

Figure 39: Stress Strain Curve, Base Material Tensile 1

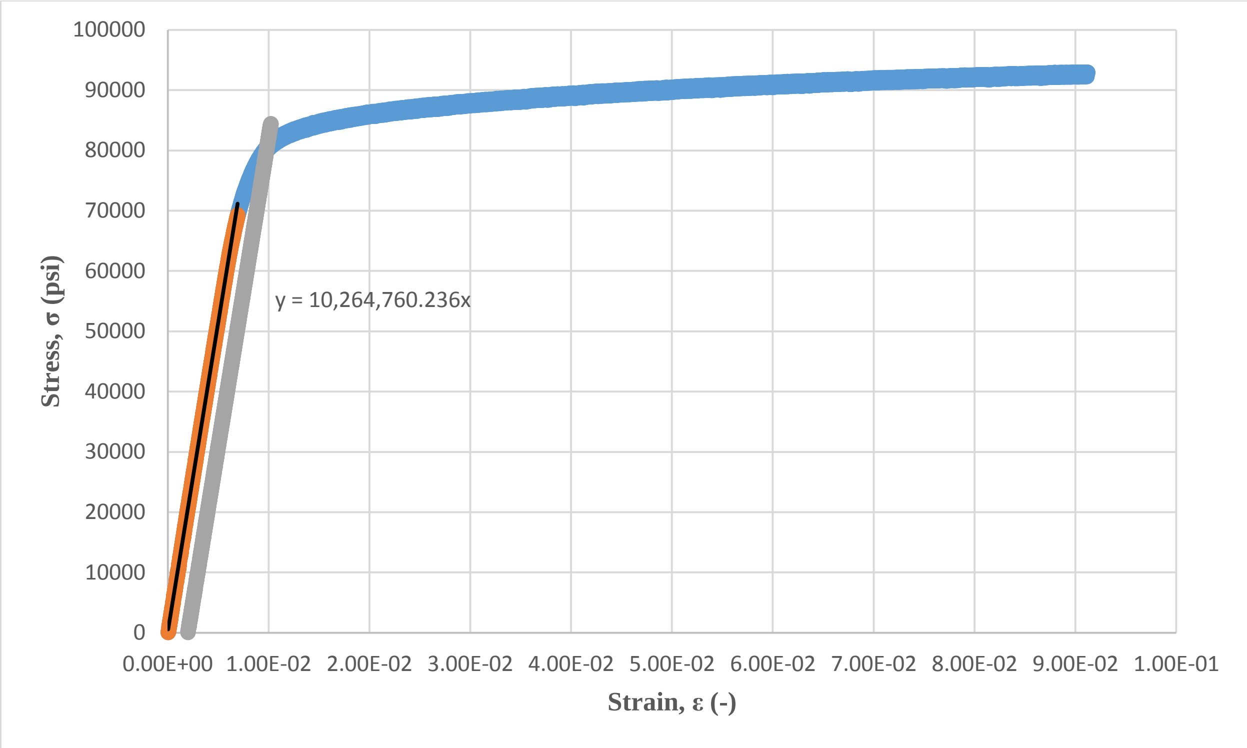

Figure 40: Stress Strain Curve, Base Material Tensile 2

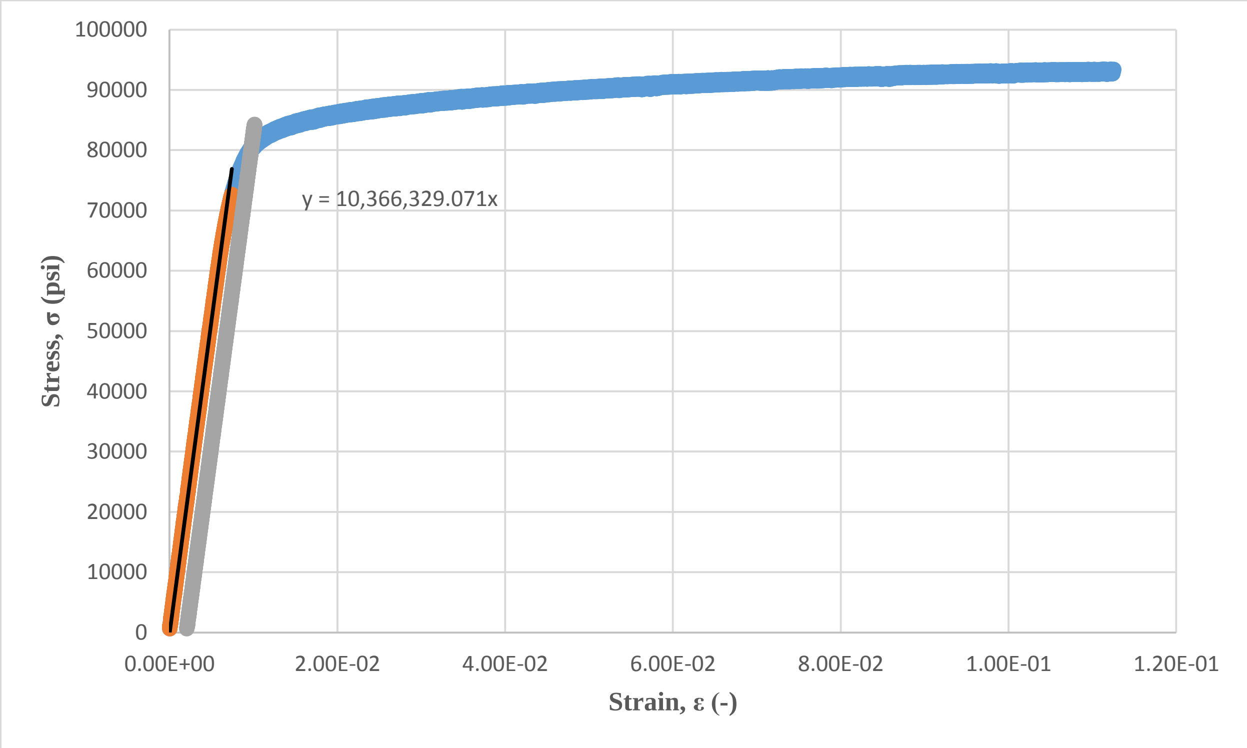

Figure 41: Stress Strain Curve, Base Material Tensile 3

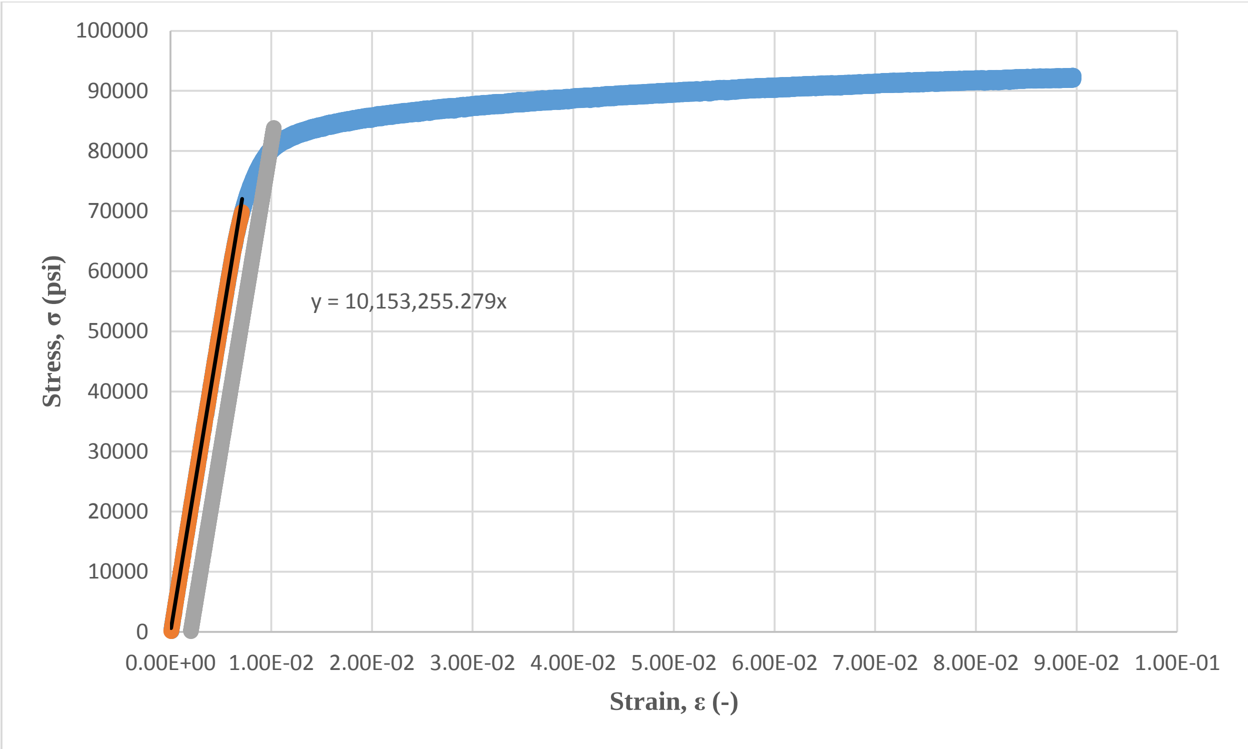

Figure 42: Stress Strain Curve, Base Material Tensile 4

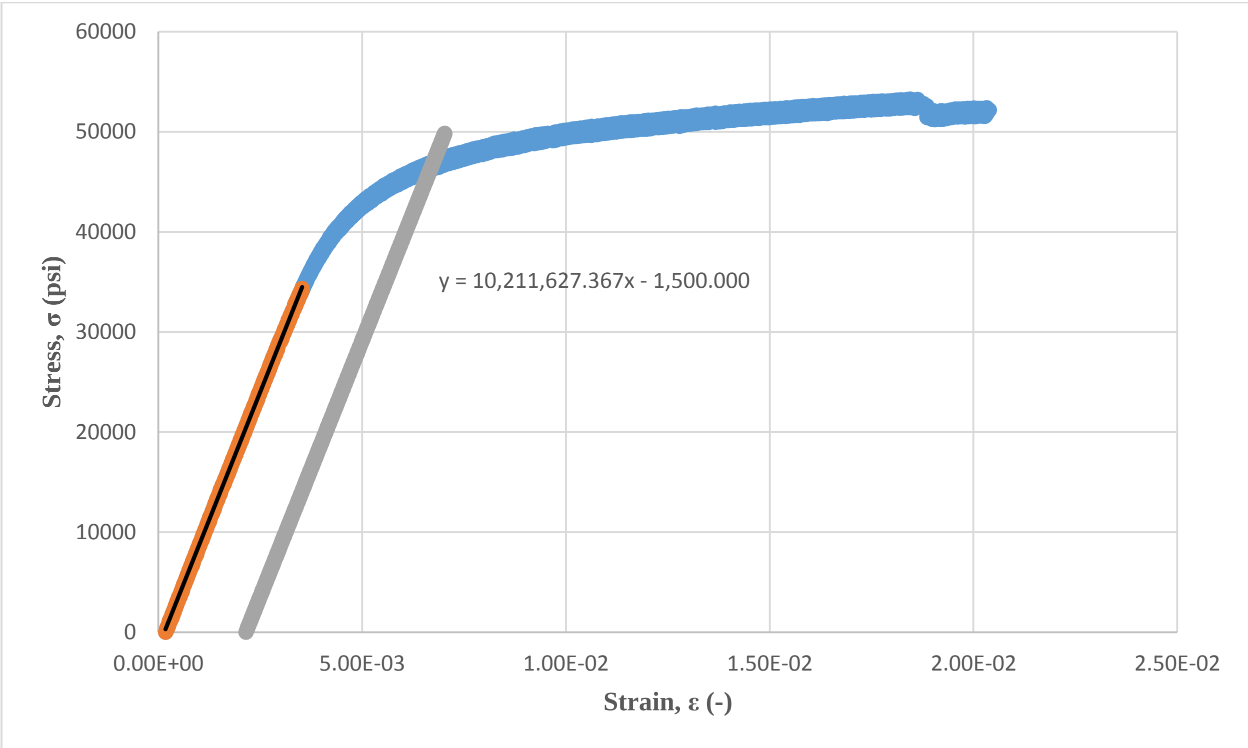

Figure 43: Stress Strain Curve, Weld Tensile 1

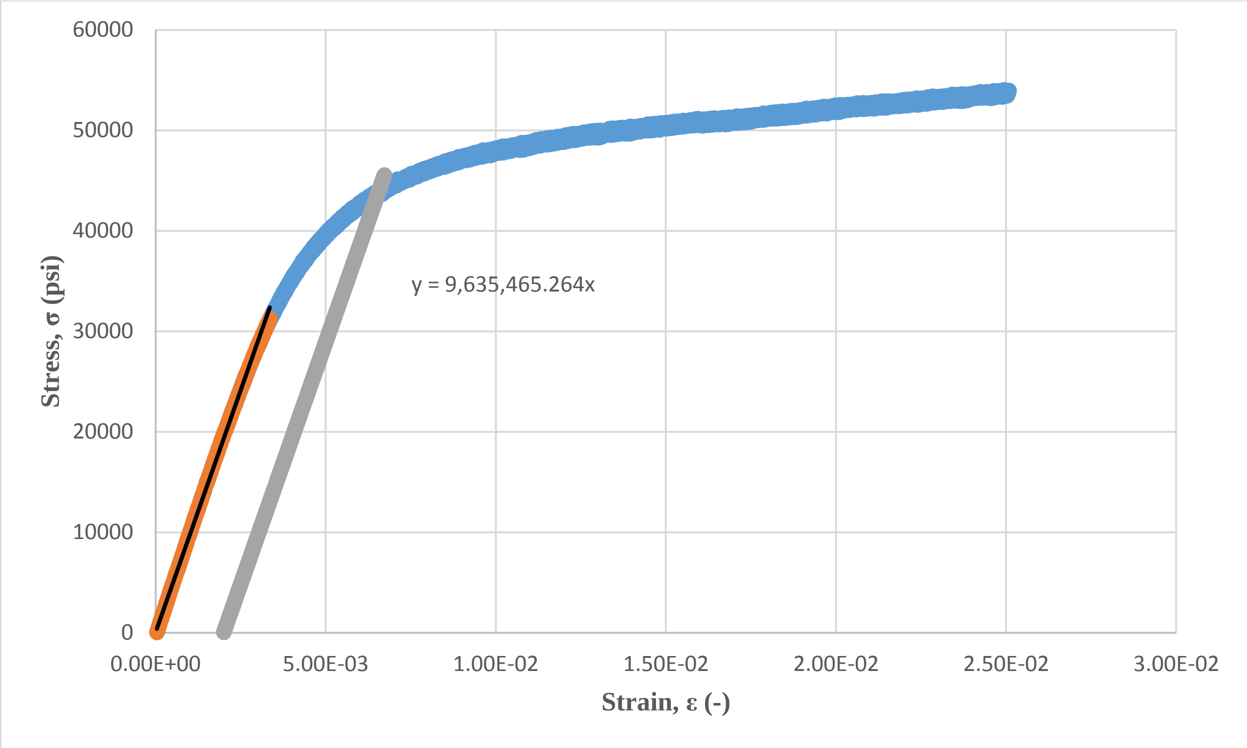

Figure 44: Stress Strain Curve, Weld Tensile 2

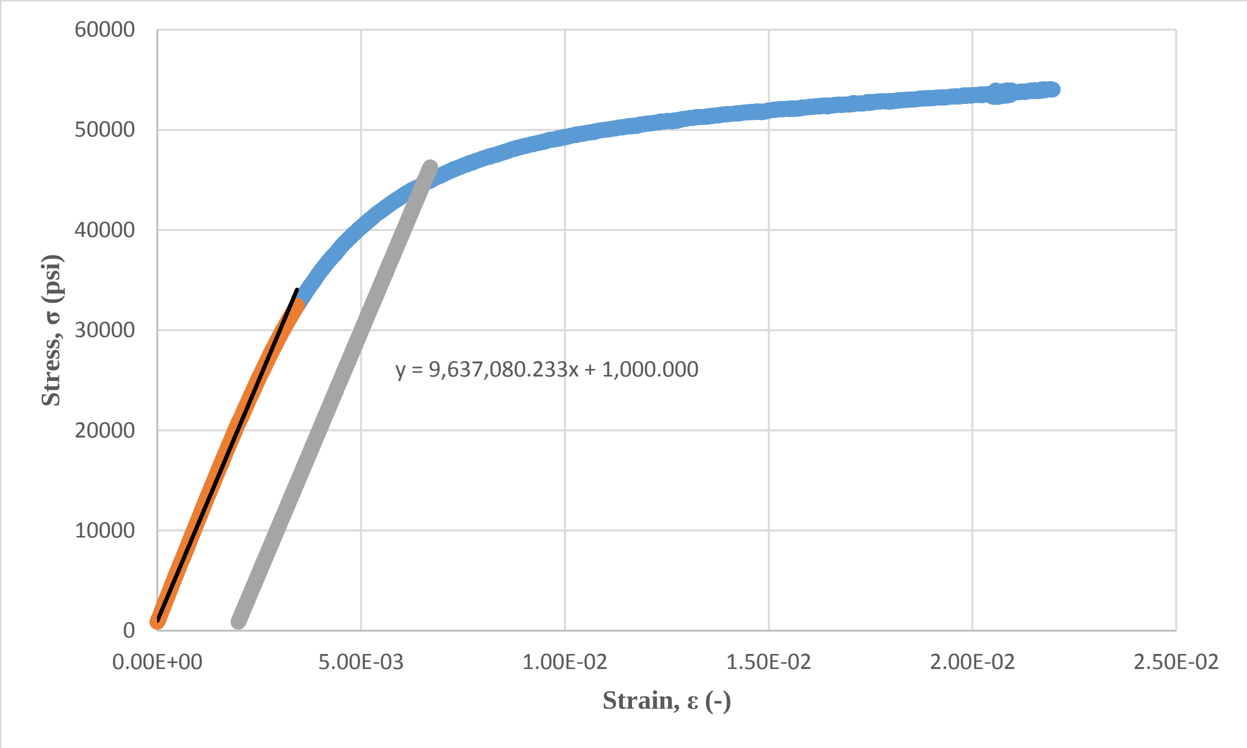

Figure 45: Stress Strain Curve, Weld Tensile 3

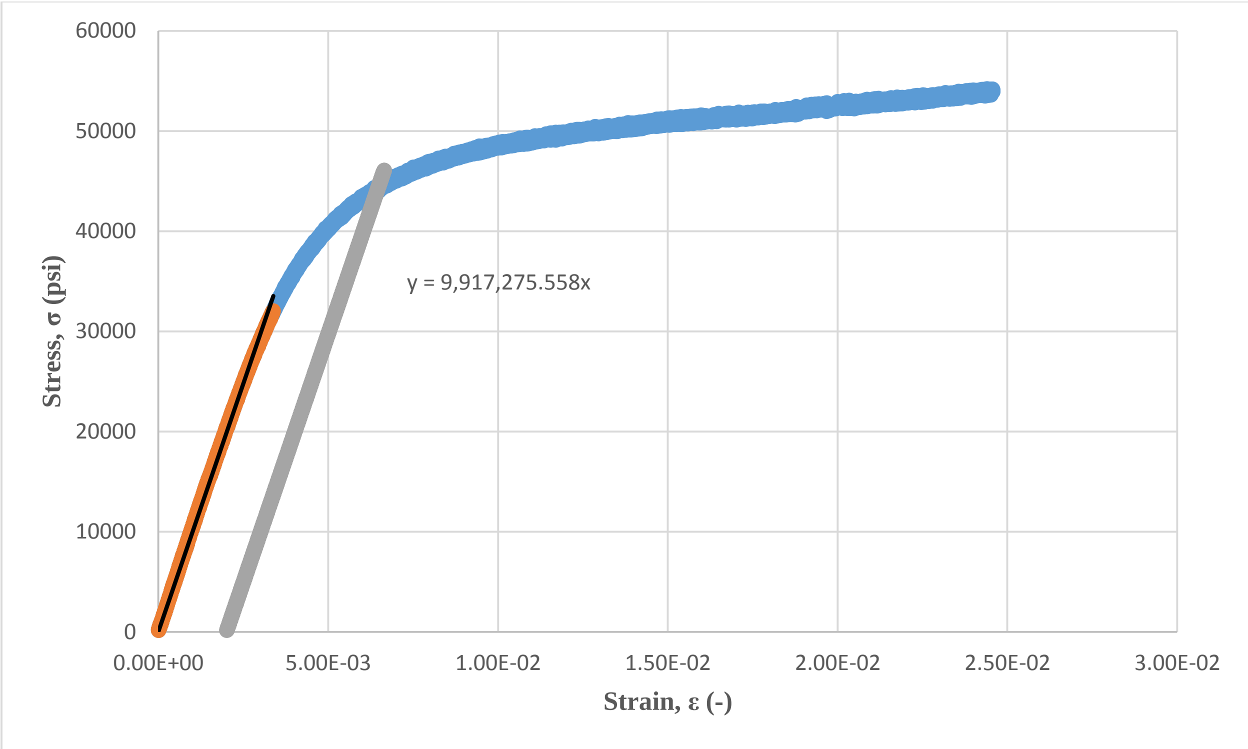

Figure 46: Stress Strain Curve, Weld Tensile 4

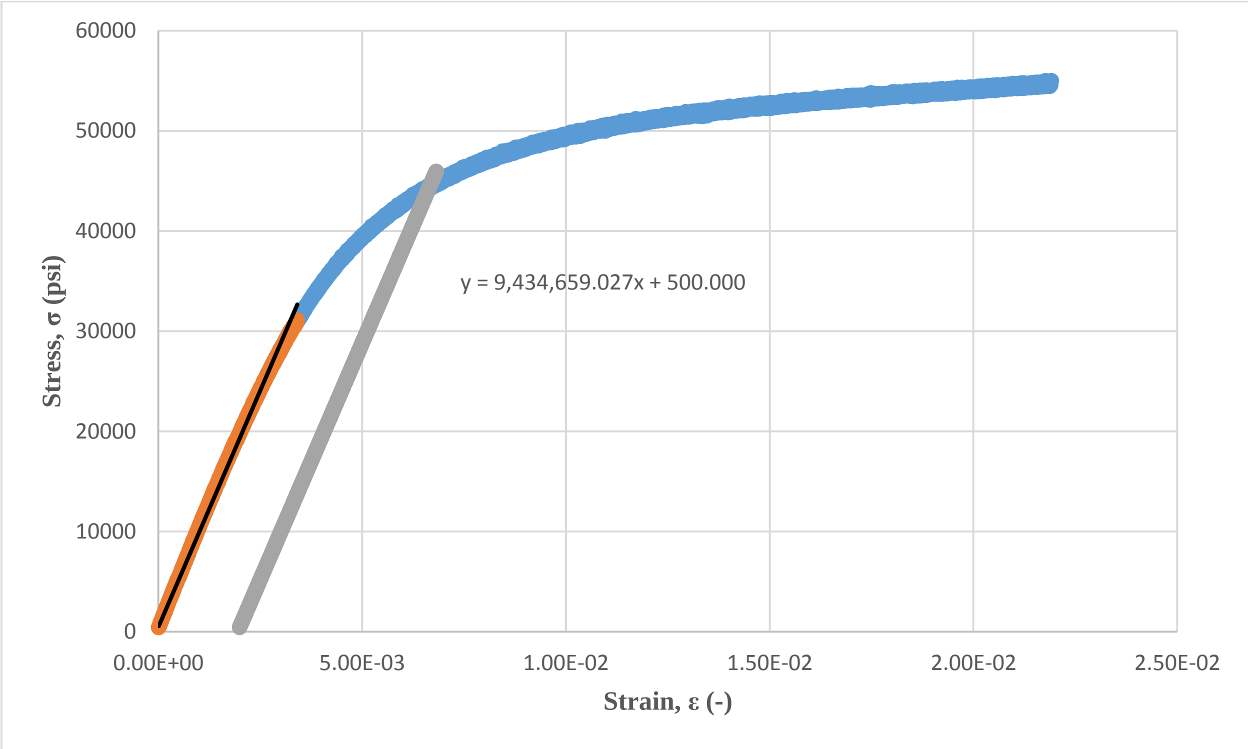

Figure 47: Stress Strain Curve, Weld Tensile 5

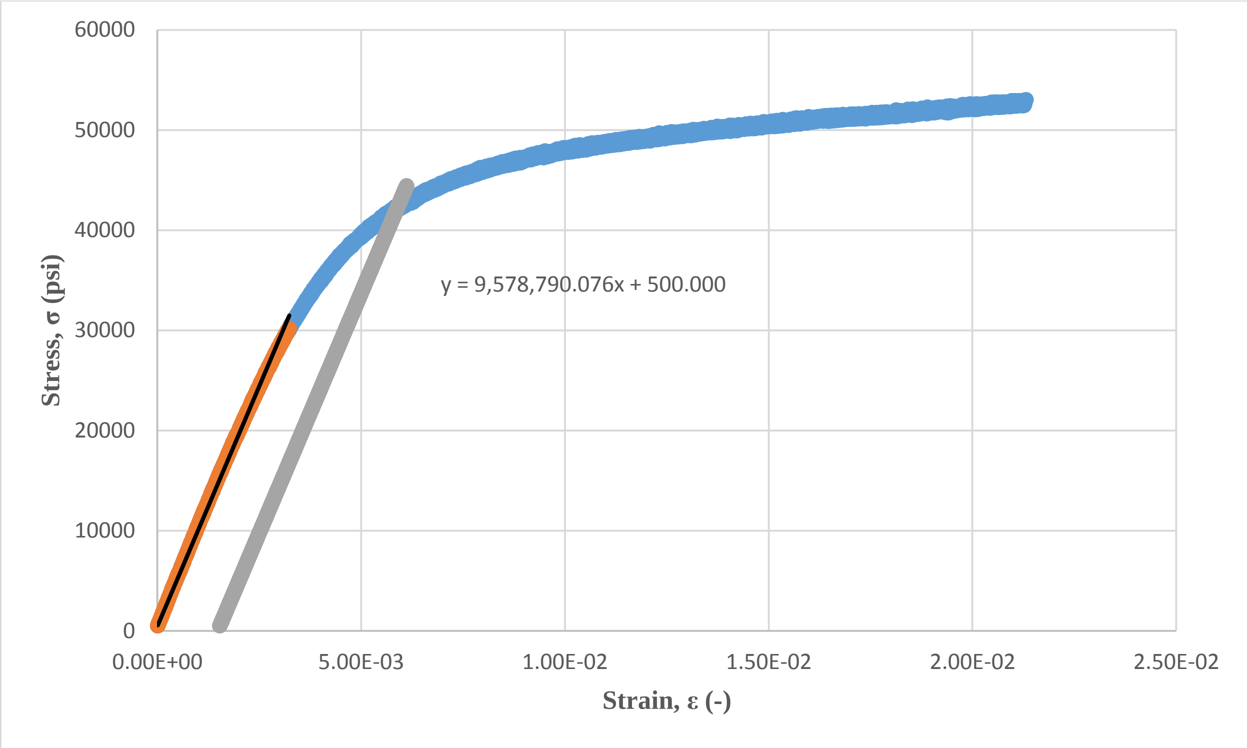

Figure 48: Stress Strain Curve, Weld Tensile 6

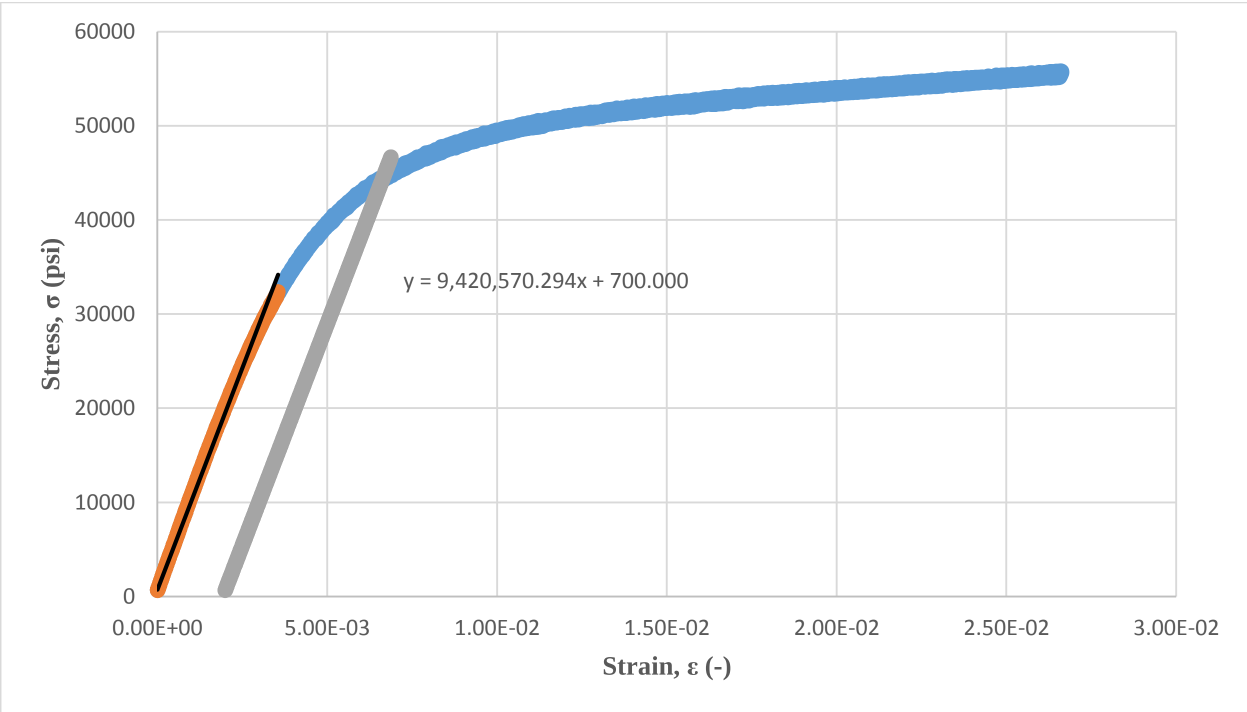

Figure 49: Stress Strain Curve, Weld Tensile 7

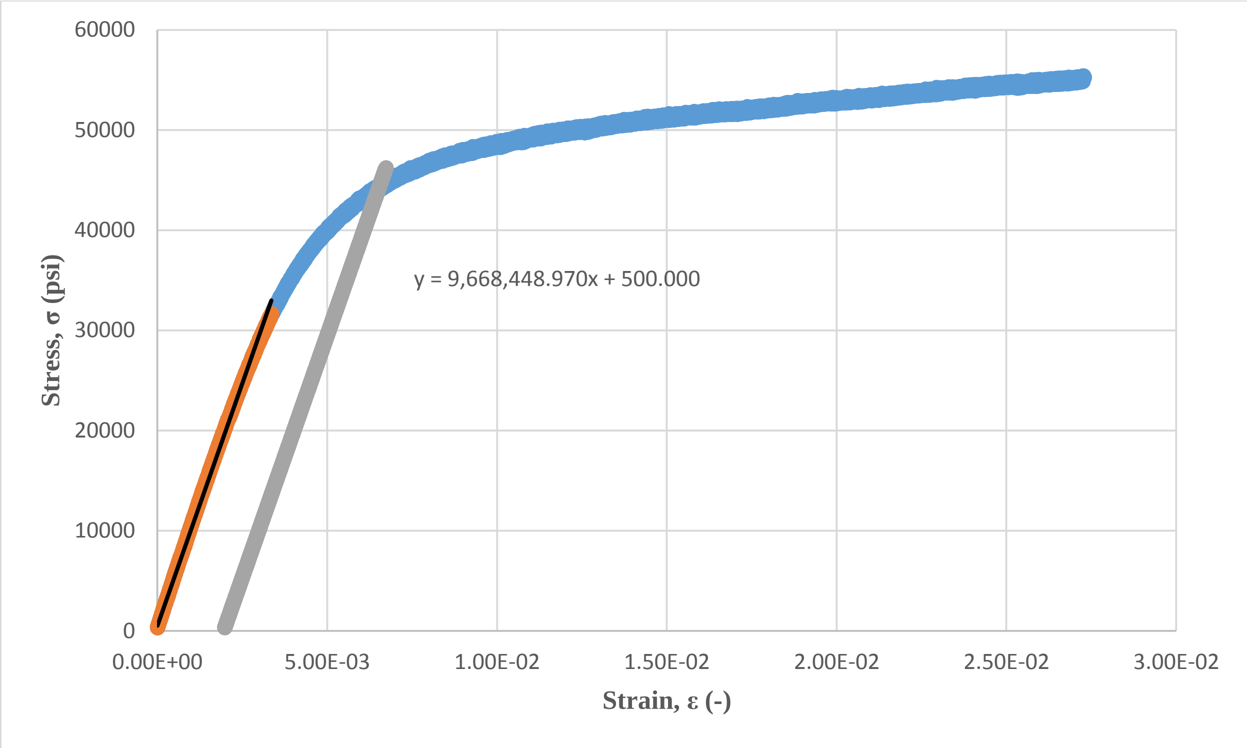

Figure 50: Stress Strain Curve, Weld Tensile 8

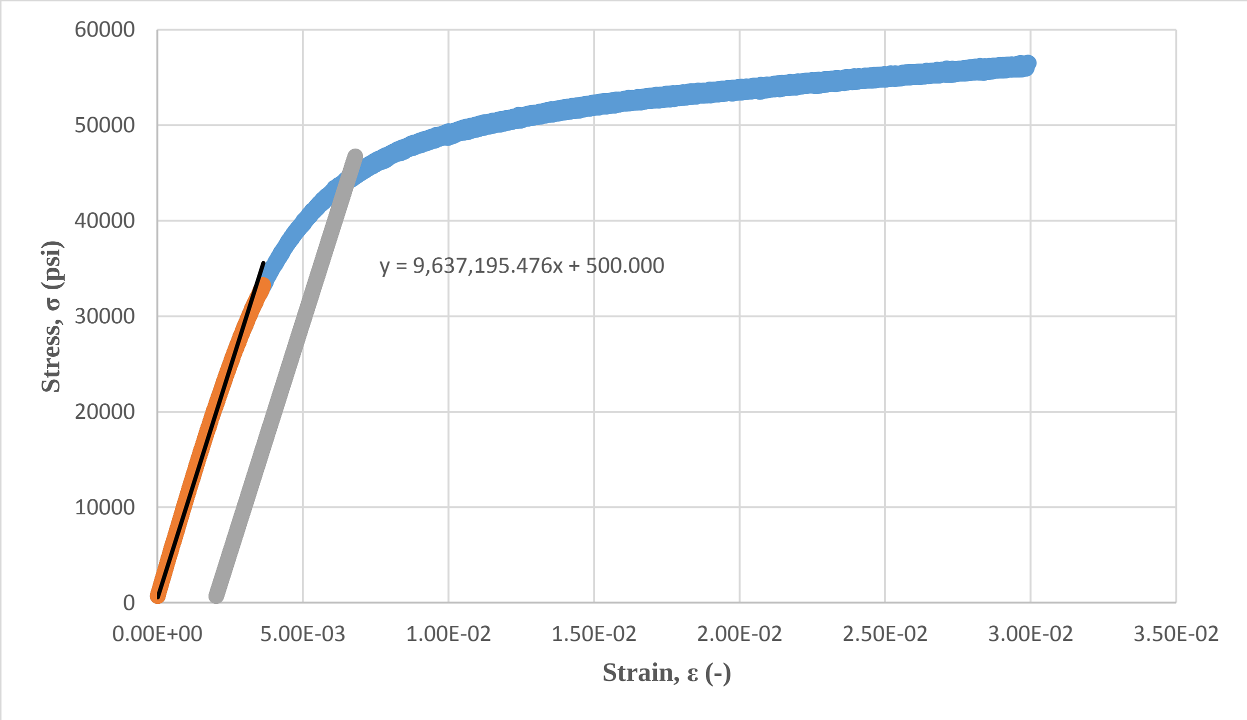

Figure 51: Stress Strain Curve, Weld Tensile 9

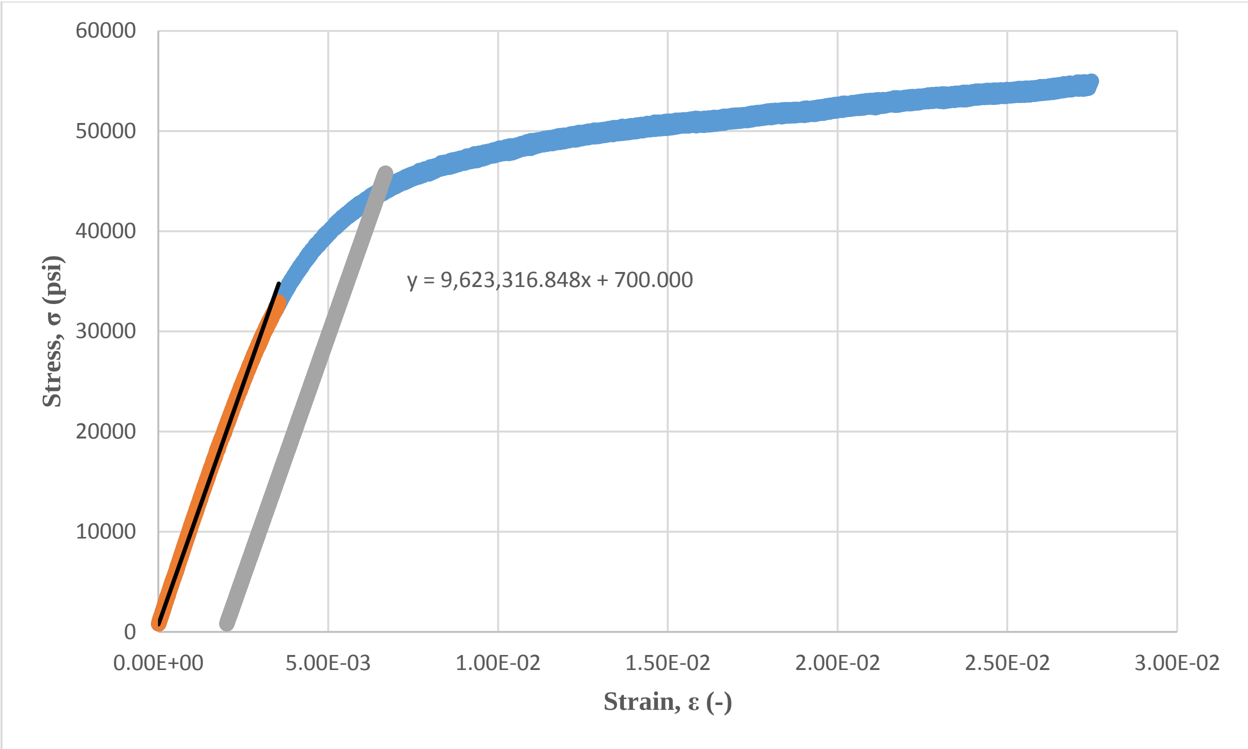

Figure 52: Stress Strain Curve, Weld Tensile 10

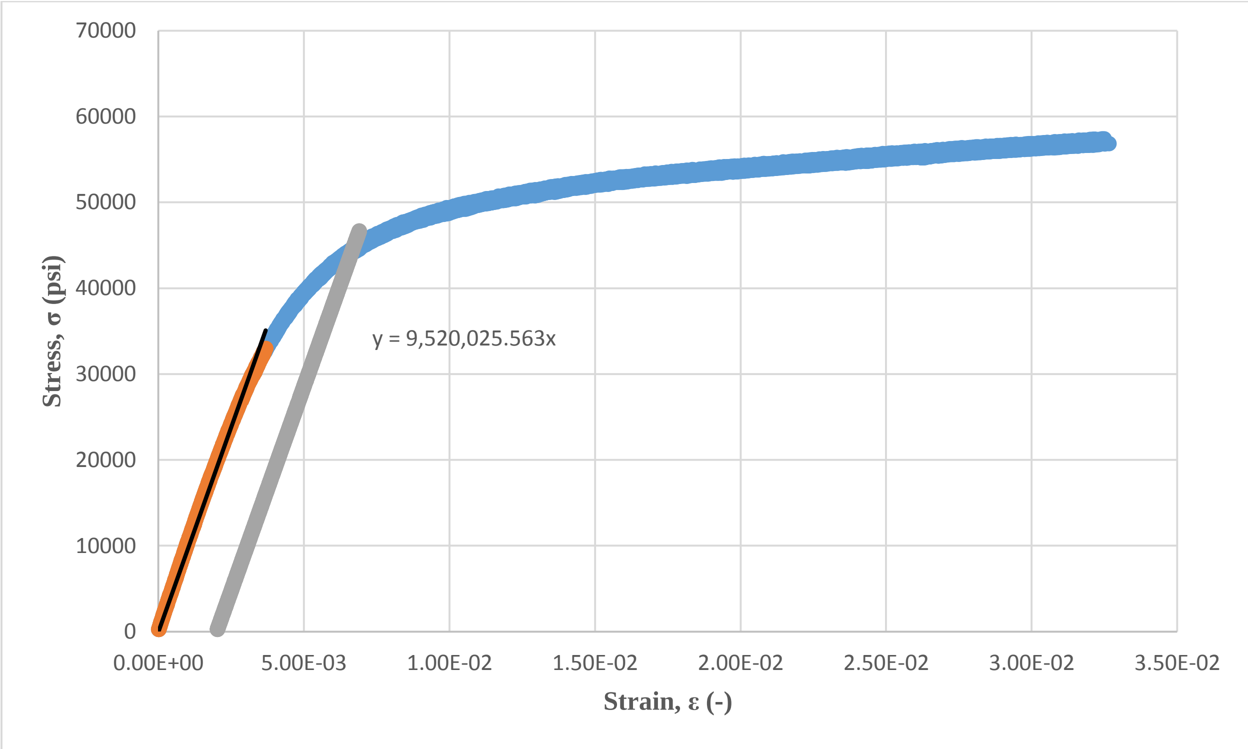

Figure 53: Stress Strain Curve, Weld Tensile 11

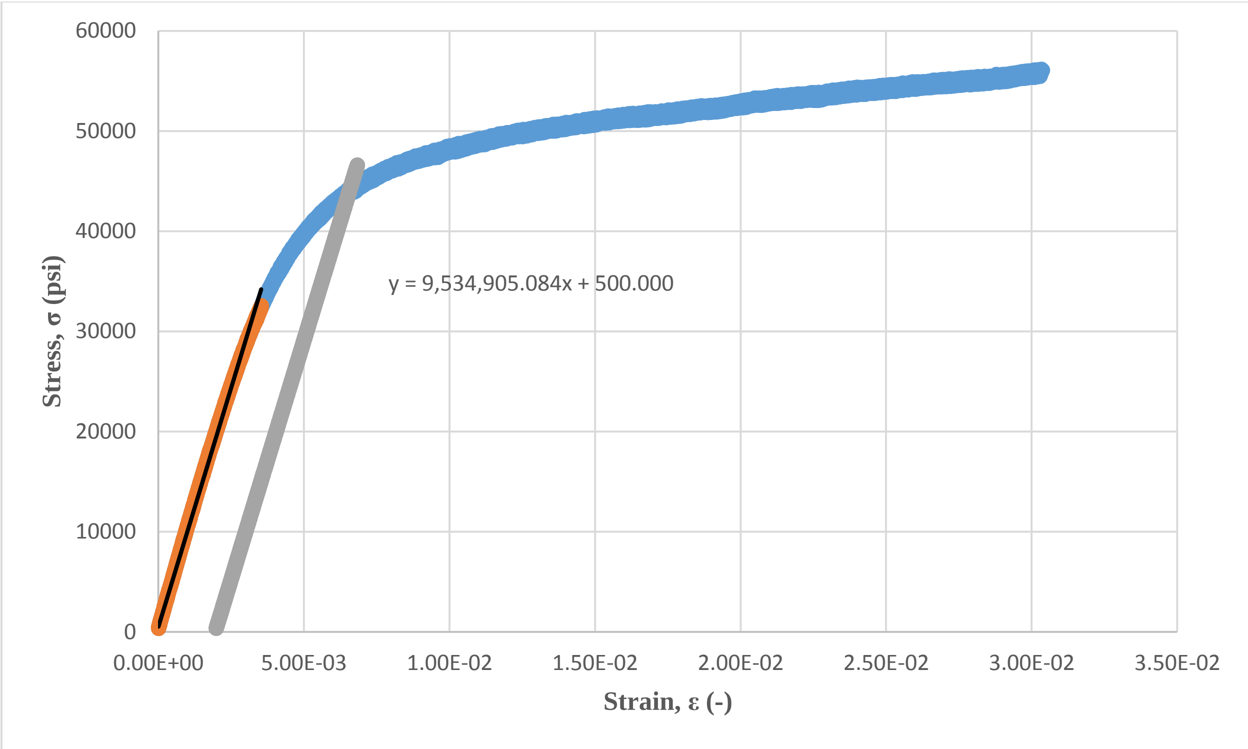

Figure 54: Stress Strain Curve, Weld Tensile 12

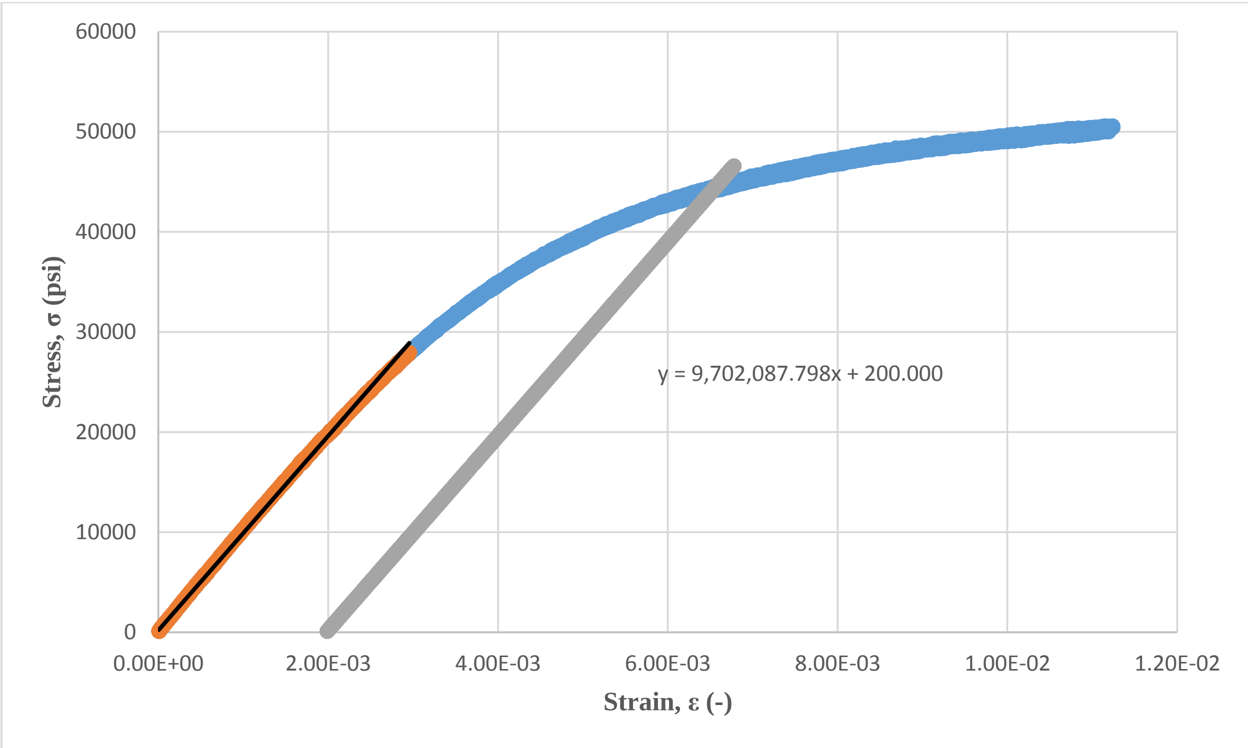

Figure 55: Stress Strain Curve, Weld Tensile 13

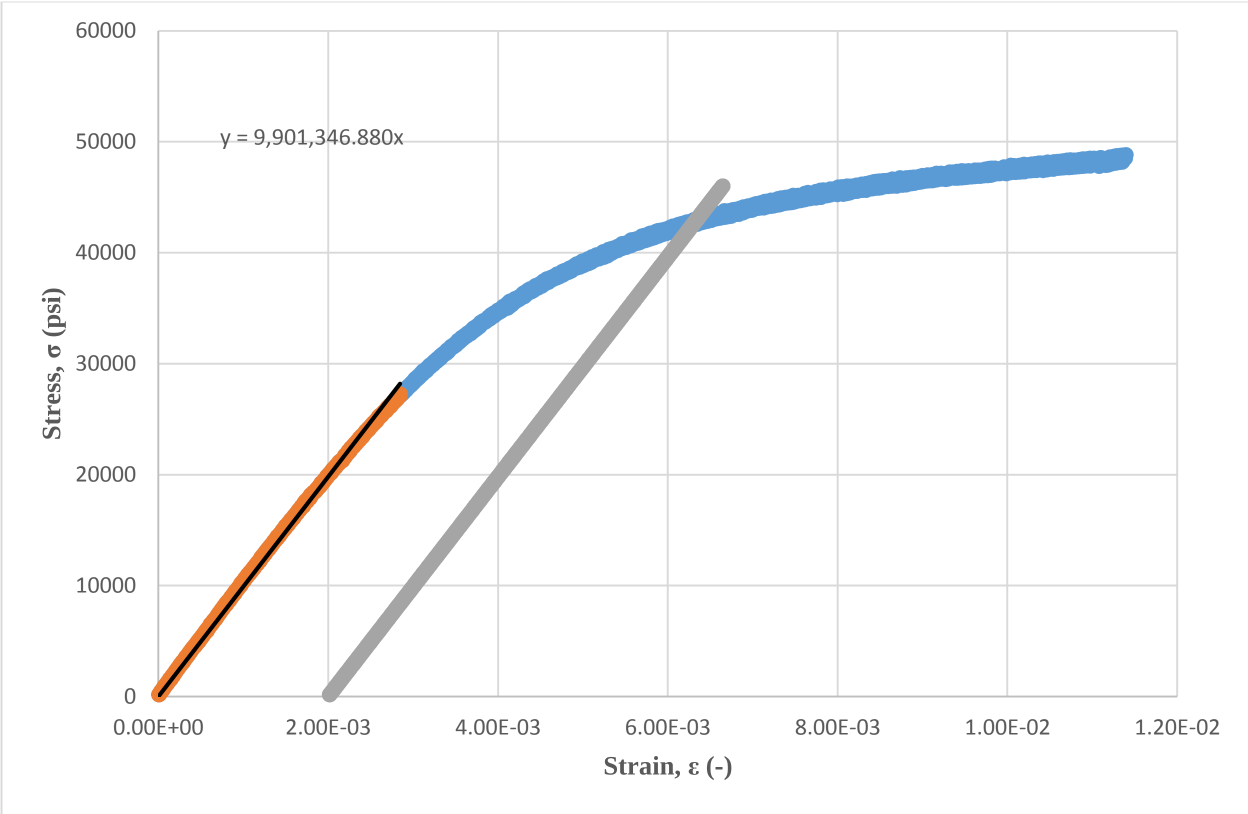

Figure 56: Stress Strain Curve, Weld Tensile 14

Pin Tool Reaction Forces

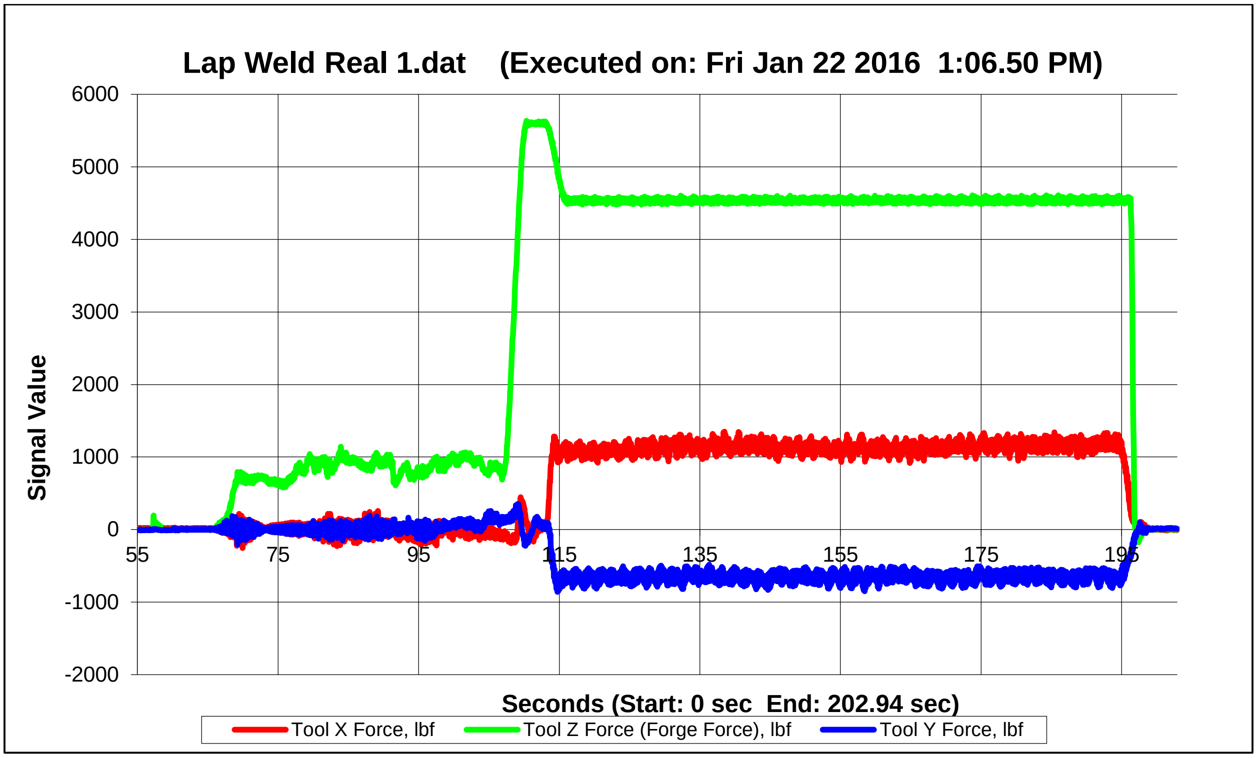

Figure 57: Pin Tool Reaction Forces, Weld Layer 1

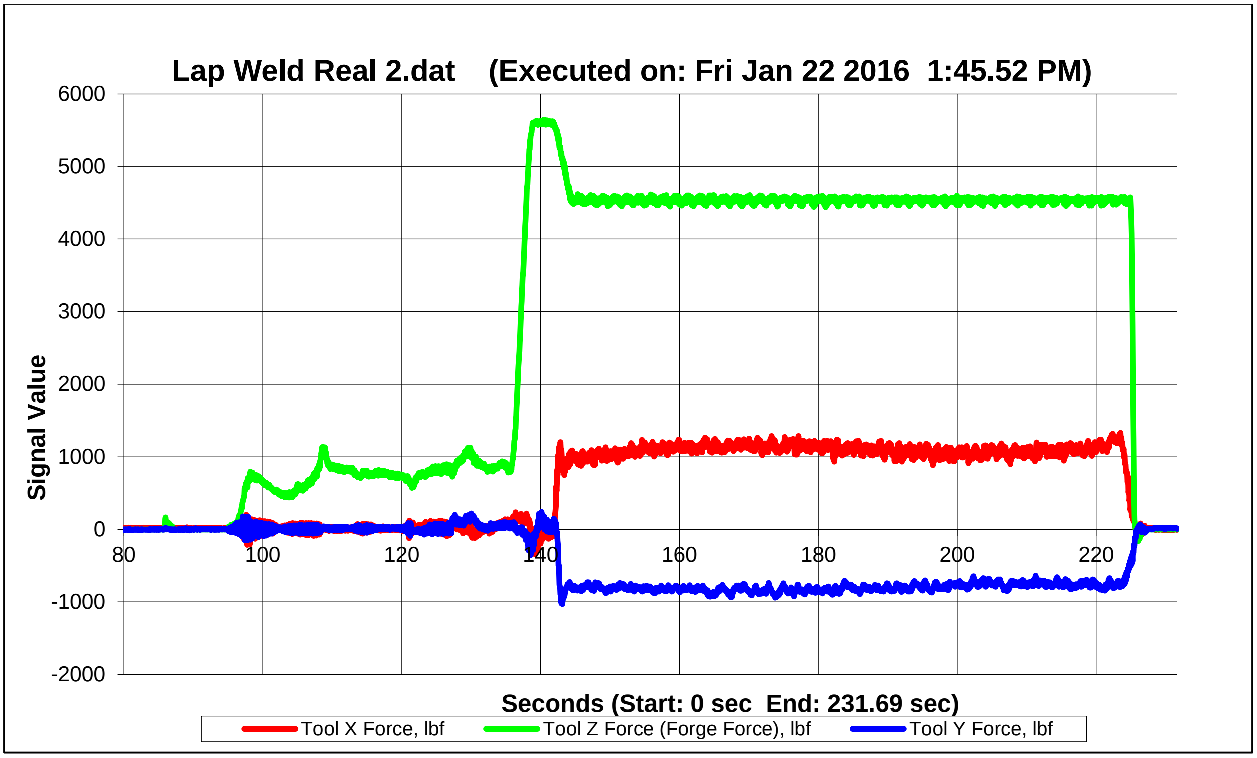

Figure 58: Pin Tool Reaction Forces, Weld Layer 2

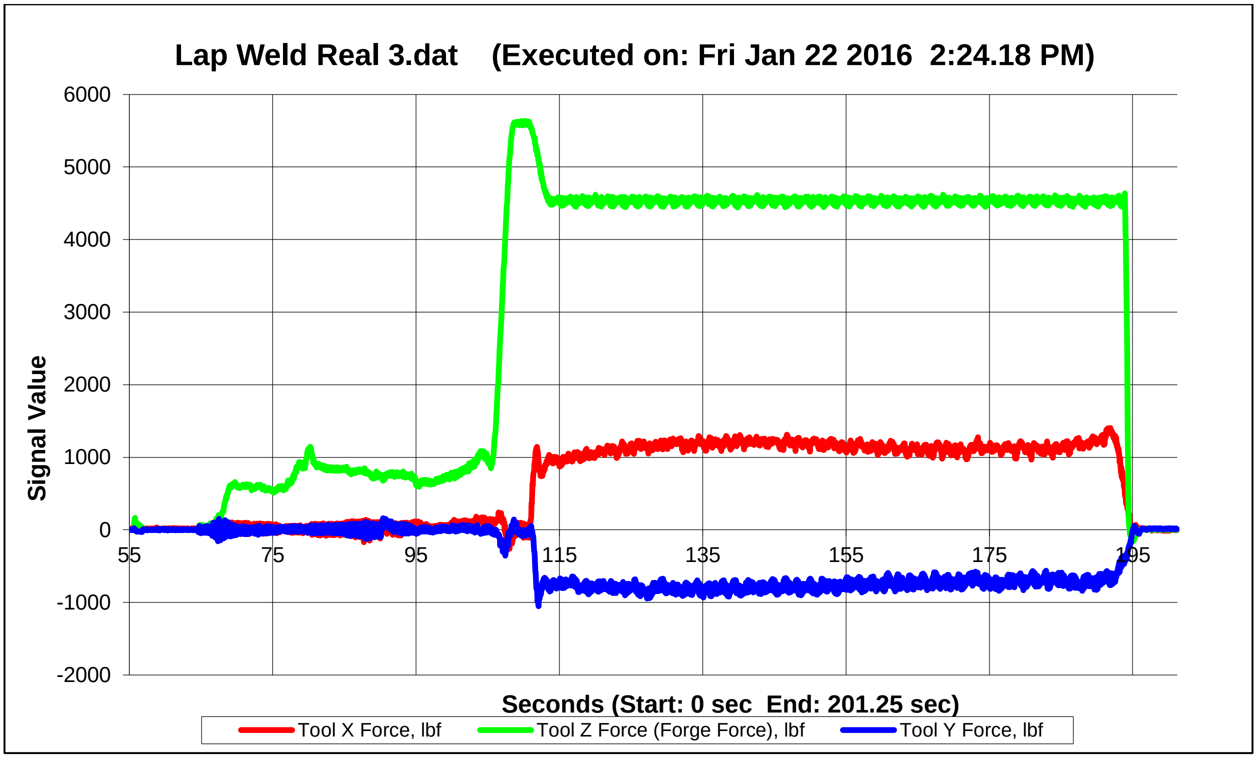

Figure 59: Pin Tool Reaction Forces, Weld Layer 3

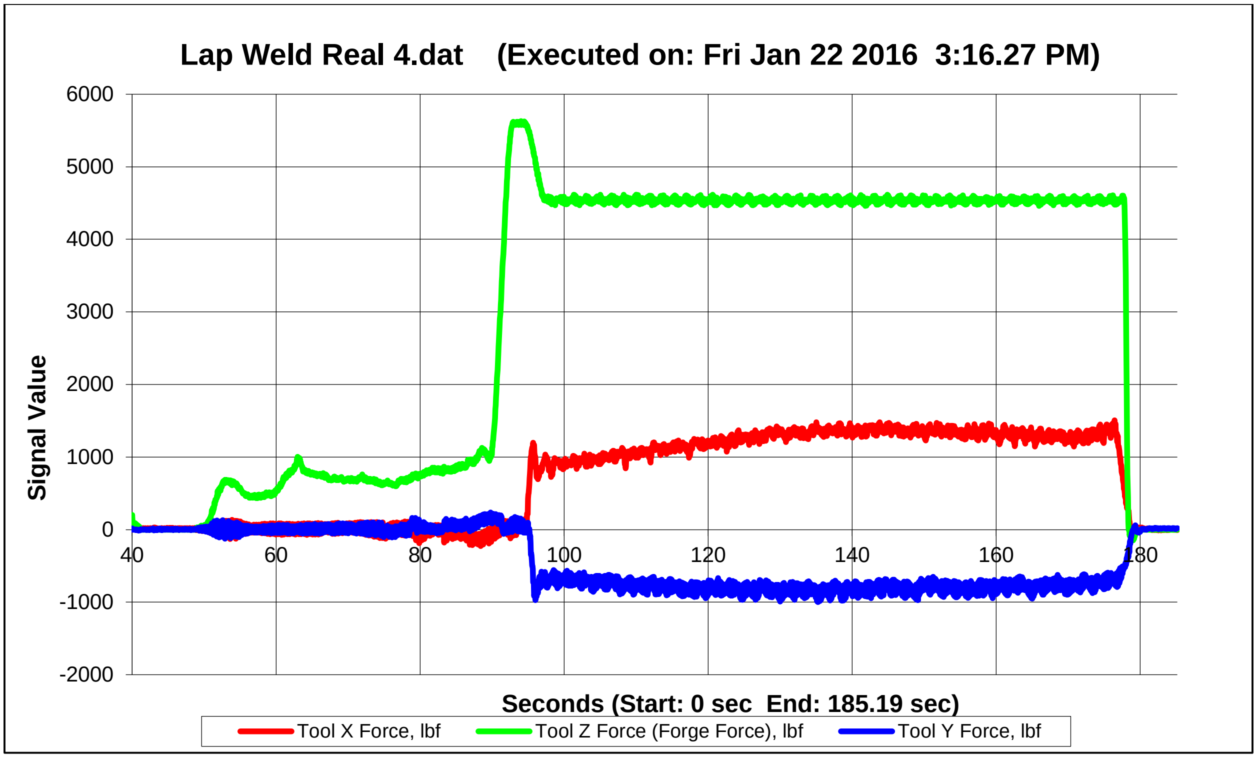

Figure 60: Pin Tool Reaction Forces, Weld Layer 4

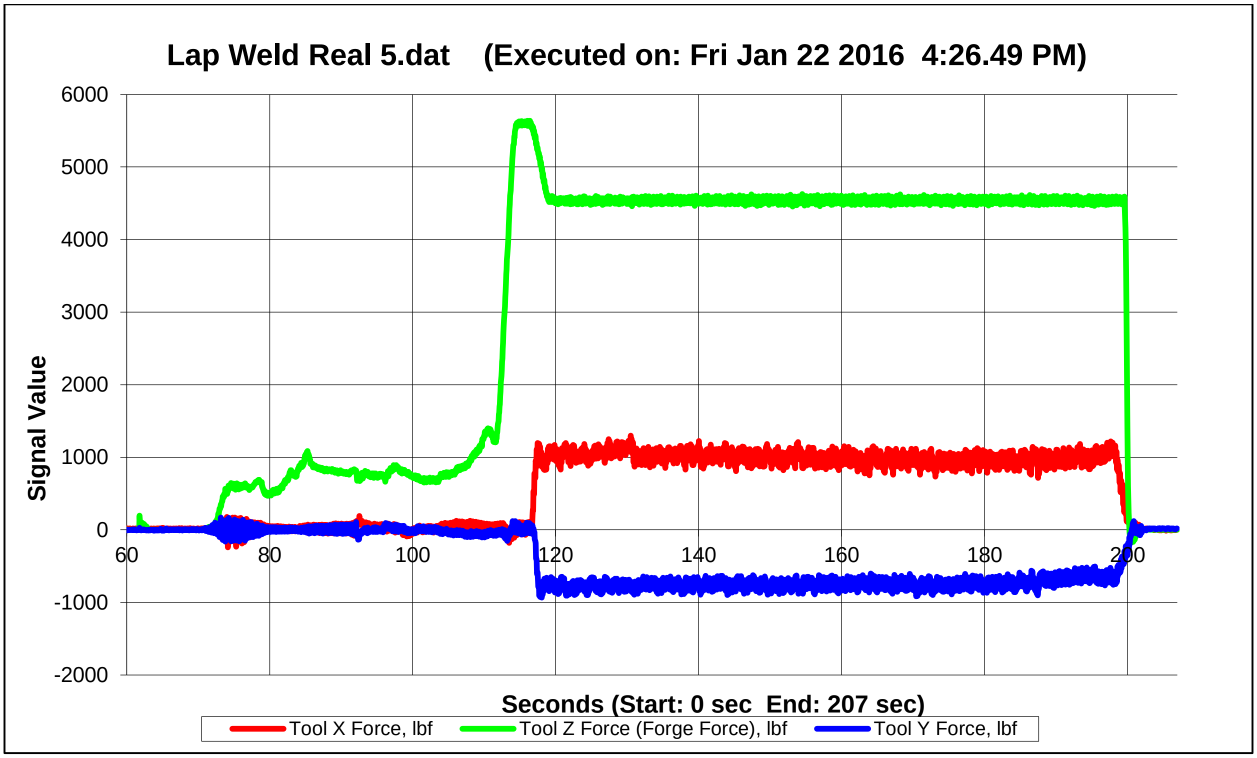

Figure 61: Pin Tool Reaction Forces, Weld Layer 5

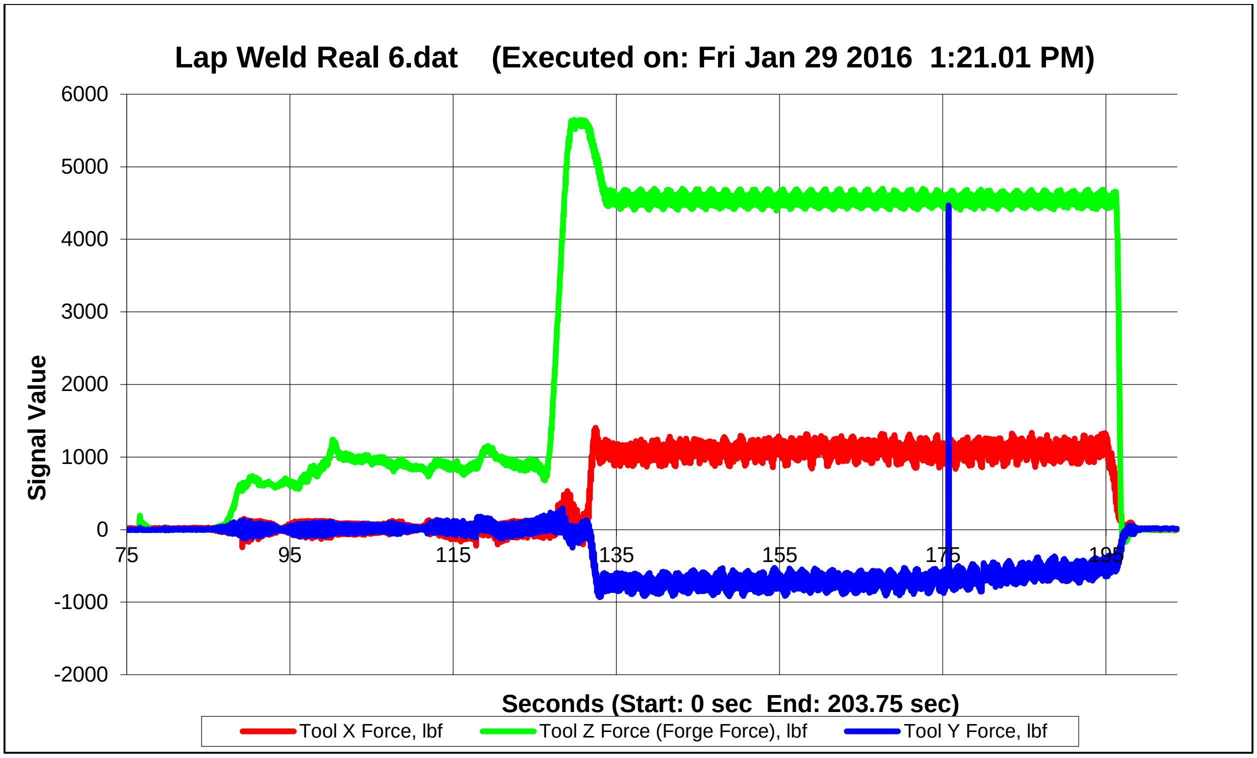

Figure 62: Pin Tool Reaction Forces, Weld Layer 6

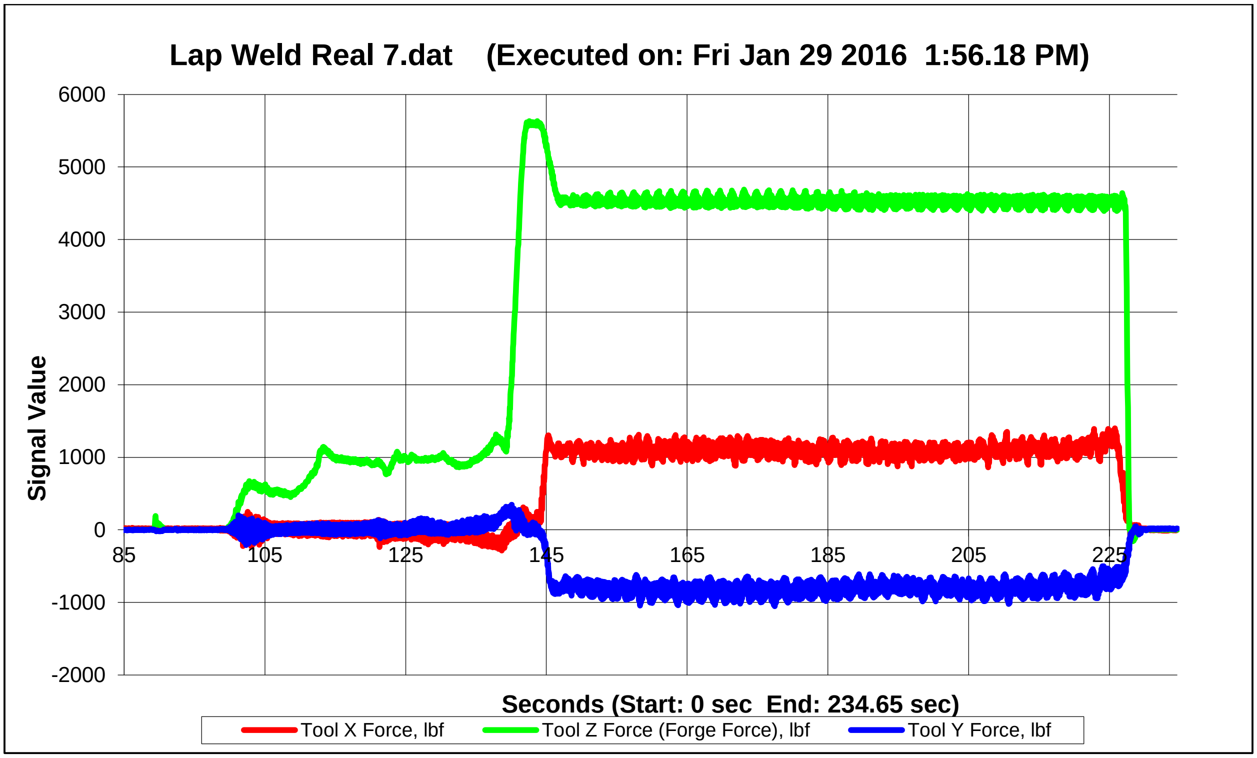

Figure 63: Pin Tool Reaction Forces, Weld Layer 7

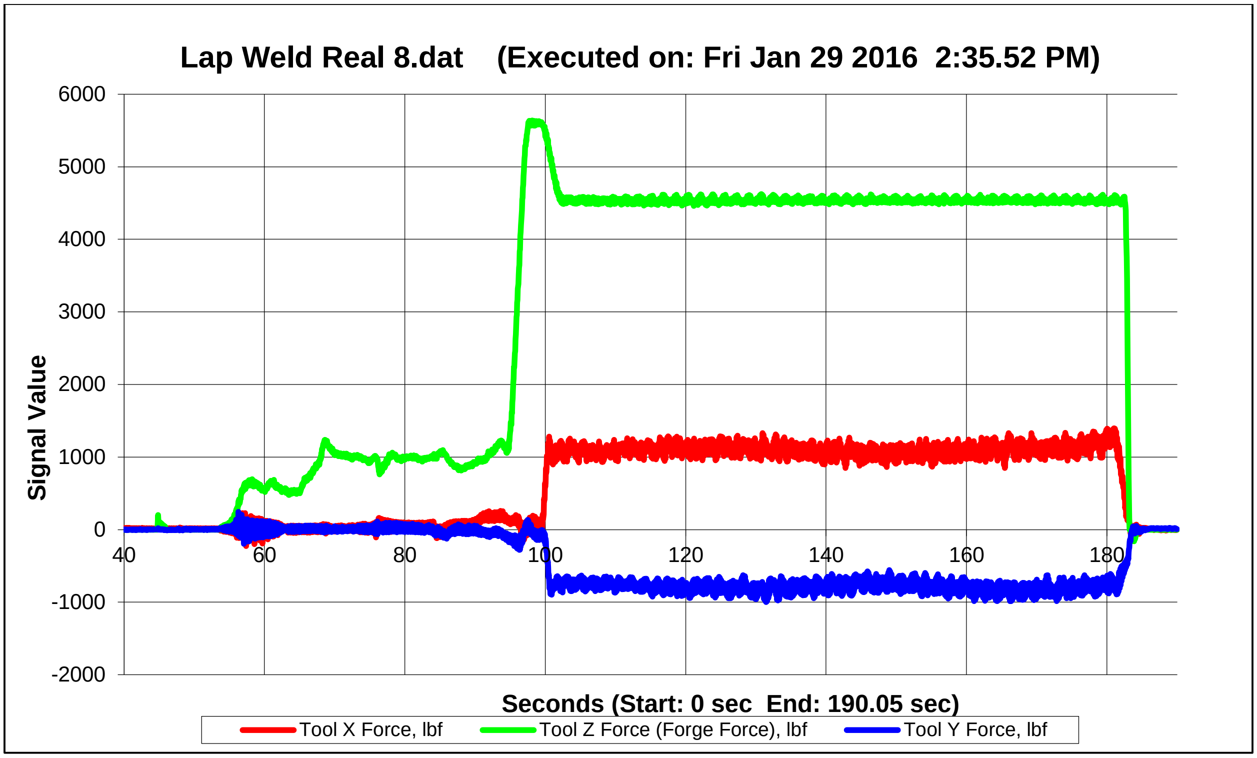

Figure 64: Pin Tool Reaction Forces, Weld Layer 8

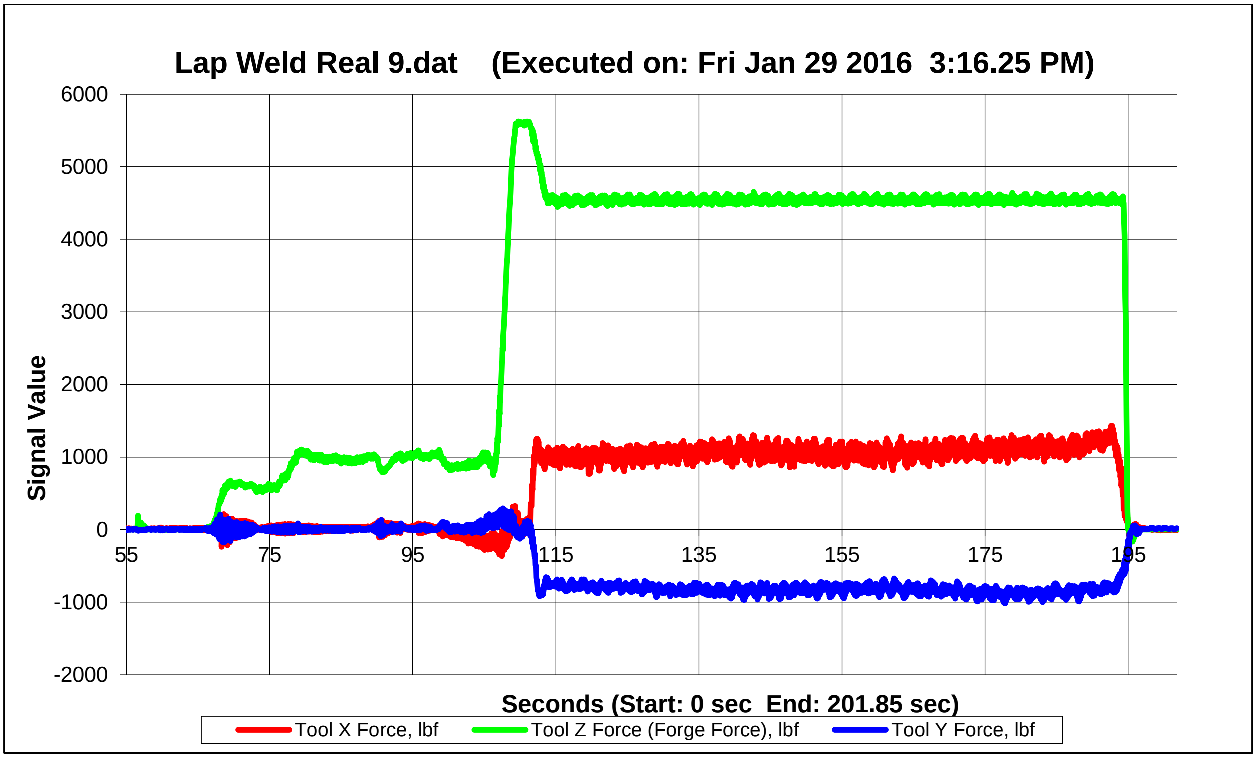

Figure 65: Pin Tool Reaction Forces, Weld Layer 9

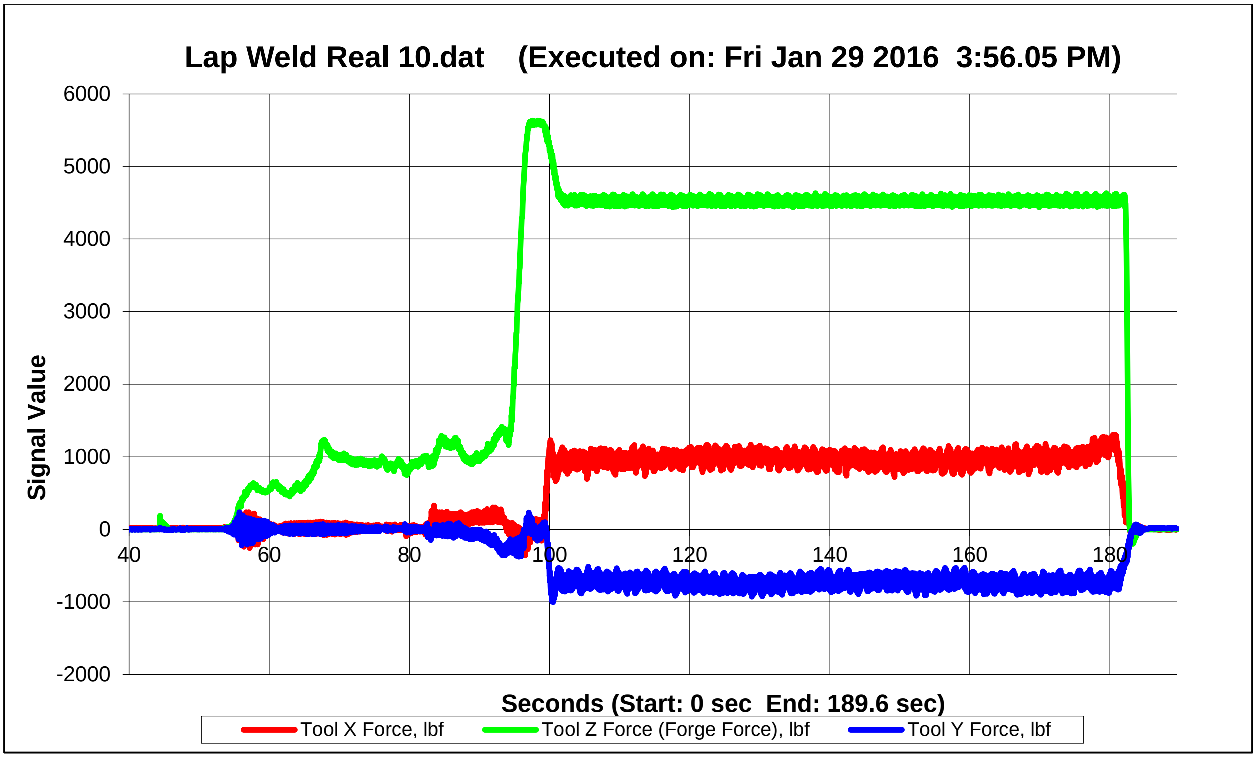

Figure 66: Pin Tool Reaction Forces, Weld Layer 10

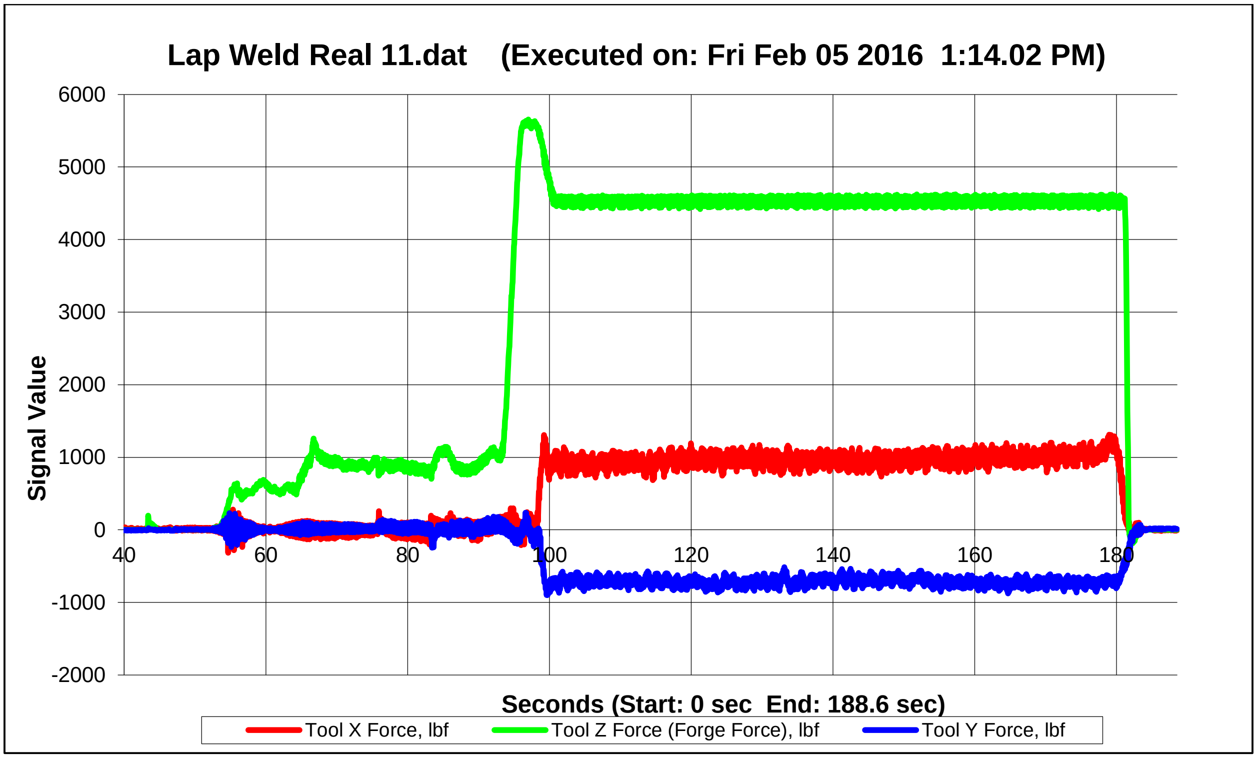

Figure 67: Pin Tool Reaction Forces, Weld Layer 11

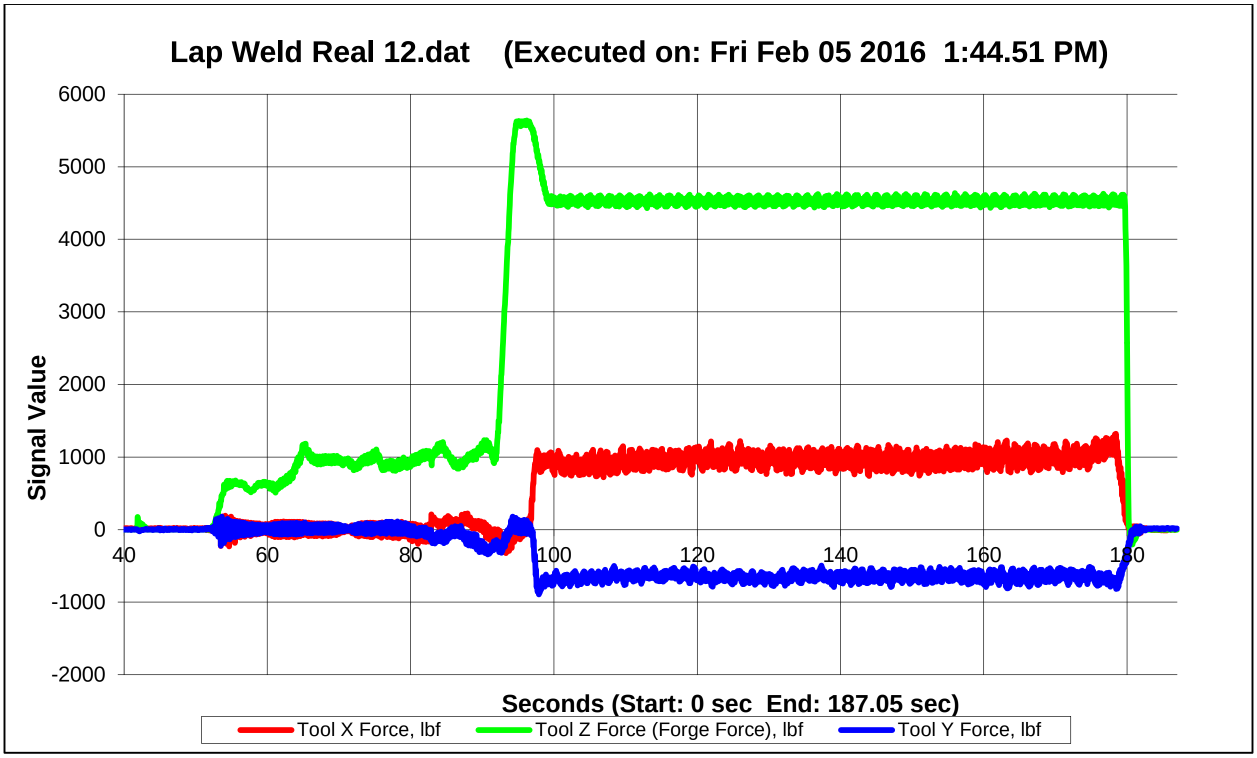

Figure 68: Pin Tool Reaction Forces, Weld Layer 12

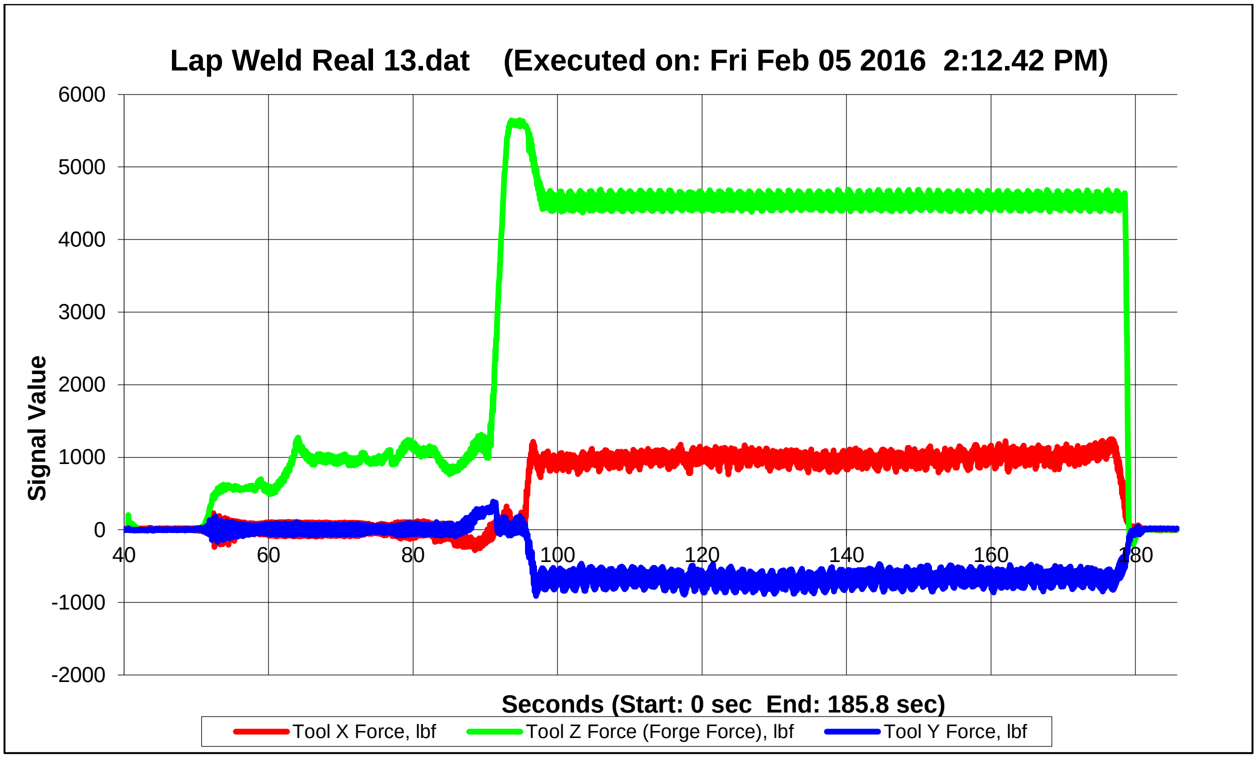

Figure 69: Pin Tool Reaction Forces, Weld Layer 13

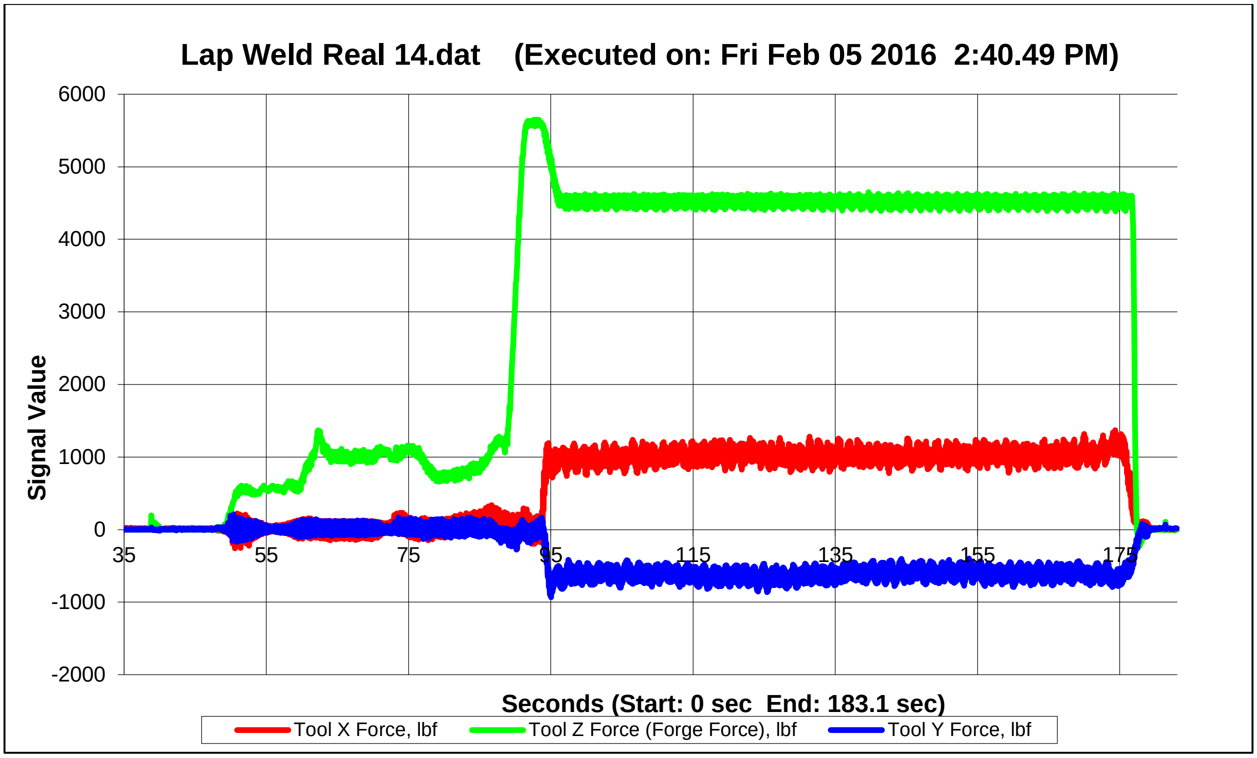

Figure 70: Pin Tool Reaction Forces, Weld Layer 14

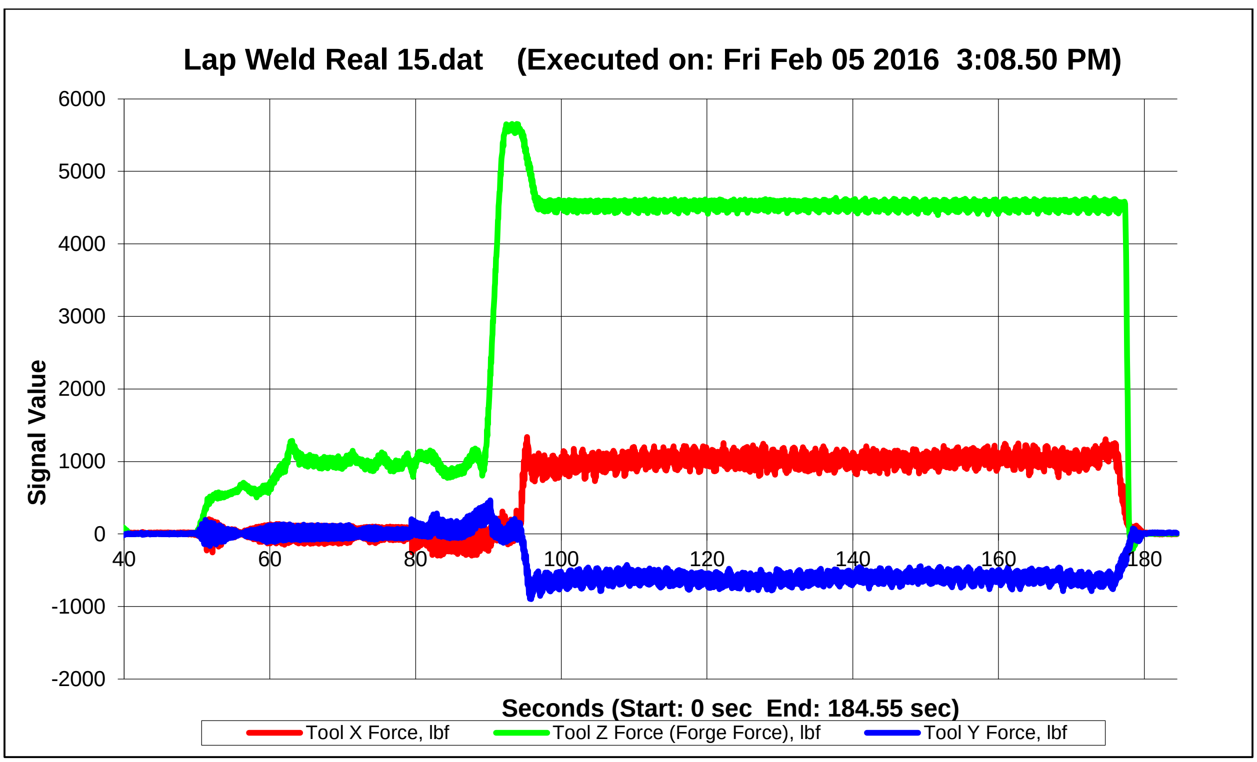

Figure 71: Pin Tool Reaction Forces, Weld Layer 15

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