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The Feasibility of Augmenting a Fixed-Gap Bobbin Friction Stir Welding Tool with Cutters to Join Enclosed Castings

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A thesis submitted to the faculty of
Brigham Young University
in partial fulfillment of the requirements for the degree of

Master of Science

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ABSTRACT

The Feasibility of Augmenting a Fixed-Gap Bobbin Friction Stir Welding Tool with Cutters to Join Enclosed Castings

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Bobbin Friction Stir Welding (BFSW) is a new application of Friction Stir Welding (FSW) that can be used to join materials together with little to no axial forces. This eliminates the need of a backplate or anvil needed to apply counter pressure against the tool. The applications of BFSW are growing every day. This new technology is helping the automotive industry and many other industries join materials more effectively and efficiently. This technology can be used to join materials with high strength to weight ratios to make cars lighter to increase fuel efficiency. This will also greatly reduce the cost of current joining technologies.

The purpose of this research is to prove the feasibility of augmenting a BFSW tool with cutters to join enclosed castings while simultaneously removing ribs and variations in thickness by (1) penetrating a BFSW tool into the material away from an edge; (2) removing any inconsistencies in the material thickness while maintaining a weld; and (3) removing a BFSW tool from the casting away from an edge leaving a clean exit hole without destroying either the casting or the tool.

Keywords: BFSW, joining cast aluminum, cast aluminum, Aural-2, automotive manufacturing

ACKNOWLEDGEMENTS

I would like to thank BYU for giving me the opportunity to perform this research. I am grateful for the people who encouraged me to push my CAD/CAM and machining skills to complete this research without any external designing/machining outsourcing. I express gratitude to all my professors who have taught me about tool design over the past couple years. I would like to thank my research comrades for their skills and time they gave to help this research move forward. I also am grateful for the love and support from my wife and daughter.

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1 INTRODUCTION

1.1 Background

The automotive industry may be one of the most competitive industries in the world. Global emission regulations will require them to improve gas mileage to 54 MPG by the year 2025, forcing the automotive industry to push technology to the limit to meet these strict standards. There are two main methods to improve fuel efficiency: improve engine efficiency or reduce the weight of the vehicle. The focus of this research is on using light-weight materials in vehicles to reduce total weight.

The automotive industry has tried everything from changing material, thickness, and geometry to create the most optimized design for high strength and weight reduction. These changes in material and thickness pose challenges for manufacturability. Some materials by nature of their processing make joining processes like traditional welding difficult. Differing thickness also poses a problem for traditional welding. Solutions have been found but these solutions come at a cost that may raise the price of vehicles beyond that which the average consumer could afford.

With technology advances like friction stir welding (FSW), some of these problems have been mitigated. Friction stir welding has been proven to be a cost effective and reliable method for joining dissimilar materials and metals with differing thicknesses (Schneider, 2014; The

Welding Institute, 2018). Friction stir welding is a process where two materials are stirred together in the solid state rather than fused together like tradition welding processes. The most common type of FSW consists of a single, spinning shoulder and probe that presses the material against an anvil. This process is advantageous not only because it can join dissimilar materials or material thicknesses, but it also keeps the temperatures low. During FSW, the material is plastically deformed and is mixed with the adjacent material. Since the process doesn't liquefy the material with heat, materials that are heat sensitive can be joined. High Pressure Vacuum Die Cast (HPVDC) aluminum alloys are one of these materials.

Cast aluminum is being used more and more regularly in production cars to reduce weight and add strength. In 2012, the Mercedes SL was 44% cast aluminum (Hartlieb, 2013b). High Pressure Vacuum Die Castings get exponentially more expensive with increase in size and complexity of the casting. Automotive manufacturers use HPVDC to produce high strength, lightweight, aluminum alloys for structural parts in vehicles. However, by nature of the casting process, microscopic voids are present that are under intense pressure. These alloys are difficult to weld together quickly using traditional methods because these microscopic voids expand to macroscopic blisters when the material heats up to the melting temperature.

Friction Stir Welding has been proven to create a superior weld for cast aluminum alloys, among many other materials, but historically has only worked in the application of straight welds on flat castings (Pan & Lados, 2017; Pietras & Rams, 2016; Tagawa et al., 2014). A modification of FSW using a bobbin tool has recently been found to fix common problems with normal FSW. In Bobbin Friction Stir Welding (BFSW), two shoulders and a pin are utilized to join the materials together. The tool has an upper shoulder, a pin that is as long as the material is thick, and a lower shoulder. This process is beneficial because it removes the need of an anvil and virtually eliminates the downward force that is required in normal FSW. This is a necessity for joining enclosed castings because the downward force from FSW would crush any enclosed casting. However, BFSW currently is not able to enter or exit a plate along the tool axis due to the bobbin itself. Furthermore, a fixed gap bobbin tool can’t compensate for the drastic changes in material thickness that are common to HPVDC aluminum castings. Thus, a new tool must be created that can join the castings regardless of ribs or varying thicknesses, and that can axially enter and exit the castings. This will allow smaller castings to be made that can be joined; thus, reducing the cost of castings exponentially.

1.2 Problem Statement

The purpose of this research is to investigate the feasibility of augmenting a bobbin friction stir tool with cutters that will allow the joining of an enclosed casting with variable thickness.

1.3 Research Questions

The question addressed during this research is the following:

1. Can a bobbin friction stir tool be augmented with cutters to allow the friction stir welding of an enclosed casting while simultaneously removing ribs and variations in thickness?

1.4 Hypotheses

This question will be answered by validating the following hypotheses:

1. A bobbin tool augmented with a lower cutter can penetrate an enclosed casting and initiate a weld away from the edge.

2. Friction stir welding using a bobbin tool with combined cutters can remove any inconsistencies in the material thickness while maintaining a weld.
3. A bobbin tool augmented with cutters can be removed from the casting away from an edge leaving a clean exit hole without destroying the casting or the tool.

1.5 Methodology

1.5.1 Materials

Only 3 mm thick Aural-2 plates were joined. Material parameters were set by sponsors to ensure that results were applicable to their needs. The plates are 5 x 12 inches in width and length respectively. All tooling was CNC machined on a mill out of H13 in its annealed state then heat treated and tempered to a hardness of at least 38 HRC. Welds were made using a FSW machine designed by TTI. Further modifications to the machine were made by the Precision Machining Lab at Brigham Young University and by students also researching FSW related topics.

1.5.2 Experiments

To answer the hypotheses, experiments were performed that tested each of the hypothesis scenarios. Tests were performed at various levels of fidelity to prove the viability of designs. Testing started by proving the strength of the pin (smallest cross-sectional area), followed by shoulder design. Once those tests were conclusive, tests to combine FSW and machining occurred. This consisted of placing the pin, shoulder, and cutters on the same tool.

Data for reaction forces acting on the tool were recorded to determine base loads and forces to act as parameters for machine selection.

1.6 Delimitations and Assumptions

Only Aural-2 was investigated for joining. No other materials besides H13 steel were investigated for tool materials. As the focus of this work is to investigate the potential of adding cutters to meet the criteria identified in each of the three hypotheses, I considered investigation of improvements in BFSW to be outside the scope of this research.

1.7 Definitions

BFSW – bobbin friction stir welding is a solid-state welding process that uses an upper and lower shoulder along with a pin to stir the metals to be joined together

CS – cutting speed

FSW – friction stir welding is a solid-state welding process that uses a pin to stir the metals to be joined together along a line.

IPM – inches per minute

IPT – inches per tooth

MPM – meters per minute

RPM – revolutions per minute

SFM – surface feet per minute

2 LITERATURE REVIEW

2.1 Introduction

Literature on the topic of Bobbin Friction Stir Welding is rare due to its recent development. A majority of the reviewed literature was to understand the current FSW technologies for joining thin cast aluminum.

2.2 The Federal Mandate

On July 29, 2011, President Obama updated the CAFE standards by mandating that automotive manufacturers raise the average MPG of their vehicles to 54.5 MPG by the year 2025. Fuel efficiency is improved by either increasing engine efficiency or by reducing the weight of the vehicle. In a survey given to car manufacturers, 72% of respondents stated that reducing the weight of their vehicles is how they plan to meet the CAFE standard (Deptula, 2015). Automotive manufacturers want “to make cars lightweight and crashworthy, while reducing costs and meeting performance mandates” (Schneider, 2014). Many new technologies, products, materials, and environmental affects will develop due to reducing weight in the automotive industry (Albrecht, 2013).

Reducing the weight of vehicles can be achieved by removing unnecessary material and by substituting in materials with better strength to weight ratios. Composites may seem like an obvious answer for their having a high strength to weight ratio, but costs and processing time are currently limiting factors which prevent composites from solving weight problems for all vehicles. Another alternative is using high strength steel or aluminum alloys. This research focusses on an aluminum alloy used in structural parts of vehicles. This alloy helps to reduce the weight of the vehicle due to its high mechanical strength to weight ratio (MAGNA, 2014; Rio Tinto, 2016).

2.3 Material Properties of Aural-2

The material used in this research is an aluminum alloy named Aural-2. The Aural alloys were designed for automotive safety and structural components. The current applications of this material are used for shock towers, engine cradles, nodes, B and C pillars, steering columns and more parts of the car's frame. These parts of the frame need to be very strong due to the loads that these parts will experience. Aural is processed in a way which yields a high strength to weight ratio. With its enhanced mechanical properties, the Aural alloys enable greater weight savings compared with equivalent steel products or less advanced castings. This allows car manufacturers to meet light weighting targets without compromising safety (MAGNA, 2014; Rio Tinto, 2016).

Current processing of this material is through High Pressure Vacuum Die Casting (HPVDC) which allows the production of thin-walled, aluminum, structural parts with complex geometry for lightweight structure components. In vacuum die casting, molten metal is forced at high pressure into a mold under vacuum. Die casting is suitable for the automotive industry because the quantities are high enough to make the cost of tooling worthwhile. This process also guarantees tight tolerances. However, porosity can be an issue with die castings, thus making traditional welding methods difficult (ASM, 2008; Hartlieb, 2013a; Hartlieb, 2013b; Hu, Xiong, Murakami, Matsumoto, & Ikeda, 2006; MAGNA, 2014).

2.4 Challenges of Joining HPVDC

Parts made by high pressure vacuum die casting are known to have porosity issues depending on the quality of the cast. As stated previously, in the casting process, micro voids are present throughout the material under high pressure. If the material is liquified, those voids expand creating blisters and pockets in the weld. Currently, the joining of HPVDC parts are only found in high end, low production cars. This is because the process is not easily automated. An experienced MIG or TIG welder is required to successfully join these materials together because when a void presents itself, he can go back and fill in the hole. An automated robot would not be able to detect these voids without some sensor or vision system. This requires time and a highly paid expert thus driving the cost of the joining process higher. This is one of the inhibitors to the automation of joining Aural-2 (Hartlieb, 2013a; Hartlieb, 2013b; Niu, Hu, Pinwill, & Li, 2000; Rio Tinto, 2016).

2.5 Machining Cast Aluminum

As part of this research is to determine if a cast aluminum can be joined while removing material, research was done in the area of tool design for machining cast aluminum. It was found that cutter design is critical for machining aluminum. Cutters designed for aluminum should have a radial rake angle of 10 to 20°, an axial rake angle of 15 to 45°, and end or peripheral clearance of 10 to 12°. The fewer the teeth and the larger the rake angle yields the best results when it comes to machining aluminum. This allows a larger area for chip evacuation which is necessary due to high rotational speeds. However, to prevent chatter, the cutter should have enough teeth so that at least two teeth are engaged at all times. Axial plunge cuts inhibit ideal chip evacuation, so it is recommended to advance laterally while plunging axially (ASM, 1989).

“Speeds and feeds” are the terms used to denote the RPM and IPM parameters of machining. RPM is considered the “speed” whereas IPM is considered the “feed”. These are calculated by using the following equations:

$$RPM = \frac{12CS}{\pi D} \tag{2-1}$$

Where RPM is the revolutions per minute, CS is the cutting speed, and D is the diameter of the tool.

$$IPM = RPM \times IPT \times N \tag{2-2}$$

Where IPM is inches per minute, RPM is the revolutions per minute, IPT is the inches per tooth, and N is the number of cutting teeth (Oberg, Horton, Jones, McCauley, & Ryffel, 2012).

2.6 Bobbin Friction Stir Welding

Friction stir welding has many variations based on the application needed. The type of FSW tool that will be used in this research will be a fixed-gap bobbin tool. In this type of welding, a shoulder is placed on the bottom of the tool in addition to the top shoulder and pin to remove the need of a backplate or anvil (see figure 3-4). This effectively removes any axial force in the process. For this reason, this method is the preferred method for joining castings that may have non-planar geometry. Hollow castings are not able to support the immense reaction forces required to support a single sided FSW tool design. The major benefit of FSW is the speed at which a weld can be made. Previous research has shown welds in 3 mm aluminum at 2.5 meters per minute which is way faster than any welding process. Other benefits of BFSW are the elimination of both weld roots and root defects, and low distortion due to uniform heat input (Threadgill, Ahmed, Martin, Perrett, & Wynne, 2010). Thin aluminum sheet as well as thick aluminum plate has been successfully joined using this method. Additionally, the temperatures present during the BFSW process are low enough that possible micro voids present in Aural-2 will not expand to create blisters or voids (Andrade, 2009; Colligan, O'Donnell, Shevock, & Smitherman, 2012; Hilgert, 2012; Pan & Lados, 2017; Pietras & Rams, 2016; Tagawa et al., 2014; Threadgill et al., 2010).

3 EXPERIMENTAL DESIGN

3.1 Summary

Tests were performed to create welds using a FSW machine. The hypotheses were tested, and research questions were answered through these tests. A variety of bobbin friction stir welding tools were produced for testing using a CNC mill and an oven for heat treating. A hardness tester was used to verify effective heat treatment. A digital video camera was used to record the welds for visual documentation. Data regarding velocity, rpm, and reaction forces in all axes were recorded for each weld. Visual inspections of welds were also used to collect information. Fixture designs changed overtime to achieve the best method for securing the plates.

3.2 Equipment

3.2.1 The Friction Stir Welding Machine

Transformation Technologies Inc. provided the FSW machine used for this research. It is a TTI High Stiffness RM2 FSW machine with a 10 Ton Spindle. The machine was fitted with a new Bond Technologies B&R based controller with high speed data acquisition and control. An external computer was connected to the PLC, and a custom MATLAB controller was used to monitor the process. Brigham Young University already had this machine for other FSW research purposes. It precisely controls RPM (maximum 6000 RPM), federate (IPM), Z-depth and dwell delays in up to four stages. The spindle has a collet that accepts a 1” diameter tool. A fixture mounted below the spindle holds the Aural-2 plates for testing. Samples were at first placed side by side creating a butt joint and clamped down with a thin aluminum strap and two screws. A more rigid design was eventually designed and implemented to address flexibility in the initial tests.

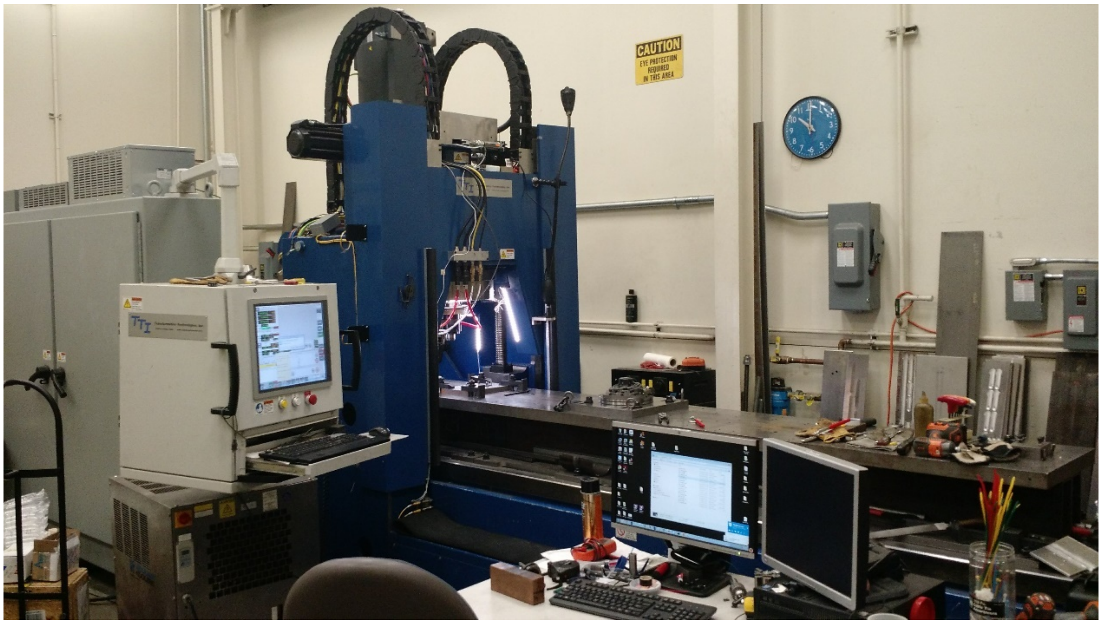


Figure 3-1: FSW Machine

A PLC and computer work in combination to process RPM, velocity, and all other parameters to control the process. The computer automatically recorded and stored weld cycle information. It kept a record of the following parameters:

- Load, torque, position, and velocity in the X, Y, Z axis
- RPM
- Weld duration

3.2.2 The CNC Mill

All tools were machined on an Acer EMC-2240 with an Anilam 6000 M controller. The Acer has been upgraded with a 4th axis to allow for 4 axis machining which was utilized to make the cutter geometry.

Figure 3-2: The Acer Machine

3.2.3 The Hardness Tester

To measure the hardness of the heat-treated pieces a Mitutoyo ARK-510 Hardness Tester was used. Hardness measurements were recorded in the table below.

Table 3-1: Rockwell Hardness Results

Specimen	Hardness (HRC)
Sample A	34.1
Sample B	42.2
Sample C	37.5
Sample D	37.0
Sample E	39.7
Cutter	46.0

Figure 3-3: Hardness Tester

3.3 The BFSW Process and Phases

The BFSW process consists of three phases. In the first phase, the bobbin is usually brought in from the side or dropped in a hole larger than the diameter of the tool. The tool then is spun at a specific RPM and slowly enters the material. This phase is critical to the initiation of the weld. Proper heating must take place to initiate good consolidation. Once this occurs the tools then speeds up to its target lateral speed creating a weld, phase 2. The final phase is called the exit. The tool either exits the material from the side or stops in place and is disassembled to be removed. Currently there is no bobbin tool that can pull out of the material without negative impacts. Bobbin tools typically leave an entry and exit "mark" described as a rooster tail.

Bobbin tools consist of an upper shoulder, a pin, and a lower shoulder (see Figure 3-4). The shoulders tend to have a spiraling scroll on it to pull material towards the center of the tool. The pin generally has a combination of flats and threads to create turbulence during the weld. The shoulders tested were typically 18 mm in diameter and the pin was 9 mm in diameter. Later versions were roughly the same size, but the geometry changed slightly which each iteration.

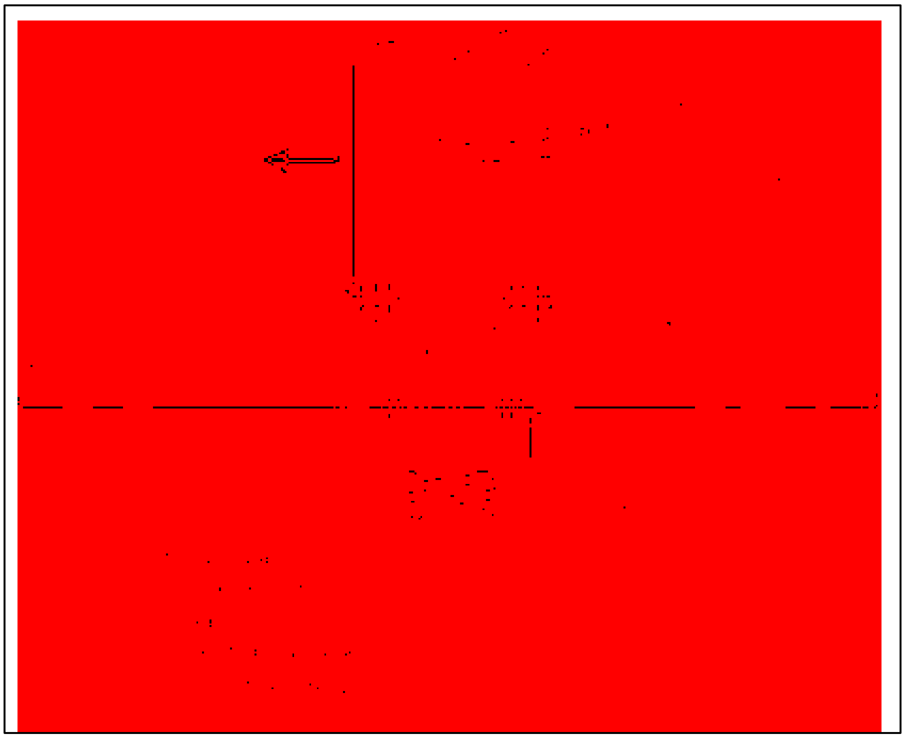


Figure 3-4: BFSW Diagram

All shoulders and pins were produced on an Acer CNC Mill. A manual lathe was used to part off the geometries from the stock material then heat treated.

3.4 Failure Modes in Testing

Due to dynamic forces in the X, Y, and Z directions and the torque acting on the tool, the first mode of failure will always occur at the point with the smallest cross-section which in this case is the pin. The pin can either fail in torsion, shear, or tension. Failure in shear will happen if the RPM is too low resulting in a lower temperature and therefore a stronger reacting force against the pin. Failure in tension can occur if the reaction forces in the Z axis exceed that of the pin strength. It is expected that failure in shear will be more common.

3.5 BFSW Tool Design Iterations

3.5.1 Initial Tool Designs

Initial parameters were given for outer diameter and pin diameter. These were 18 mm and 6 mm respectively. Knowing that the tool needed to cut material axially, drill geometry was examined. Center drills were also considered which led to the drawing below.

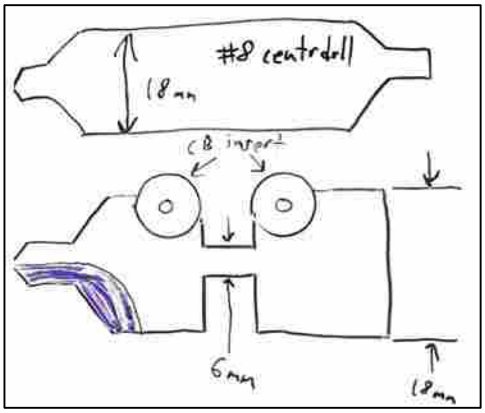


Figure 3-5: Center Drill Design

This design featured carbide inserts that would be screwed in or mounted somehow to the side of the center drill. This design was initially thought of as a single tool, but it was soon realized that a single tool would be extremely difficult to manufacture. FSW geometry is usually characterized by pins and shoulders. The pins typically have a combination of flats and threads while the shoulders have some sort of tapered scroll feature. These features make it very difficult with today’s technology to create a BFSW tool out of a single piece of metal. A modular design was then considered and pursued which will be talked about later on in the paper.

3.5.2 FSW Design

For the design of the pin or sleeve in this case, previous research showed that a good design consists of a square pin with alternating threads every 90 degrees placed on the corners of said square. This has been shown to improve distortion and breakup of the residual oxide band (Colligan et al., 2012). Much of the pin design hasn’t change much throughout the course of this research, only it’s length has changed to correctly space the shoulders.

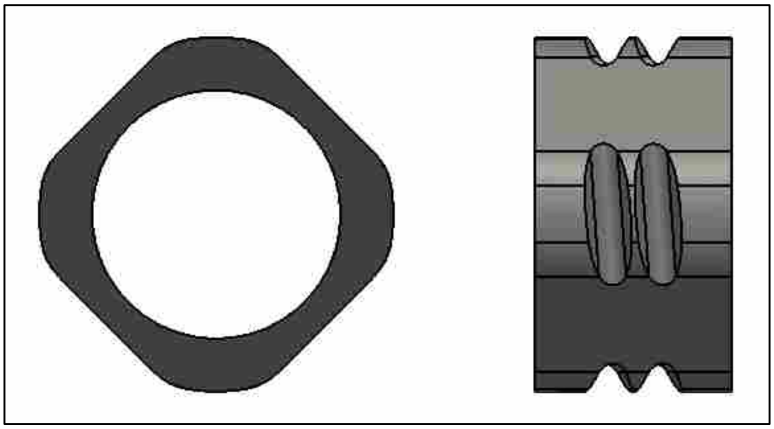


Figure 3-6: Pin Design

Shoulder designs for FSW tools typically have a scrolling feature to help pull material towards the pin. Initially the design started out as circular pucks but soon changed to hexagonal pucks with rounded edges to next inside the bobbin and tool shank. Two scrolls were used with a semicircular groove with a width of .0625”. The top shoulder and the bottom shoulder were mirror images of each other so that as the tool spun clockwise, the scrolls pulled material from the outside towards the center. The scrolls were flat to begin but then changed to a tapered scroll in hopes to add a larger range of variability in thickness and Z height offset. The thickness of the puck increased to accommodate the tapered shoulder design and the pocket for the pin was increased to allow for a greater surface area of contact.

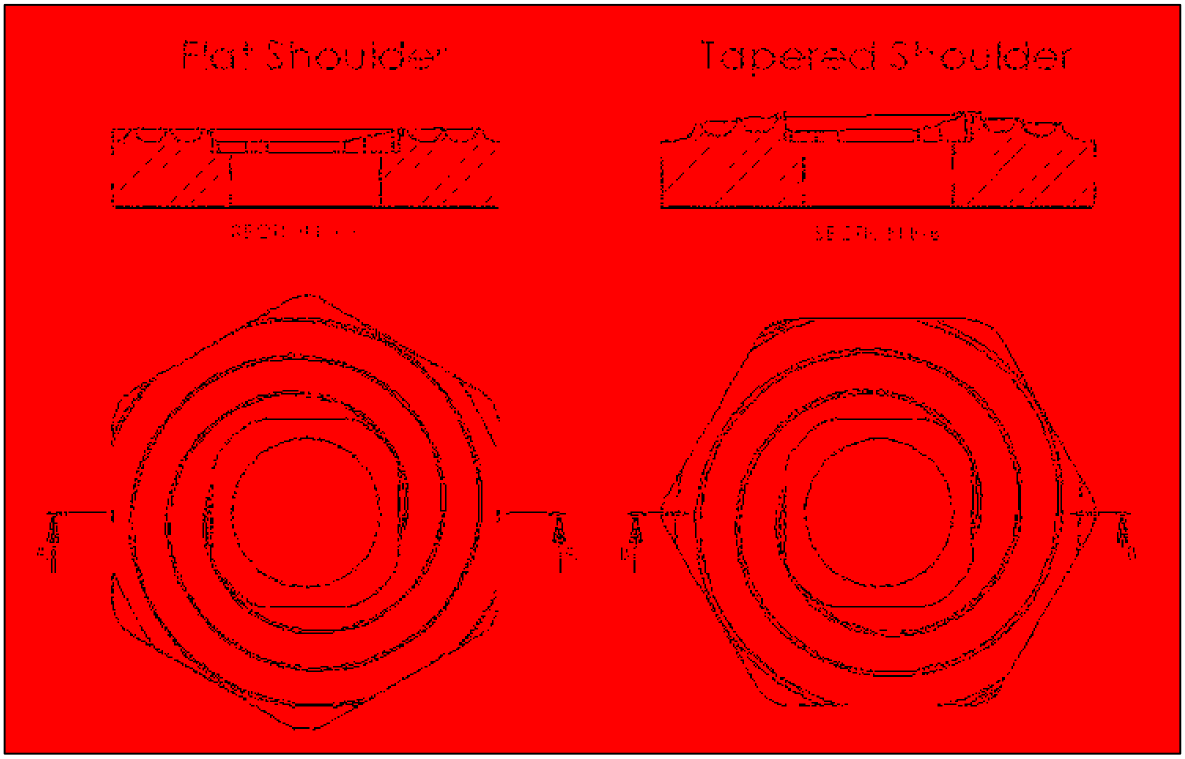


Figure 3-7: Top Shoulder Designs

In place of cutter geometry, circular shafts were utilized for initial testing until cutters were designed and manufactured (see Figure 3-10). All tools were made from annealed H13 Tool Steel that were then heat treated in an oven to a Rockwell Hardness of 37+ HRC.

3.5.3 Cutter Design

Inserts seemed like a viable option due to their low cost and various shapes. However, circular inserts were found to be difficult to mount due to the location of the set screw. Various types of insert shapes were examined in hopes of finding a mounting point far enough away from the edge to mount properly. Each shape considered was either too large or could not cut in the directions that were required. It was concluded that any OEM carbide insert would not work.

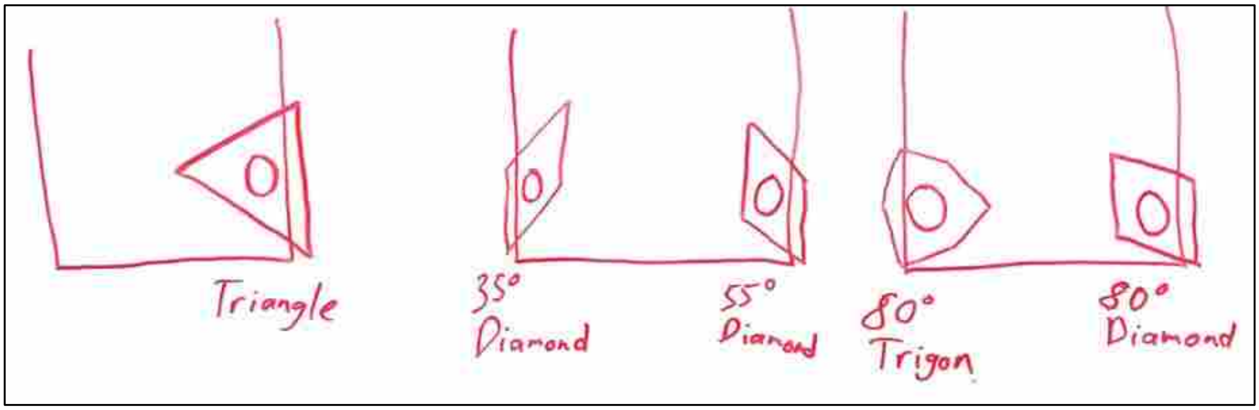


Figure 3-8: OEM Carbide Insert Designs

Another type of insert was considered: a tangentially mounted insert. This allows for the insert to be mounted on the side of a tool instead of the traditional mounting technique. This type of insert was investigated do to the low profile of the mounting method and its enhanced strength. Tangential mounted inserts are used for very aggressive machining in steel. However, upon contacting the sales representative for those inserts, he said that they are designed specifically for steel, not aluminum. Further discussion was made regarding possible inserts but upon seeing the application he mentioned that there are no OEM inserts that would fit this application. However, a custom insert could be designed and manufactured to fit this application but due to limitations in resources, carbide inserts would no longer be pursued.

Figure 3-9: Normal vs Tangential Mounted Inserts

Other types of cutting designs such as a hole saw, a drill, a fly cutter, and a variety of specialty cutters. All these designs were beneficial to examine but none were able to be directly used as cutters for the final design. The best cutter design turned out to be simpler than anticipated. End mills, if it is center cutting, can cut axially and laterally. Returning to the initial center drill idea, if the center drill was switched out for an end mill, the design, in essence, allows for axial and lateral cutting while allowing a small area for friction stir welding. The tricky part was to figure out how that FSW design would fit into an end mill.

A modular design was drawn up to allow for an end mill design that could have interchanging FSW shoulders that could be changed easily. This would allow for easy replacement of parts or even different shoulder inserts depending on the weld needed. For research purposes it allowed for a quick turnover for trying different geometries without building a whole new tool. Figures 3-8 and 3-9 show this design: the red parts are the end mill, the green parts are the FSW shoulders, and the brown piece is the pin or shaft.

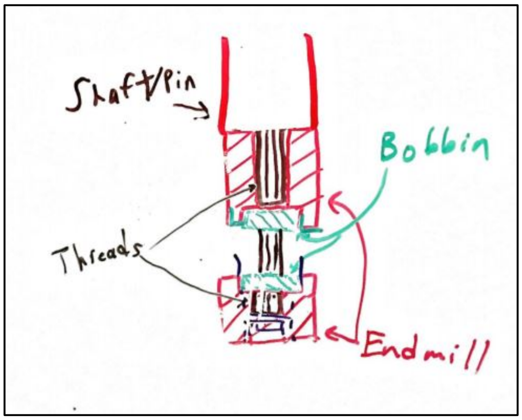


Figure 3-10: The Modular End Mill Design

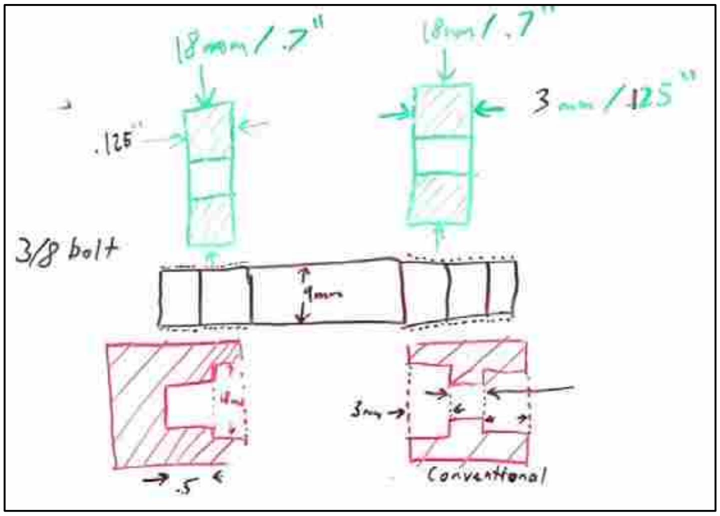


Figure 3-11: The Modular Assembly

Once the idea was visualized, an investigation of how to attach everything commenced. All parts of the end mill would have to be fixed with the FSW shoulders. Everything threading onto a center shaft was the first thought but then unthreading all the pieces would be a problem. Furthermore, how would the shoulders be spaced properly or be secured in place. Typical rotating tools are cylindrical by nature but in order to hold everything in place different shapes were utilized to interlock the different pieces together.

The final methodology of the modular design consisted of a bolt that screwed into the upper end mill securing on its shaft an upper shoulder, a sleeve, a lower shoulder, and the lower end mill. CAD models were then created using Solidworks and prototypes were 3D printed to get a more accurate representation of tool handling and assembly. The shoulders were designed to be hexagonal in shape so that they could nest inside the end mill pieces. The sleeve is square in shape and nests inside the shoulder pieces. This ensures that all the pieces will rotate with each other. This also makes manufacturing simple because the pieces individually aren't too complex to machine. However, this design would require a custom made end mill.

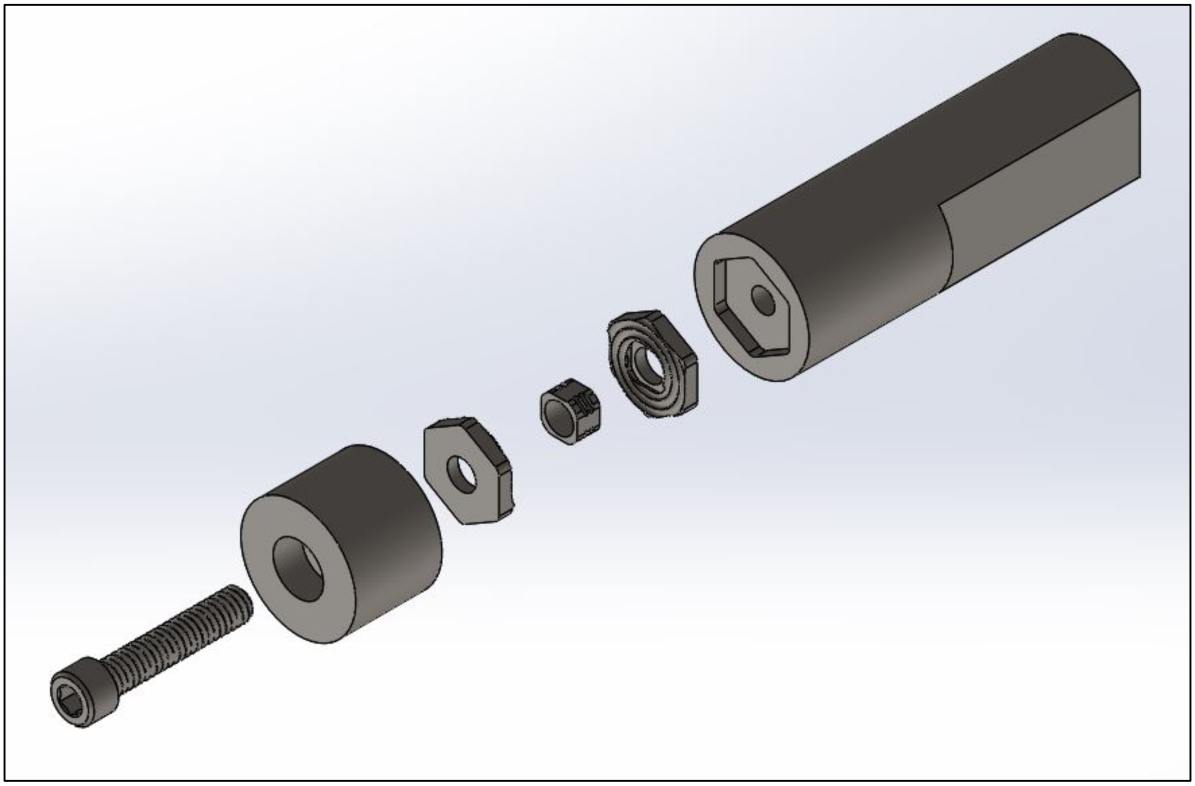
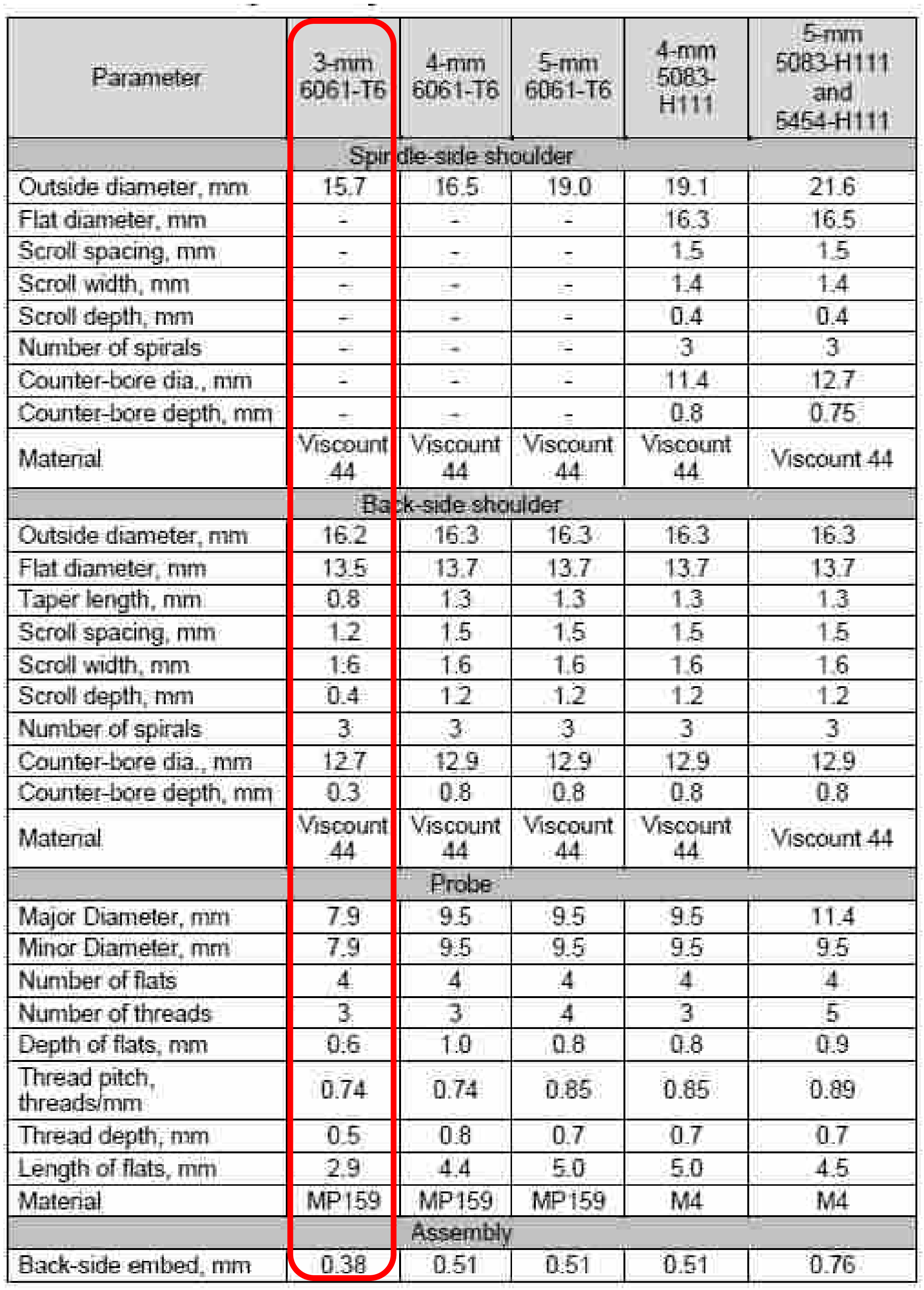


Figure 3-12: The Prototype Assembly

Sizing and dimensions of the tool came from previous research done by Kevin Colligan. Most dimensions and geometry were taken from his findings. The table below shows the parameters he used (Colligan et al., 2012).

Table 3-2: Kevin Colligan's Tool Parameters



Parameter	3-mm 6061-T6	4-mm 6061-T6	5-mm 6061-T6	4-mm 5083-H111	5-mm 5083-H111 and 5454-H111
Spindle-side shoulder					
Outside diameter, mm	15.7	16.5	19.0	19.1	21.6
Flat diameter, mm	-	-	-	16.3	16.5
Scroll spacing, mm	-	-	-	1.5	1.5
Scroll width, mm	-	-	-	1.4	1.4
Scroll depth, mm	-	-	-	0.4	0.4
Number of spirals	-	-	-	3	3
Counter-bore dia., mm	-	-	-	11.4	12.7
Counter-bore depth, mm	-	-	-	0.8	0.75
Material	Viscount 44	Viscount 44	Viscount 44	Viscount 44	Viscount 44
Back-side shoulder					
Outside diameter, mm	16.2	16.3	16.3	16.3	16.3
Flat diameter, mm	13.5	13.7	13.7	13.7	13.7
Taper length, mm	0.8	1.3	1.3	1.3	1.3
Scroll spacing, mm	1.2	1.5	1.5	1.5	1.5
Scroll width, mm	1.6	1.6	1.6	1.6	1.6
Scroll depth, mm	0.4	1.2	1.2	1.2	1.2
Number of spirals	3	3	3	3	3
Counter-bore dia., mm	12.7	12.9	12.9	12.9	12.9
Counter-bore depth, mm	0.3	0.8	0.8	0.8	0.8
Material	Viscount 44	Viscount 44	Viscount 44	Viscount 44	Viscount 44
Probe					
Major Diameter, mm	7.9	9.5	9.5	9.5	11.4
Minor Diameter, mm	7.9	9.5	9.5	9.5	9.5
Number of flats	4	4	4	4	4
Number of threads	3	3	4	3	5
Depth of flats, mm	0.6	1.0	0.8	0.8	0.9
Thread pitch, threads/mm	0.74	0.74	0.85	0.85	0.89
Thread depth, mm	0.5	0.8	0.7	0.7	0.7
Length of flats, mm	2.9	4.4	5.0	5.0	4.5
Material	MP159	MP159	MP159	M4	M4
Assembly					
Back-side embed, mm	0.38	0.51	0.51	0.51	0.76

The number of flutes or teeth was determined using well known machining formulas. These formulas are used to determine the rpm and ipm a.k.a. “feeds and speeds” of machining. Since the tool will be primarily be used for FSW, a tool needed to be designed around the feeds and speeds of FSW. The max speed set by sponsors of the project is 3 meters per minute (mpm) or 120 inches per minute (ipm) and a lower speed of 1.5 mpm or 60 ipm. This tool will be used in the automotive industry, so high speeds are necessary to meet the demand.

Research done by Kevin Colligan on 3 mm thick 6061-T6 aluminum found that a recommended rpm for initiating a weld was 1,400 rpm. Once the weld was initiated, the rpm slowed to 1,100 rpm (Colligan et al., 2012). Although 6061-T6 is not Aural-2, its composition is very similar with the exception that Aural-2 has a higher percentage of silicon (MakeItFrom.com, 2018). It was close enough to get rough estimates for weld parameters. Given the mentioned rpm range and the ipm of 60-120 ipm, a table was made in excel to plot the inches per tooth (ipt) given standard number of end mill flutes for aluminum. The ipt range for machining aluminum is .005-.020”. The number of flutes considered were 2, 3, 4, and 6.

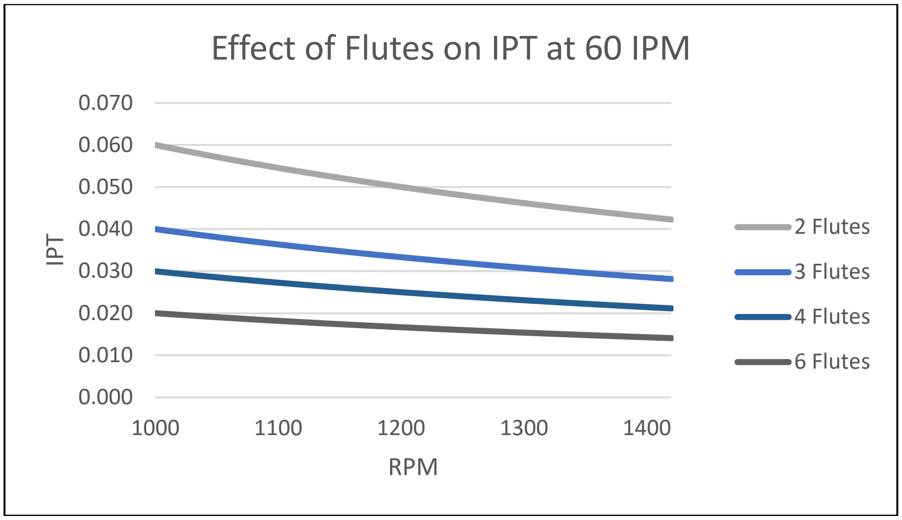


Figure 3-13: The Effect of Number of Flutes on IPT at 60 IPM

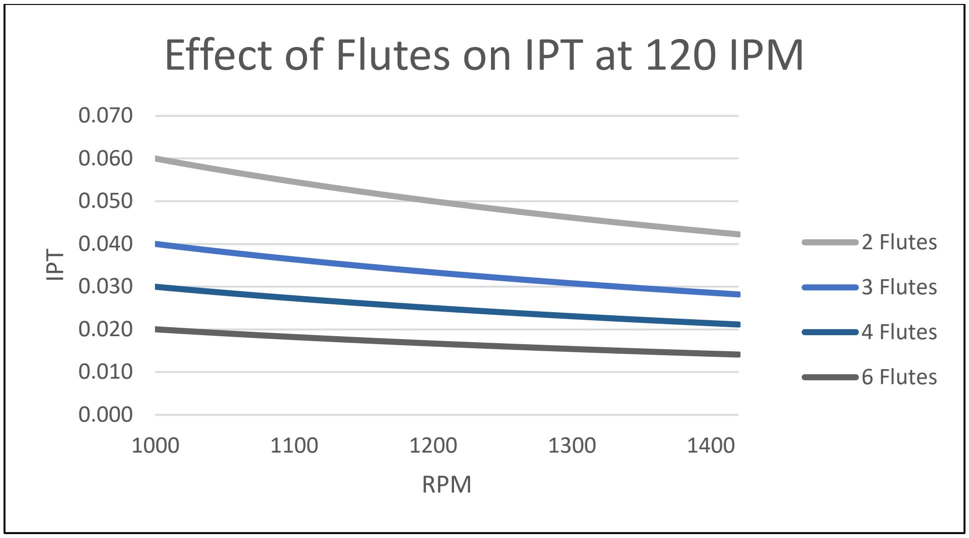


Figure 3-14: The Effect of Number of Flutes on IPT at 120 IPM

Based on the calculations at 60 ipm, all but the 2 fluted end mills are within the recommended chip load range. However, the only number of flutes that falls in the recommended ipt range of .005-.020 at 120 ipm is a 6 fluted end mill. The design for the spindle side end mill is pretty similar to regular 6 flute end mills just with the addition of a pocket and a tapped hole. The real trick was how to design the lower “bobbin” end mill. In conventional machining, the flutes are designed to lift chips out of the area. However, the bobbin end mill would need to lift chips up when plunging and pull chips down once it has initiated welding. This requires a change of flute direction which isn’t a new concept. Compression end mills are designed for cutting laminates and have alternating flutes to compress the material together to prevent delamination.

Figure 3-15: A Compression End Mill

Using this knowledge, a compression type end mill was designed. The bottom side of the bobbin has upwards cutting flutes then switches to downward cutting flutes. This creates a chevron design that is not ideal for grinding. If this bobbin cutter is to be professionally ground, it would be wise to alter the flutes so they do not touch, much like the compression end mill in Figure 3-12. Due to time and resources, this chevron design was left for simplicity in machining. The bobbin cutter is roughly ¾” tall and the material it will be cutting is only 3 mm thick. This ensures that by the time the material reaches the peak of the chevron, no chips will be forming. This design could be improved to enhance tool life and cutting efficiency but again, time and resources were limiting factors.

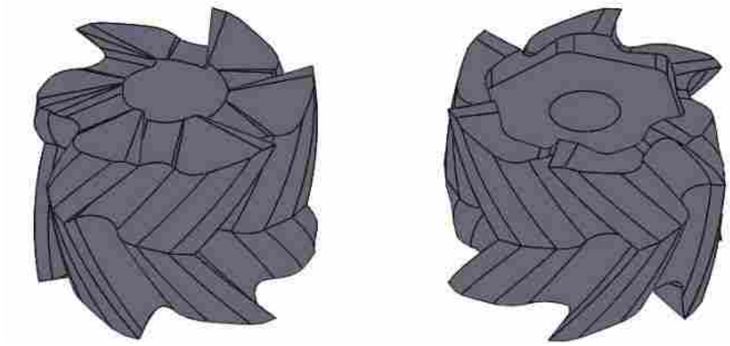


Figure 3-16: The Bobbin End Mill Design

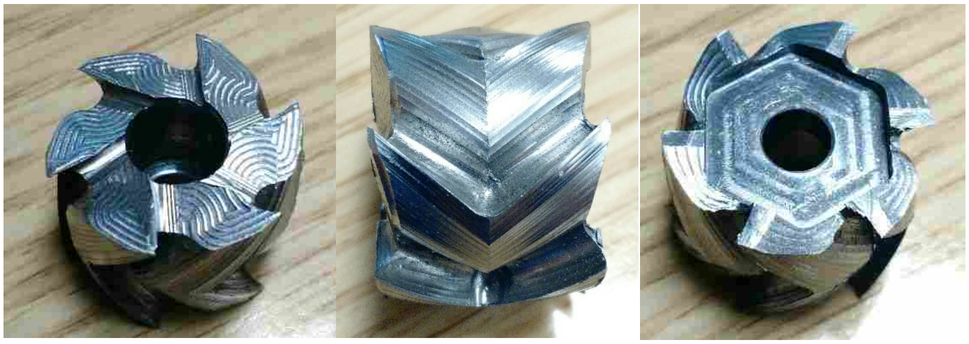


Figure 3-17: The Bobbin End Mill Machined Part

Figure 3-18: The BFSW End Mill After Heat Treatment

4 RESEARCH RESULTS AND ANALYSIS

4.1 Pin Testing

Initial testing was done using a fixture that held two plates side by side making a butt joint. The first tests investigated the strength of a 9 mm pin and a 18 mm bobbin. This preliminary design monolithic tool body with a groove cut out of steel cylinder, which allowed for smooth features on the pin and shoulder. Runs with this tool were done at speeds and feeds of 1200 rpm and 120 ipm respectively. Several passes were made without failure, and loads were captured to determine acceptable loading conditions for a 9mm pin. The base material, Aural 2 sheet in 3mm thickness, was plastically deformed and pushed away from the pin without significant consolidation. This test case, deforming the material without consolidation, was considered to be the upper limit design case for the tool. As the tool survived numerous runs, the loads obtained from these tests were used to establish a baseline safety case for future design efforts.

Figure 4-1: 9 mm Smooth Pin

Figure 4-2: 9 mm Smooth Pin Results

Force data taken from these tests are shown in the following tables and show that the peak lateral forces were 3671 Newtons and the max axial force was 474 Newtons. These turned out to be pretty typical forces for following welds. See Appendix for more graphs and pictures of tests.

Table 4-1: Weld 1 Force Results

Weld 1	
Max RPM	1500
Max X Force (N)	3466
Max Y Force (N)	3671
Max Z Force (N)	474
Max Velocity (mmpm)	1000

4.2 BFSW Testing

4.2.1 Two Plate Welds

Initial tests were performed in the butt joint configuration. As tests were done it was found that the plates would deflect separately from each other making consolidation extremely difficult. Slower rpm and ipm parameters were used to try to reduce to forces exerted on the plates. Tear out, similar to what Kevin Colligan reported, was common thus preventing consolidation even further. After many unsuccessful iterations, it was determined that a more rigid fixture was necessary and that instead of welding a butt joint (which was out of the scope of this research), a single plate would be used. The figures below show the butt joint fixture and a typical weld sample.

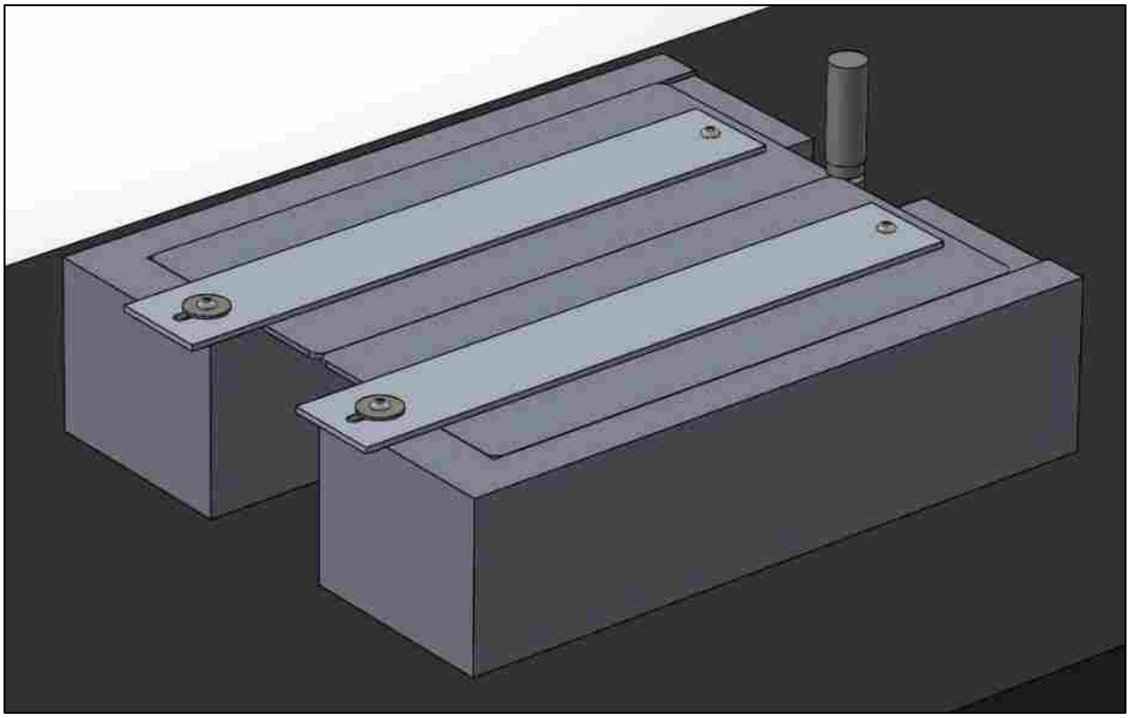


Figure 4-3: Butt Joint Fixture Design

Figure 4-4: Typical Butt Joint Welds

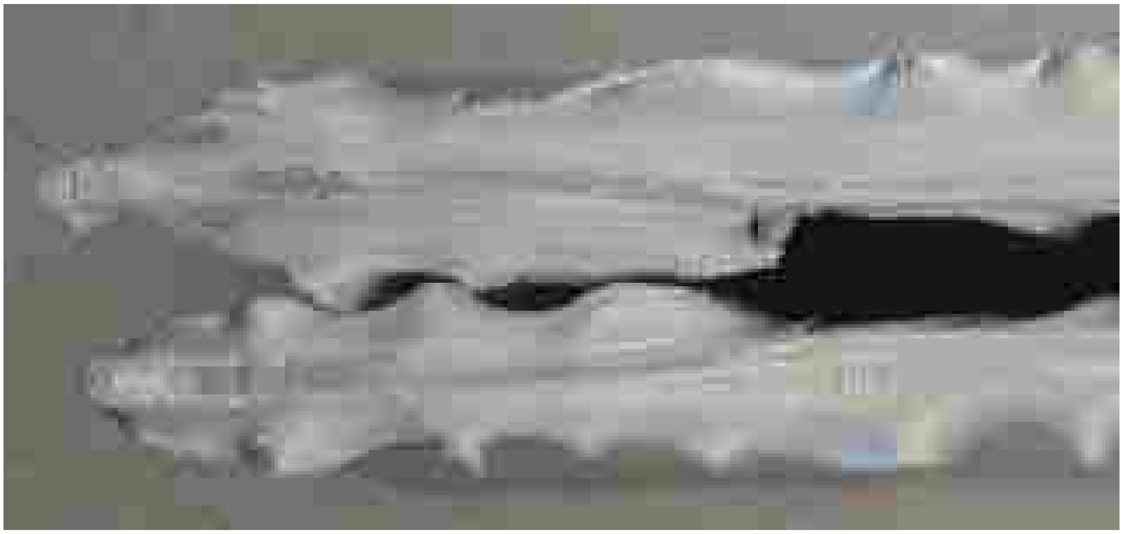


Figure 4-5: Visible Deflection of Plates

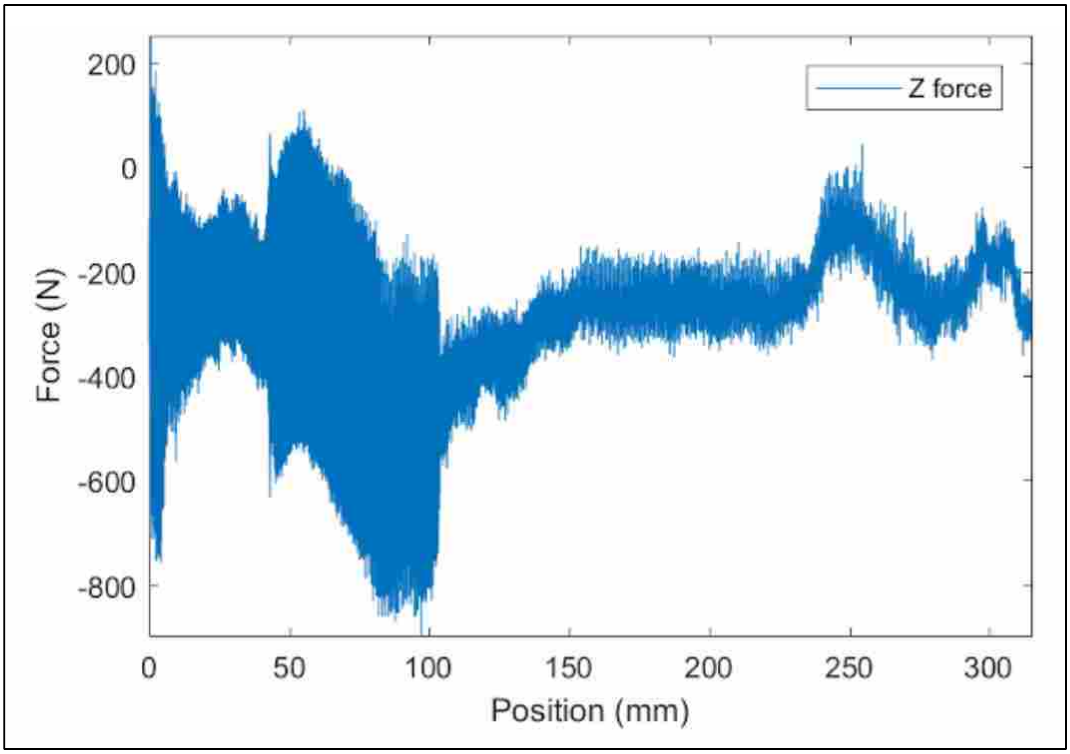


Figure 4-6: Deflection in Z Force

The average lateral force for these tests was 5400 Newtons and the average axial force was 600 Newtons. There was one tool failure when the lateral forces exceeded 6000 Newtons. However, successive forces exceeded that without tool failure. Looking at the graphs below we can see that there were impulses that exceeded 6000 Newtons but overall, were steady around 3500 Newtons. This graph also points out something interesting. For the most part the X and Y forces are somewhat symmetric but for Weld 8 it was not. This may have had something to do with the failure. The difference between the two test parameters was a longer and slower acceleration in Weld 9. There is also some other factor whether it be torque or temperature that plays an important role in tool failure.

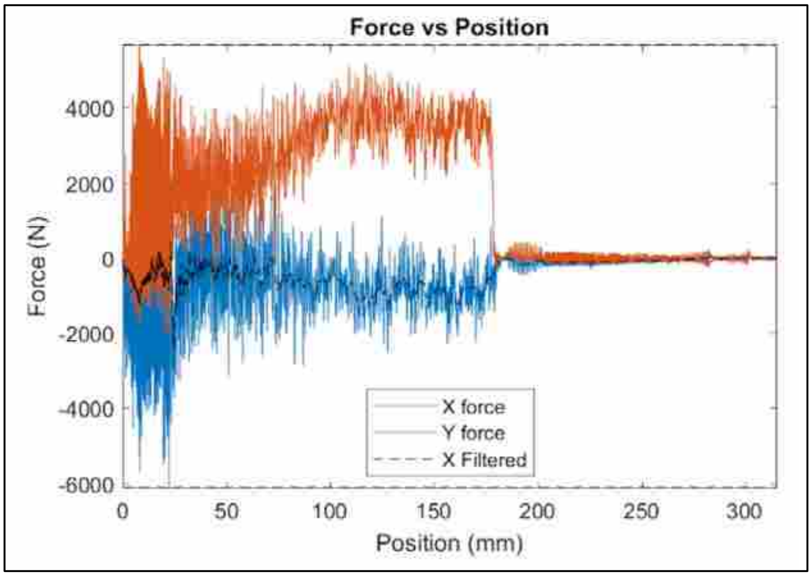


Figure 4-7: Weld 8 Later Forces (Tool Failure)

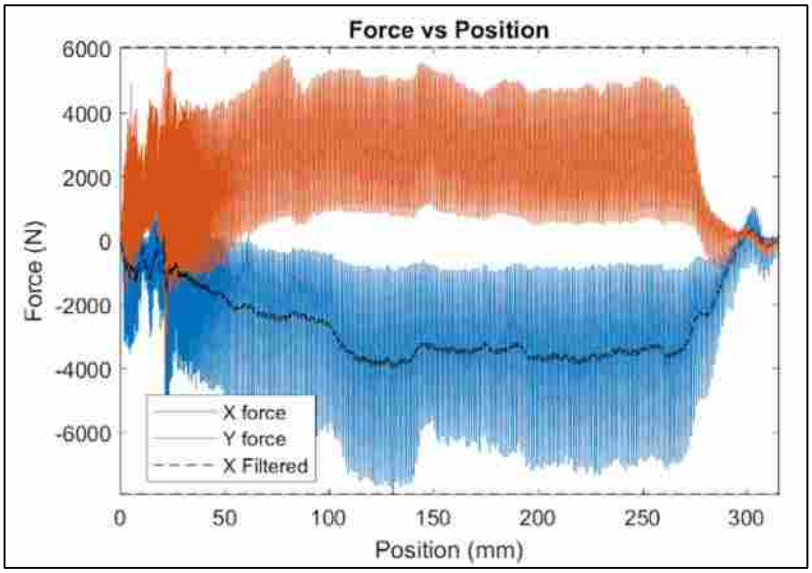


Figure 4-8: Weld 9 Lateral Forces

4.2.2 Single Plate Welds

Once the new fixture was setup, previous run parameters were repeated but led to failure of the pin. The weld parameters for that test were 400 rpm and 20 ipm. The new fixture and single plate design proved to prevent any plate flexure. The forces exerted on the tool showed forces in excess of 5000 N. With a more rigid fixture, the rpm and ipm was changed back to Kevin Colligan's recommended rpm of 1400 and an ipm of 98. During this weld, consolidation occurred from the beginning for about an inch but once the rpm dropped and the ramp up to the final ipm begun, consolidation was lost, and a wormhole effect occurred.

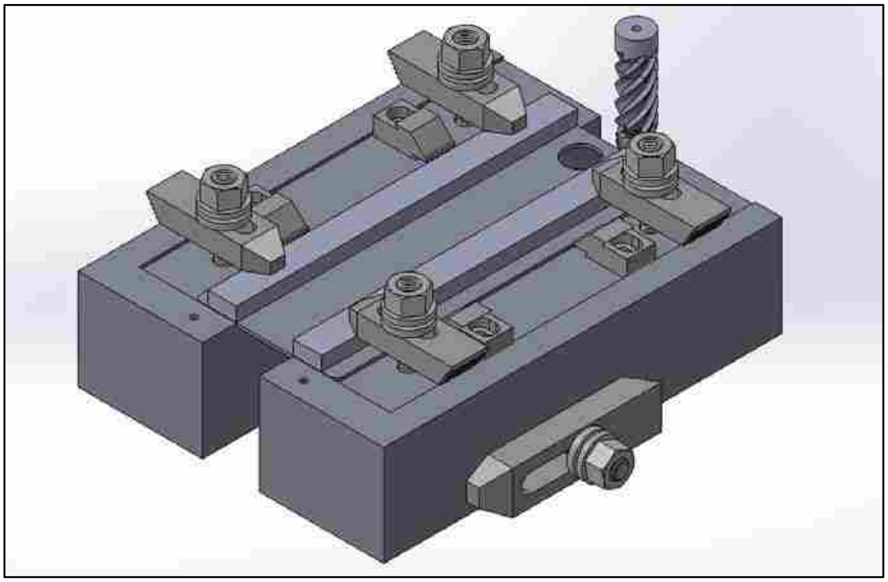


Figure 4-9: Improved Fixture Design

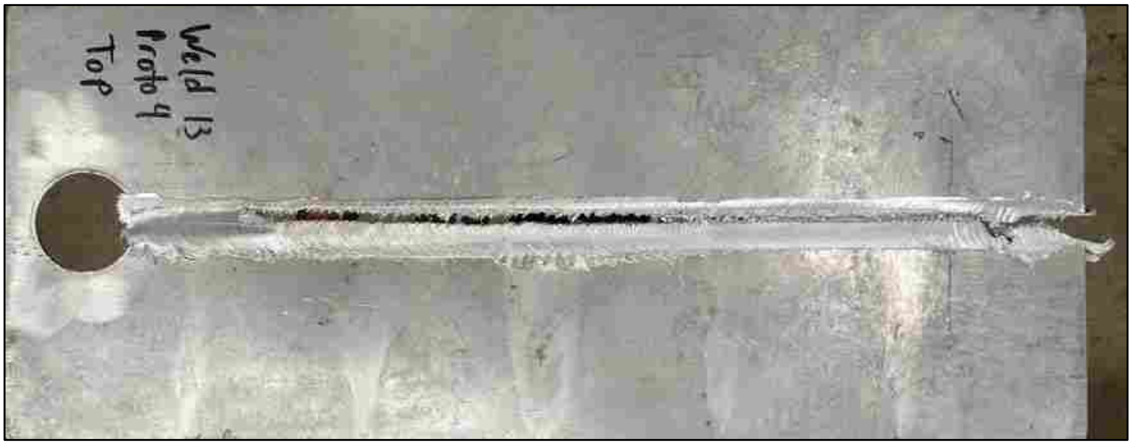


Figure 4-10: Typical Consolidation Success

This test was repeated to see if the process was repeatable. Later welds had similar results, but the results were not successive. Some of the factors to why this may have happened is pin length, Z offset, or a clean tool vs. an aluminum coated tool (from previous weld). The average lateral forces of these welds was 5000 N with the max being 5400 N and a tool failure occurring at 4980 N. This again shows that there is some other factor than force that causes the tool to fail.

Initiating a weld was successful but maintaining consolidation throughout the entire length of the weld proved to be difficult with the combined tool with cutters. However, as noted in the delimitations, development of the BFSW process parameters was outside the scope of this research, as others have successfully joined 3 mm thick aluminum plates.

4.3 Cutter Testing

4.3.1 Axial Entry and Exit

Initial testing of the BFSW tool with cutters consisted of evaluating the feeds and speeds of the combined tool. Axial plunges and lateral movements were investigated at different depths on a manual mill. The tool experienced some chip weld while plunging which was expected. Chip weld is when the material being cut gets too hot and instead of being cut, it becomes soft and sticky much like the plastic flow in the traditional FSW process. This might be a problem due to the heat generated in FSW. Side milling and end milling tests were conclusive that the tool could successfully cut Aural-2 at the calculated RPMs that yielded the best consolidation during the FSW tests (discussed in the next section). The cutters ideal speed and feed is 1000 rpm and 90 ipm which is right in the range of the parameters set for FSW. The bobbin cutter effectively cleared chips during initial testing. The lower portion evacuated the chips upwards and the upper portion evacuated the chips downwards.

Investigation of the cutters consisted of two parts. The first test consisted of axially entering a plate, initiating a weld and then axially exiting the same plate. This test investigates the following hypotheses:

1. A bobbin tool augmented with a lower cutter can penetrate an enclosed casting and initiate a weld away from the edge.
2. A bobbin tool augmented with cutters can be removed from the casting away from an edge leaving a clean exit hole without destroying the casting or the tool.

The BFSW end mill successfully entered the material, initiated a weld, and exited the casting without damaging the tool or the casting. However, after about 30 mm, consolidation was lost consistently due to the lack of knowledge in regards to the speeds and feeds of BFSW (which was out of the scope of this research). Because the bobbin cutter did not have center cutting geometry, lateral 5 mm back and forth movements along the X-axis (weld line axis) while plunging down in the Z-axis 1 mm at 75 mmpm. This was repeated until the tool successfully pierced the material. The forces for this weld are found in the table below.

Table 4-2: Weld 20 Force Results

Weld 20	
Max RPM	1402
Max X Force (N)	1697
Max Y Force (N)	1741
Max Z Force (N)	1480
Max Velocity (mmpm)	76

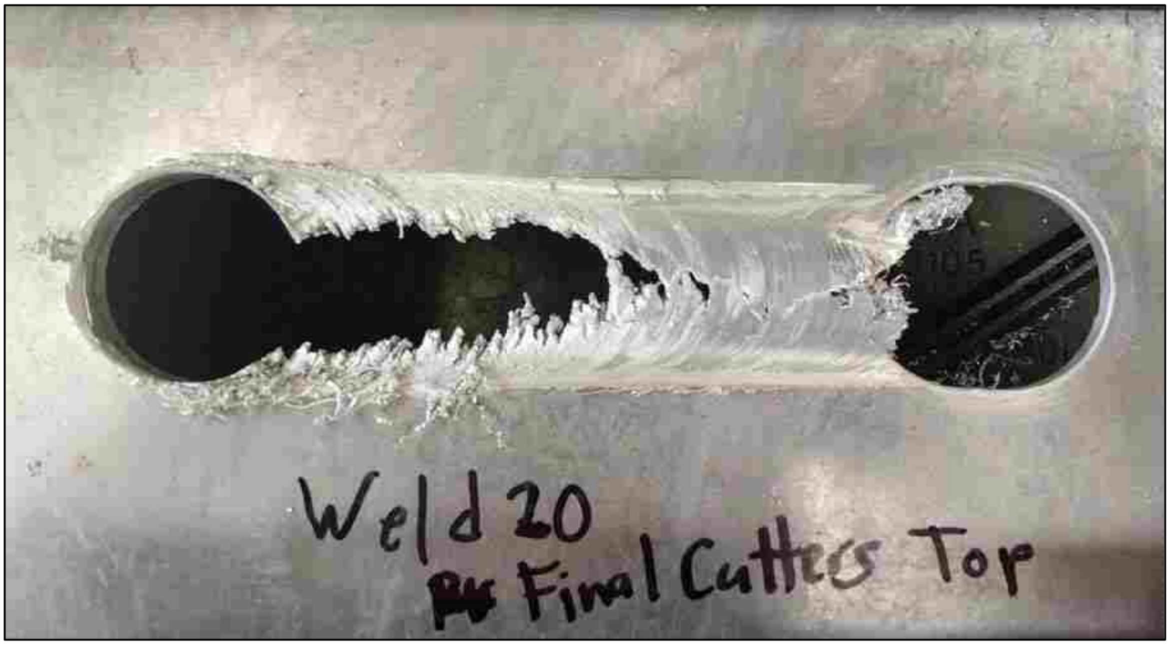


Figure 4-11: Weld 20 Test Result

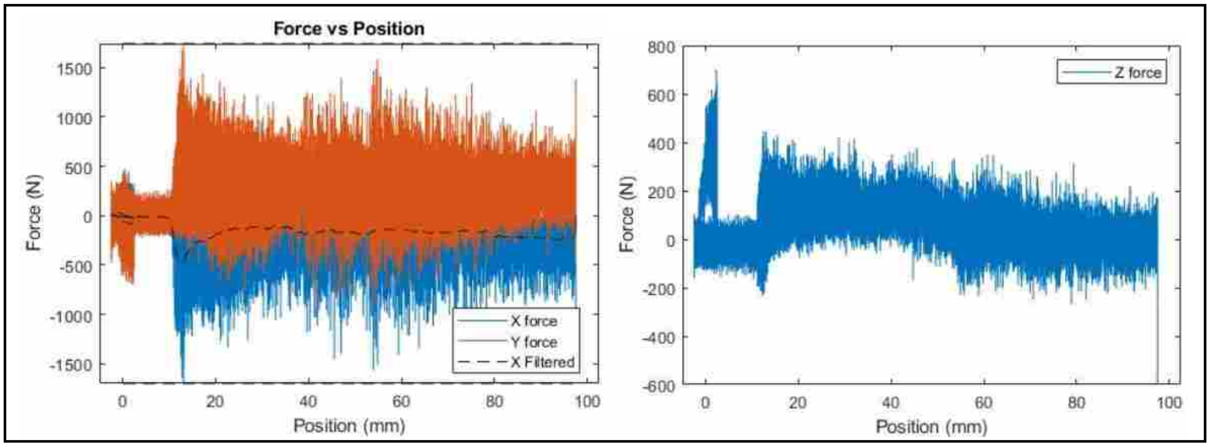


Figure 4-12: Weld 20 Force vs Position Data

Many attempts were done to recreate weld 20, but repeated results were scattered. There was some factor of BFSW that was preventing good consolidation. Some of the factors possibly involved are: pin length, shoulder scroll engagement, top shoulder engagement, the parallelism between the top and bottom shoulder, rpm, ipm, or even scroll geometry. Factors involved in improving the BFSW of the process were considered out of the scope of this work, so efforts were concentrated on establishing the validity of the three hypotheses rather than improving the character of the BFSW results.

Typical forces experienced during these welds were around 2277 Newtons in the X and Y axis and around 1389 Newtons in the Z axis. It was observed that the average lateral forces decreased 42% with the addition of the cutters. This greatly reduced the loads which probably explained why the tool only failed once at the pin when the forces exceeded 4900 Newtons laterally.

4.3.2 Rib Removal

The other cutter test consists of cutting through varying thicknesses to simulate ribs which are common in a HPVDC part. This test was designed to validate the hypothesis that friction stir welding with a bobbin tool with combined cutters can remove any inconsistencies in the material thickness while maintaining welding. This test was carried out by adding ribs to a plate in different places to simulate different scenarios. The scenarios tested were as follows:

- Rib above the weld line
- Rib below the weld line
- Rib above and below the weld line
- Varying rib length

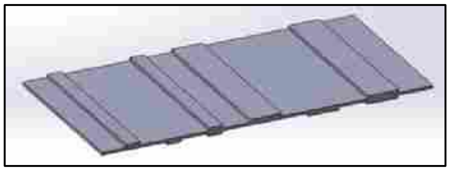


Figure 4-13: Rib Cutting Test Design

Because weld parameters were not ironed out, a slot was cut out of the center panel to allow room for the pin to spin freely while the cutter still engaged the ribs allowing for the testing of the cutters effectiveness. The ribs were epoxied on and then clamped down to keep them fixed. After the first test running at 1000 rpm and 40 ipm the cutters made it halfway through the first rib when the rib broke free and started moving with the cutters. It is important to note the chip weld started to form just before the rib broke free. This was due to the heat generated by the tool and the plate. Once the tool heated up, the plate material became sticky or gummy and filled in the flutes thus preventing further cutting. This lack of cutting created forging forces in excess of 9,000 Newtons resulting in tool failure at the pin.

Figure 4-14: Modified Rib Cutting Test Sample

Figure 4-15: Rib Cutting Test (Top)

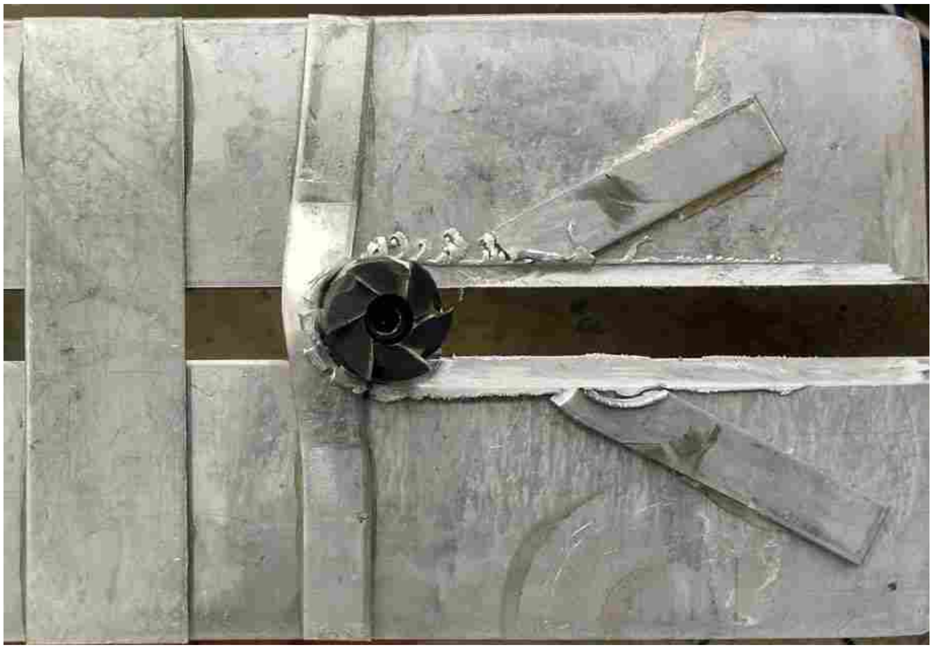


Figure 4-16: Rib Cutting Test (Bottom)

Figure 4-17: Chip Weld in Final Cutter

Table 4-3: Rib Removal Force Results (Tool Failure)

Rib Removal Test	
Max RPM	1002
Max X Force (N)	9066
Max Y Force (N)	4460
Max Z Force (N)	1657
Max Velocity (mmpm)	800

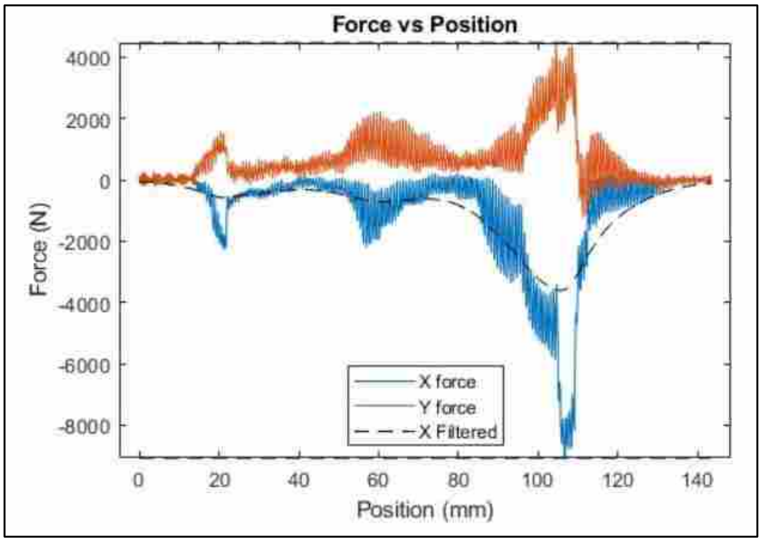


Figure 4-18: Rib Removal Test Lateral Forces

When cutting metal, it is important that the temperatures remain low, this is why coolant is used in all CNC mills and lathes, even some bandsaws have coolant. However, FSW works on the premise of heat which is necessary to plastically deform the material, while machining works on the premise of cold shearing. Furthermore, the calculations for cutting speeds and feeds assume that coolant is being used. If coolant is not used, then the speeds and feeds need to be slowed down to help keep the temperature low. Unless a material like carbide or PCBN was used for the cutters and is thermally isolated from the FSW process, then chip weld will most likely form on any cutting tool.

Further testing was done with OEM end mills of similar size. Running at the same speeds as the first test, chip weld still occurred with a 6 fluted end mill. Another test with a 3 fluted end mill at 800 rpm and 25 ipm proved successful but left a poor surface finish. The test was repeated at 600 rpm and 20 ipm in hopes to get a better surface finish but ended up creating chip weld after about 2 inches of travel. It is important to note that both the OEM end mills and the machined end mill created the same peeling effect in front of the cut (see figures 4-15,16,21). This area of machining gets fuzzy as large end mills aren't used frequently and definitely not for the application of cutting .125" plate in one pass. Further research should be done with large end mills with the intent on finding the optimum speed and feed for machining this material.

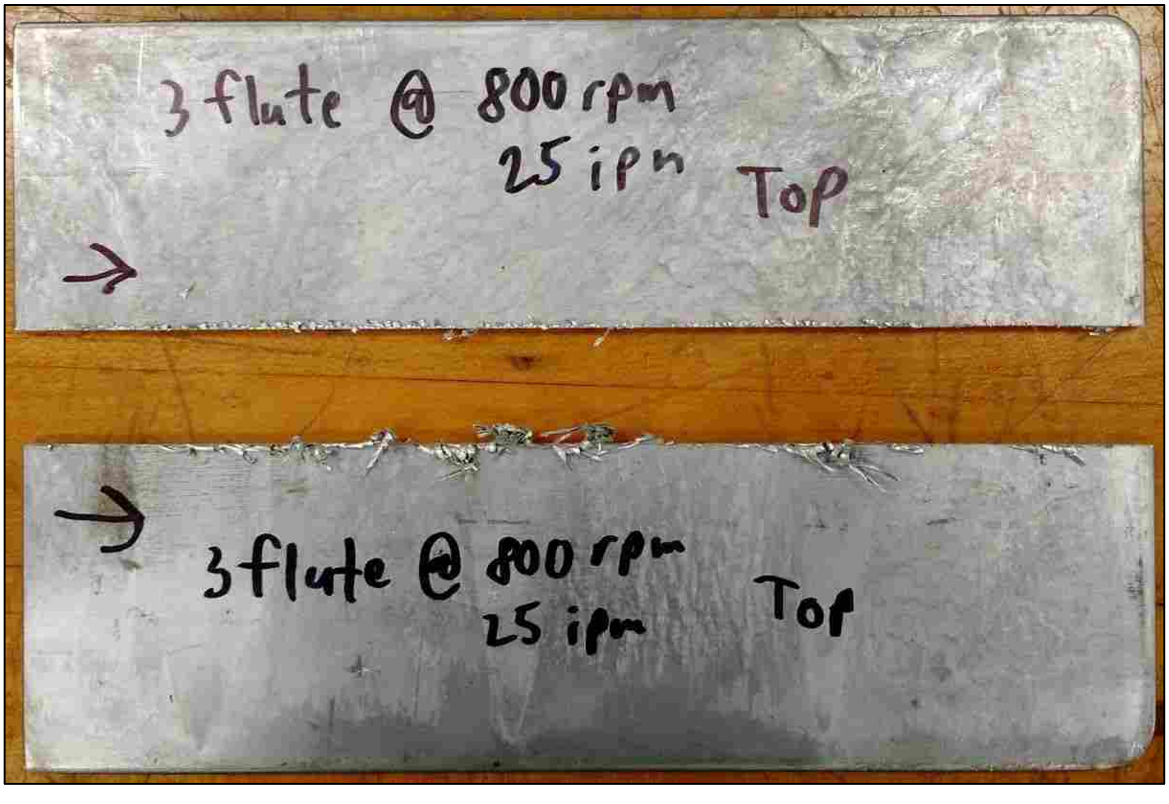


Figure 4-19: 3 Flute Cutting Test 1

Figure 4-20: 3 Flute Cutting Test 2

Figure 4-21: 3 Flute Cutting Test 2 (Peeling)

Figure 4-22: Chip Weld in 6 Flute End Mill

Figure 4-23: Chip Weld in 3 Flute End Mill

Force data was recorded while performing the end mill tests and is tabulated below. It is important to note that all end mill tests were aborted (with exception of the 3 flute end mill run 1) shortly after chip weld build up started to forge the material instead of cutting it.

Table 4-4: OEM Six Flute End Mill Results (Aborted)

Six Flute End Mill	
Max RPM	1002
Max X Force (N)	3649
Max Y Force (N)	2315
Max Z Force (N)	433
Max Velocity (mmpm)	800

Table 4-5: OEM Three Flute End Mill Run 1 Results

Three Flute End Mill Run 1	
Max RPM	802
Max X Force (N)	689
Max Y Force (N)	946
Max Z Force (N)	124
Max Velocity (mmpm)	635

Table 4-6: OEM Three Flute End Mill Run 2 Results (Aborted)

Three Flute End Mill Run 2	
Max RPM	602
Max X Force (N)	2547
Max Y Force (N)	1453
Max Z Force (N)	53
Max Velocity (mmpm)	500

5 CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

The purpose of this research was to test the feasibility of augmenting a BFSW tool with cutters to join enclosed castings. To achieve this goal, three hypotheses were investigated and are concluded as follows:

1. A bobbin tool augmented with a lower cutter can penetrate an enclosed casting and initiate a weld away from the edge.

This hypothesis is not rejected. Through testing, it was found that a bobbin with cutters can indeed enter a casting and initiate a weld. Depending on the tool geometry, lateral movements are recommended when axially cutting (as mentioned in chapter 4).

2. Friction stir welding with a bobbin tool with combined cutters can remove any inconsistencies in the material thickness while maintaining welding.

This hypothesis is rejected under the current scope of this research. This hypothesis was rejected due to the results of initial rib removal tests. When performing rib removal tests using end mills made of H13 and high-speed steel (HSS) at the speeds that BFSW operates at, chip weld occurred thus preventing the cutting of the ribs. It may be possible to simultaneously weld and machine if the two processes could be thermally isolated, or if different materials are used.

However, for the feeds, speeds, and tool materials investigated herein, it was determined that these two processes were not compatible.

3. A bobbin tool augmented with cutters can be removed from the casting away from an edge leaving a clean exit hole without destroying the casting or the tool.

This hypothesis is not rejected. Initial tests had successful exits even though the tool was filled with aluminum.

5.2 Recommendations

As stated previously, this research was solely to test the feasibility of a BFSW end mill. Areas of further research would include:

1. Tool material optimization for prolonged tool life and machining ability.

Tools were made using the current capabilities at BYU. They could be outsourced and made out materials other than H13 or HSS. Tool geometry could differ from an end mill to more of a sleeve. The bobbin design could be improved so that it can center cut and truly plunge axially.

2. Optimized speeds and feeds for joining Aural-2.

As this was out of the scope of this research, I recommend purchasing a BFSW tool if possible and perform many welds to figure out proper speeds and feeds for joining Aural-2 specifically.

3. Temperature measurement of the weld.

It seemed like consolidation was lost at around 250 °C. Embedding a thermocouple in the tool would help to measure temperatures. This would be beneficial for a temperature-controlled algorithm.

4. Optimizing speeds and feeds for 3 and 6 fluted end mills that are larger than 1” in diameter.

Calculations work really well for end mill sizes between .125” and .75” but anything other than that has not been tested heavily. Further testing could be done to better understand how larger diameter tools cut at high feedrates.

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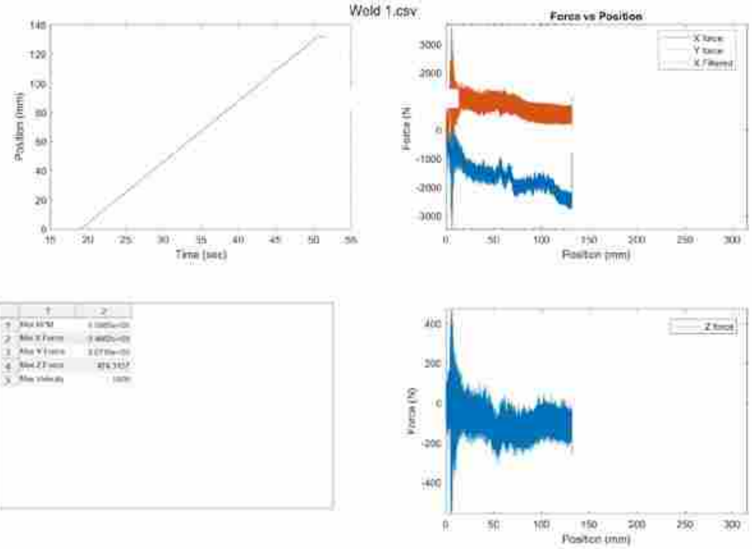
APPENDIX

Test Run Data (Pictures and Force Diagrams)

Weld 1 - 9mm pin

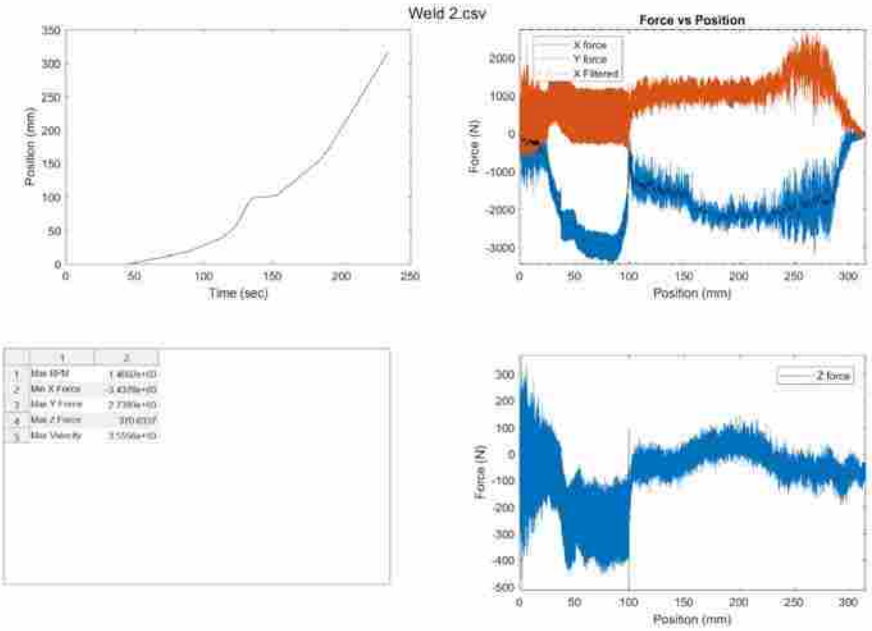
Weld 1
9mm pin



	1	2
1	Max RPM	[illegible]
2	Max X Force	[illegible]
3	Max Y Force	[illegible]
4	Max Z Force	474.3157
5	Max Velocity	1000

Weld 2 - Proto1

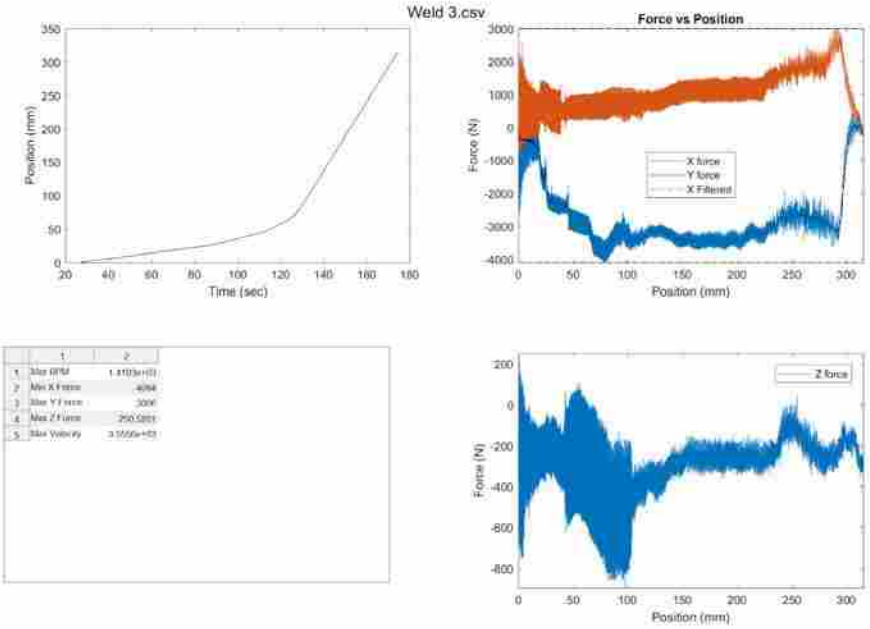
Weld 2
Proto1



	1	2
1	Max RPM	[illegible]
2	Min X Force	[illegible]
3	Max Y Force	[illegible]
4	Max Z Force	[illegible]
5	Max Velocity	[illegible]

Weld 3 - Proto1

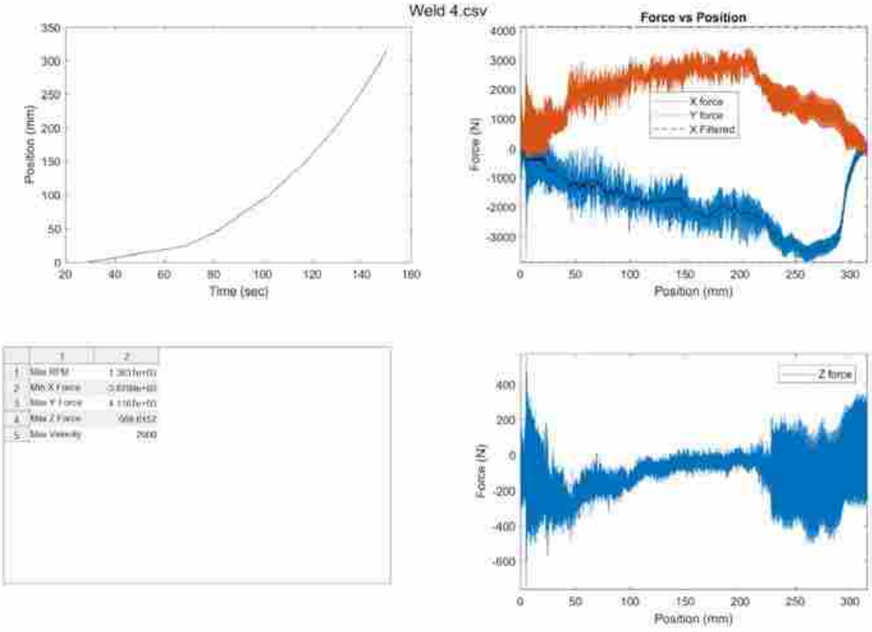
Weld 3
Proto1



	1	2
1	Max RPM	1.4103e+03
2	Min X Force	4094
3	Max Y Force	3000
4	Max Z Force	250.5201
5	Max Velocity	3.1550e+03

Weld 4 - Proto1

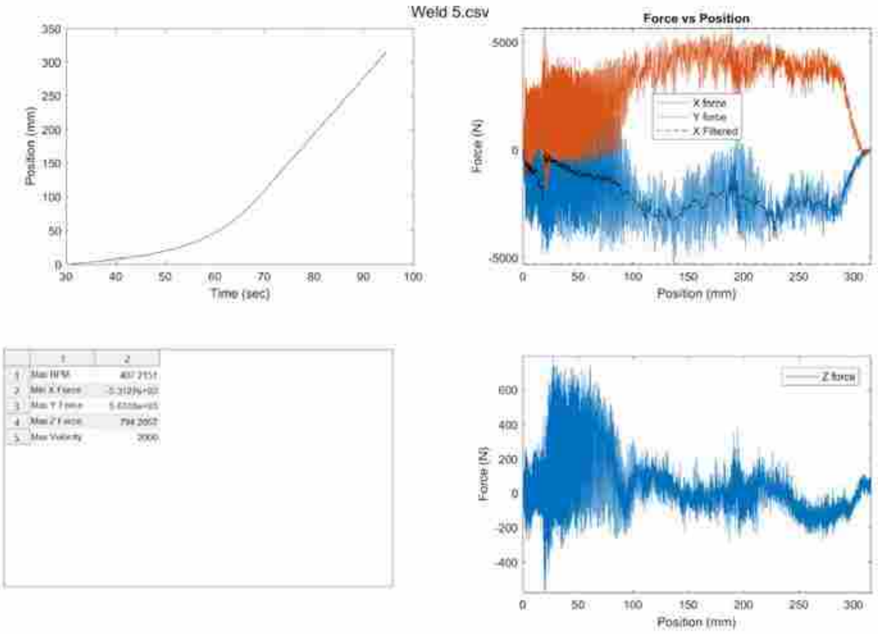
Weld 4
Proto1



	1	2
1	Max RPM	1.3831e+03
2	Min X Force	-3.8398e+03
3	Max Y Force	4.1167e+03
4	Max Z Force	508.6157
5	Max Velocity	2000

Weld 5 - Proto2

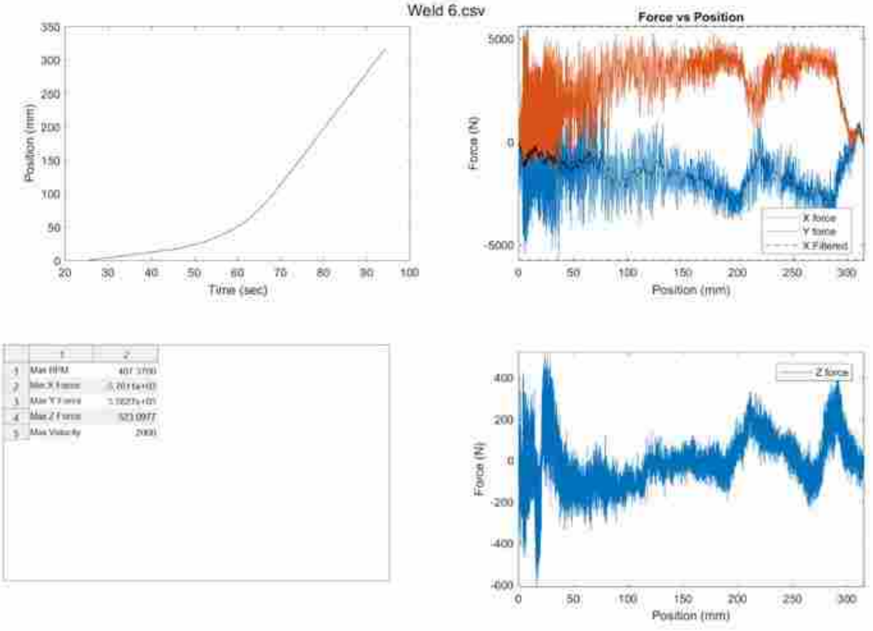
Weld 5
Proto2



	1	2
1	Max RPM	407.2151
2	Min X Force	[illegible]
3	Max Y Force	[illegible]
4	Max Z Force	794.2062
5	Max Velocity	2000

Weld 6 - Proto2

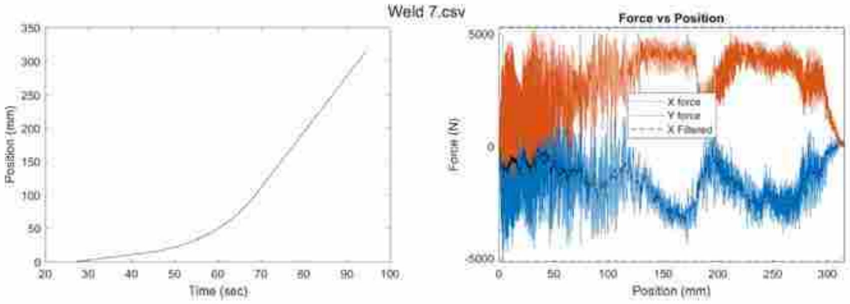
Weld 6
Proto2

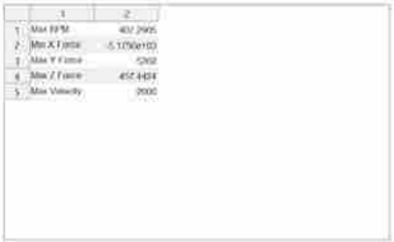


	1	2
1	Max RPM	407.3700
2	Min X Force	-5.7011e+03
3	Max Y Force	5.1027e+03
4	Max Z Force	523.0977
5	Max Velocity	2000

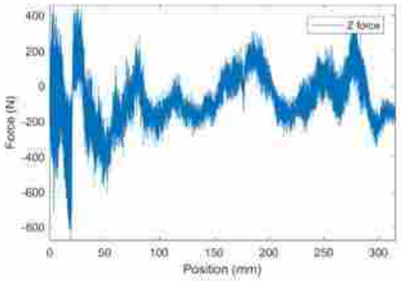
Weld 7 - Proto2

Weld 7
Proto2



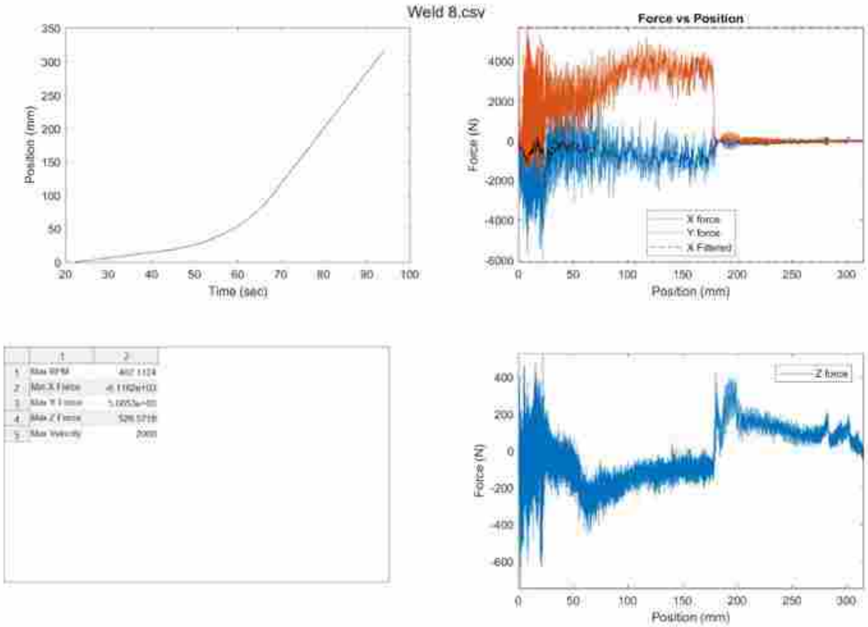


	1	2
1	Max RPM	407.2995
2	Min X Force	-5.1050e+03
3	Max Y Force	5262
4	Max Z Force	457.4404
5	Max Velocity	2000



Weld 8 - Proto2

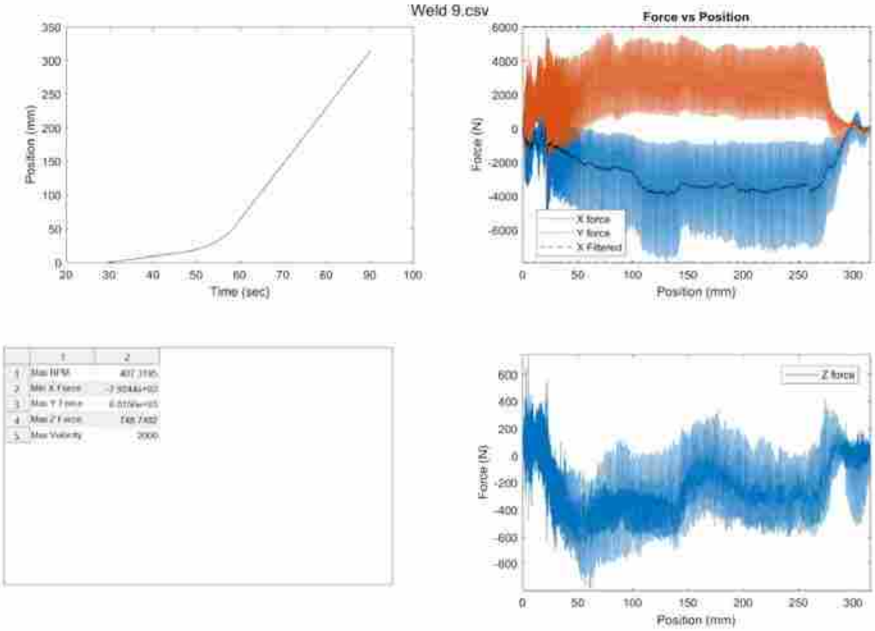
Weld 8
Proto2



	1	2
1	Max RPM	402.1124
2	Min X Force	-6.1192e+03
3	Max Y Force	5.0053e+03
4	Max Z Force	526.5719
5	Max Velocity	2000

Weld 9 - Proto3

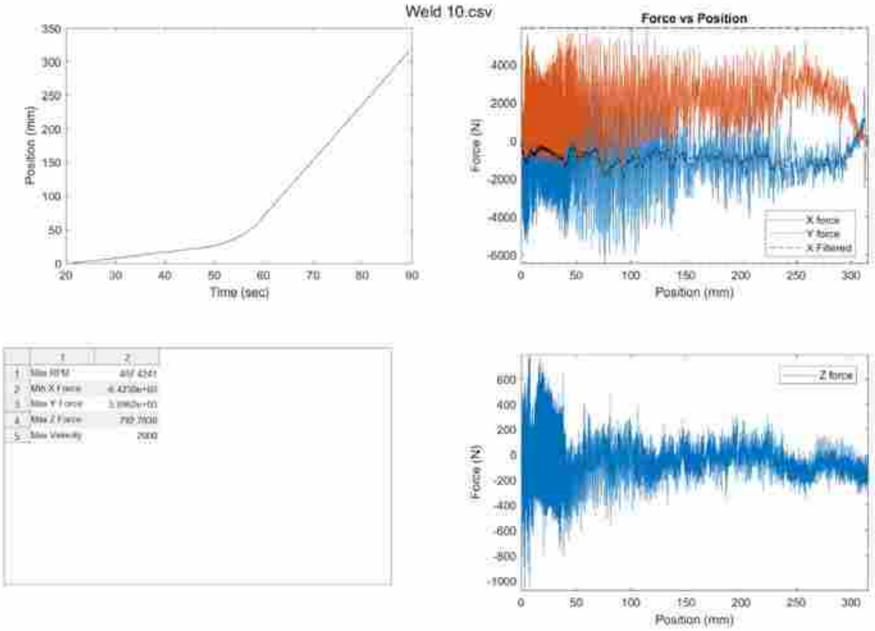
Weld 9
Proto3



	1	2
1	Max RPM	407.3195
2	Min X Force	-7.5044e+03
3	Max Y Force	6.0156e+03
4	Max Z Force	748.7402
5	Max Velocity	2000

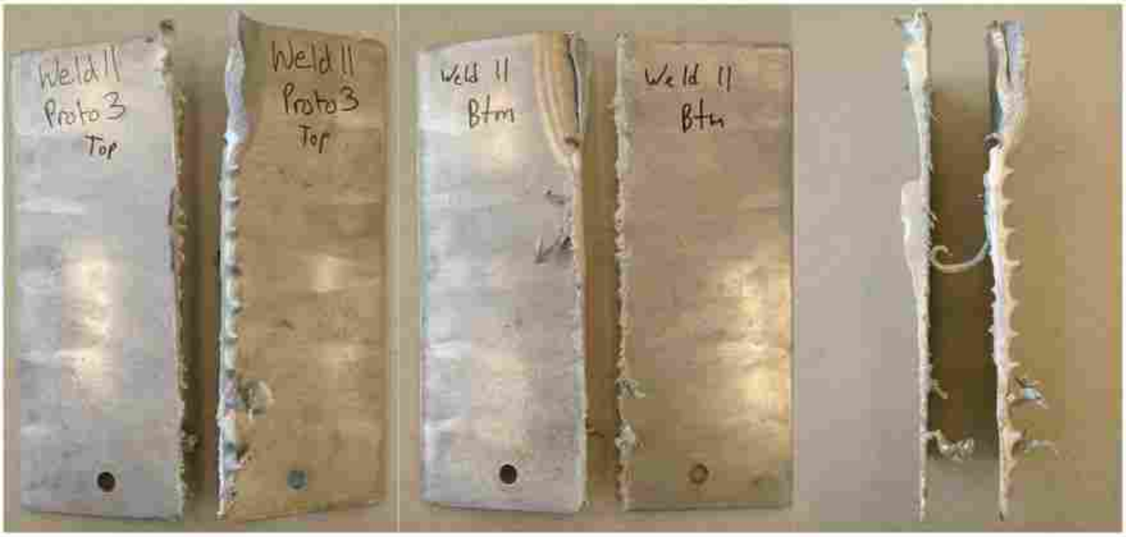
Weld 10 - Proto3

Weld 10
Proto3

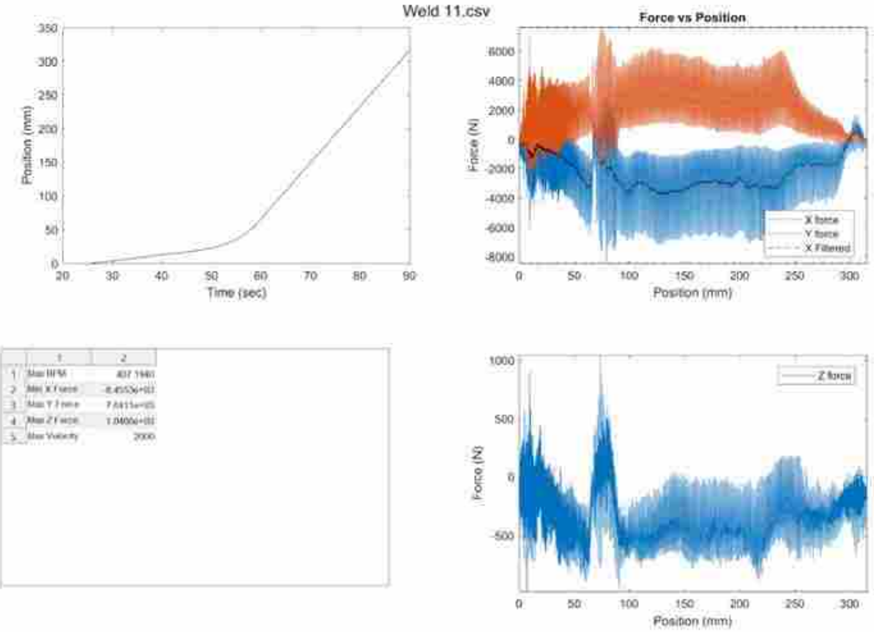


	1	2
1	Max RPM	497.4241
2	Min X Force	-6.4230e+03
3	Max Y Force	5.0962e+03
4	Max Z Force	792.7830
5	Max Velocity	2000

Weld 11 - Proto3



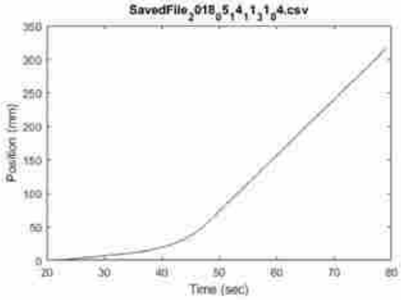
Weld 11
Proto3

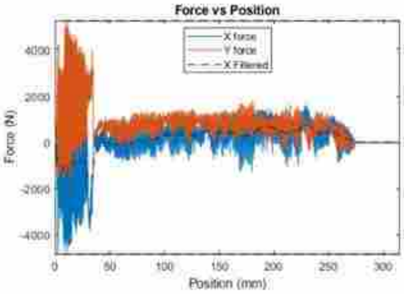


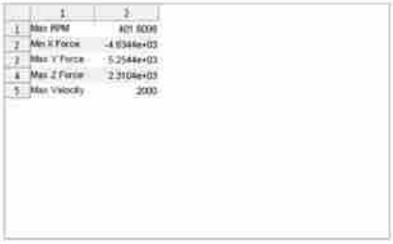
	1	2
1	Max RPM	407.1940
2	Min X Force	-8.4553e+03
3	Max Y Force	7.6411e+03
4	Max Z Force	1.0400e+03
5	Max Velocity	2000

Weld 12 - Proto4

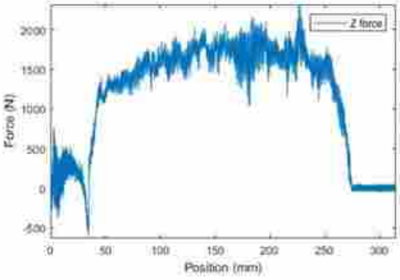
Weld 12
Proto4



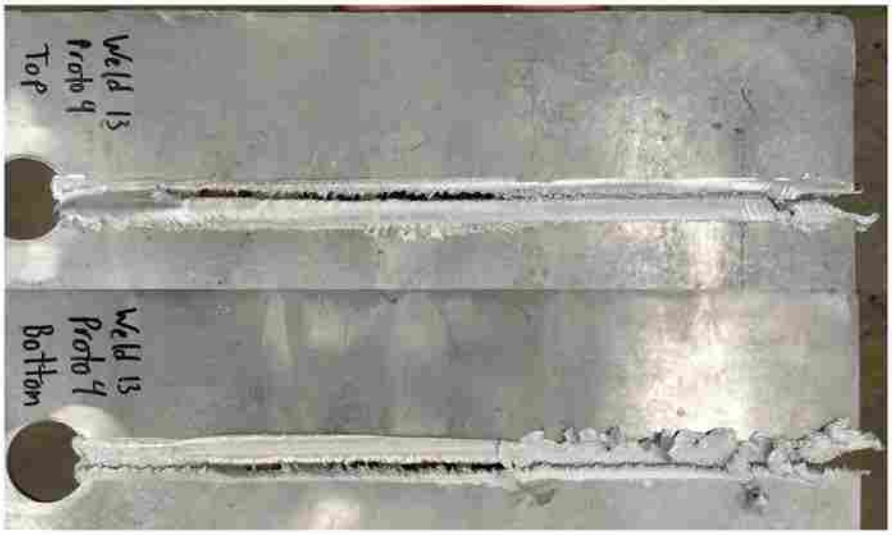




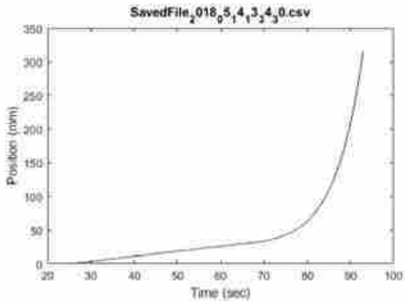
	1	2
1	Max RPM	401.8006
2	Min X Force	-4.6344e+03
3	Max Y Force	5.2544e+03
4	Max Z Force	2.3104e+03
5	Max Velocity	2000

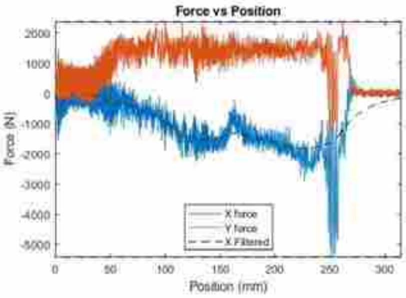


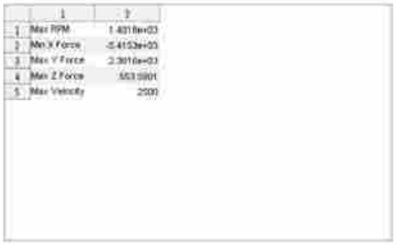
Weld 13 - Proto4



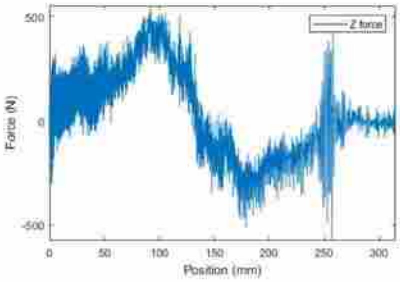
Weld 13
Proto4



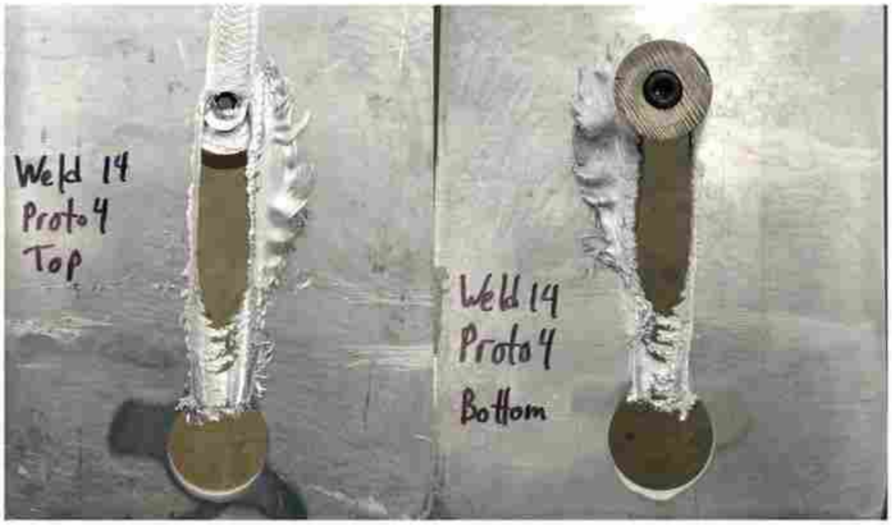




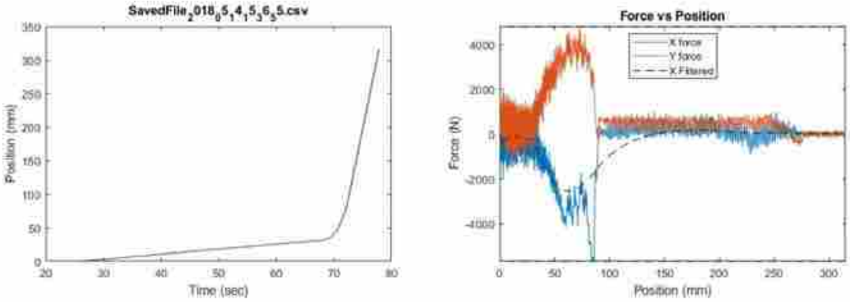
	1	2
1	Max RPM	1.4318e+03
2	Min X Force	-5.4153e+03
3	Max Y Force	2.3916e+03
4	Max Z Force	553.5901
5	Max Velocity	2500

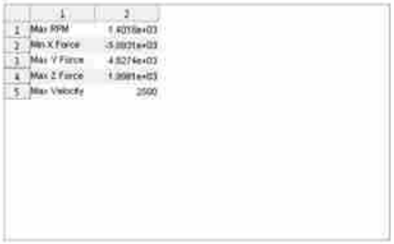


Weld 14 - Proto4

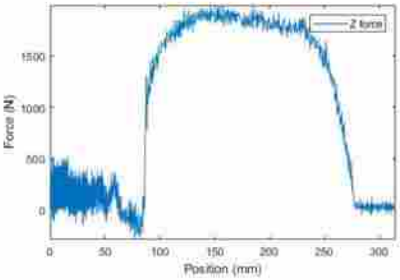


Weld 14
Proto4



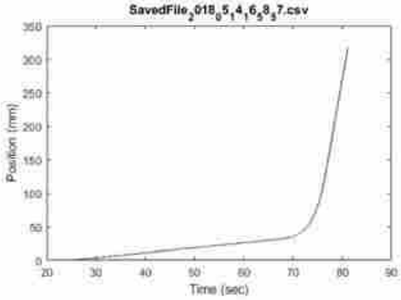


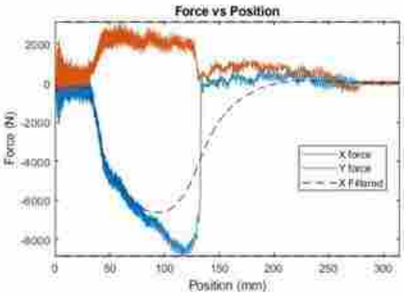
	1	2
1	Max RPM	1.4018e+03
2	Min X Force	-5.0831e+03
3	Max Y Force	4.8274e+03
4	Max Z Force	1.8981e+03
5	Max Velocity	2500

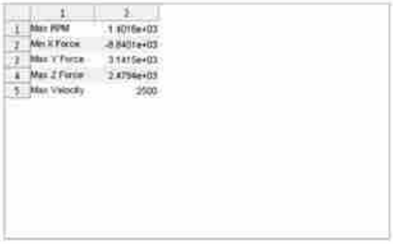


Weld 15
Proto4

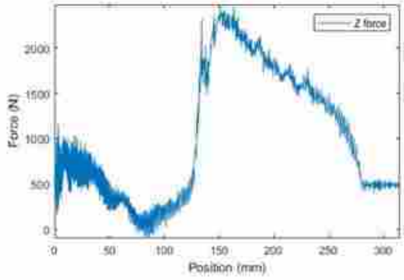
Weld 15
Proto4



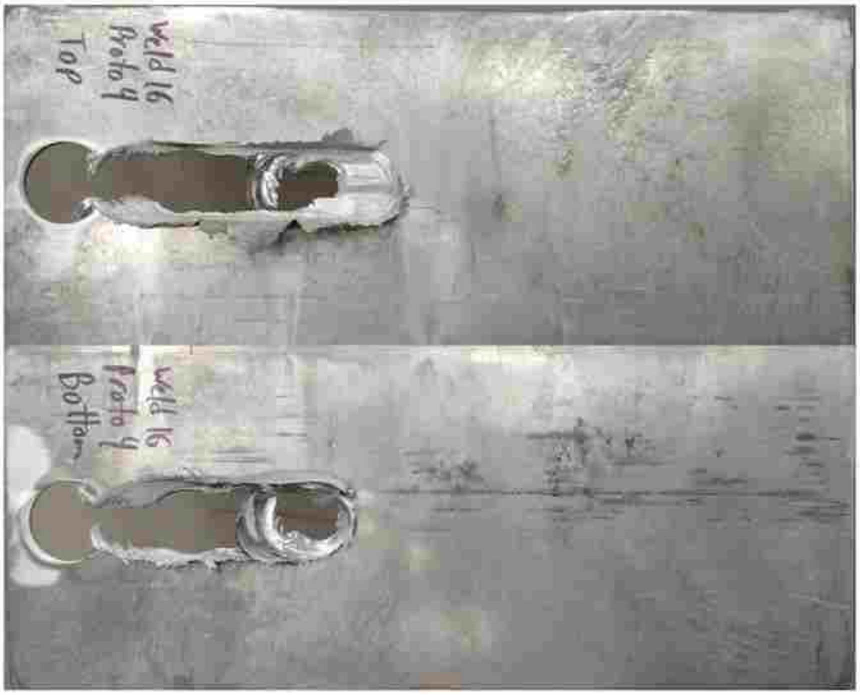




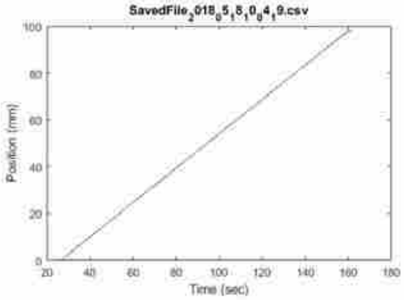
	1	2
1	Max RPM	1.4016e+03
2	Min X Force	-8.6401e+03
3	Max Y Force	3.1415e+03
4	Max Z Force	2.4794e+03
5	Max Velocity	2500

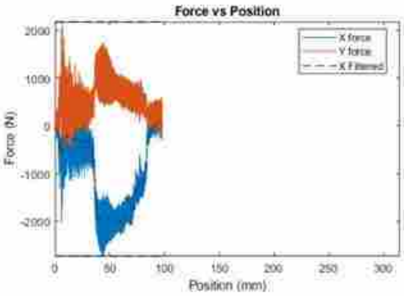


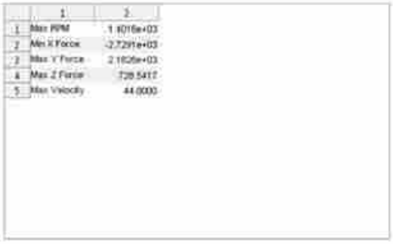
Weld 16
Proto4



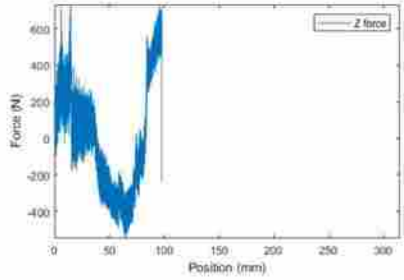
Weld 16
Proto4



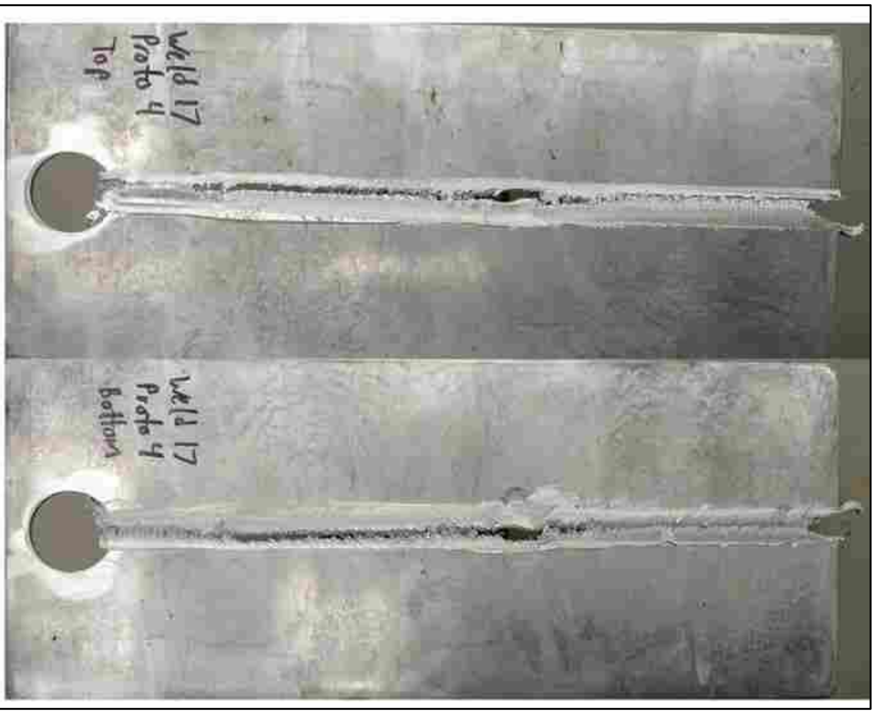




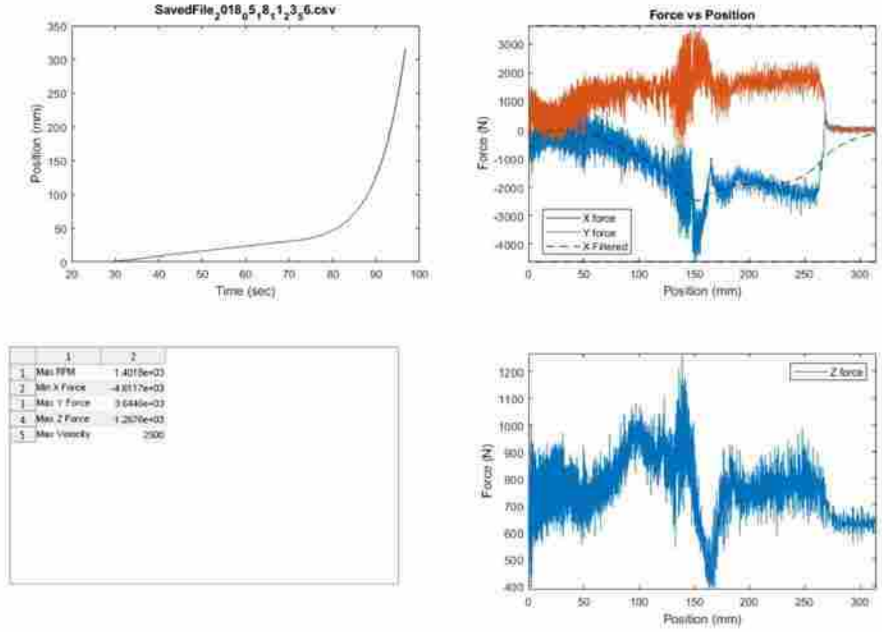
	1	2
1	Max RPM	1.4016e+03
2	Min X Force	-2.7291e+03
3	Max Y Force	2.1626e+03
4	Max Z Force	728.5417
5	Max Velocity	44.0000



Weld 17
Proto4

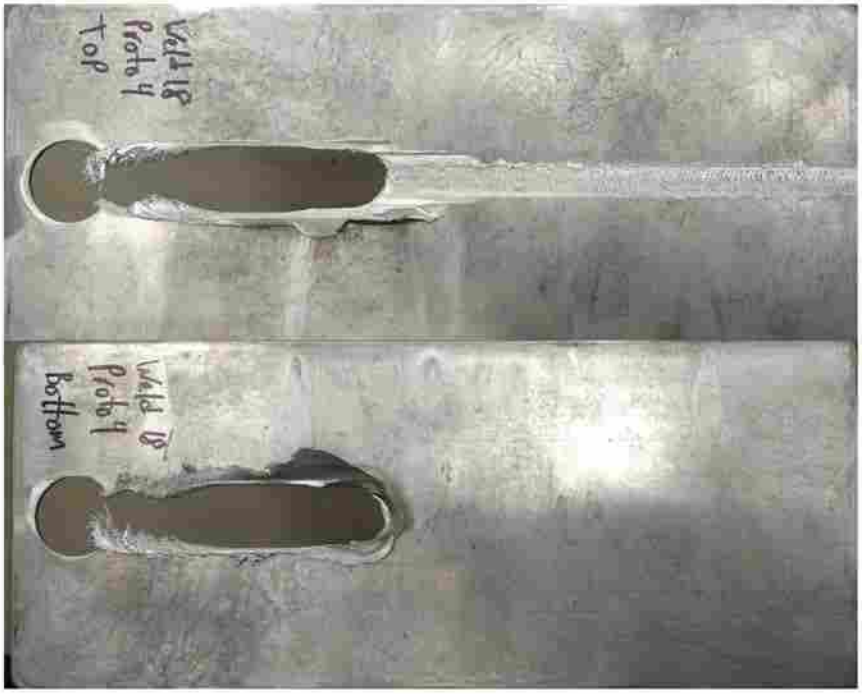


Weld 17
Proto4

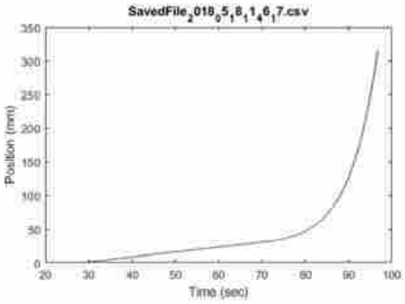


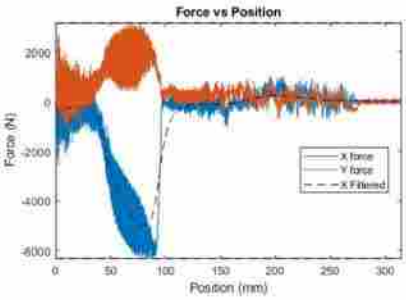
	1	2
1	Max RPM	1.4018e+03
2	Min X Force	-4.6117e+03
3	Max Y Force	3.6446e+03
4	Max Z Force	1.2676e+03
5	Max Velocity	2500

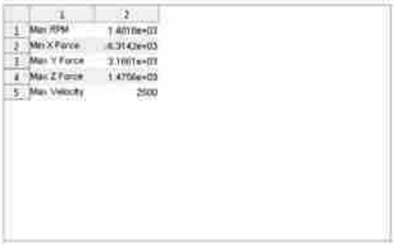
Weld 18
Proto4



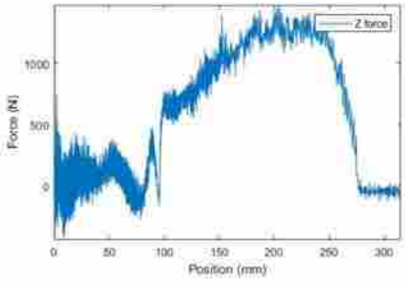
Weld 18
Proto4



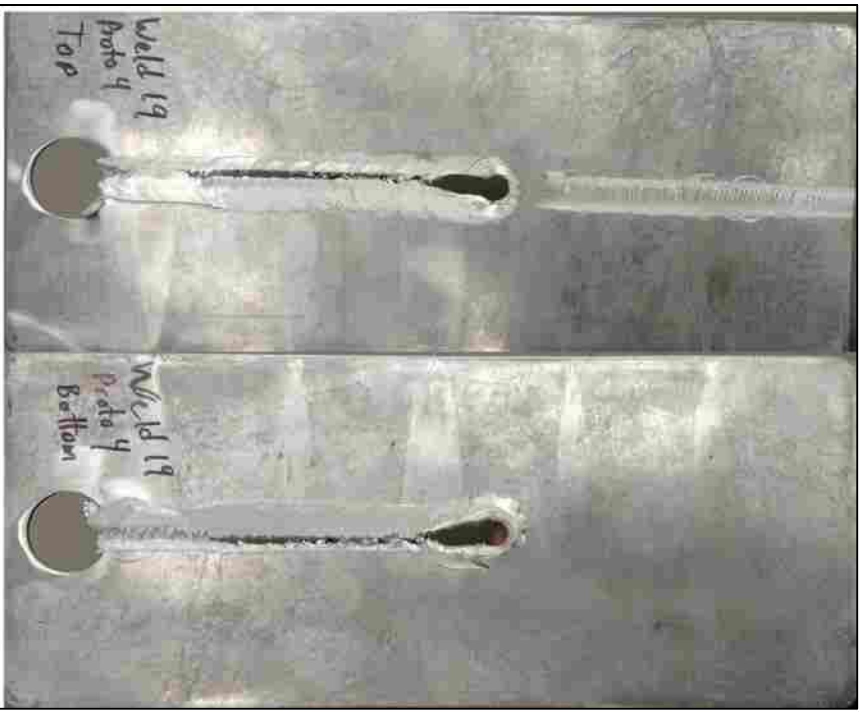




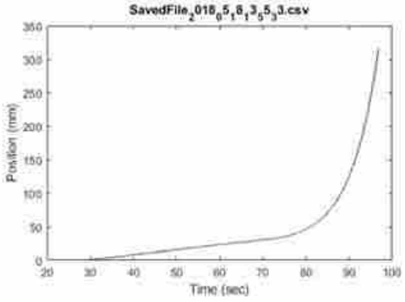
	1	2
1	Max RPM	1.4010e+03
2	Min X Force	-6.3142e+03
3	Max Y Force	3.1661e+03
4	Max Z Force	1.4706e+03
5	Max Velocity	2500

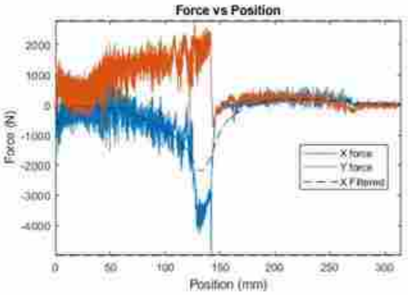


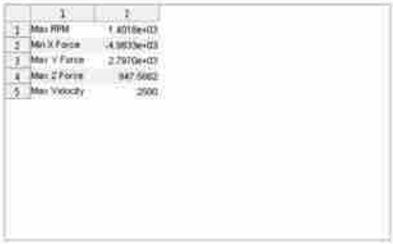
Weld 19
Proto4



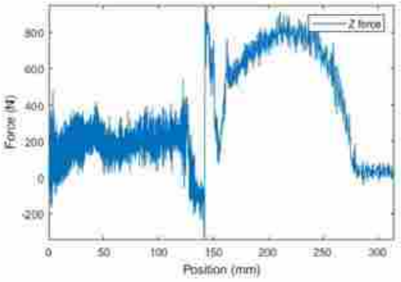
Weld 19
Proto4

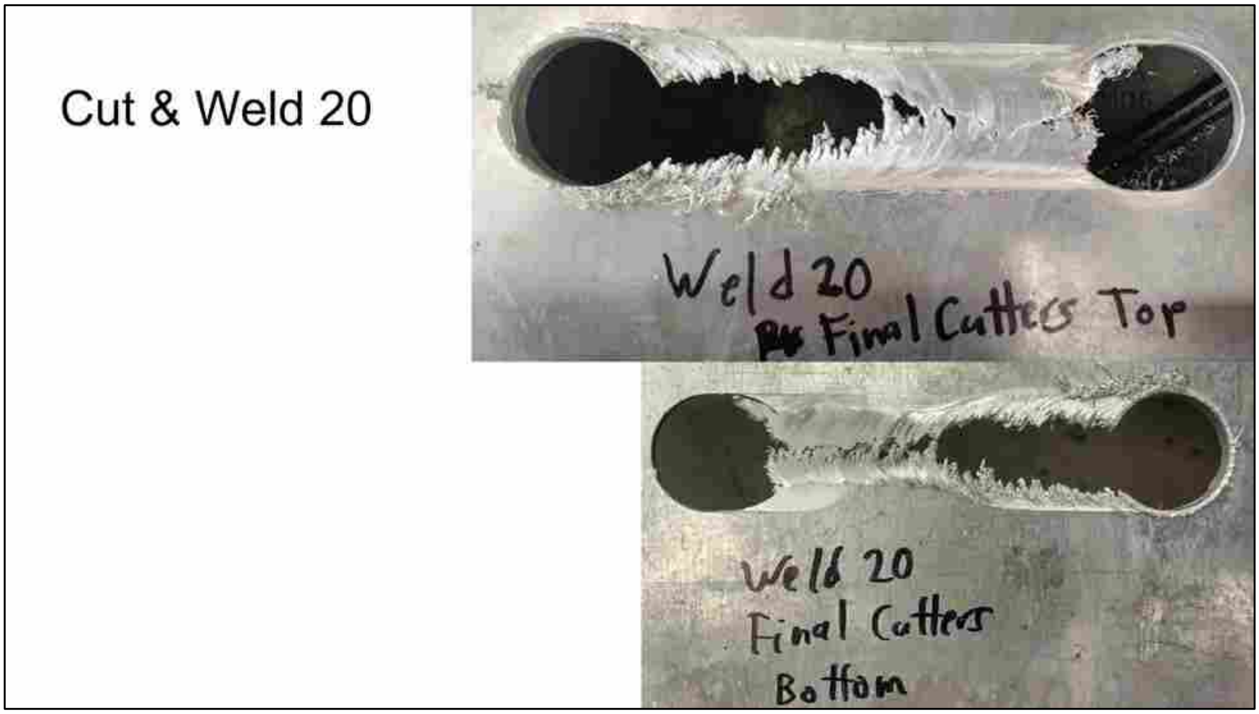




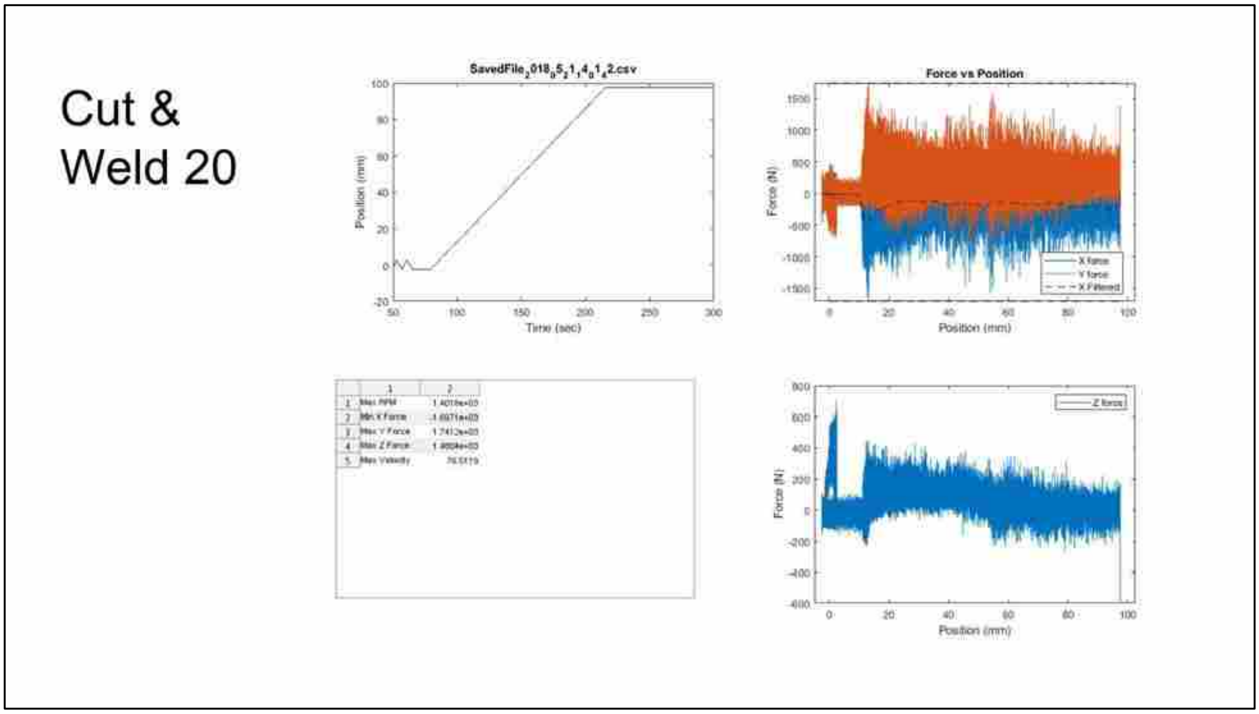


	1	2
1	Max RPM	1.4018e+03
2	Min X Force	-4.9833e+03
3	Max Y Force	2.7970e+03
4	Max Z Force	947.5662
5	Max Velocity	2500





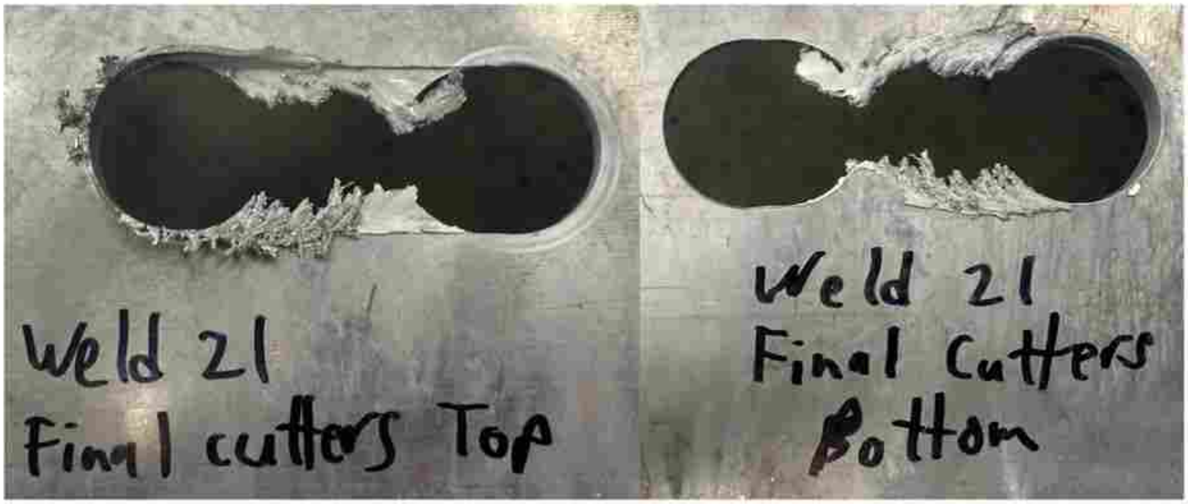
Cut & Weld 20



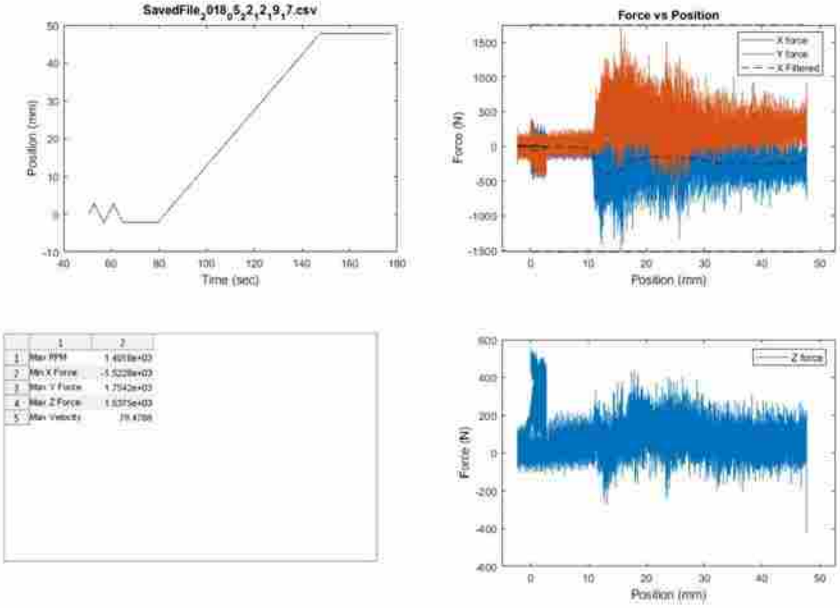
Cut & Weld 20

	1	2
1	Max RPM	1.4018e+03
2	Min X Force	-1.6971e+03
3	Max Y Force	1.7412e+03
4	Max Z Force	1.4804e+03
5	Max Velocity	76.5119

Cut & Weld 21



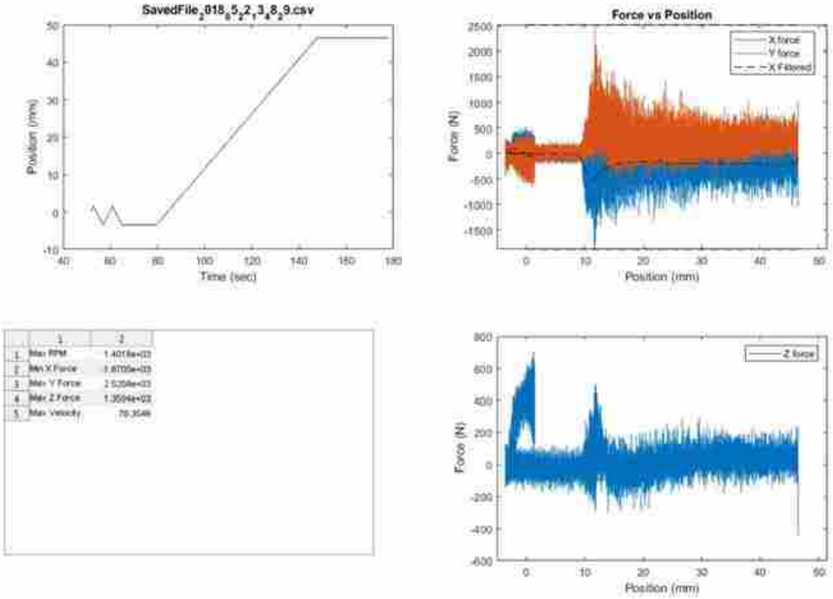
Cut & Weld 21



	1	2
1	Max RPM	1.4018e+03
2	Min X Force	-1.5228e+03
3	Max Y Force	1.7542e+03
4	Max Z Force	1.5375e+03
5	Max Velocity	39.4788

Cut & Weld 22

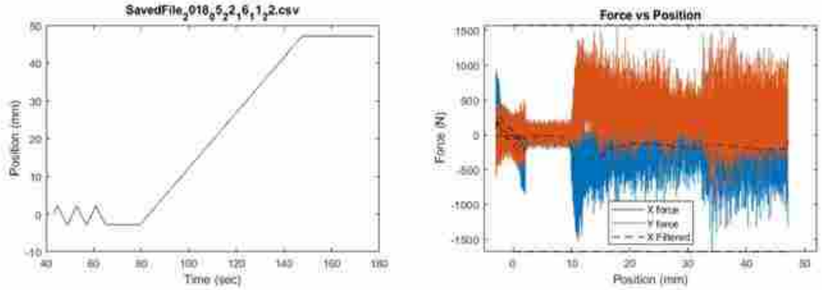
Cut & Weld 22



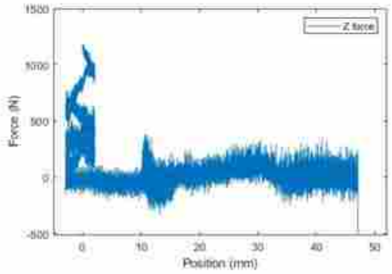
	1	2
1	Max RPM	1.4016e+03
2	Min X Force	-1.8700e+03
3	Max Y Force	2.5208e+03
4	Max Z Force	1.3504e+03
5	Max Velocity	78.3546

Cut & Weld 23

Cut & Weld 23

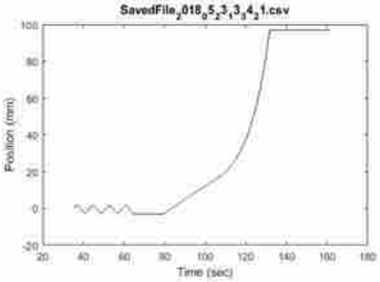


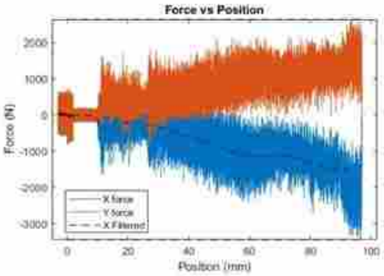
	1	2
1	Max RPM	1.4010e+03
2	Min X Force	-1.6740e+03
3	Max Y Force	1.5700e+03
4	Max Z Force	1.4570e+03
5	Max Velocity	77.2194

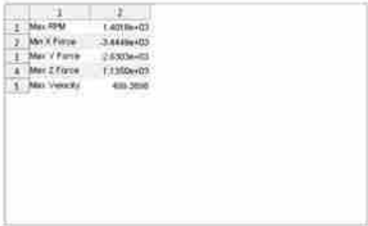


Cut & Weld 24

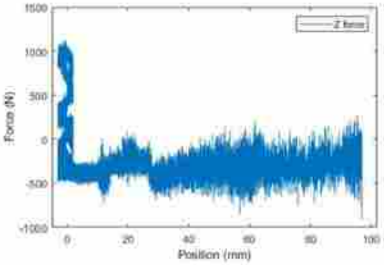
Cut & Weld 24



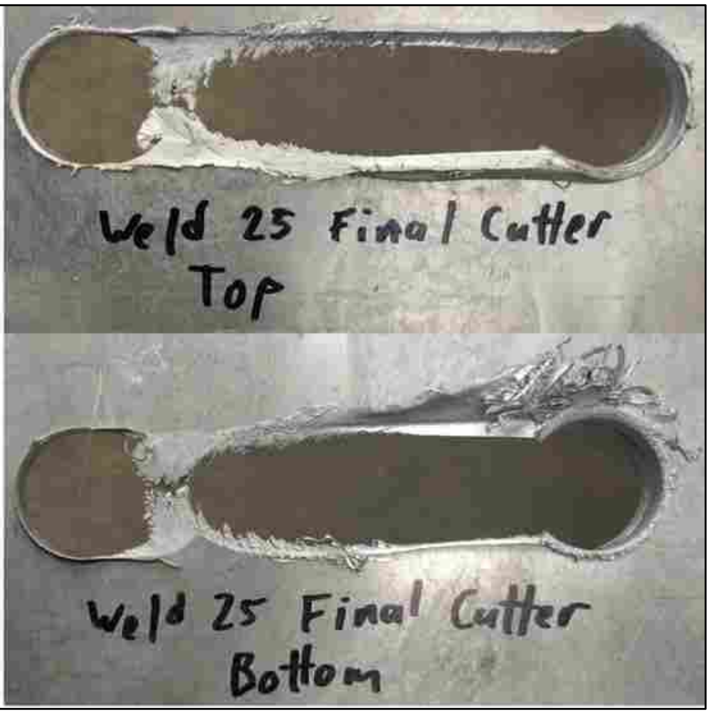




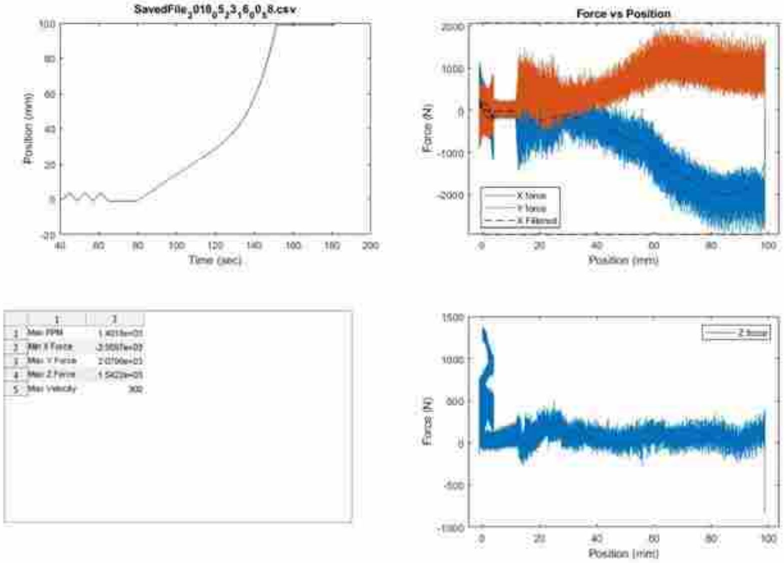
	1	2
1	Max RPM	1.4018e+03
2	Min X Force	-3.4449e+03
3	Max Y Force	2.6303e+03
4	Max Z Force	1.1350e+03
5	Max Velocity	400.3898



Cut & Weld 25



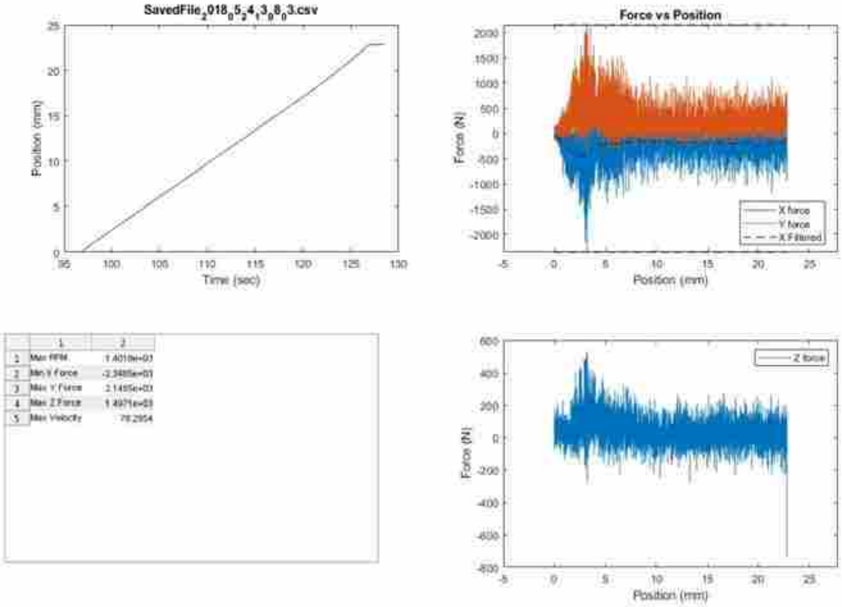
Cut & Weld 25



	1	2
1	Max RPM	1.4018e+03
2	Min X Force	-2.5697e+03
3	Max Y Force	2.0706e+03
4	Max Z Force	1.5422e+03
5	Max Velocity	300

Cut & Weld 26

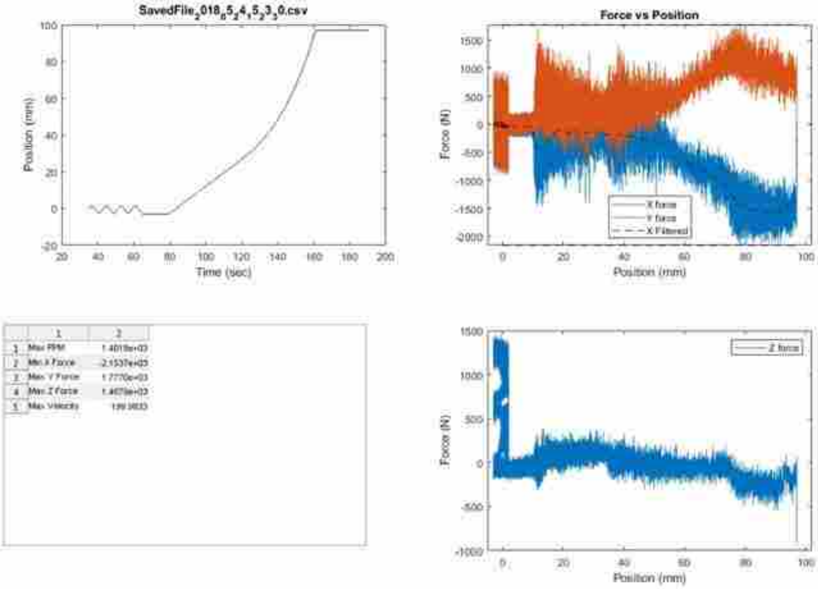
Cut & Weld 26



	1	2
1	Max RPM	1.4010e+03
2	Min Y Force	-2.3485e+03
3	Max Y Force	2.1455e+03
4	Max Z Force	1.4971e+03
5	Max Velocity	78.2954

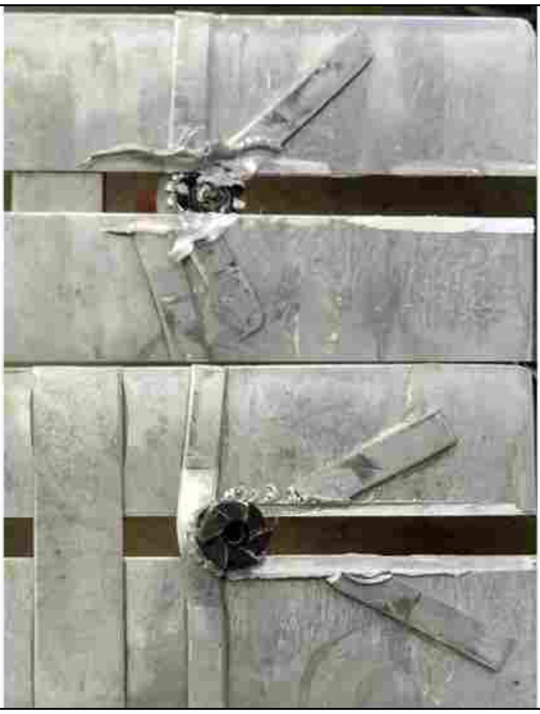
Cut & Weld 27

Cut & Weld 27

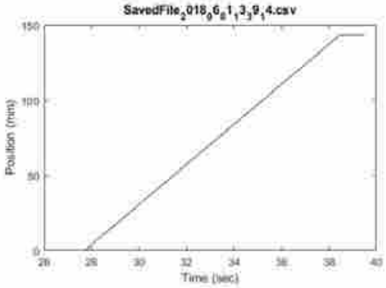


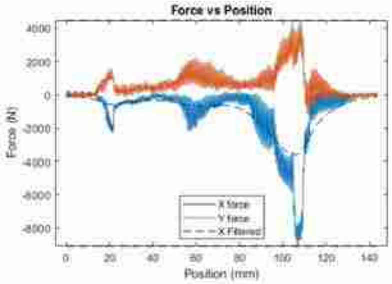
	1	2
1	Max RPM	1.4019e+03
2	Min X Force	-2.1537e+03
3	Max Y Force	1.7770e+03
4	Max Z Force	1.4079e+03
5	Max Velocity	199.9833

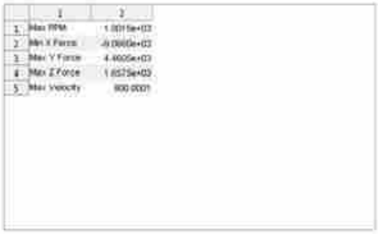
Lateral Cut 1



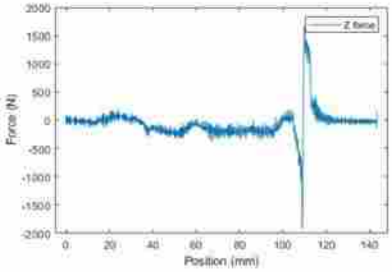
Lateral Cut 1







	1	2
1	Max RPM	1.0015e+03
2	Min X Force	-9.0860e+03
3	Max Y Force	4.4605e+03
4	Max Z Force	1.6575e+03
5	Max Velocity	900.0001



6 Flute OEM Endmill

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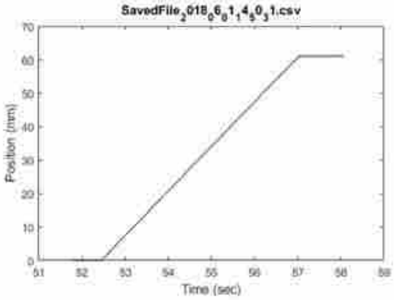
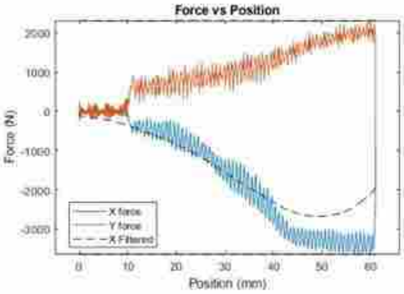
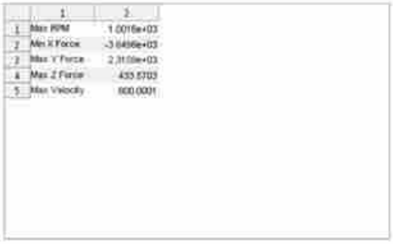
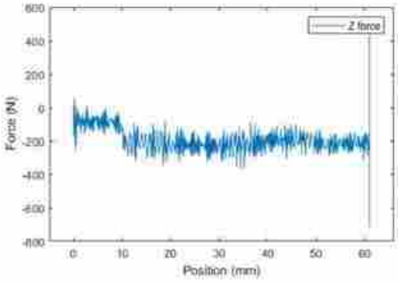
6 Flute OEM Endmill





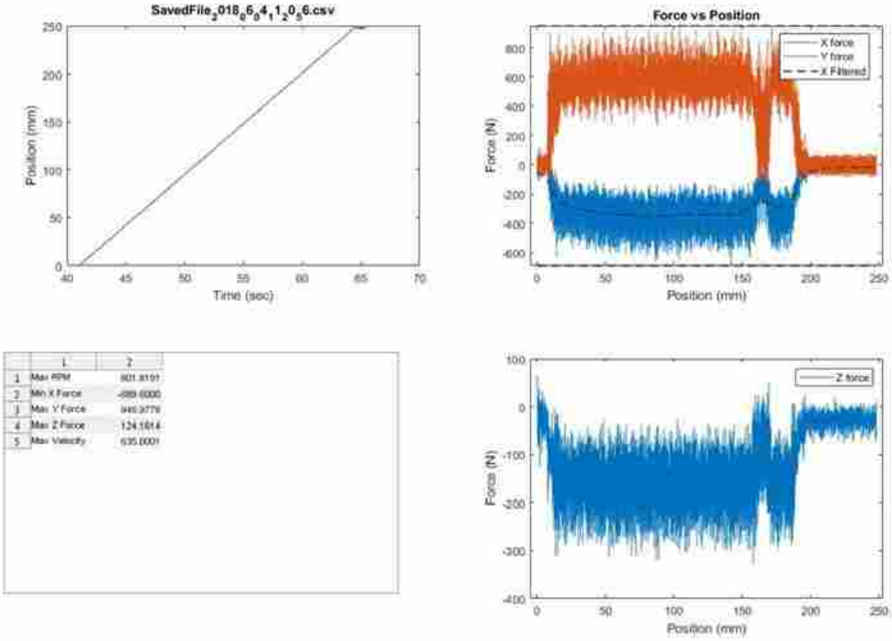


	1	2
1	Max RPM	1.0016e+03
2	Min X Force	-3.6498e+03
3	Max Y Force	2.3109e+03
4	Max Z Force	433.5703
5	Max Velocity	600.0001



3 Flute
OEM
Endmill

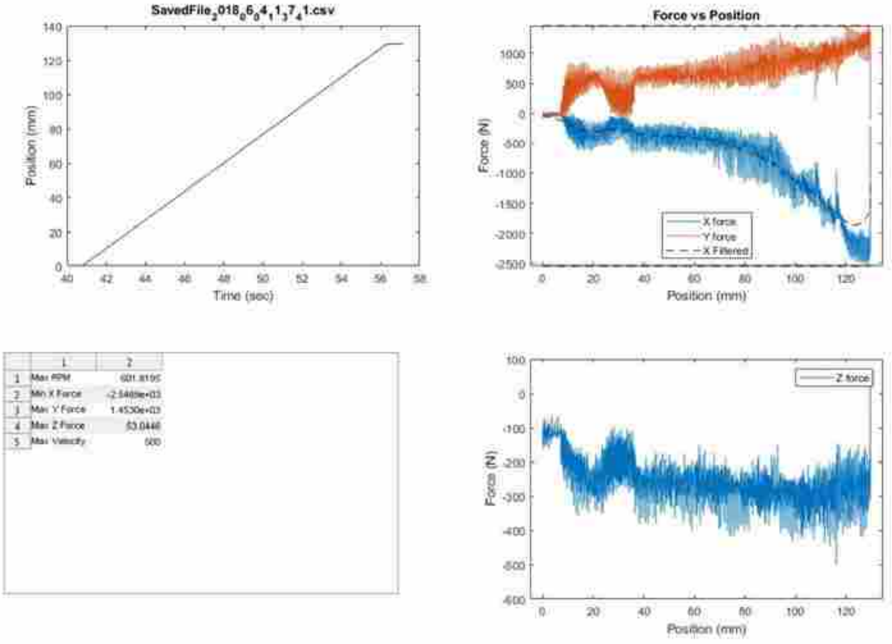
3 Flute
OEM
Endmill



	1	2
1	Max RPM	801.8191
2	Min X Force	-689.6000
3	Max Y Force	946.3778
4	Max Z Force	124.1614
5	Max Velocity	635.0001

3 Flute
OEM
Endmill

3 Flute
OEM
Endmill



	1	2
1	Max RPM	601.8195
2	Min X Force	-2.5469e+03
3	Max Y Force	1.4530e+03
4	Max Z Force	53.0446
5	Max Velocity	500