California Polytechnic State University, San Luis Obispo

Additive Manufacturing for Post-Processing

AMPP

Final Design Report

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Introduction

Additive Manufacturing for Post Processing (AMPP) is a team comprised of two Cal Poly Mechanical Engineering students: Nathan Goodwin and Andrew Furmidge. The project is focused in the area of metal additive manufacturing (AM) machines, which are still a developing technology. Improvements have been made to the quality of the machines in the past years, but many limitations still exist. One of these is the inability to print parts that are larger than the build volume. In an effort to solve this problem, whole parts are divided into pieces that are printed individually. This team's senior project is to create a joining method for Lawrence Livermore National Laboratory's (LLNL) AM department. An employee at LLNL, Stephen Knaus, is providing the requirements of the joining method, and Professor Peter Schuster is advising the team through the design process.

Background

What is Additive Manufacturing?

Additive manufacturing (AM) is a process that can quickly create a final part or prototype. This process assists designers and administrators when making decisions on the development of a part by allowing them to hold and visualize a model. AM encompasses a variety of methods that create a part layer by layer from a specific computer aided drawing (CAD) file. Generally, the CAD file is made by a designer or engineer who uses a program to create a solid model based off a concept that the designer envisioned. CAD files can also be created through a scanning process of an existing part. The solid model is converted into a STereoLithography (STL) file, a file format recognized by most solid modelling programs. The STL file is imported into an editing program that generates the necessary code for the machine to print the part in layers. The editing program has the ability to create a lattice structure within the model. A lattice is a repeated framework of patterned elements that occupies the space within a model. It reduces the mass of a printed part, which results in a shorter print time and a strong, lightweight model. The general types of AM processes for adding layers of material are liquid polymer, discrete particle, and molten material. This project utilizes selective laser melting which is a discrete particle method.

Lawrence Livermore National Laboratory is a lab funded by the government that is investigating AM through experiments and simulations (1). They have developed models that analyze the process at the part level and the powder level as seen in Figure 1.

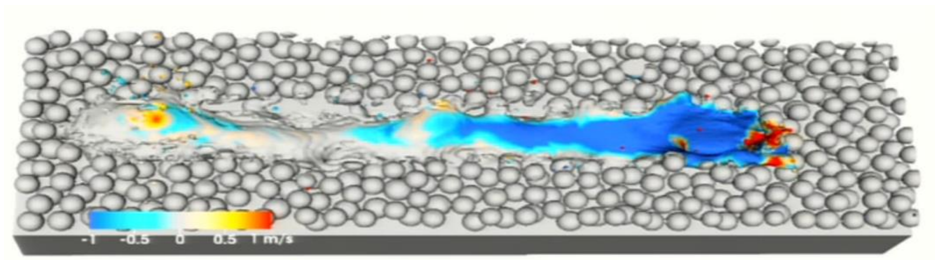


Figure 1. LLNL powder level simulation of selective laser melting (1)

Ideally, the results from these models are compared to the measured material properties of the final part along with data from sensors during the print. The purpose of these simulations and experiments is to find the correct parameters that the machines should be operated at to yield a high success rate of prints and to predict the properties of the part before the part is made. One of the AM processes that LLNL uses is selective laser melting (SLM). A distinction should be made between the process called SLM and the company called SLM. The company named SLM manufactures machines such as the SLM 125HL, SLM 280HL, and SLM 500HL in Figure 2 below, which create AM parts through the process of SLM. The post processing of these parts is essential to the final form of the part.

Figure 2. SLM 125HL (left) and SLM 280HL (right) (2)

Selective Laser Melting

SLM is a discrete particle powder bed fusion process that uses a laser to melt layers of metal powder (3). Since SLM is a welding process, it can only produce parts that are made from a weldable material. As with other welding processes, the liquid metal must be contained within an inert environment, usually consisting of Argon (4). Certain metal powders such as aluminum and titanium are composed of individual particles 5-50µm in diameter. The small size of these particles can cause them to react with the oxygen in the air and cause safety hazards, which is the reason why they will not be used in this project. Only stainless steel 316L will be used to create parts because it is not combustible in powder form. When creating a part, the powder is swiped across the top of the build plate in layers as the build plate lowers. In the simplified model of an SLM

machine in Figure 3, the powder layer that the laser is melting stays at a constant height relative to the laser to keep the beam focused.

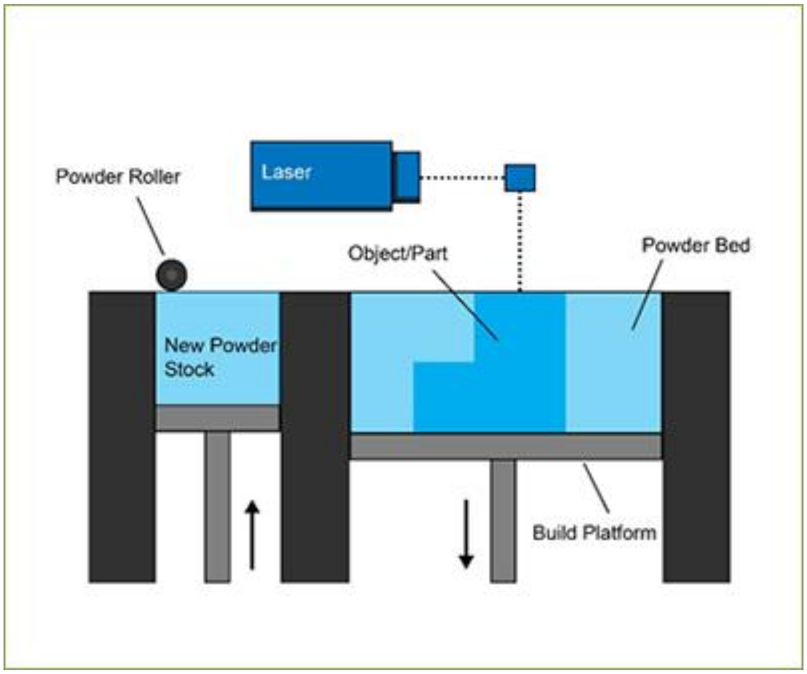


Figure 3. Selective laser melting machine components (4)

The difference between the model in Figure 3 and the SLM printer is that the SLM printer has a gravity-fed powder stock that drops powder in front of the powder roller for application of a new layer to the powder bed. The area of the powder bed, or build platform, limits the extents of the build volume. A larger build volume is often times desired, but increasing the size of the powder bed requires changes to the components of the machine such as the laser, mirror, and the actuator under the build platform. To compensate for having a smaller build volume, larger parts can be scaled down to fit within the build volume, although this may be insufficient for some prototypes. Some prototypes require dimensions that cause the part to be larger than the build volume; therefore, one of the limitations of the SLM process is the build volume. Additionally, the size of the printed part is proportional to the build time, so there is a tradeoff between the size of the part and the printing time.

In the case of this project, the desired part is slightly bigger than the build volume of the SLM 125HL model. The SLM 280HL model would be required; however, a bigger model printer is more expensive. This drives the need for joining method to be developed that will be applicable to axisymmetric parts of any scale. This method will allow axisymmetric AM parts to be made that are larger than the build volume of the largest AM machine. The joining method will require the part to be printed in sections and joined.

Joining Methods

For centuries, artists and designers have encountered the problem of not being able to build their masterpiece in one single part. One of the oldest examples dates back to the Egyptians and their pyramids. This issue still plagues the endeavors of today's designers and engineers as they strive to create things that were once thought to not be possible. Since then, there have been several methods tried and revised to connect pieces together. Some of these discoveries are more recent as technology has advanced, allowing designers to use a larger breadth of materials. This project will not utilize hardware fasteners, as required by the customer, narrowing down the number of potential joining methods. The first type of joining methods that will be discussed are mechanical fastening methods that use locking geometries, such as puzzle pieces and zippers. The next type of joining methods discussed will be adhesive joining methods that create a bond between two surfaces using a liquid bonding agent. Adhesives contrast with the next joining method of welding because welding melts the two surfaces together rather than adhesives use a different material for bonding. Lastly, shrink fits will also be investigated because this method is similar to welding since it does not require additional materials for joining.

Puzzle Pieces

One of the oldest joining methods is the use of physical connections or interlocking pieces to lock two pieces together. A puzzle piece is a prime example of how this method works. It involves one end of a part to be cut into a specific geometry such that there is a protrusion from the surface known as the male connector. The other part requires a similar cut on the necessary end, but instead, an inward cut that reflects the outline of the protrusion from the male end. This part is called the female connector and when the two parts are designed correctly, they can lock into place simply by sliding the male (key) side into the female (lock) side. The benefits are profound since a designer can design a fully completed part then choose the sections to split the part into by drawing simple or complex geometries to lock them together. The woodworking industry generated one of the first examples of this methodology in medieval times, using what is known as a mortise-and-tenon joint seen below in Figure 4.

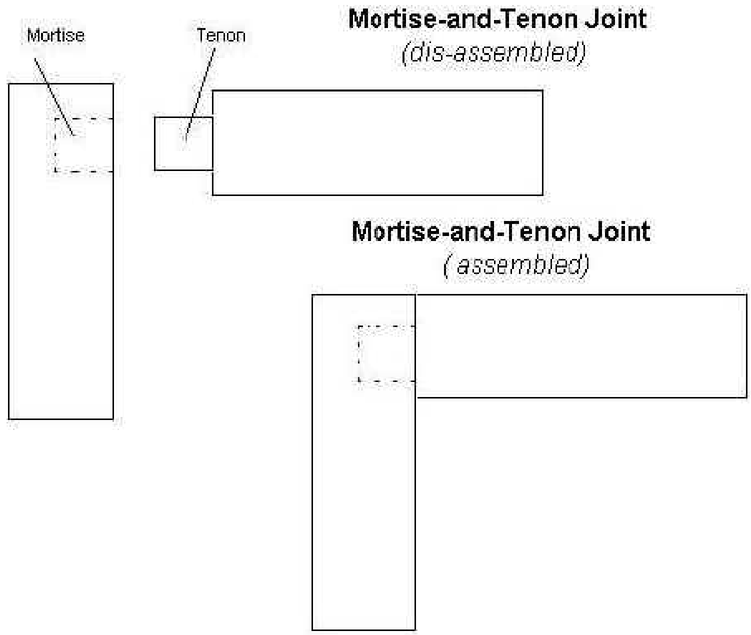


Figure 4. Mortise-and-Tenon Joint developed in medieval times (5)

Since the Mortise-and-Tenon Joint, hundreds of more joints were created and utilized in different mediums from wood to stone to metal. More recently, the plastic 3D printing industry has created a process of turning any CAD model into multiple puzzle pieces that fit together. The program can create interlocking pieces in such a way that they become fixed in all three directions. Figure 5 below shows how this computer program can take a CAD model and split it into multiple pieces.

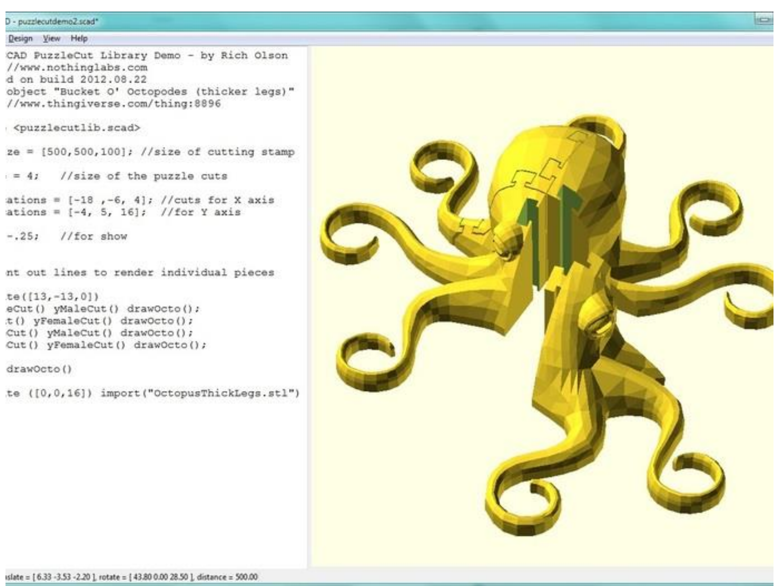


Figure 5. 3D CAD part split into pieces using computer program (6)

Potential disadvantages to the puzzle piece method lies in the strength of the projected ends, the tightness of the fits, and the effects of the direction of the applied force. If the puzzle piece end of

a part is poorly designed, it may create areas of high stress concentration and may cause those areas may fail before the rest of the part. Cutting creates tolerances in parts and if not calculated properly can lead to the puzzle pieces having either too much clearance or interference. In addition, if the puzzle piece experiences a force in the direction that it was slid together, there is a chance that the connection may undo itself, rendering the joint useless.

Zippers

A zipper is a joining device that integrates the basic hook and hollow geometries. The teeth of a zipper interlock to join the surfaces of two materials that are generally flexible. Shown in Figure 6, the slider of the zipper consists of a wedge and each tooth has a hook and hollow. Each opposing tooth is offset from one another so that their hooks and hollows can latch together in sequence (7). The track of the zipper is the pattern of dozens to hundreds of teeth. Generally, the wedge shaped slider forces the teeth of each track together at an angle. Parts made through AM are generally not flexible enough to deform to the angle required to allow the teeth to lock together, however, the idea of interlocking hook and hollow geometries may be useful to lock pieces together.

Figure 6. Cross section of a zipper joint (8)

Gluing

Another form of joining that has existed for quite some time is gluing. The specific substrate for gluing varies depending on the application, but all substrates function to adhere two pieces together. Glue usage ranges from mortar (used to hold concrete and brick) to epoxy (used to bond metal, Figure 7) and almost everything in-between. Glue is a widely used joining method because it can be quick and completed without much dexterity. The substance is applied to the end of one

part and is pressed tightly against the end of another part. Once again, the type of glue will determine how long it takes for the glue to cure (harden and complete the joint). The strength of the glue is dependent on how well the substance can adhere to the part, how strong the substance is when it has finished hardening, and how tight the fit is between the mating parts. The company Henkel/Loctite claims that out of the entire surface area of the desired joint, only about 15% of the joint's surface area is actually forming metal to metal contact (9). Glue or retaining compound should be added to the joint to fill the gaps and increase the area of contact. Despite the advantages of glue, there are restrictions on the applications glue can be used for. Possible drawbacks occur when there is poor adhesion between the glue and part, when the operating temperature exceeds the limit of the glue, or when the glue reacts with other liquids such as water. Glue can be combined with geometric joining features, such as a puzzle piece, to increase the strength of the joint by improving load transmission.

Figure 7. Loctite Epoxy Weld Bonding Compound (10)

Chemical Bonding

Chemical bonding is another unique process which requires little effort from the user to obtain a strong connection. This process is similar to gluing since the bonding strength is dependent on the joining material used, but it utilizes the interactions between elements to ignite chemical reactions. One use of chemical bonding involves the elements Indium and Gallium. The bonding surfaces are initially coated with a layer of angled rods. One side has rods coated in Indium and Gallium coats the other side shown in Figure 8.

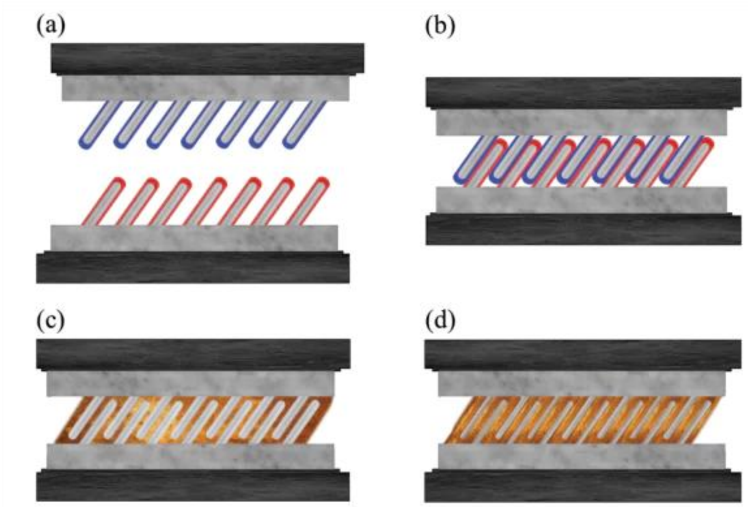


Figure 8. Indium and Gallium coated rods from separation to connection and solidification (11)

When the two sides are slid into one another, similar to a zipper, the elements come into contact and form a liquid due to their elemental properties. This liquid reacts chemically and begins to solidify until it hardens completely. The chemical reaction between Indium and Gallium occurs at room temperate and requires no pressure while it is curing, which makes it similar to gluing, but it solidifies as a full metallic piece. The drawbacks are in the amount of time it would require to coat each side with the elements and the precision of the rods' incidence angle.

Welding

The most common form of modern welding was first discovered in the early 1800s when an arc was created to melt metal in order to fuse parts together. Since its conception, the process has been iterated to account for different metals and applications. There are multiple benefits of welding compared to the previous two joining methods. Welders can choose what type of metal will be used to melt the two parts together based on the need of the designer. Once the weld solidifies. The weld bead typically surpasses the strength of the base material, however the heat affected zone besides the weld bead experiences a decrease in strength. There are other limitations to welding such as creating large amounts of heat. Too much heat could burn a hole through the metal, but not enough heat could cause the metals to fuse incompletely. An improper weld could contain porosity or other impurities that can decrease the strength of a weld. Another problem with welding is the amount of skill required to perform an acceptable weld. Below in Figure 9 is an example of the Tungsten Inert Gas (TIG) welding technique that utilizes a tungsten electrode to create the arc that melts filler rod, which must be applied by hand.

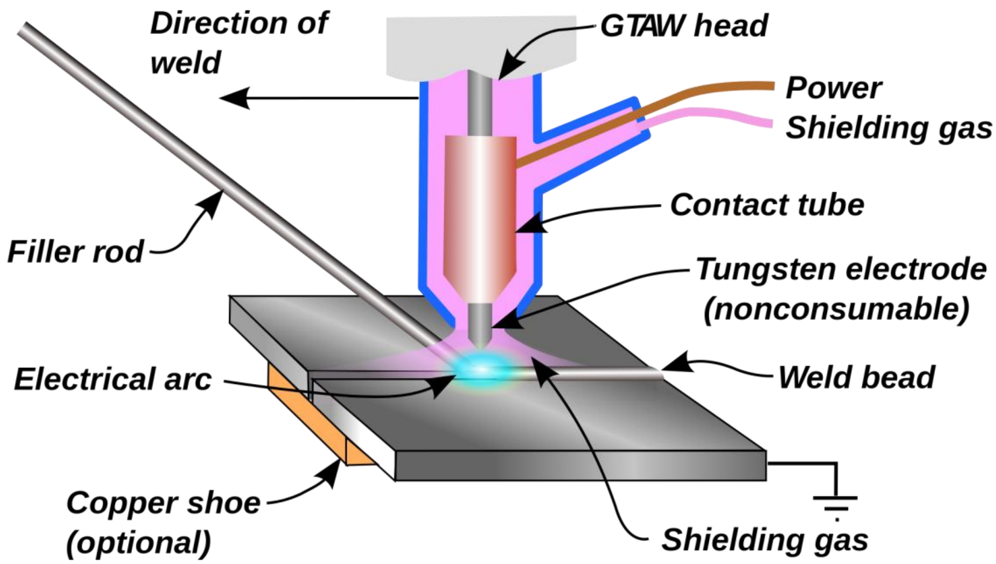


Figure 9. Diagrammatic example of TIG welding (12)

Shrink Fitting

When extra material is not desired due to the nature of the application, heat shrinking can be used to join objects together. One use of heat shrinking is in underground piping. These pipes are buried under the surface, leaving them prone to wear and deterioration from moisture and other environmental factors. To combat this, wraps made from a flexible material are wrapped over or slid around the tube and then heated so that they constrict around the pipe, creating a protective barrier. This process is more desirable than fitting a rigid casing around the pipe because those casings need to be specifically dimensioned for each pipe whereas the heat shrink material can fit any size that it needs to. In addition, casings may require external fixtures or an adhesive to hold themselves together while the heat shrink only requires intense heat. This heat shrinking process is also used to fit piping together. By heating up the end of the pipe with the larger inner diameter, the tube is thermally expanded enough such that another pipe’s end can be easily inserted. The larger pipe then shrinks radially as it cools back down, creating a strong fit between the two pipes. The key to this process is dimensioning the inner diameter of the outer pipe to be slightly smaller than the outer diameter of the inner pipe so that when the heated outer pipe cools down, the outer pipe attempts to return to its original dimension, therefore uniformly “squeezing” the inner pipe. Since this process is repeatable and can be performed manually or automatically, shrink fitting is used to insert motor stators into motor bodies, re-fit gas turbine impellers, and assemble high precision roller bearings. (13) There are many more applications of this technique in several industries. Figure 10 and Figure 11 below show a sample procedure for shrink fitting an assembly.

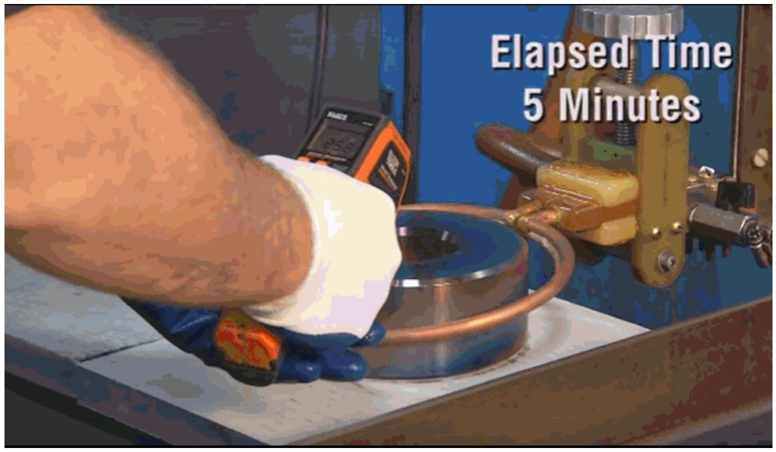


Figure 10. Heating of casing for shrink fit (14)

Figure 11. Inserting carbide into heated casing (14)

Manufacturing Considerations

Drawn Over Mandrel Tubing

Drawn over mandrel (DOM) is a process of making metal tubing and has been used in industry for years. A sheet of metal is first rolled out between rollers and slowly bent into a round tube. Then, an electronic resistance weld is applied to seal the tube together. After the tube is cleaned, one of the ends is crimped to a point so that it can be held by a machine. The tube is pulled through a die and over a mandrel which define both the outer diameter and wall thickness. (15) In addition to allowing fabricators the ability to create tubing with specific dimensions, the drawing process improves the tubes strength and concentricity, making it a much more desirable process for creating tubes than turning down long pieces of stock on a lathe. Figure 12 below shows the drawing of the tube over a mandrel.

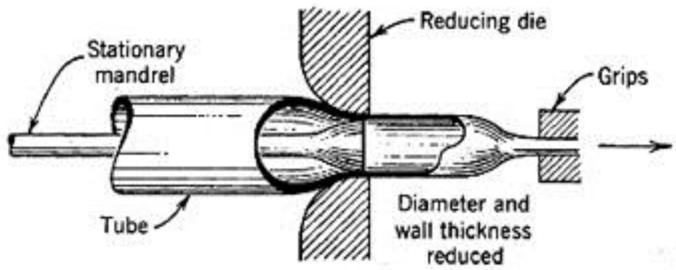


Figure 12. Drawn over mandrel process of creating tubing (16)

Heat Treatment

Most steels can be distinguished by specific grain patterns or colors that are characteristic of the material. However, it isn't safe to assume the nature of the steel purely based on looks because metals within the same family can have different microstructures. These microstructures have to do with the internal and very miniscule crystal-like structure of the atoms. This structure can be adjusted by heating the metal to a specific temperature range for a controlled amount of time, then quenching the steel by dunking it into water. Charts depicting this information have been developed for most steels based on carbon content. For additively manufactured parts made using selective laser melting, heat treating them post print is vital since the metal microstructure is not the same as parts that are made through other techniques such as casting or forging. They may experience very high cooling rates which can cause unwanted effects including the formation of inclusions and carbides. (17)

Relevant Patents

US patent #3336657 – Scarfing Tool in Method for Joining Metal Bands. (18) This patent describes a method for coating the surface of stainless steel with an oxide from a certain group of metals which improves the weldability of the part. This technology allows for full penetration into the stainless steel even at increased welding speeds. If welding is considered as the main or auxiliary method of joining parts this technology may be utilized in order to achieve a high quality finish.

US patent #3584187 – Method of Welding Stainless Steel. (19) This patent describes a method for joining two metal bands together using a special tool that creates grooves which interlock onto a thin piece of metal to create a tight connection. These metal bands are used as belts in high speed pulley systems so the tension is a high priority in the strength of the connection.

Interviews

After receiving an informative tour of the LLNL facility and specifically the AM division, the team was able to conduct an interview with the sponsor. During the interview and tour, safe working procedures were discussed since it was a major concern of the Industrial Manufacturing Engineering Department. LLNL disclosed that their operators must wear a full-face respirator,

coat, and nitrile gloves. Once the safety procedures were covered, the sponsor explained certain restrictions about the desired part. AMPP and the sponsor discussed that the final part is to be constructed without bolts or fasteners and there cannot be any step changes in density in the radial and axial direction. LLNL suggested for AMPP to use Magics, a computer software, to convert CAD geometry to small slices for the SLM machine to interpret. Lastly, the scope of the project that LLNL desired was compared to the scope that AMPP could complete within the school year. It was decided that by the end of the school year a joined part would be constructed using the technique developed. Also, test results, design process documentation, and prototypes will be provided to LLNL to justify the performance of the joining method. The documentation will clearly address the potential improvements and drawbacks of the joining method and how it may be applicable to other parts LLNL may manufacture.

Objectives

Problem Statement

Additively manufactured parts are currently restricted to a specific build volume which requires users to split large parts into multiple sections. Lawrence Livermore National Laboratory needs a way to join axisymmetric segments such that the mechanical properties approach those of a uniform part.

Customer Requirements

During multiple meetings with Lawrence Livermore National Laboratory, requirements were established regarding the development of a post processing method for joining an axisymmetric part. LLNL provided a preliminary drawing of an axisymmetric part with geometric dimensions and tolerances (GD&T) prior to AMPP's tour of the AM facilities at LLNL. The final, joined part must meet the GD&T since a singularly printed part can also meet those specifications. The axisymmetric part will be made of stainless steel 316L and consists of an inner wall, outer wall, and a lattice between the two walls.

After the tour, LLNL specified that the joined part must have no step changes in density in the angular and axial directions, and if a material other than stainless steel 316L is used in the joining method, it must have a similar density to stainless steel 316L. This poses a challenge when designing a joining method because the lattice in one section will be difficult to join to the lattice in another section. The small strut sizes of the lattice will deter the joining methods from attempting to join lattice sections, especially since the density of the lattice must not have sudden changes around the cylinder. Similarly, there must not be any lumped masses as a function of angular position around the axis of revolution. This requirement was implemented to prevent the edges of the lattice from transitioning into another geometry that could be easily joined.

Whether another material or adhesive are used in the joining process, the functionality of the part must not change within a temperature range of -60°F to 180°F. Also, LLNL requests for no bolts or fasteners to be used when joining the segments of the part. Similar to what was mentioned in the problem statement, the axisymmetric part will be split into at least three segments due to the SLM 125HL's small build volume. LLNL desires the joined axisymmetric part to approach the strength of a fully printed part and to be identical to a fully printed part. The post-processing time and the costs involved will be optimized without sacrificing the joined part's strength, stiffness, and quality.

QFD

A QFD (quality function deployment) matrix was completed to evaluate all of the customer requirements with respect to the following categories: relevance to each customer, engineering specification, and current solutions to the problem. The full matrix can be found in Appendix 2: QFD and includes the weighted percentages of each category. Some of the customer requirements that are included in the QFD were not explicitly stated by the project sponsor but were determined by the team to be relevant factors. The list of customers was created after thinking about the full cycle of the final part and every person that may be involved in the process, from the design engineer who creates the part to the metrologist who tests final material properties. It is important to note that for this project, most of the engineering specifications located in the 'HOW' row of the QFD were provided by the project sponsor.

Engineering Specifications

Engineering specifications were determined from LLNL's customer requirements that define the scope of the project. The following is an explanation of the specifications found below in Table 1.

Table 1. Engineering specifications derived from customer requirements

Spec #	***Specification Description***	***Target (units)***	***Tolerance***	***Risk***	***Compliance***
1	Outer Diameter	200 mm	±0.15	L	T
2	Inner Diameter	166 mm	±0.15	L	T
3	Wall Thickness	2 mm	±0.20	H	T
4	Height	115 mm	±0.10	L	T
5	Bolts & Fasteners	0	±0	L	I
6	Cylindricity	.05 mm	±0.10	L	T
7	Radial Hoop Force	5000 lb_f	-0%	H	A,T,S
8	Temperature Range	-60F to 180F	±10%	M	A,T,S
9	# Printed Parts	3	±0	L	I
10	Surface Finish	3.2μm	±.05μm	L	T,I
11	Safety Factor	3	-0%	H	T,A

The engineering specifications table lists the descriptions of ten requirements that the final part must meet. To quantify the specification, each description has an associated numerical target. The tolerance defines the allowable range around the target that the final part must lie within. These targets and tolerances can also be found on the engineering drawing in Appendix 4: Pugh Matrix.

The table also identifies the risk associated with meeting each engineering specification. For example, the tolerance on the wall thickness may be difficult to achieve because the lattice between the inner and outer shell will restrict the accessibility of measuring tools. Therefore, the wall thickness specification has a high risk associated with it, denoted by an “H”. Specifications with a medium and a low risk are marked by an “M” and an “L”, respectively.

The compliance column in the engineering specifications table identifies how the final part will be verified against each specification. Most specifications are dimensions that can be measured on the part, which is a form of testing that corresponds to a “T” in the compliance column. Visual inspection is another method that is used to check the parts against the specifications and is noted by an “I”. Analysis, “A”, can also be used to numerically validate the joining method against the engineering specifications. The final type of compliance is similitude, which allows a similar part with known properties to be compared to the engineering specification. Similitude is abbreviated with an “S”.

All specifications which refer to part geometry are given the “T” compliance because in order to ensure that each dimension is within the allowable tolerance range, the final part will be inspected using the optical comparator in the Cal Poly IME department. The two specifications that only require visual inspection, “I”, are the number of bolts and fasteners and number of printed parts. The surface finish requires both a visual inspection as well as more in-depth testing using the Micro Vu in the IME department. The visual inspection is to initially gauge how much smoother the finish needs to be. The specifications that have analysis in their compliance - radial hoop force, temperature range, and safety factor – will be used in hand calculations to confirm that the final design can withstand the required forces and meet the proper safety factor. To test the radial hoop force and safety factor, the final part will be loaded into an Instron machine using the testing fixture, see Final Design Details for full description, to apply an opposing internal tensile force on the inner band until the part yields.

Design Development

Ideation

The initial stage in the method of approach presented in the project proposal was ideation and modeling. Since the submittal of the project proposal, multiple ideation sessions were held to discuss all possible ideas and to further analyze the top three concepts. Further, detailed analysis

of these concepts was included in the Critical Design Review, CDR. The following is a list of the ideation techniques performed after the project proposal.

- Brainstorming
- Brainwriting
- SCAMPER (Substitute, Combine, Adapt, Modify, put to other use, Eliminate, Reverse/Rearrange)

Brainstorming

Innovation occurs the most when people work together and share ideas because when someone generates a new idea another person within the group can build off of it or use that idea as inspiration to create other solutions. There are different approaches that groups can take when brainstorming but the process remains as follows; for twenty to thirty minutes everyone on the project is allowed and encouraged to express any and all potential solutions to a given problem. All ideas are written on a large board and the goal is to maximize the quantity of ideas rather than the quality. By not worrying about the specifics of each solution the group was allowed to exhaust all solutions at the beginning of the project, even if some turned out to not be feasible or realistic. If quality was the focus of brainstorming, many ideas that are extraneous would have been discredited which would not be beneficial because sometimes the ideas that are "way out there" are a catalyst for a potentially great solution. Figure 13 below contains all of the Post-It Notes that were used during the ideation process.

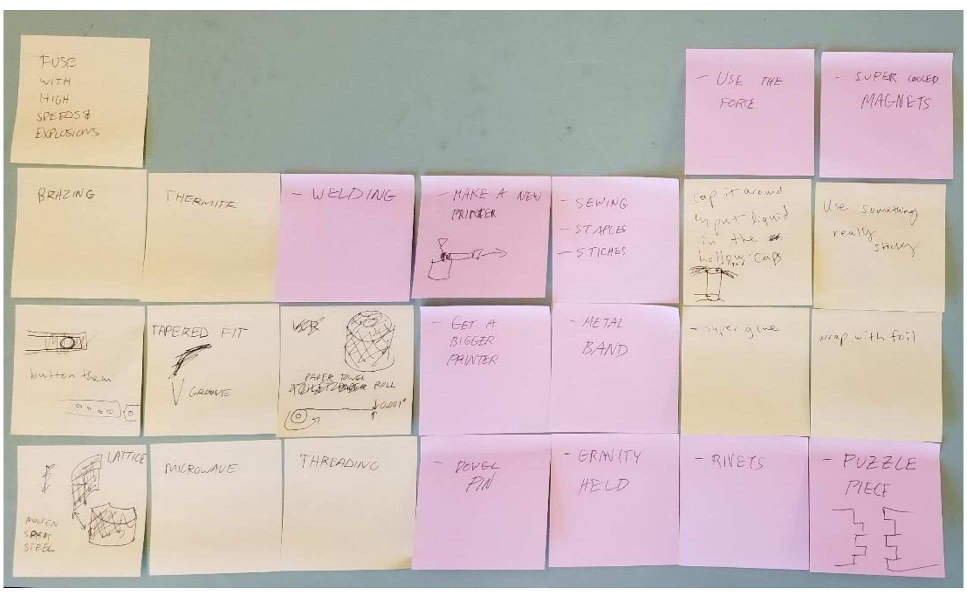


Figure 13. All ideas generated during the brainstorming process, some containing sketches to explain general concept, most left ambiguous on purpose

Note that some of the ideas in Figure 13 are extreme and not within the scope of the project, including "make a new printer" and "fuse with high speed explosions".

Brainwriting

Brainwriting is almost the opposite of brainstorming because in the brainwriting process, each team member spent around five minutes jotting down ideas in a notebook, including sketches and explanation if necessary. The focus of this exercise was to let each person come up with ideas devoid of influence from other persons. After the time limit was reached the notebooks rotated counterclockwise and another five-minute timer was set. During this second set of time each person added on to what was already in the notebook, providing sketches and notes when needed. The rotation continued until each notebook ended up back with its original owner. Two brainwriting sessions lasting fifteen minutes each were held, yielding more practical solutions than the brainstorming session including heat shrink bands on the inside or outside of the lattice and a combination of puzzle piece geometry and adhesive.

SCAMPER

SCAMPER stands for; substitute, combine, adapt, modify, put to other use, eliminate, and reverse/rearrange. This method is less of a standalone ideation process than brainstorming and brainwriting because the focus was on deriving new solutions by analyzing an already proposed solution and altering it using one of the previously mentioned factors. SCAMPER was utilized during all ideation sessions; for example, during the brainwriting session a solution was proposed which combined two joining methods, puzzle pieces and adhesive.

Description and sketches

AMPP produced multiple concept drawings for potential joining methods of the model’s three partitions. In each concept, the end faces of each component are joined together with the aid of a fixture that aligns the segments such that each component's mating surface is coincident with the adjacent partition’s joining surface. To create a permanent adhesion between multiple parts, a weld could be performed on each line of contact, or another an adhesive could be applied to each component's mating surfaces before joining the three partitions together. Nine concept models were generated from the ideation processes and compared in the following evaluation matrices. Some of the concept models had two variants due to two possible methods of adhesion: welding and adhesive.

Concept 1

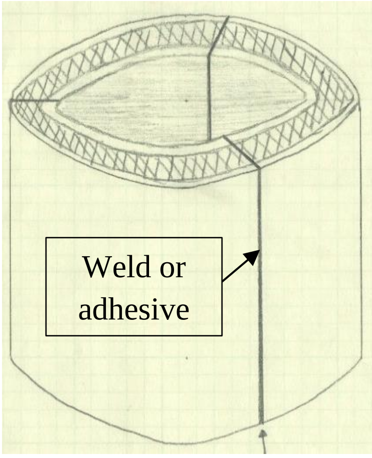


Figure 14. Straight joint weld (1a) and straight joint adhesive (1b)

In concept 1a, the mating surfaces of each component are flat surfaces normal to the tangent of the arc. The mating surface terminates the outer wall, lattice, and inner wall thicknesses. After the faces of the components are placed together, a weld is performed down each of the joints. Concept 1b is a similar process, however an adhesive is applied to the mating surface before assembling the three components.

Concept 2

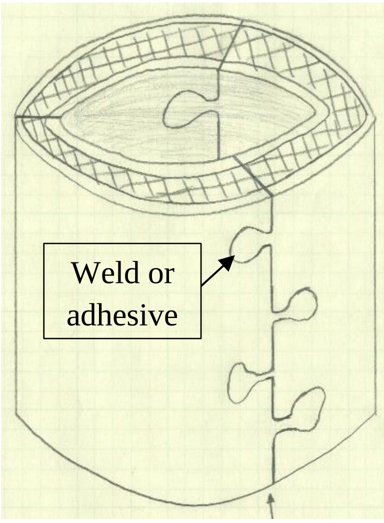


Figure 15. Puzzle piece weld (2a) and puzzle piece adhesive (2b)

For concept 2, each component contains a combination of multiple tabs and slots cut into the end faces. Each component's male tabs fit into adjacent component’s respective female slots. During this process, the part will be located cylindrically with the use of an assembly fixture. For concept 2a, a weld is applied to the part's three joints. Concept 2b is a similar process; however, an adhesive is applied to the mating surfaces before placing the three components together.

Concept 3

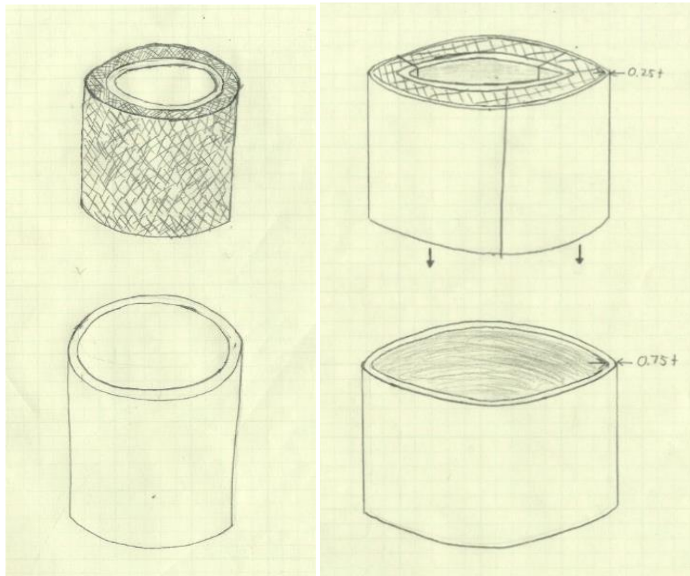


Figure 16. Full thickness outer shell - heat shrink (3a, left) and partial thickness outer shell – heat shrink (3b, right)

For concept 3a, the three components are printed without an outer shell. The end faces of each component are also flat like in concept 1, but a stainless steel band is heated and placed around the lattice. The band is the same height as the part and will be dimensioned to achieve the desired compressive forces on the lattice while obeying the engineering specifications. After cooling, the outer band's resting state compresses the lattice, and the band will be designed so that the friction between the two prevents any relative motion. Concept 3b differs from concept 3a in that a thin portion of the outer wall is printed with the three components. The outer band, now a fraction of the full wall thickness, is heat shrunk around the three joined components.

Concept 4

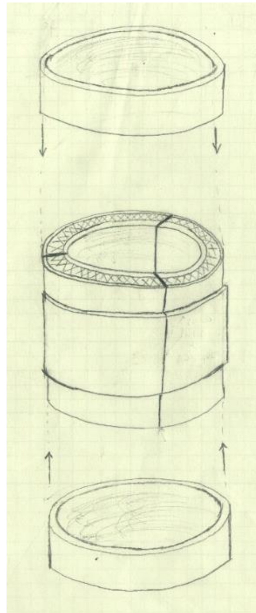


Figure 17. Full thickness outer band (4a) and partial thickness outer band on both ends (4b)

For concept 4a, each component is printed similarly to concepts 1 and 2, however the top and bottom portions of each component are printed without an outer shell. Two steel bands are heat shrunk over the two missing outer shell portions of the part. Each of the band's inner diameters are slightly smaller than the outer diameter of the top two portions of the part so that the bands can hold the printed parts tightly. Each band is the specified outer shell thickness and the same height as the two missing outer shell portions of the part. Concept 4b, is similar to concept 4a, however the top two portions of the components are printed with a thin outer shell of stainless steel. Two thinner bands, relative to the bands of concept 4a, are than heat shrunk over the part.

Concept 5

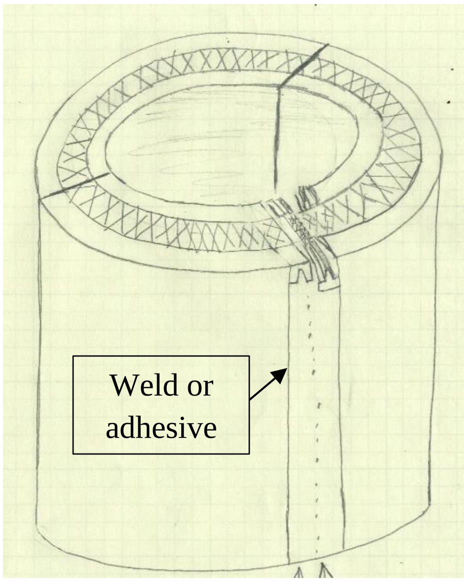
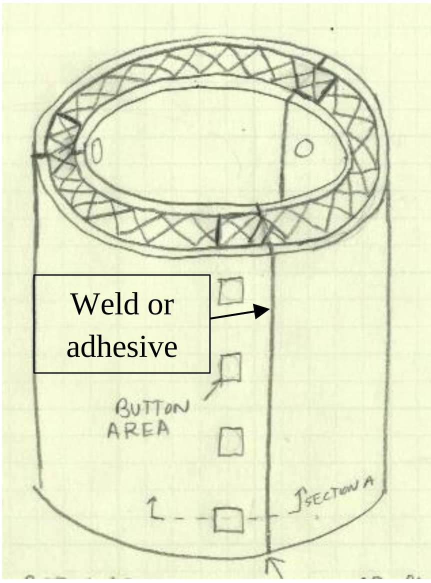


Figure 18. Hook joint weld (5a) and hook joint adhesive (5b)

Similar to the puzzle piece method, the hook joint method, concept 5, utilizes a male and female joining mechanism. Each component is printed with a vertical track of male teeth sequenced down a mating surface and a track of female teeth sequenced down the other mating surface. A male tooth is a hook intruding through the component’s entire thickness, while a female's respective tooth is hollow. The male teeth are meant to slide into and engage in the female teeth. For concept 5a, after the components teeth are latched together, a weld is applied down the part's three lines of contact. For concept 5b, an adhesive is applied to the end faces of each component, before assembling them together.

Concept 6



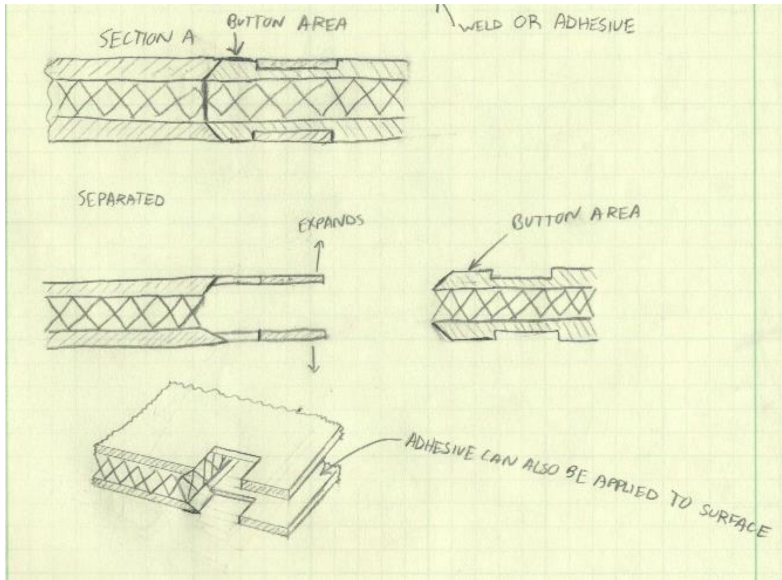


Figure 19. Button joint weld (6a) and button joint adhesive (6b)

Similar to the puzzle piece and hook joint method, the button method incorporates a male and female joining mechanism. Each component is printed a male end and a female end. The component's female end face contains a lattice-less rectangular slot with two inner and outer shell fins extending off the base. Two square holes in the inner and outer shell female end, are located a small distance from the female's end face. The component's male end contains a small, square notch placed down the inner and outer shell. The notches are located a small distance off the male's respective end face. The edges of the male's inner and outer shell are cut at angles to pry the female end open. The inner and outer shell of the female slot deflect during the initial process of inserting the males face into the hole; however, the female's shell returns back into place after the wedges pop through the two small square holes.

Concept 7

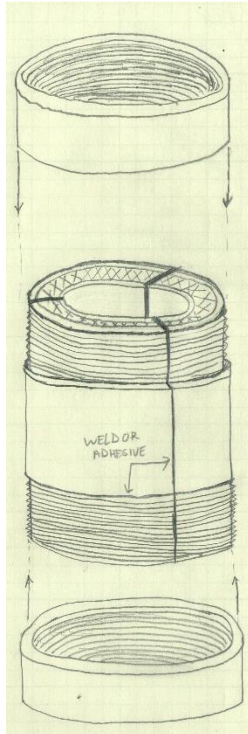


Figure 20. Threaded cap band inside and outside with weld (7a) and threaded cap band inside and outside with adhesive (7b)

Similar to Concept 4a and 4b, the top and bottom portions of each component are printed with a thinner outer wall thicknesses relative to the middle portion. The thin top and bottom outer wall portions are threaded with a lathe. Two stainless steel bands that have the same outer diameters as the top and bottom portion of the part are then internally threaded. The two bands are first screwed to the top and bottom portions of the part. For concept 7a, a weld is applied to the part's lines of contact. For concept 7b, an adhesive is applied to each end face of the three parts before assembling them together. In addition, adhesive is applied to the inner walls of each band before screwing them to the part.

Concept 8

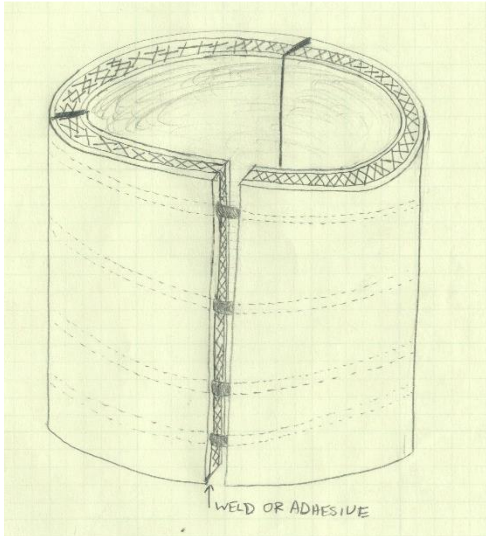


Figure 21. Internal band weld (8a) and internal band adhesive (8b)

The respective components of this concept have multiple hollow tunnels running through the perimeter of the part. When the end faces of each of the components are placed together, the tunnels should be continuous around the part. Small stainless steel bands are first heated and then placed inside the continuous tunnels of the three components. After cooling, the internal bands shrink the part together tightly. For concept 8a, after the internal bands have tightly connected the three components together, welds will then be applied to the part's three lines of contact. In concept 8b, the heated internal bands are placed inside the tunnels and an adhesive is applied to the flat portions of end faces.

Concept 9

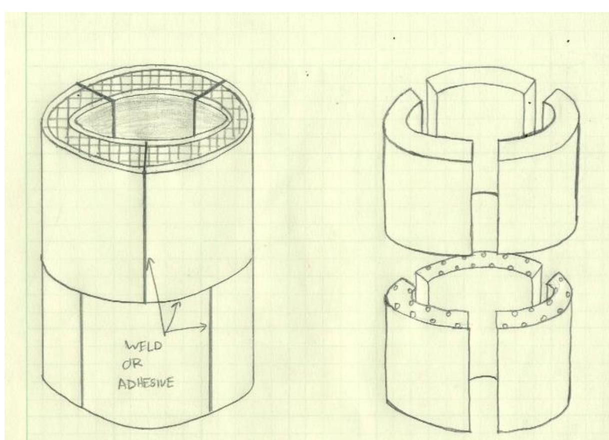


Figure 22. Dowel pin weld (9a) and dowel pin adhesive (9b)

Six components are printed with small vertical holes spaced along the perimeter of three component's top faces, and three component's bottom faces. The holes along the perimeter of the components are placed along the outer wall sections of the components. The three components are placed together while the three bottom components are also placed together; however, the bottom components offset the vertical seems of the top three components. These top and bottom components are then joined together by dowel pins which align them axially.

Selection Process

Initial analysis on all possible ideas was conducted in order to create a list of three top concepts. The process started with creating a Pugh matrix to determine the weaknesses and strengths of each concept. After the Pugh matrix was completed, a weighted decision matrix was produced to compare the concepts to each other based off each concepts' performance in certain criteria. Three models were selected from this process and will continue in the design process.

Pugh Matrix

In order to qualitatively rank each concept against one another a Pugh matrix was created with specific criteria and can be found in Appendix 4: Pugh Matrix. The following criteria were decided upon as a group and reflect the major requirements and concerns of the project: amount of parts, post processing difficulty, post processing time, tangential strength, post processing safety, part cost, quality of joined part, and temperature resistivity. The concepts that were added came from the ideation sessions and some new ones were added after. In order to compare each concept a datum needed to defined; a straight joint with a weld was chosen as the datum because each group member could easily understand and compare it to other concepts. Each concept was then analyzed one at a time for all criteria and compared to the datum, receiving either a "+ - better than", "- worse than ", or "S - same" rank. There are multiples of concepts because after completing the matrix it was noticed that each concept could either incorporate a weld or adhesive to assist in the joining. For this reason, each concept was split into two separate concepts, one for a weld and one for an adhesive joining method. However, this does not apply to the heat shrink shells or bands.

Weighted Decision Matrix

The results from the Pugh matrix helped in estimating which concepts were the best but a weighted decision matrix was needed to derive a more definitive result. The layout was reversed from the Pugh matrix because in addition to providing a rank of each concept within each given criteria, each criteria was weighted as a percentage out of one-hundred. Criteria with higher percentage points were considered to be more critical to the project. Similar to the Pugh matrix execution, each concept was evaluated at each criteria receiving a value from one to ten. A ten meant that the concept would yield the best result for its given criteria. For example, the straight weld joint was given a ten for the criteria "amount of parts" because this method does not require any more parts than the project already specifies. On the other hand, the internal band with a weld was given a one for the criteria "post processing difficulty" because of the complexity of precisely navigating a band through the lattice structure and then performing a weld on the outer wall contact areas

between segments. For the other criteria, a higher tangential strength, less post processing time, less cost, higher safety, higher quality, and higher temperature resistivity all correlate to a higher numerical value. After all criteria were considered, the values were multiplied by the weight of their respective criteria and added together to create an arbitrary number. After all concepts were analyzed their corresponding arbitrary numbers were sorted to determine the highest ranking concept. The full values of the weighted decision matrix can be found in Appendix 5: Weighted Decision Matrix. The top three concepts were pulled directly from the results and are as follows: heat shrink outer shell, button with a weld, and puzzle piece with a weld. Note that the top two concepts based on the weighted decision matrix are both heat shrink methods, only varying in the thickness of the unprinted shell, so they were considered to be one concept.

Description of Top Three Methods

Outer Shell Heat Shrink

The heat shrink shell is a method in which only the inner wall and lattice are printed. The outer shell that will be heat shrunk over the printer part must be made separately using other methods. The first method that may be used is called drawn over mandrel (DOM). The process starts with a coil of steel that is cut and then the plate is pulled over a series of rollers to form a tube that is sealed by an electronic resistance weld. This tube is then placed around a mandrel with the leading end crimped so that it may be gripped and pulled through a die. A better visual of this process is in Figure 23.

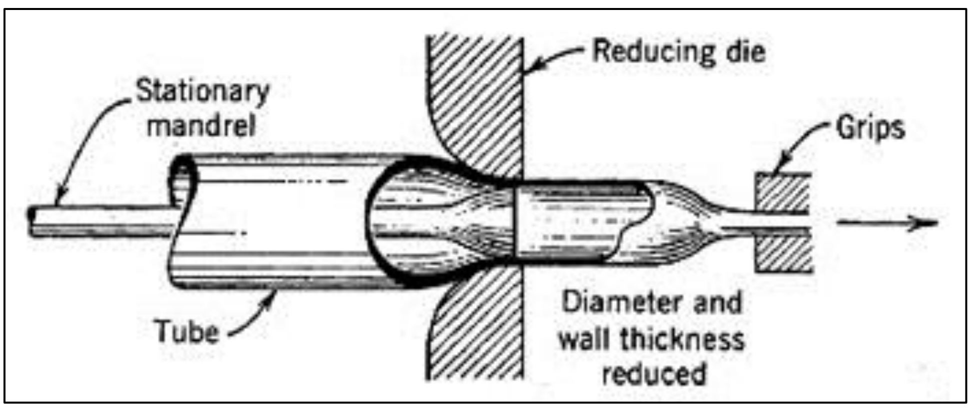


Figure 23. Drawn over mandrel (DOM) method (16)

The die combined with the mandrel help to create a tube with a specific outer diameter and wall thickness. This DOM tubing would be purchased from an outside source due to the tooling required in this method. The second method in which the shell may be produced is by purchasing metal stock and turning it down on a lathe to the necessary diameter and wall thickness.

As mentioned in the previous section, the heat shrink shell can either be the same wall thickness as the inner, printed wall or it can be a fraction of the thickness. This shell will be sized such that its inner diameter is equal to the outer diameter of the printed parts. In order to expand the material,

the shell will be placed in an oven and allowed to heat until it has expanded enough in all radial directions to easily slide over all of the segmented parts. A fixture will be used to locate all three printed parts so that the heated shell can be placed over the printed parts as concentrically as possible. The shell is then allowed to cool at room temperature so that it shrinks itself over the parts evenly. Figure 24 below shows a layout drawing of the final part.

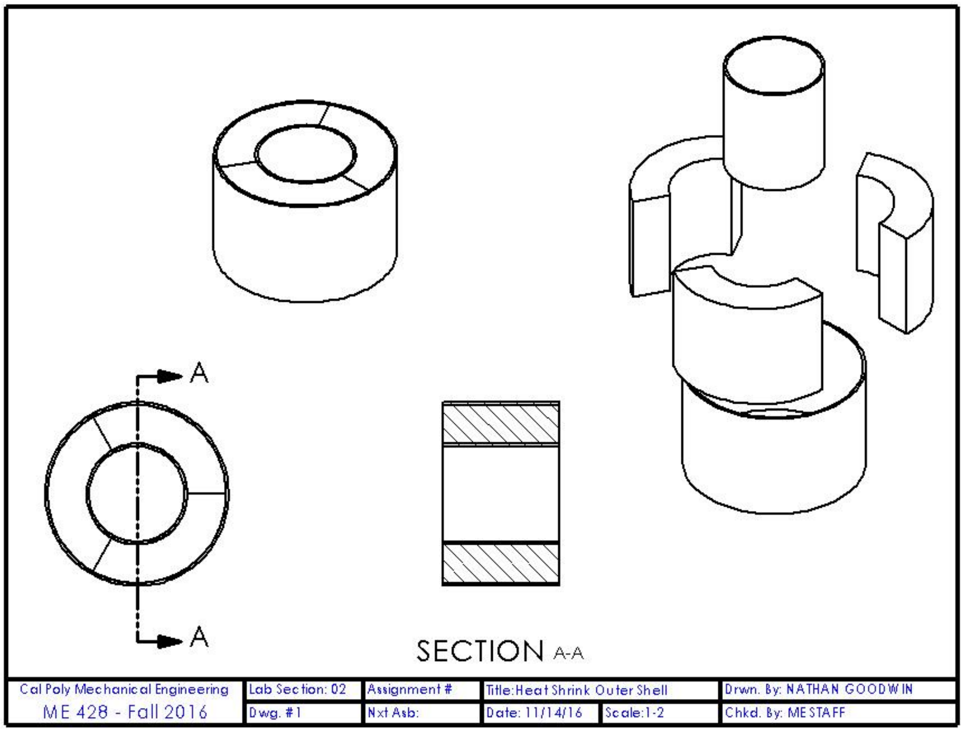


Figure 24. Layout drawing of the heat shrink outer shell joining method. This drawing is based on a full thickness band

Note that if the outer shell can be easily fabricated or purchased then an inner shell may be used to help increase the strength of the completed part.

Button with Weld

The button method can be understood by the clipping mechanism of buckle clips, seen in Figure 25 below.

Figure 25. Buckle clips found on backpacks, fanny packs, and various other gear (20)

The figure above can be viewed as a top down view of the final part with the inner and outer walls corresponding to the two prongs of the buckle. One end of the segment would have a male component which slides into the female component. For this project however, instead of the male component deflecting inward, the female part would deflect outward and the male part would remain rigid. Multiple of these "buttons" would be placed vertically along the edge of each segment to create a stronger total hold. After all buttons are clipped into place a weld would be applied along the seam where the two components meet. Figure 26 below is a layout showing how the parts would be assembled (vertically sliding) and the geometries of each segment.

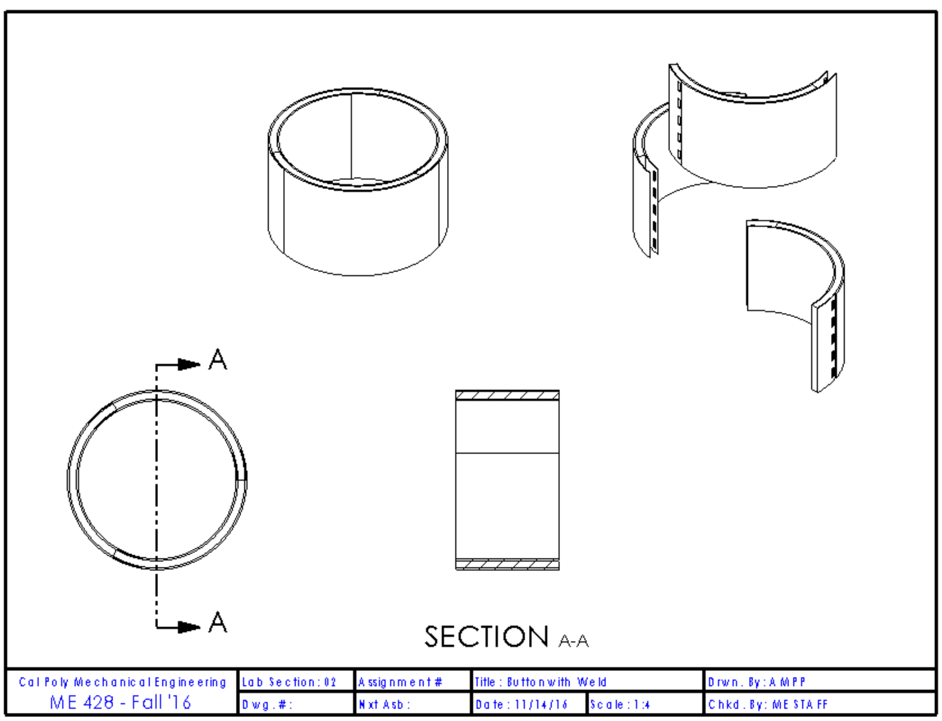


Figure 26. Layout drawing of the button method to show assembly orientation

Puzzle Piece with Weld

The puzzle piece method is another geometric fitting but secures differently than the button. Each segment is split into a male and female end that fit into each other; however, instead of each protrusion appearing like a piece from an actual puzzle set, the pieces are straight horizontal cuts. Figure 27 below shows how the puzzle pieces can slide together radially at one time. Once all three pieces are fitted into one another, a weld would be applied, following the line of contact between both segments.

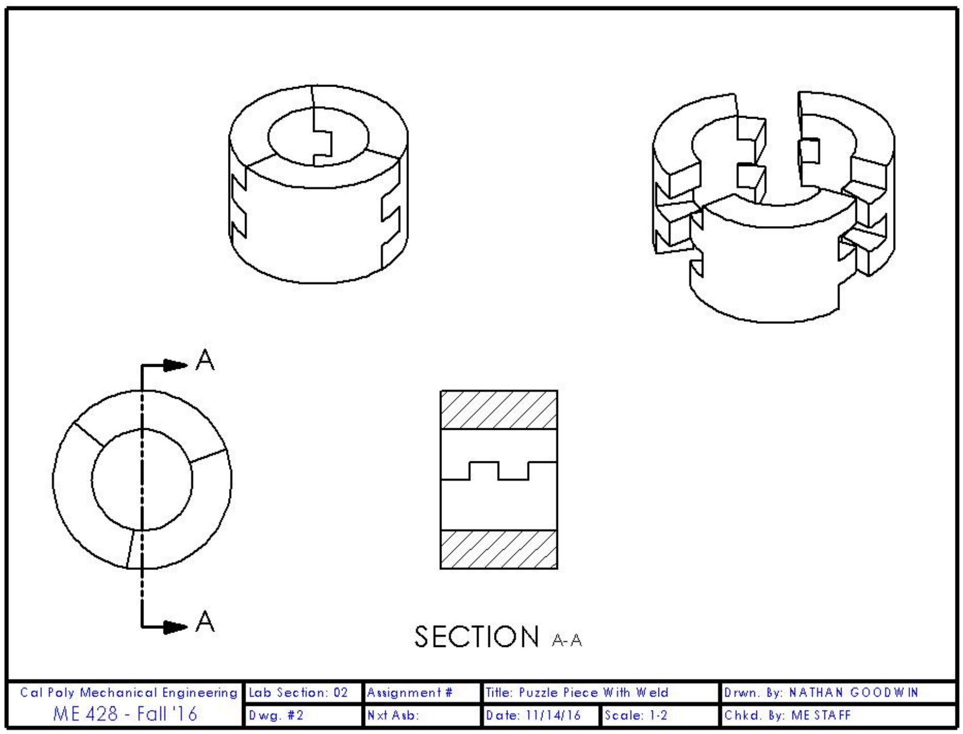


Figure 27. Layout drawing of puzzle piece joining method

Justification of Top Three Methods

Sound engineering judgment was used during the decision making process; the following analysis provides concrete explanations as to why each of the top three concepts are valid and the best ones to continue analyzing.

Outer Shell Heat Shrink

This method is different than all of the other methods because there is no need for a weld since the outer shell is made as one piece and does not need to be joined. This seamless surface also helps to reduce the amount of post processing time since there is no need to lathe off residual material from welding. A basic calculation was performed to determine the approximate safety factors based on both a fully and partially thick outer shell. The outer shell was treated as carrying all of the load (this calculation assumed that only an outer shell would be fabricated). The following Table 2 shows the yield and ultimate tensile strengths used for stainless steel 316L.

Table 2. Yield and ultimate tensile strength properties of stainless steel 316L from two different sources

	AK Steel (21)	Lincoln Electric (22)	
σ_y	42	30	KSI
σ_u	81	78	KSI

The calculation, see Appendix 6: Hand Calculations for the full solution, for a full thickness outer shell came out to a maximum force of 1500 lbf, equating to a factor of safety of 3. The partially thick shell has an approximate factor of safety of 2.2. If an inner shell were to be fabricated the factors of safety would both increase since the inner shell would assist in carrying the load.

Button with Weld

The button method has benefits since there is no need to fabricate any more parts than those that are printed and the assembly process is quick. Similar to the puzzle piece method a weld would be applied along the contact faces of each segment which would serve as the main source of strength. An analysis was performed on the possible shearing of the buttons as they are slid into place as well as the strength of the partially thick inner and outer wall. The factor of safety for possible shearing is 2.3 and the 1.1 for the walls. The full calculations and assumptions can be found in Appendix 6: Hand Calculations.

Puzzle Piece with Weld

The puzzle piece method is similar to the button method because they both mainly assist in locating the pieces together so that a fixture is not needed to hold them together when the weld is applied. It has the same benefits as the button method but fits radially which may prove to be easier than the parts fitting vertically. However, the heat affected zones due to welding will be the weakest areas of the part. For this reason, the puzzle piece method may possibly be combined with the heat shrink method to remove the need for a fixture to locate the parts while the shell is shrinking over them.

Preliminary Plans for Construction and Testing

The three top designs selected from the decision matrix will advance into the manufacturing stage of the design process. The steps of the manufacturing process lead up to a print of the final part on the SLM 125HL machine. Since the resulting part will be larger than the SLM 125HL's build volume, the manufacturing process will achieve the ultimate goal of this senior project. The manufacturing process will begin with printing prototypes on a plastic extrusion printer due to the quick print durations and low part cost. Plastic models will reveal information that may not be evident from the CAD models, which will lead to improvements in the geometry of the CAD model. The concepts will be iterated on the plastic extrusion printers until the joint geometry is

nearly finalized. The joint geometry will be implemented into a flat joint that can be tested for the desired loading requirements. AMPP will request some of the flat joint geometries to be printed on LLNL's SLM machines while the test and assembly fixtures are fabricated. Around the same time that the fixtures are created, any non-printed parts pertinent to the final design, such as the heat shrink outer band, will be sourced and machined. Finally, all of the printed parts, non-printed parts, and an assembly fixture will be used in the assembly process to create the joined part.

Extrusion Printing

Additively manufacturing stainless steel prototypes is an expensive process that should be saved for some of the most refined models. A single print with an SLM 125HL can take approximately nine days, which compared to the length of the senior design process, is an exceptionally long print time. To further discourage printing parts on the SLM 125HL machine at Cal Poly, the machine is not currently operational and will tentatively remain inoperable until January. For these two reasons, concepts will initially be printed using one of the LulzBot Taz 6 thermoplastic extrusion printers in the Wind Tunnel Laboratory at Cal Poly, seen in Figure 28 below. AMPP has experienced print durations of approximately eight hours with this particular printer, and this will allow for about one iteration per day. Iterating the geometry with the extrusion printer will minimize the amount of models that will be printed on the SLM machines.

Figure 28. LulzBot TAZ 6 (23)

Flat Joint Design and Testing

Once the geometry of the joint is finalized on the extrusion printers, the joint geometries will be implemented on a flat joint rather than a curved joint. Approximating a curved joint as a flat joint is valid because an internal tangential force acts in the direction of the flat joint. The internal force

that the joint will be designed for can be applied in a tensile testing machine, such as the Instron in Figure 29. Testing just the flat joint reduces costs in the printing process since less material would be printed and the print duration would be shorter. The results obtained from testing flat joints would be analyzed in order to decide on the best joining method for the final part, which would be printed on an SLM machine.

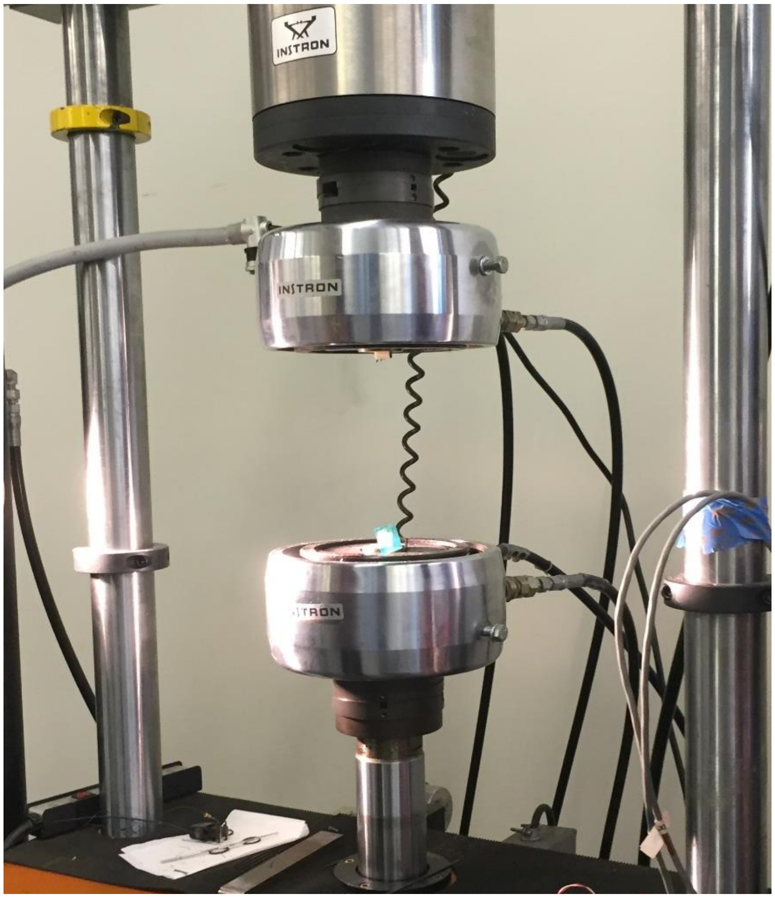


Figure 29. Tensile testing Instron in Cal Poly's Composites Lab

Fixture Fabrication

The assembly technique of the final part would require a fixture, especially if the segmented parts need to be welded together. It is necessary for the assembly fixture to be rigid, relative to the part, to prevent warpage during either the heat shrink or welding process. The assembly fixture would be lathed from metal stock to either match the inner or outer diameter depending on the joining method. This would be fabricated in parallel with the testing of the flat joint and the printing of the final part to ensure that the fixture is functional before the segments are ready to be joined. A test of the functionality of the assembly fixture may include joining plastic parts before the final parts are joined.

Another fixture that is likely to be fabricated is a testing fixture. The purpose of the testing fixture is to test the maximum, internal, tangential force that the joined part can withstand. The test fixture

would be two identical attachments for the Instron jaws that would use hemi-cylindrical extrusions to pull the cylinder apart from the inside. A hemi-cylindrical extrusion on each attachment would fill the inner volume of the joined part. This would also be fabricated in parallel with the flat joints and the printing of the final part.

Heat Shrink Band Fabrication

Two methods for creating the heat shrink bands have been proposed. The first method would require AMPP to find a source for DOM tubing since the DOM process cannot be conducted at Cal Poly. If DOM tubes cannot be obtained in the particular size required for this project, the inner diameter, outer diameter, and length could be changed on a CNC lathe at Cal Poly. Lathing tubular stock is the second method to create a heat shrink band. Although the first method may include lathing DOM stock to the target dimensions, the second method focuses on lathing any tubular stock to the target dimensions. The stainless steel tubular stock required is 8” Schedule 100, which is about 7.5 times thicker than the outer shell (24). Lathing the tubular stock to the target diameter and thickness would require most of the material to be removed and consequently increase tooling costs and operation time. Sourcing DOM tubing that is a similar size to the outer shell may be preferable, but further research will be conducted.

Final Part Fabrication

The final part will ideally be printed within the SLM 125HL at Cal Poly in three segments. If external parts are needed, such as the heat shrink shells, they will be sourced and fabricated prior to the print of the three segmented parts. In the event that the SLM 125HL at Cal Poly is not operational, the parts will be requested to be printed at LLNL and shipped to Cal Poly. AMPP will be conducting the final assembly with the assembly fixture. The general assembly procedure is known, but depending on which concept performs best in the flat joint tests, the procedures will change. For the heat shrink fit shell concept, the temperature ranges and dimensions of the shell prior to the shrink fit are unknown. Also, the final dimensions of the fixtures are still unknown. The entire process will be extensively documented and presented to LLNL.

Safety Hazard Identification

Safety is key to a team’s happiness and productivity. Cal Poly and AMPP plan to contribute to a safe and healthy environment. One of the biggest goals AMPP tries to achieve is maintaining a safe workplace environment for its team members and technicians. Efforts will be made to reduce the amount of hazards to keep AMPP team members safe. Professional technicians will assist AMPP with the operation of the SLM machine and post-processing machines.

- Mechanical
    - Part Kinetics
        - Part may fall off lathe and cause injury.
    - Failure
        - Part may shatter under the 5,000-pound tensile load applied to a tester.

    - Lacerations
        - Surface finish of printed part may be rough, and cause lacerations to hands if not handled with gloves.
        - Connection points of the axisymmetric part may cause pinching if not handled with care.
- Heat
    - High Degree Burns
        - High degree burns can occur from heating treating of the metal bands if safety precautions are not taken. Serious burns can occur if printed parts are immediately handled.
    - Explosion
        - An explosion may occur if the SLM printer is not properly cooled, and ventilated.
- Electrical
    - Shock
        - Shock may occur if the SLM machine, or person is not grounded. Shock can occur if a liquid spills onto the SLM machine while it is running. It may also occur if the axisymmetric part is electrically conducted.
    - Fire
        - A fire may occur if the SLM machine overheats.
- Chemical
    - Toxic
        - If the metal powder is ingested, may require hospitalization.
- Ergonomic
    - Human Error
        - If machines are not properly operated, serious death or injury may occur.
    - Noise
        - The lathe may get loud when operated.

Final Design Details – CDR

Continuing onward from the Preliminary Design Review, the top three methods were further analyzed to converge on a single design. This section of the report will describe the design of the joint geometry and joining method that AMPP has devised to meet LLNL's requirements. The final design incorporates ideas from the initial concepts to assist in the locating of the parts when joining. The report further justifies the use of these design decisions based on engineering concepts and feasibility. AMPP created the final design in SolidWorks and produced engineering drawings to convey dimensions to the manufacturing lead. The dimensions of the part originated from the supporting data and are included last in this section. Any alterations to the design occurring after the Critical Design Review will be stated in the following section, Final Design Changes.

Design Description

Final Part for CDR

The final design builds upon and combines the best aspects of each of the top three designs from the Preliminary Design Review. Drawing from the puzzle piece idea, each segment will be printed with teeth at the end of either face such that they will align in the axial direction quicker than if the edges were flat. This geometry feature has no additional cost since total volume of printed material does not change, only the pattern in which the material is printed changes. This feature will be referred to as teeth where each part has three male teeth that joins the two female teeth on the adjacent part. Male and female teeth are shown in Figure 30 below.

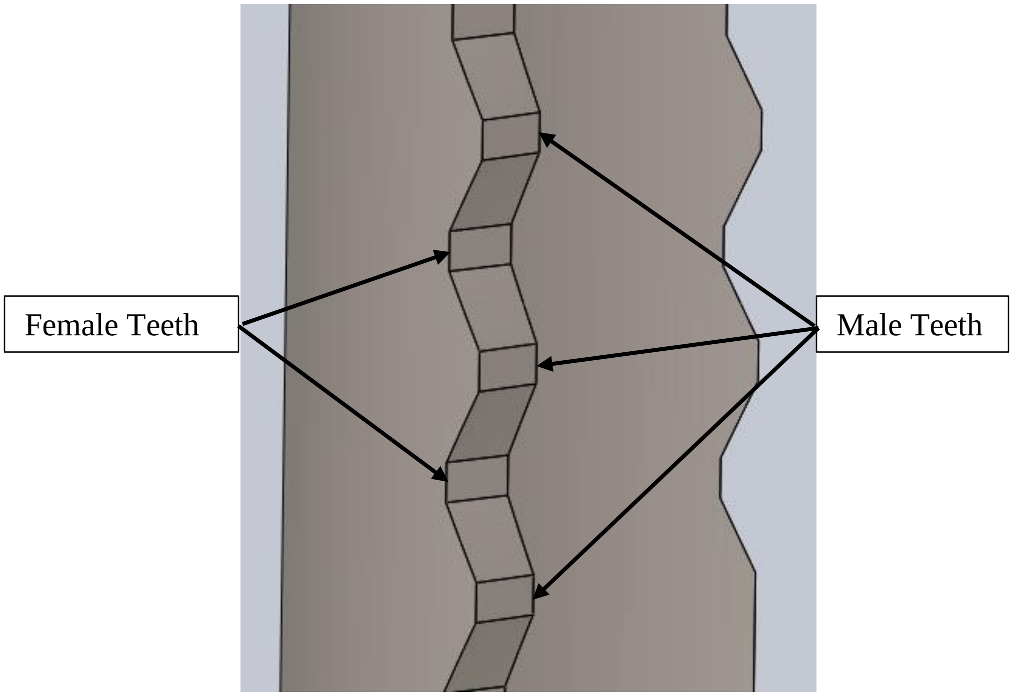


Figure 30. View of the three male teeth and two female teeth at the end of each printed part

Another major feature of the printed part prevents movement in the radial direction and holds the segments together rigidly. This feature will be referred to as the collar since the design is similar to a shaft collar. The collar design involves printing an extra 15mm of solid material to the top and bottom of each segment along with a pilot hole perpendicular to the face of the mating surface, shown in Figure 31. In post-machining processes, the pilot hole will be drilled, counter bored, and tapped in order to bolt the parts together with ¼-28 screws. Once the parts are joined together and turned, the heat shrink processes can be performed to fit the inner and outer bands. The final machining operation will turn the assembled part to the final inner and outer diameter and part off the collars in the lathe. Sufficient clearance will be printed between the bolt and the lattice to allow for a smooth part off operation since there will be no interrupted cuts or changes in density of the material being parted.

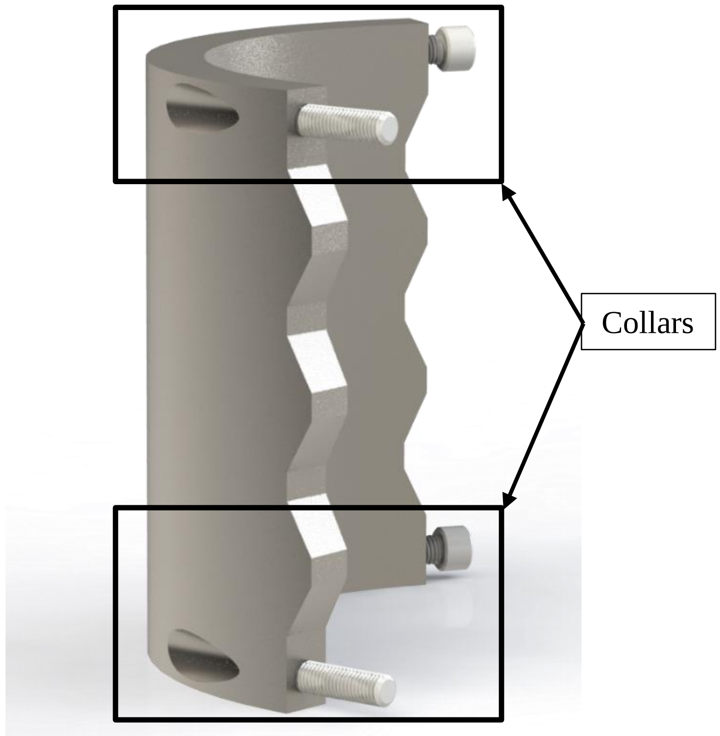


Figure 31. Collar added to the top of the printed part.

Test Piece Assembly

To prove the results from Appendix 6: Hand Calculations of the Minimal Band Thickness, three different test assemblies will be manufactured using three sets of inner and outer bands with varying thicknesses. The first band thicknesses will be machined to the large value of 1.8 mm while the second set of bands will be machined to the nominal value 1.7 mm thick and the third set will be machined to 1.6 mm thick. The shell thickness of each set is 0.2 mm, 0.3 mm, and 0.4 mm, respectively to maintain a total wall thickness of 2 mm. The final height of each set, which is equal to the height of the lattice, is 20 mm with a 15 mm layer of solid material between the sections so that each segment of each set can be printed vertically on top of each other. Figure 32 below shows a cross section of what one side of this test piece assembly looks like. Note that the radial scaling of the figure is 10:1 while the axial scaling is 1:1 so that the cross section can be clearly seen. Also, the axis of revolution is not shown on the drawing. The bottom set consists of the 1.6 mm bands and the 0.4 mm printed shells. The middle set consists of the 1.7 mm bands and the 0.3mm printed shells. Finally, the top set consists of the 1.8mm bands and the 0.2 mm shells.

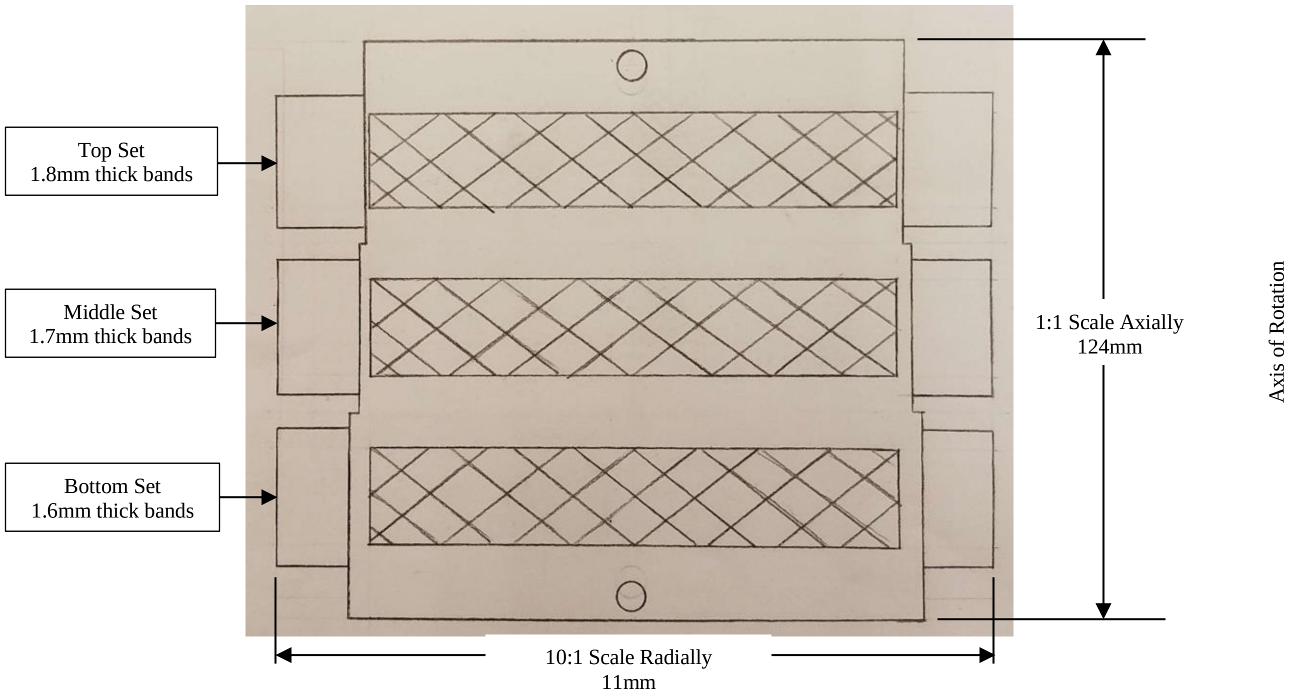


Figure 32. Cross section of one side of the test piece assembly.

Justification

Each feature of the final design has a specific purpose and each dimension can be proven that it is either sufficient or ideal. After presenting the preliminary design report to LLNL it was brought to the AMPP's attention that the part must be designed to have a safety factor of no less than three. Also, the yield strength value from Table 2 was determined to be too high, and a new value of 25 ksi was designated as the max yield strength. This information had a large impact on the final design decision.

Welding

Some of the first few ideas that came out of the ideation process at the beginning of the project involved welds of the seams between the face of each printed part. While this method was still considered during the preliminary design review, the team conferred with a specialist in IME department, David Otsu, to understand how welding would affect the materials integrity. The results received from Mr. Otsu revealed that the heat affected zones that would result from the welding would alter the microstructure of the stainless steel and therefore change the physical properties of the material. With this result and the knowledge that the weld area would need to be machined to obtain the required surface finish, welding is no longer considered as for this project.

Button Method

One of the top three methods that came out of the preliminary design review was the button with weld method. However, during the presentation of this method to the sponsor there was concern

with the female tabs since the metal would have to deflect outward. The sponsor advised that this should be avoided if possible due to the amount of force that would be required to snap the parts together. Also, lining up the buttons parallel to the axis of revolution requires an increasing amount of force to be applied the more that the part is slid into place. To prove that this method is invalid, hand calculations were completed in order to find the yield strength that would be required of the material. A straight beam approximation was used since failure under this condition necessitates failure under a curved beam in bending analysis. The analysis showed that the material would need to have a yield strength of over 71 ksi, which is 46 ksi more than the maximum allowable stress. The work for this calculation is composed in Appendix 6: Hand Calculations-Button Method.

Inner Band

Hand calculations of the outer shell heat shrink that were presented in PDR were based on old yield strength values and also calculated a safety factor of under three, therefore this method needed to be adjusted. Using the new parameters, a calculation of the minimum band thickness for the heat shrink method showed that having a single outer band was no longer sufficient. The maximum thickness allowable in a single band is 2mm and the calculations required a minimum thickness of 3.4mm. Introducing an inner band allowed for each band to share the load and split the maximum allowable thickness. Complete hand calculations can be found in Appendix 6: Hand Calculations in the Minimum Band Thickness section. Fortunately, an inner band does not add much complexity to the process since it is treated similarly to the outer band. However, instead of being heated, the inner band will be cooled while the assembled printed parts and outer band are heated together so that the inner band can be placed inside and allowed to expand.

Blunt Tooth Geometry

As mentioned in the design description of the final part, each segment has a puzzle-piece style geometry to help with radial alignment of the segments so that they can be held together accurately for the outer band to heat shrink over. Two geometries were considered: a sinusoidal wave and a series of blunt teeth. The sinusoidal wave would work well but does not provide a strong axial locking feature since there is a chance that two segments could slide past one another. The blunt tooth, however, provides a better axial locking feature since the sharp features create a definite location for mating surfaces to meet and would not rely on bearing stresses like the sinusoidal tooth geometry would. The number of teeth is of importance because increasing the amount of teeth decreases the depth of the teeth for the same angle. Shorter teeth would be difficult to clean once the parts come out of the printer and they would have a higher chance of running into interference issues. Additionally, when the SLM printers are creating support material for a part, the angle between the direction perpendicular to the build plate and any surface is known as the overhang angle. When the overhang angle exceeds 45°, the printer is instructed to print support material. If this were to happen, the final parts would require more machining to remove this material and may lead to lower quality finish. The puzzle pieces that were created for the preliminary design review had overhang angles of 90°. They were adjusted to have an angle of less than 45° and shaped more like protruding trapezoids rather than protruding rectangles. This

low overhang angle means that there cannot be a large amount of teeth printed at a depth that allows for solid locating. Considering all of these variables, three teeth were designated as the maximum number of teeth on the male end. Figure 30 shows what these teeth look like.

Step Joint

For further alignment assistance, a step joint was considered at the ends of each segment, which allows the part to be held together in the radial direction. In order to prevent the pieces from locking one another out radially, each segment would have different end step joints. For clarity, male joint ends are those which have a step joint such that the arc length is longer along the outer diameter of the part and have three teeth protrusions; female joint ends are therefore have a longer inner diameter arc length and have two teeth protrusions which are offset from the male teeth so that both surfaces can fit together. However, since the blunt tooth already has a two-planar surfaces due to the protrusions, the step joint introduces a third plane with the exposed lattice. This presents a problem since a sharp internal corner has been introduced, as seen in the Figure 33 below. As previously mentioned, when the parts come out of the printer, they need to parasitic material must be removed on any exposed surface. Therefore, this corner needs to be machined clean, but since it is nearly impossible to access, the tooling needed to perform this process is not feasible, and the step joint method is longer considered.

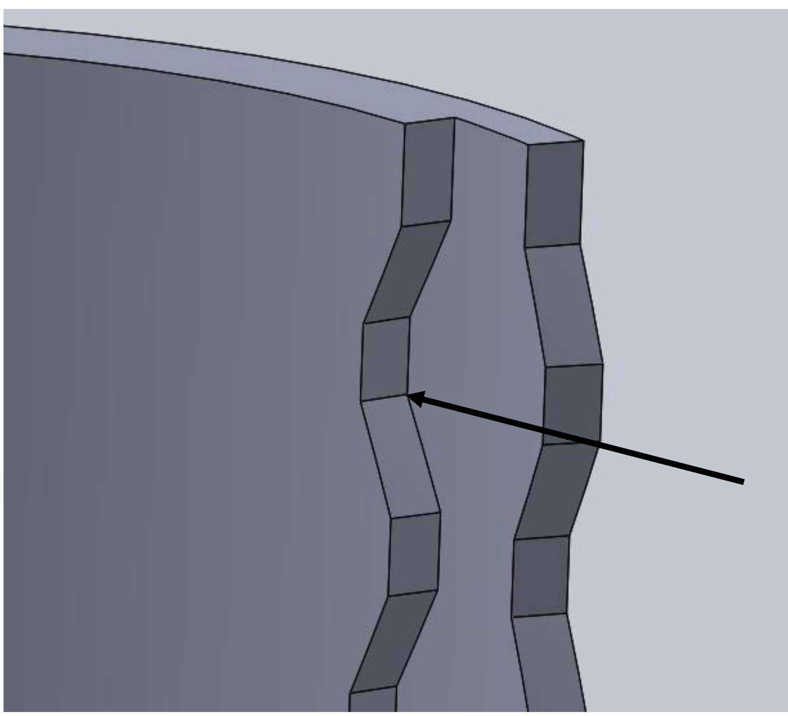


Figure 33. End of a printed segment. The arrow indicates the corner that forms between the three planar surfaces. Note that this idea has been rejected because of the corner's difficult accessibility to clean

Collar

Since the parts will have parasitic material after the print is complete, all segments need to be turned on a lathe to meet the surface finish and diametric requirement. However, there are a few problems that need to be addressed. When the parts come out of the printer they are each a radial third of the final cylinder. It is not safe to fit one segment at a time into the jaws of the chuck and turn the segment down because it is not continuous around the axis of the lathe. This creates interrupted cuts, wherein the turning tool is not in constant contact with the work piece, which can negatively affect cutting edge integrity, process security, and part quality. (25) Also, the internal lattice is not as structural sturdy as a solid material, restricting the jaws from securely holding the part while it is spinning. A brainstorming session was conducted to create a fixture that provides structural support during the machining processes and also be scalable since one of the main goals of the project is to create a process that can be replicated for any reasonably sized axisymmetric part. Several potential solutions were sketched and can be seen in Figure 34 below.

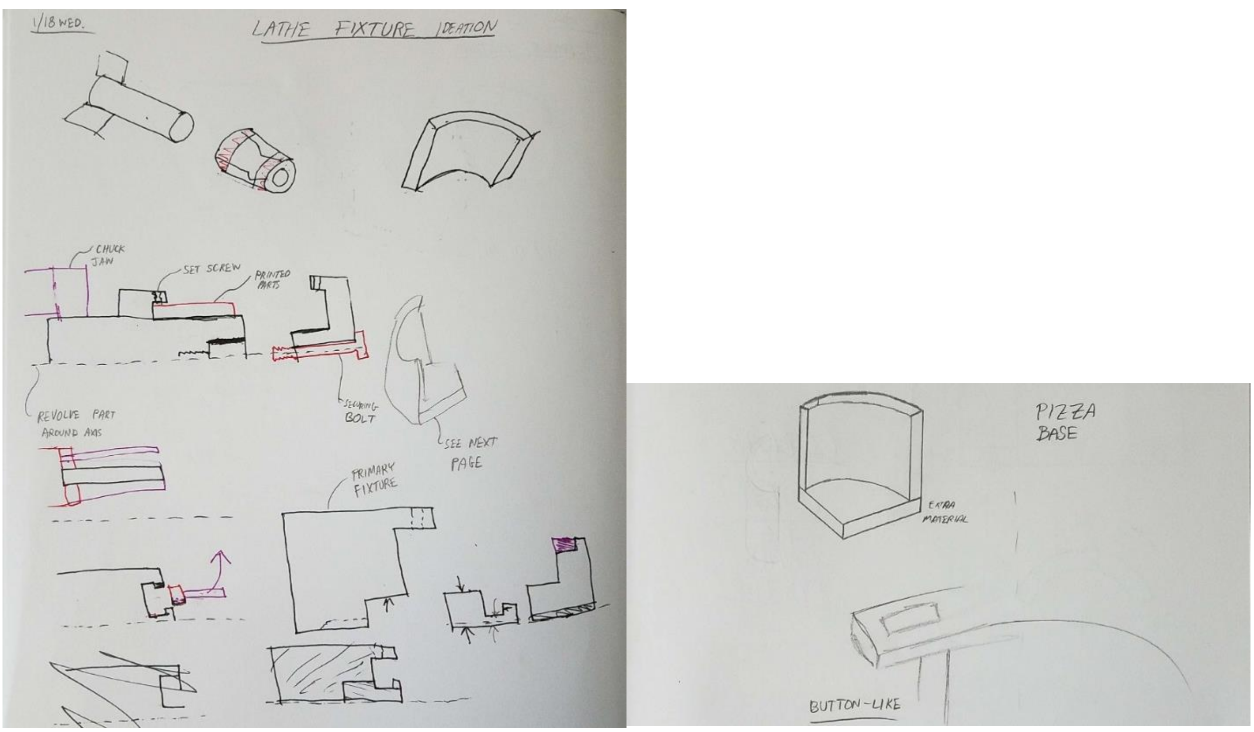


Figure 34. Sketches of lathe fixture ideas

These solutions could all potentially work, but the time and cost investment involved in each one was not reasonable. During the ideation, a shaft collar was proposed to hold all of the segments together. This would only require extra solid material to be printed in the axial direction so that the collar could grip onto something sturdy. With this idea, it was discovered that the collar could be printed within the part further reducing the amount of parts that would need to be created. This idea is known as the collar method and negates the need for a lathe fixture altogether since the

CAD model of each segment can be created such that one face has a tapped hole and the other face has a through hole with a counter bore for the head of a bolt to sit in. The collar is added axially to the top and bottom of each segment and has a solid infill so that the jaws of the chuck in the lathe can securely grip the part. Refer to Figure 31 for how this collar affects the look of the overall part.

Change in Part Dimensions

The part that was given by the sponsor specified a 200 mm outer and 175 mm inner final diameters. Using these dimensions to create a CAD model of an individual segment, it was observed that one segment cannot fit on the build plate in any orientation. Additionally, the outer band and inner band will be purchased from a supplier and can only be bought in standard sizes. The only tubes that could be used to make a 200 mm band would require an excessive amount of turning which is time intensive and not efficient for a proof of concept. An analysis was done in Excel to determine the optimal inner and outer diameters based on standard tube sizes, available area on the build plate, and minimal amount of material to be removed. The results from the Excel sheet show that the best combinations of diameters and tubes are an outer diameter of 165mm and an inner diameter of 135mm corresponding to pipe sizes 6 schedule 40 and 5 schedule 40, respectively. These diameters are near the center of the thickness of the tubes which allows for sufficient depths of cuts when turning in the lathe. This change was relayed to the sponsor and accepted. Figure 35 and Figure 36 below show both final band dimensions as well as the dimensions of the pipe that will be purchased and turned down to create them.

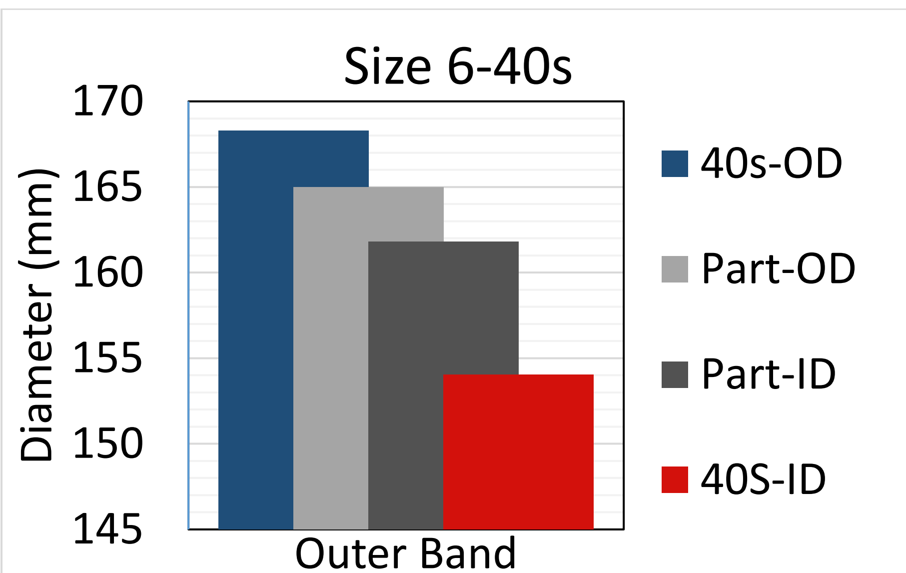


Figure 35. Inner and outer diameter of the outer band compared to standard pipe size 6 schedule 40s. The distance between the max heights of each bar (OD and ID respectively) represents the amount of material that will need to be removed from that side.

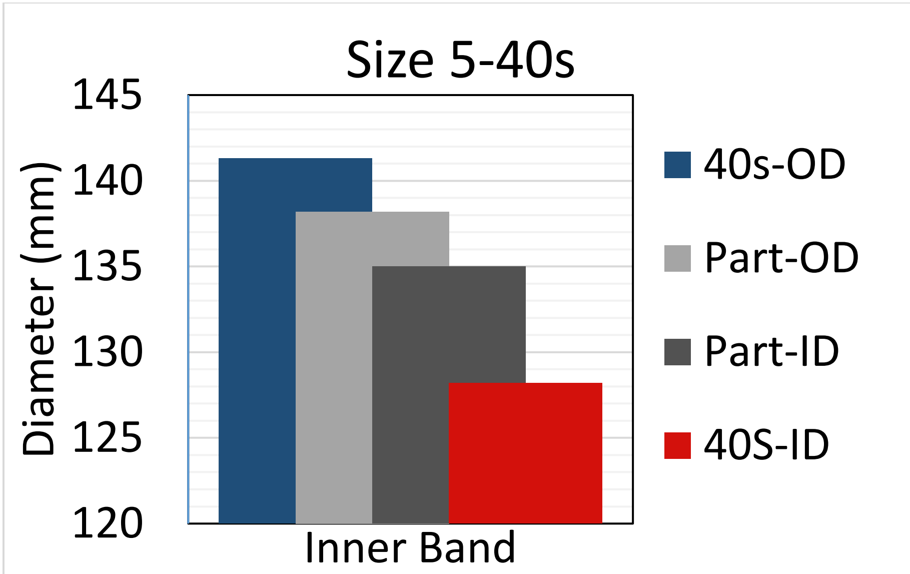


Figure 36. Inner and outer diameter of the inner band compared to standard pipe size 5 schedule 40s. The distance between the max heights of each bar (OD and ID respectively) represents the amount of material that will need to be removed from that side.

Test Piece Assembly

Recall from Appendix 6: Hand Calculations that both the inner and outer band can be no less than 1.68mm thick. To prove that this calculation is correct, three sets of inner and outer bands will be machined with varying thicknesses and heat shrunk over their corresponding printed parts. In order to maintain the required 2mm total wall thickness without altering the thickness of the lattice, the shell thicknesses of the printed part changes depending on the thickness of the bands. If the hand calculations hold true, the nominal thickness bands of 1.7mm should be able to withstand the load while a smaller 1.6 mm band should yield and a larger 1.8mm band should easily withstand the load. Note that the outer dimension of the outer band and the inner diameter of the inner band will remain the same no matter the thickness. However, printing three sets of printed parts and machining six total bands, all at an axial height of 115mm, presents a few issues. First, completing this task requires excessive material and time to complete. Second, in order to provide the force needed to test the part at this height, the Instron must provide a tensile force of 30000lbs, which the machine is not capable of exerting. In order to reduce both of these restrictions, the height of each set was reduced to 20mm. This is possible since the tangential force is scalable according to the height of the part as can be seen in the Appendix 6: Minimum Band Thickness calculations. The height of the bands, however, is 24mm to provide clearance during the heat shrinking process. Finally, as mentioned in the design description section and seen in

Figure 32, a 15mm layer of solid material is printed between each set to create clear separation that may be parted through with ease on the lathe.

Heat Shrink Interference

Interference between the printed parts and the inner and outer bands is necessary for the part to remain intact during machining, handling, and its final application. To begin the process of calculating how much interference is ideal, the mechanical properties of the lattice and bands must be considered. Figure 37 shows the relationship between compressive stress and strain of the lattice. Using the average of both test results, the average bulk modulus was determined to be 40.6 ksi, which is calculated in Appendix 6: Hand Calculations using equations from (26).

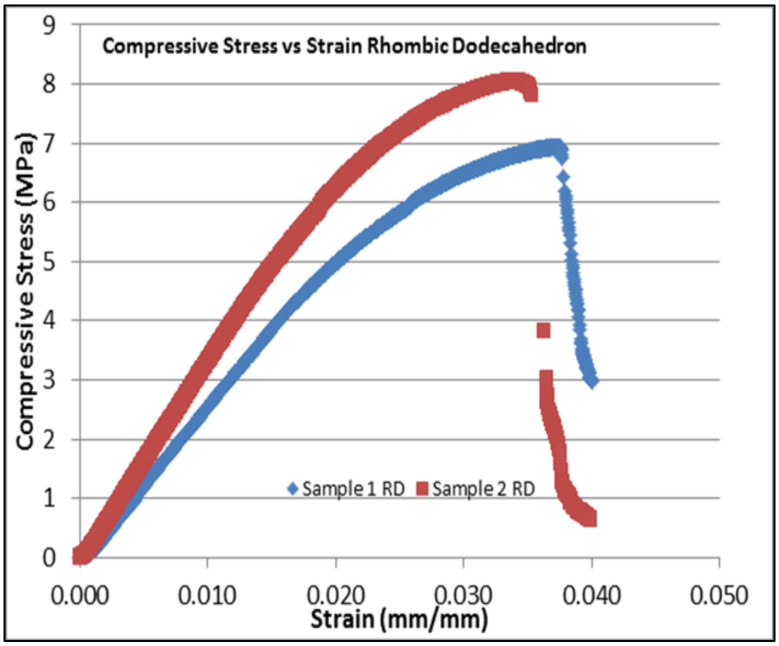


Figure 37. Compressive stress versus strain of lattice

The maximum allowable strain of the lattice is about 3% which results in a stress of about 1 ksi. To obey the customer's requirement of a safety factor of 3, a maximum lattice strain was chosen to be 1% which results in a stress of about 400 psi. Since the lattice is 11 mm thick, the goal for the amount of radial interference is about 0.1 mm or about 0.004 in. Now that the target stress and strain is known, it can be difficult to calculate the dimensions that the printed parts and bands should be before the heat shrink process since both will deflect until they achieve an equilibrium. An assumption was made to treat the bands rigidly such that the dimensions before and after the heat shrinking procedures is the same. This is a valid assumption to make because the bulk modulus of the bands is about 450 times stiffer than the bulk modulus of the lattice. Furthermore, the elastic modulus of the bands is nearly 700 times stiffer than the bulk modulus of the lattice considering that outer band will be in tension and the inner band will be in compression. For equal amounts of forces, the bands will deflect insignificant amounts compared to the lattice.

It is desirable to know the amount of pressure on the inner shell and outer shell of the lattice to verify that the friction of the press fit will hold the part together without slipping. Since the amount of radial strain is known, the printed parts can be treated like a thick-walled pressure vessel with

an internal and external pressure. The calculations that determined the pressures are also included in Appendix 6: Hand Calculations. The pressure at the interface of the outer band and the outer shell of the printed part is 244 psi and the pressure at the inner interface is 266 psi. The original height of 115 mm was to calculate the surface area, and the coefficient of friction was assumed to be 0.58. (27) Surface area, friction coefficient, and pressures were used to calculate the separation forces of 12,000 lbf for the inner band and 13,000 lbf for the outer band.

Heating ranges

Since the deflection of the lattice is known, the minimum amount that the bands will have to expand or shrink to fit over the printed parts can be calculated. The heat shrink process begins with heating the outer band and then inserting the parts into the band. For the outer band, this will be achieved by increasing the inner diameter more than 0.1mm to fit over the printed parts. This corresponds to a temperature difference of about 50°C, which would result in a final temperature of about 75°C, assuming a 25°C room temperature. Although this temperature would work in theory, it would not provide sufficient clearance. A temperature difference of about 300°C would result in a final temperature of 325°C and increase the outer band's inner diameter by 0.7 mm providing 0.6 mm of diametric clearance. This temperature was chosen by staying safely below the maximum allowable temperature of 425°C while still providing over 0.5mm of clearance, as shown in Figure 38 with the thermal expansion trend.

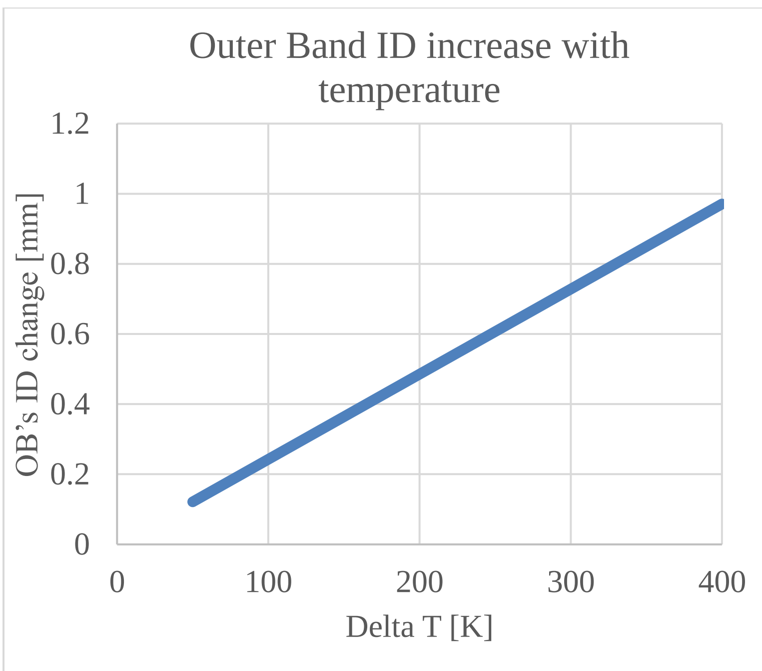


Figure 38. Thermal expansion trend of the outer band

The inner band must shrink to fit within the printed parts and outer band assembly. Not only is the inner diameter of the lattice's shell smaller than the outer diameter of the inner band, but the outer band is compressing the parts inward as well. This added deflection results in a decreased printed

part's inner diameter of about 0.1 mm. Similarly, to the outer band, a 300°C temperature difference is the goal which will achieve a clearance of about 0.4 mm as seen in Figure 39.

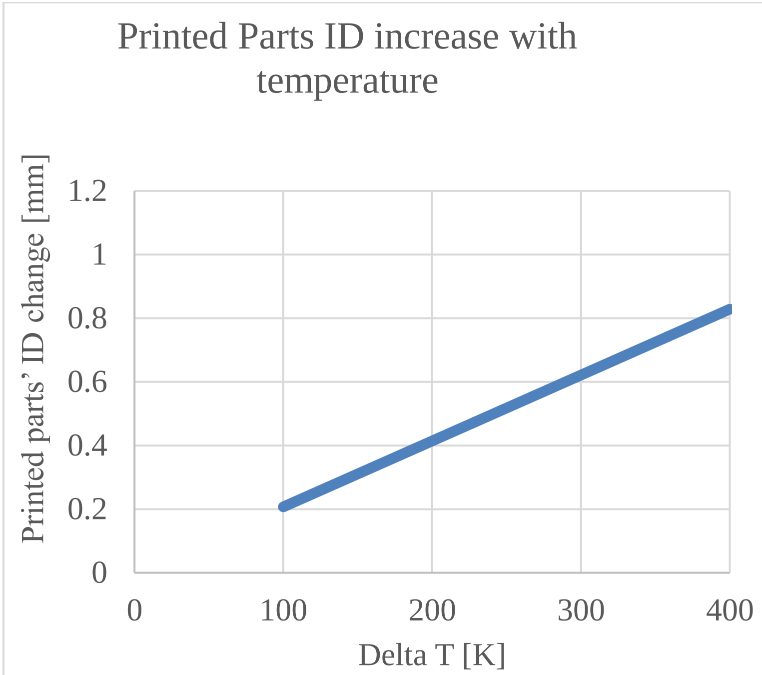


Figure 39. Thermal expansion trend of the inner band

Project Plan

The final design was developed with careful consideration to the manufacturing feasibility. As explained in the heat treatment background section, the printed parts must first be heat treated such that after treatment they reflect the microstructure of a part made from SS 316L. Manufacturing considerations are also necessary for the bands. They will be sourced from a common supplier of stainless steel tubing and turned to the desired dimensions on a lathe. Finally, there are two fixtures that are going to be used in this project and they must be fully designed, from sourcing to fabrication.

Manufacturing Plan

Assembly Fixture

The fixture used to contain the heat shrink process is known as the assembly fixture and is fabricated out of a single sheet of general purpose low-carbon steel sheet metal. A base will be sheared from the sheet to provide a solid, flat surface for the parts to rest on while cooling. The support walls will be individually sheared to the proper dimensions and fillet welded on the inside seam to form a square. This square will then be fillet welded to the base plate. See Appendix 8:

Drawing List and Part Drawings for detailed drawings. A square was chosen as the final shape to make the housing since it provides full containment of the part and it is easier to fillet-weld four pieces together at 90º each than attempting to make a triangle and have to worry about non-standard angles between each piece. See Appendix 9: BOM for the cost breakdown.

Alignment Fixture

The alignment fixture is to be machined out of a solid block of 6061 aluminum. A mill will carve out the ‘H’ shape of the fixture and drill the holes for the two 10-32 screws. The two 10-32 screws, made out of alloy steel, are being purchased from McMaster Carr.

Part

The final part will be made through the following joining process seen in Figure 40. The process is organized in a way that yields the shortest production time. The parallel branches of the flow chart indicate process paths for individual parts until they are joined. Tasks that are horizontal to each other are not dependent on each other and can be completed simultaneously. Tasks can only start after the task above it has been completed. The flow chart starts with three branches (one for the inner band, outer band, and printed parts from left to right) and ends in one branch for the final joined part. Throughout the joining procedure, there are three machining sections and two heat shrink sections that alternate, starting and ending with machining. The machining sections are referred to as “M#” where the number refers to a particular section. Likewise, the heat shrink sections are referred to as “H#”. There are a total of 14 individual tasks that must be completed in the joining process, and each task will be described in detail.

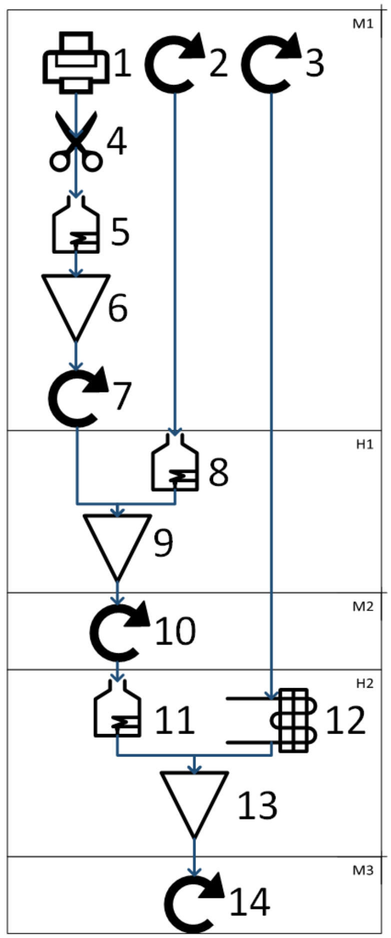


Figure 40. Joining process flowchart

M1: Step 1

The first branch corresponds to the printed parts and starts with the initial print in the SLM machine, step 1. AMPP can either print the parts on the SLM125HL at Cal Poly SLO or can have the parts printed at LLNL.

M1: Step 2

The second branch corresponds to the turning process of the outer band on a lathe. A stainless steel 316L tube with an inner diameter of 152.4mm (6in.) will be bored to a diameter of 161.8 ± 0.15mm (6.370 ± 0.006in). The outer diameter will not be turned at this point for two reasons. The first reason is that a thicker band will provide more support in the lathe for M2: Step 10. The other reason is that a thicker band will lose heat slower during the heat shrink procedures, which allows for more handling time. The band will be parted off the lathe at an axial length that matches the printed parts' length of 124mm.

M1: Step 3

The third and final branch corresponds to the process path of the inner band. Another stainless steel 316L tube with an outer diameter of 5.75in. will be turned on a lathe to 138.2 ± 0.15mm (5.440 ± 0.006in).

M1: Step 4

If the parts are printed at Cal Poly SLO, 4mm of extra material will be printed between the build plate and the parts to allow 3.2 mm for the kerf of the vertical band saw blade. The ideal option would be to print the parts at LLNL since LLNL has the capability to wire EDM the parts off the build plate.

M1: Step 5

Step 5 is the heat treatment procedure of the printed parts. If the parts are cut at LLNL, they can be heat treated with the other parts that LLNL is also heat treating. If the parts are printed at Cal Poly, the parts will be heat treated under the supervision of David Otsu and Dr. London in the Materials Engineering (MATE) department. Another option may be to print and cut at Cal Poly, then send the parts to LLNL for heat treating.

M1: Step 6

This step involves removing material from the printed parts to allow them to be screwed together. The mating surfaces of the teeth will be slightly sanded with very fine sand paper to remove parasitic material. Next, the pilot holes within the collar will be drilled to accommodate a counter bore and threads. First, the part will be clamped axially in a vise on the drill press as shown in Figure 41. The operators will ensure that the collar's mating surface is flush with the top of the vise.

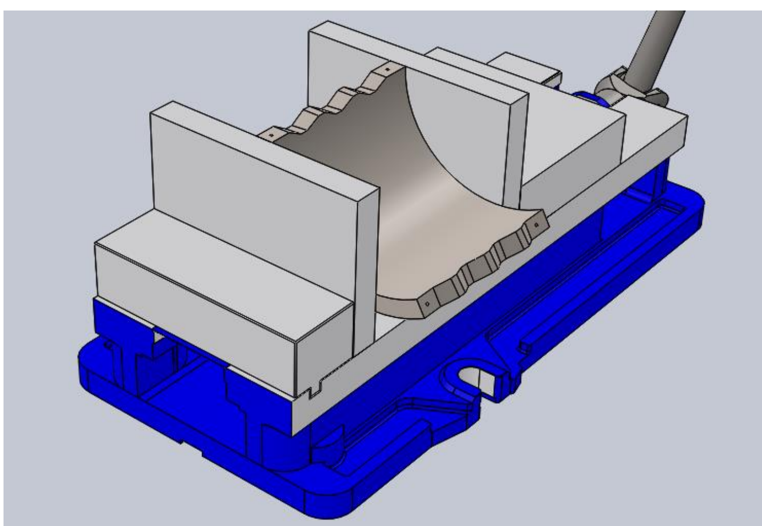


Figure 41. Printed part with pilot holes

The pilot holes will be drilled with a number 21 drill bit, and tapped to a 10-32 thread. Since these threads are only temporary, they will not affect the form of the assembled part since the outer diameter of the 10-32 screws is smaller than the tap size of the ¼-28 screws that will be used to hold the part together. Once all four threads are created in the printed part, the printed part is taken out of the vise and attached to the alignment plate as shown in the exploded view of Figure 42.

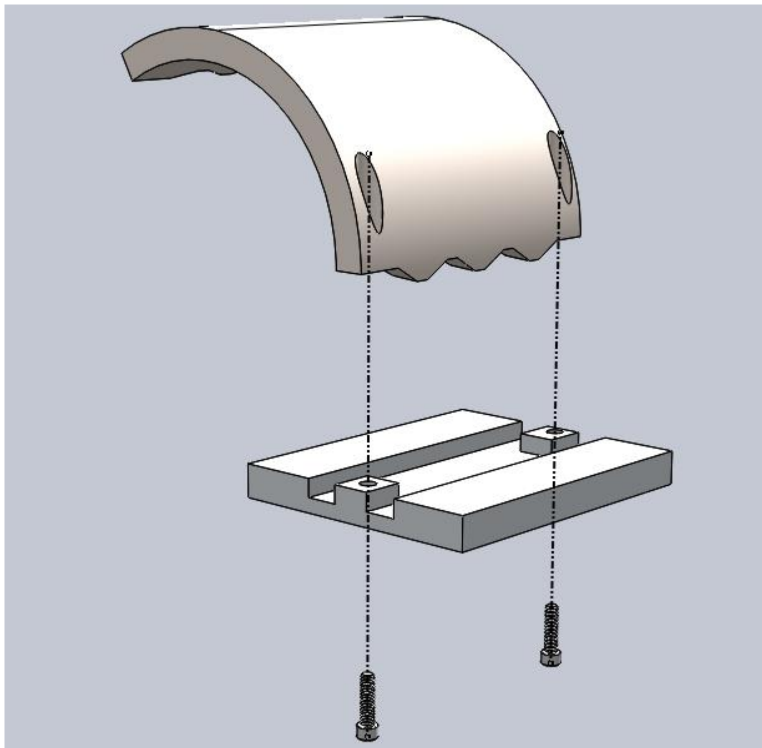


Figure 42. Alignment plate being fixed to the printed part

The vise alignment plate allows for accurate alignment of the segmented part in a vise. It allows the mating surface of the printed part to be held parallel to the top of the vise, which will be perpendicular to the Z axis on a mill or drill press. Once the printed part is bolted to the alignment plate, it will be placed on a 1-2-3 block in a vise on a mill, which is modeled in Figure 43.

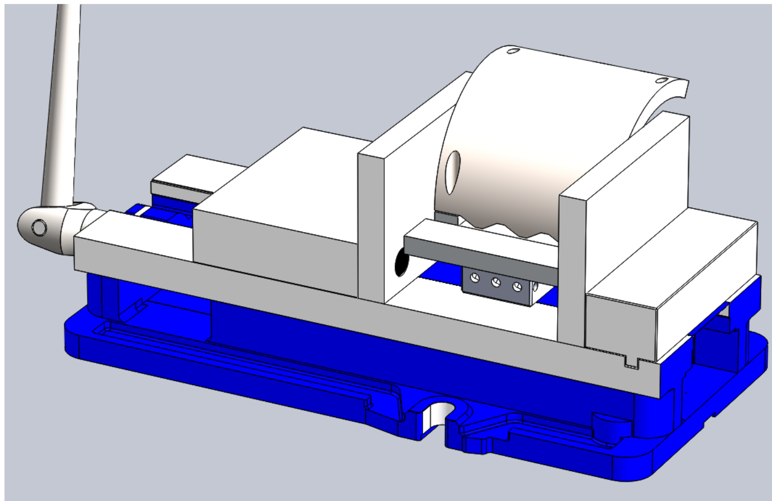


Figure 43. Printed part, alignment plate, and 1-2-3 block in a vise

The part is clamped in the axial direction. The screws are removed from the printed part, which allows the 1-2-3 block and the alignment plate to be removed from the vise. Since the alignment plate is slightly narrower than the printed part, it can be removed once the vise is clamped. Then, the 0.375” counter bore, 0.25” through hole, and #3 tap hole can be drilled. All three printed parts are then assembled with ¼-28 screws in the configuration shown in Figure 44.

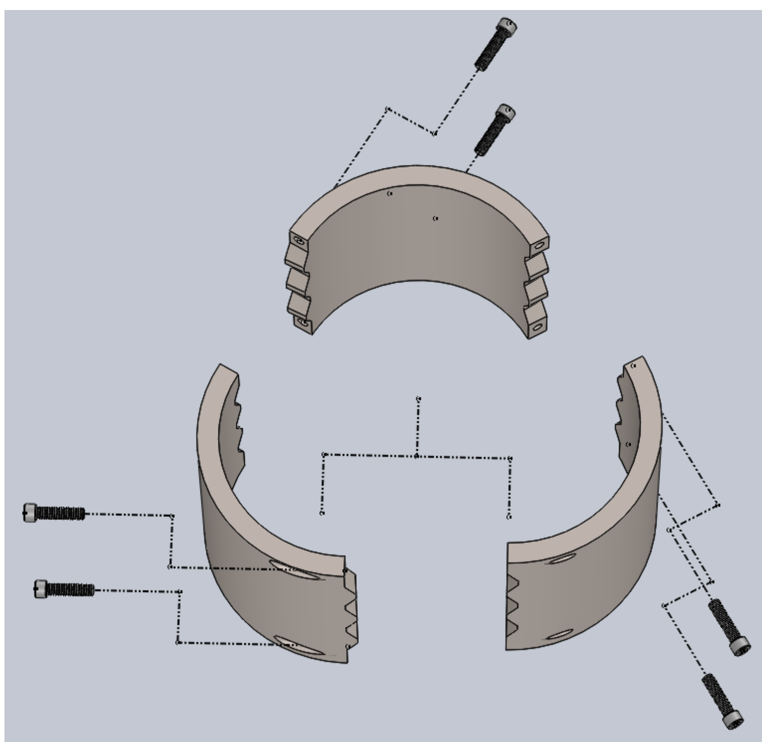


Figure 44. Assembly pattern of printed parts

M1: Step 7
After the parts are assembled, the assembly is inserted into the lathe and held by the inner diameter. The outer diameter is turned down to 161.90 ± 0.15mm.

H1: Step 8
The outer band from step 2 is inserted into a furnace in the MATE department and heated to 325°C for XX minutes. David Otsu will be operating the furnace.

H1: Step 9
The heated outer band will be carried from the furnace to the assembly fixture with tongs. Quickly, the assembled printed parts will be inserted completely into the hot outer band. The assembly will be allowed to reach equilibrium temperature, which will result in a press fit joining the outer band to the printed parts.

M2: Step 10
The assembly will be inserted into the lathe and held from the outer diameter. Using a boring bar, the inner diameter will be bored to a final diameter of 138.1 ± 0.15mm.

H2: Step 11
The printed parts and outer band assembly will be heated in the same furnace to 325°C for XX minutes.

H2: Step 12
As the assembly is heated, the inner band will be cooled to about 0°C in the Aero Department's freezer next door to the MATE department.

H2: Step 13
The heated parts will be inserted into the assembly fixture again, and the chilled band will be inserted into the heated parts. All of the parts will be allowed to reach room temperature again before handling.

M3: Step 14
Finally, the assembly is held in the lathe by the inner diameter and the outer diameter is turned to achieve the desired diameter of 165 ± 0.15mm. Before the part is taken out of the lathe, one of the collars will be parted off and the surface will be faced. Then, the assembly will be flipped around in the lathe and held by the outer diameter. The inner diameter will be bored to 135mm and the other collar will be parted off. Finally, to achieve the desired axial length of 90mm, the part will be faced until the length is within tolerance.

Test Piece Assembly

Each set will be printed with the same outer and inner diameter and utilize the built-in collar feature so that each set can be turned to the following outer/inner diameters, respectively: 162.1mm/137.9mm for the small bands, 161.7mm/138.3mm for the nominal bands, and

161.3mm/138.7mm for the large bands. Note that all diametric tolerances are ±0.15mm. As mentioned in the justification section, the outer diameter of the outer band and the inner diameter of the inner band remain constant for each set. Three axial cuts at 24mm each will be made into the purchased tube for the outer bands and each set will have its inner diameter turned on the lathe to the appropriate dimension: 162mm for the small band, 161.6mm for the nominal band, and 161.2 for the large band. Similarly, the inner bands will be turned to the final inner diameters of: 138mm for the small band, 138.4 for the nominal band, and 138.8 for the large band. The final dimensions for each set are listed in Table 3 below.

Table 3. Dimensions for all pieces in the test piece assembly

		"Large" Band Set	"Nominal" Band Set	"Small" Band Set
Band Thickness	(mm)	1.8	1.7	1.6
Printed Parts	OD (mm)	161.3	161.7	162.1
	ID (mm)	138.7	138.3	137.9
Outer Band	OD (mm)	165.0	165.0	165.0
	ID (mm)	161.2	161.6	162.0
Inner Band	OD (mm)	138.8	138.4	138.0
	ID (mm)	135.0	135.0	135.0

The process of assembling the test piece assembly is nearly the same as the joining process flowchart of the final part in Figure 40. Some steps require minor additions or alterations and are listed below.

M1: Step 2
Using a lathe, turn three different inner diameters: 162mm, 161.6mm, and 161.2mm. Then part the size 6 schedule 40s pipe at an axial height of 24mm for each band.

M1: Step 3
Using a lathe, turn three different outer diameters: 138mm, 138.4mm, and 138.8mm. Then part the size 5 schedule 40s pipe at an axial height of 24mm for each band.

M1: Step 5
Heat treat the entire test piece assembly to 1038°C using the IME furnace, and avoid staying in the temperature range of 816°C-538°C when cooling.

M1: Step 7
Start at the end of the collar that was not attached to the build plate and turn the outer diameter of the test piece assembly to 161.3mm for an axial length of 42.5mm, corresponding to the thick band set. From this point, turn the outer diameter to 161.9mm for an axial length of 35mm, corresponding to the nominal band set. From this point, turn the outer diameter to 162.1mm all the way to the end of the assembly, corresponding to the thin band set.

H1: Step 8
Each outer band will need to be heated individually since the furnace does not have the room to hold all three bands at the same time. Once one band has reached 325°C, expanding 0.8mm, follow Step 9 before heating another band.

H1: Step 9
Insert the test piece assembly in the assembly fixture. Place a 17mm spacer at the base of the assembly fixture and near the outer diameter of the printed parts so that the thinnest outer band can be placed over the test piece assembly and allowed to cool at the correct axial height. Repeat step 8 for the nominal outer band, then place over the test piece assembly and ensure that it does not slide down to the bottom. Repeat the same process for the thick outer band and again ensure that the band does not slide below the top set.

M2: Step 10
Place the test piece assembly and outer bands into the lathe and, starting at the end of the collar that was not attached to the build plate, turn the inner diameter to 138.7mm for an axial length of 42.5mm, corresponding to the thick band set. From this point, turn the inner diameter to 138.1mm for an axial length of 35mm, corresponding to the nominal band set, and 137.9mm all the way to the end of the assembly, corresponding to the thin band set.

H2: Step 11
Place the entire test piece assembly along with the outer bands into the IME furnace and heat to 325°C to expand 0.7mm.

H2: Step 12
Place all three inner bands into the freezer and cool down to 0°C.

H2: Step 13
Insert the test piece assembly and outer bands in the assembly fixture. Place the thinnest inner band inside the test piece assembly. Once in position, place the nominal inner band inside the test piece assembly. Once in position, place the thickest inner band inside the test piece assembly. Allow all of the parts to reach equilibrium before continuing. Note that the three inner bands need be inserted as quickly and accurately as possible so that the test piece assembly and outer bands do not reach room temperature and shrink back to their original size.

M3: Step 14
Place the entire set of parts into the lathe and turn the outer diameter of each outer band to 165mm. Similarly, turn the inner diameter of each inner band to 135mm. Part off the collars at the top and bottom of the assembly and face the ends until the lattice is exposed. Then, part off each entire set and face down the cut surfaces so that the lattice is exposed. The end product will be three sets of printed parts and inner and outer bands, all at varying band thicknesses.

Design Verification Plans

Once the final part is completely manufactured there are a few tests that need to be performed to confirm that all of the sponsor specifications and requirements have been met. A dimensional test will be conducted using an optical comparator in the IME department which will ensure that the final dimensions match the customer requirements. The second test is to verify the surface finish of the part and will be completed using the Micro Vu Vision system located in the IME department. The final test will be a tangential load test using the Instron machine in the IME department or the ME composites lab. In Appendix 10: DVP, a full design verification plan can be found that describes tests, testing equipment, and testing responsibilities. All tests are scheduled to begin after the manufacturing and test review on March 16th.

Bill of Materials and Cost Analysis

The total budget allocated for this project is $3,000. The costs of the sub-assemblies are listed below in Table 4 and a full break down of all of the required components is compiled in Appendix 9: BOM.

Table 4. Breakdown of costs for each assembly (tax not-included)

Assembly	**Price**
Final part	$975.06
Test Part Assembly	$0.00 (included in Final Part cost)
Assembly Fixture	$8.73
Soft Jaw Assembly	$48.00
Test Fixture (Estimate)	$144.56
Shipping	$71.94
Total	**$1176.35**

Manufacturing

After CDR, a few changes and additions were made to the final design. These edits originated from peers' and the sponsors' feedback and are explained in the following sections. New printed part geometry altered some steps in the manufacturing flowchart; therefore, the flowchart will be

restated below for the final version of the joining process. This section also includes the manufacturing plan that was followed in the fabrication of all parts and the final BOM.

Final Design Changes

Tooth Design

The printed parts presented in CDR were designed with a very specific tooth pattern that assisted in axial alignment. However, the sponsor commented during the CDR presentation that it may be difficult to remove parasitic material from the teeth surfaces, which is necessary for a tight fit between printed parts. When considering this advice, AMPP determined that the tooth geometry was not necessary since the collar should provide sufficient radial and axial support during the manufacturing process. The teeth were reformed to flat surfaces, which is reminiscent of some of the preliminary concepts. Figure 45 below is the final geometry of each segment.

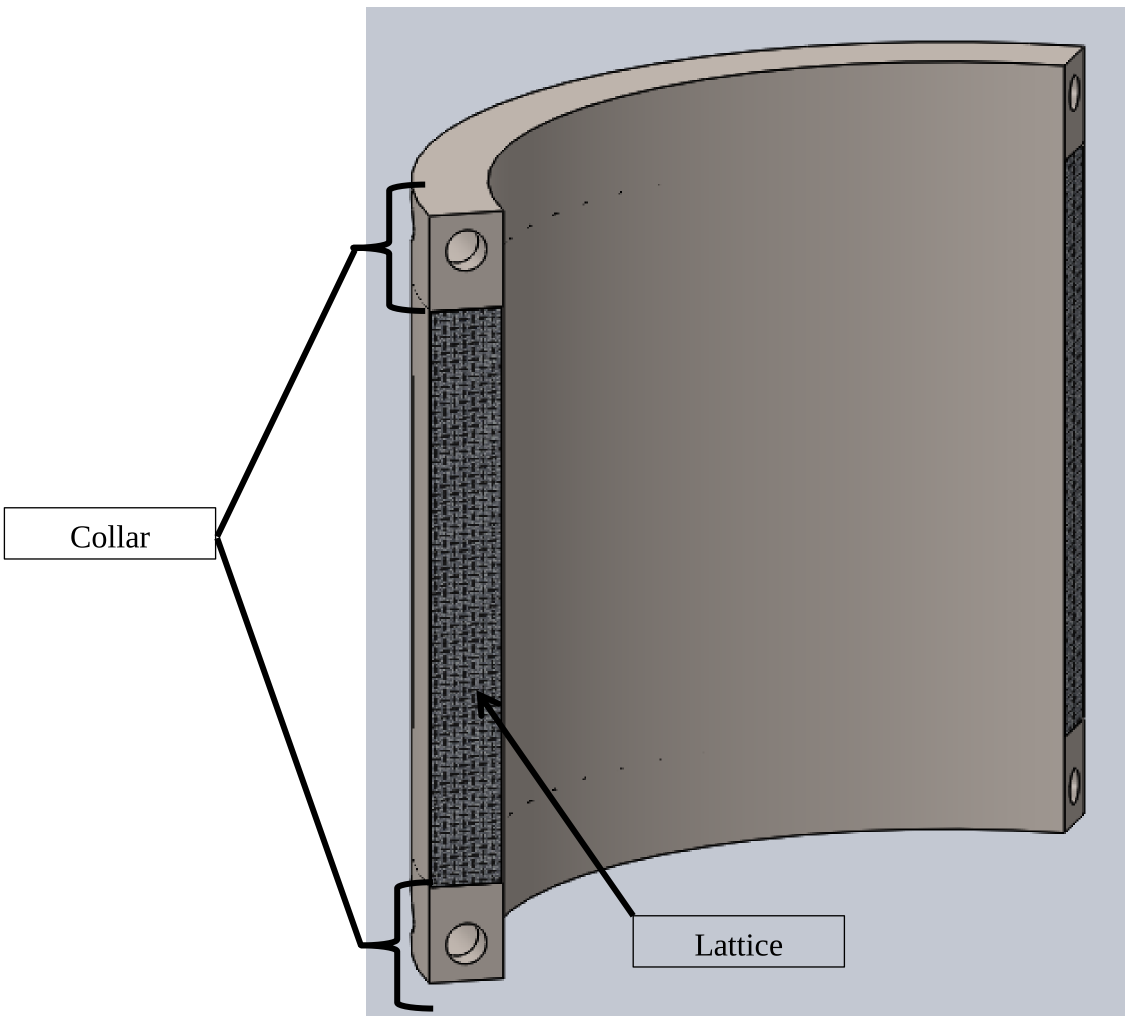


Figure 45. Final part segment with a flat mating surface

Recall that one end of each segment has tapped holes and the other end has counter-bored holes, as the design from CDR specified. The flat face makes it easier to machine off parasitic material and will lead to a tighter fit between segments.

Soft Jaw Assembly

The soft jaw assembly replaces the alignment fixture described in the manufacturing plan from CDR. There were a few issues concerning the alignment fixture that needed to be addressed and ultimately led to the creation of the soft jaws. The first issue involved the safety and accuracy during the process of drilling holes into the collars of each printed part. The only method of securing the part was the friction of a vise, but nothing was supporting the block from the bottom and did not create a safe, secure, or accurate hold. In addition, the manufacturing plan specified that the holes would be drilled in a drill press, which would result in inconsistent results. The second issue focused on the insertion and removal of screws on the underside of the alignment block. It was noted that it might not be easy or possible to reach the screws while the part is clamped into the vise. Although there is clearance to access the screws, there is not much room to rotate a tool, which will result in lengthy setups. This leads into the alignment fixture's final issue: the amount of time that it would take to set-up each part because the screws would need to be inserted and removed every time the collar holes needed to be drilled. The culmination of these three issues necessitated the need for a more innovative solution to secure segments in the vise such that the collar holes can be drilled and counter-bored. Instead of adding more complexity to the fixture, it was noticed that if soft jaws were machined to have an impression of the part cut into them then they could hold each part in the same orientation every time without the need for any initial drilling. The final design of the soft jaw assembly is seen below in Figure 46.

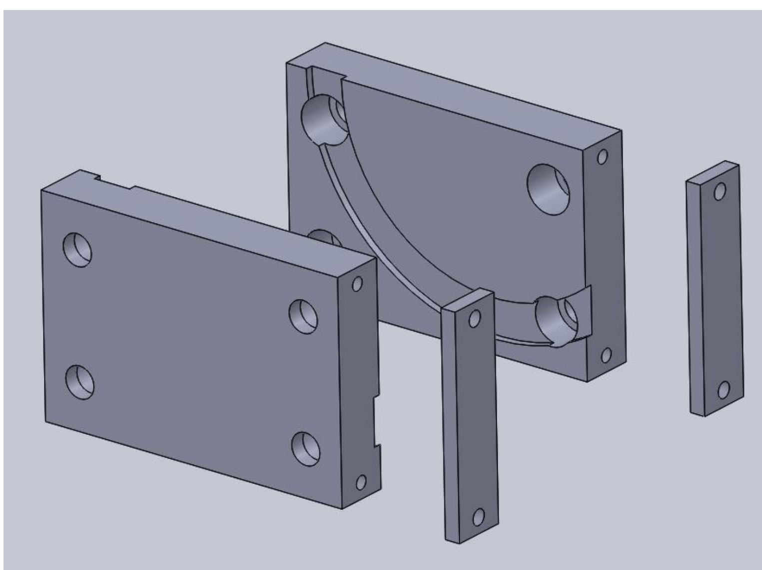


Figure 46. Soft jaw assembly

Both soft jaws have arcs that mirror one another such that a printed part can fit into the groove. The two end pieces are screwed to the sides of the soft jaws to create a sharp interior corner used as an end stop to locate the printed part. This allows each segment to be loaded into the vise at the same location every time. The counter-bored holes in the soft jaws were dimensioned to the bolt holes of a Kurt vise since that is what AMPP will use to hold the parts in the mill. The orientation of the soft jaws in Figure 46 is set so that segments can have their faces milled smooth and holes drilled. In order to drill the counter-bores on one end of the segment, the soft jaws can be flipped 180°, reorienting the arc concave down.

This is the design that will be used for the AMPP senior project, but the soft jaw design could be slightly improved by altering the soft jaw. AMPP estimates that the improved design will produce more accurately machined parts. This design will be included in the Future Works section.

Testing Fixture

The part needs to be loaded in the Instron such that when the machine pulls the joined parts apart, an evenly distributed force is applied at opposing axial locations on the inner band. The final design of the fixture can be seen below in Figure 47 and Figure 48.

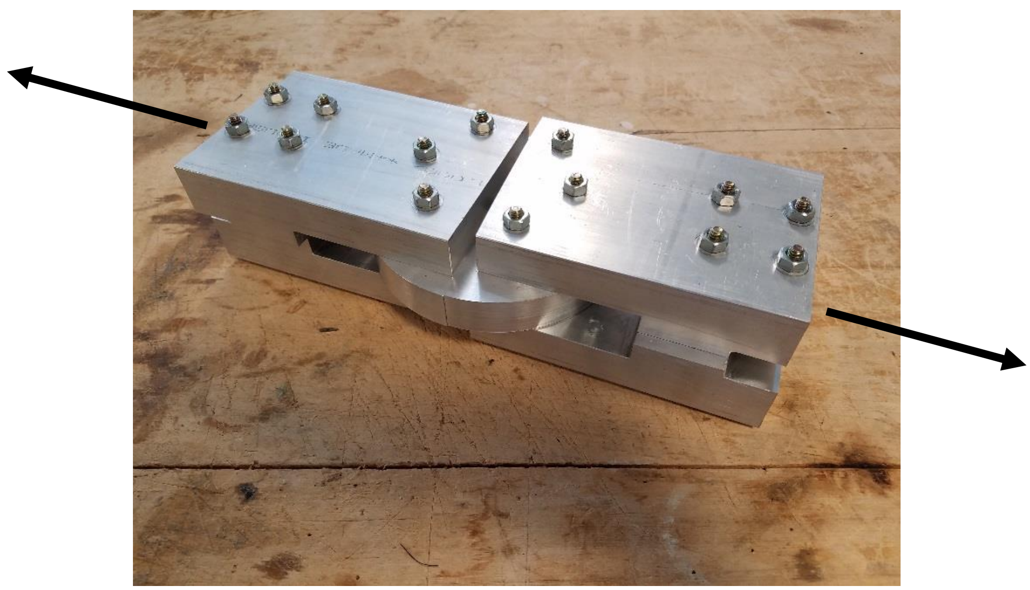


Figure 47. Testing fixture fully assembled with directional arrows to show how the Instron will pull the test parts apart

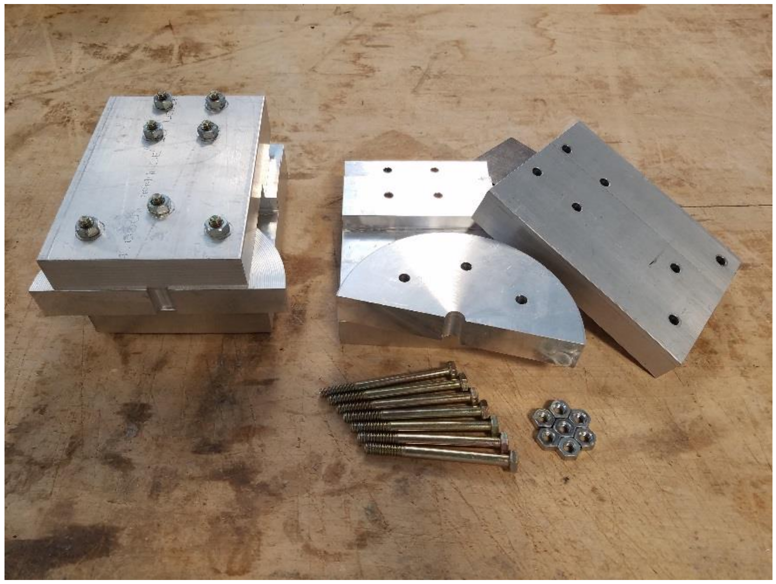


Figure 48. Testing fixture disassembled

There are three main components to this assembly: side arms, Instron clamps, and hemi-cylinders. The hemi-cylinders direct the load from the Instron into the inner band are what the part will fit around. The radius of each hemi-cylinder is the same as the inner radius of the inner band. Bolted on both sides of the hemi-cylinders are the side arms, which connect the hemi-cylinder to the Instron clamp. The Instron clamp has been designed to fit the maximum gripping thickness of the Instron machine, and is not shown in the figures. Grade 8 steel bolts secure all of these components together. When completely assembled, the Instron clamps will be set into place and the Instron machine will pull one half of the fixture away from the other. This load will transfer through the side arms and into the hemi-cylinder which then applies pressure along the inner surface of the inner band. The areas that will experience the most tension are along the sides of the part. See Appendix 8: Drawing List and Part Drawings for the full specifications of each part.

Updated Flowchart

The flowchart has been expanded to account for all of the necessary machining operations which were finalized following CDR. Note that the size 6 schedule 40s and size 5 schedule 40s pipes which were going to be purchased and machined to create the outer and inner bands have been replaced with two tubes. The tube which will be used for the outer band has an outer diameter of 6.75in and the tube for the inner band has an outer diameter of 5.75in. Both tubes have a thickness of 3/8in. The final step has been separated into two separate operations to account for the final inner and outer dimensions as well as the removal of the collars. Additionally, M1: Step 6 has been adjusted since the alignment fixture was replaced with the soft jaws. Please see Figure 49 for the final flowchart and note the following revised steps. Appendix 11: Owner's Manual contains the final flowchart and describes the joining process in detail.

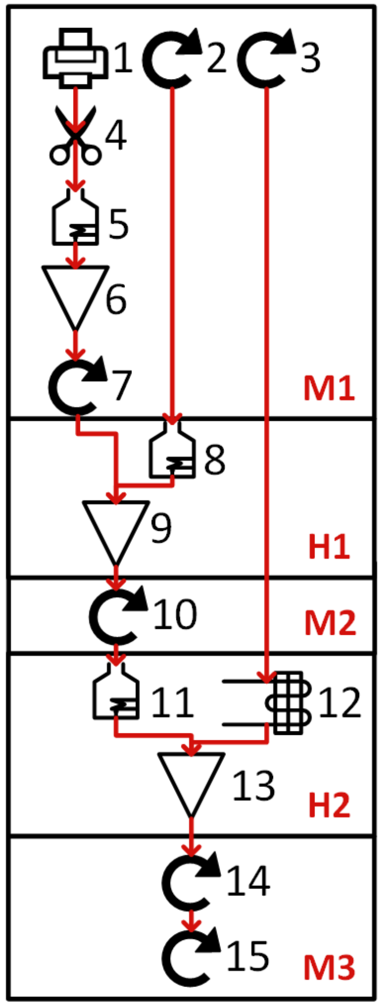


Figure 49. Final flowchart of joining process

M1: Step 6

The soft jaws will hold the printed parts in the vise so that they can be faced, drilled, and counter-bored with minimal set-up time. Figure 50 and Figure 51 below are set-ups of a segment loaded into the vise so that the mating surface can be milled and holes drilled.

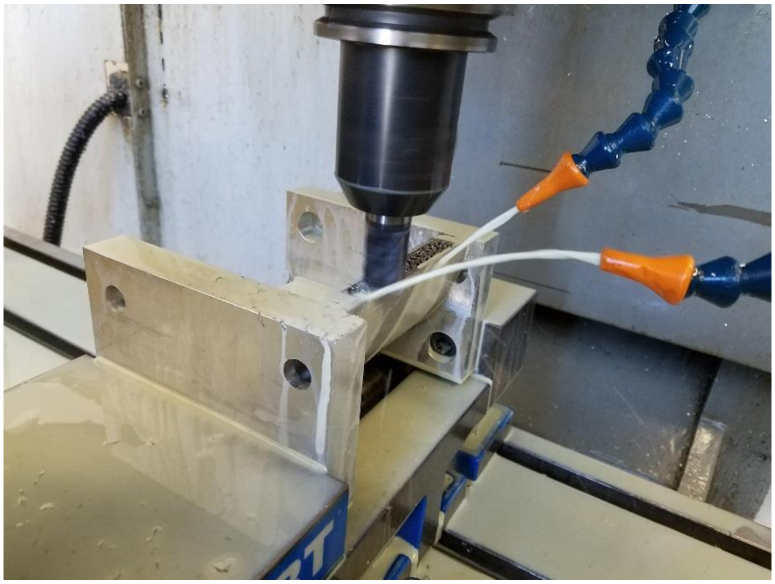


Figure 50. Soft jaw holding segment to mill face

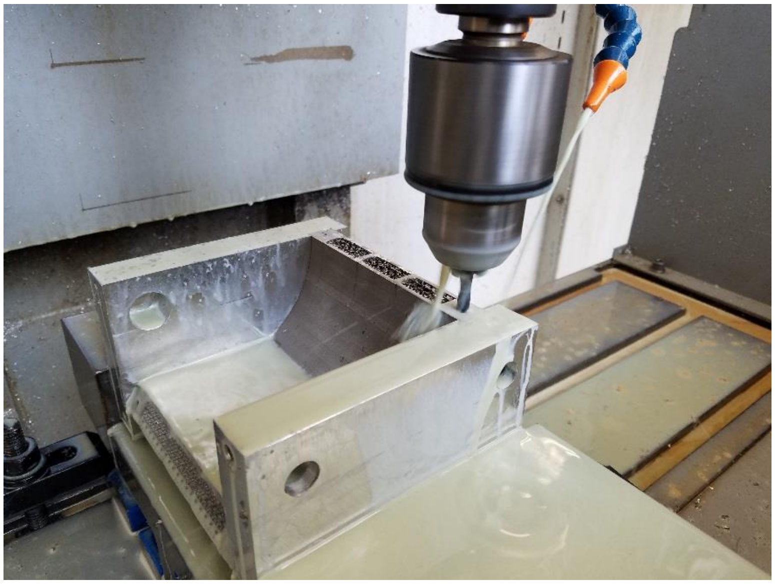


Figure 51. Same set-up used to drill holes

Load the segments by securing both ends within the groove, then slide the part until the face is flush with the top of the soft jaw. Next, mill the segment face clean to remove parasitic material and leave a smooth finish. Finally, use a #3 drill bit to drill the holes, using the pilot holes as a guide, which are later tapped using a ¼-28 tap. Repeat this step on all segments. The soft jaws are then switched with one another so that the groove remains concave up but allows the opposing face to be milled and drilled using a ¼" drill bit. See Figure 52 below to see how the part was set-up in the mill.

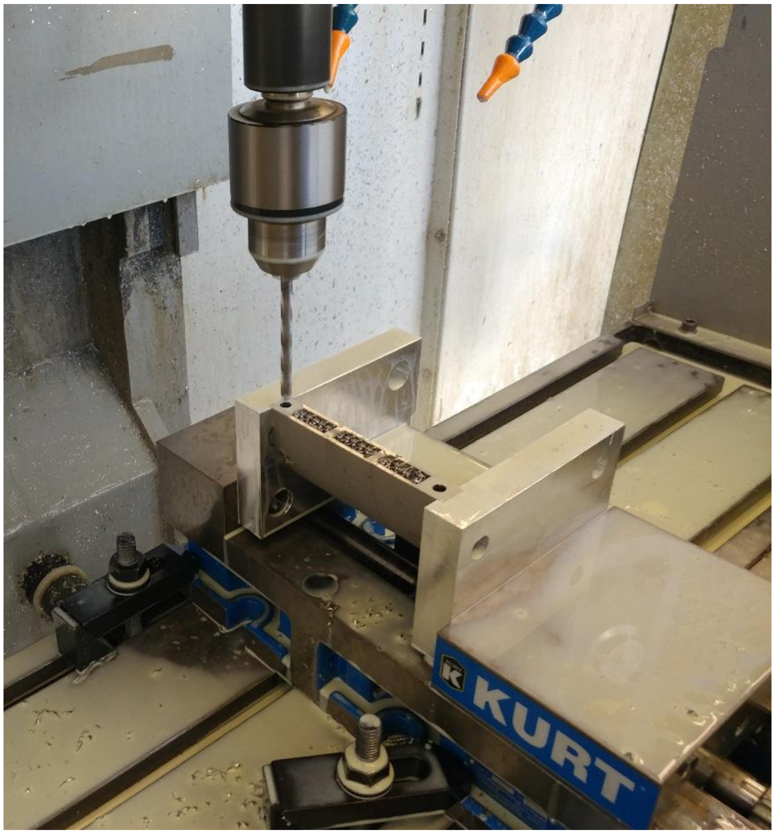


Figure 52. Soft jaw set up to mill and drill holes of opposite face

Once that operation is complete, remove the part and flip the soft jaws 180° so that the groove is concave down. Load the part such that the face is flush with the bottom face of the soft jaw and the hole to be counter-bored is sticking out from the soft jaw. See Figure 53 below for a picture of the set-up. The counter-bores are drilled such that the heads of the screws, which secure the parts together, can sit in the collar and not interfere when turning the outer diameter of the printed parts on the lathe.

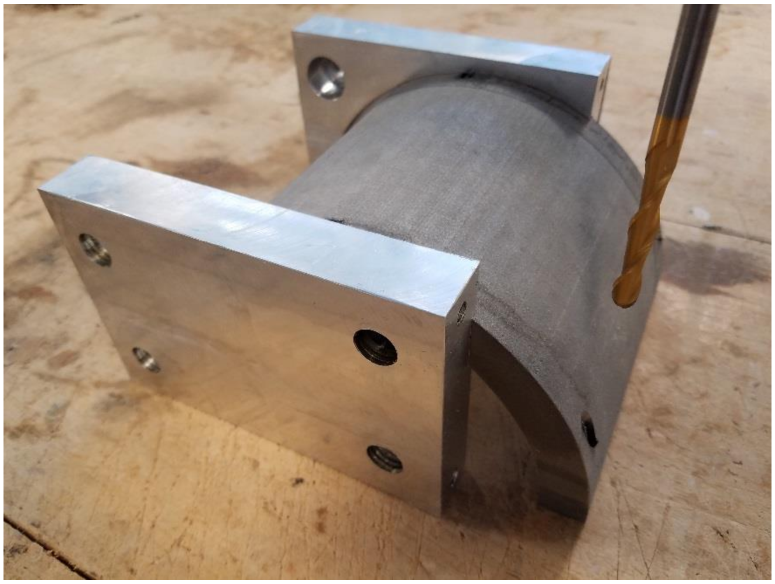


Figure 53. Set-up of part for drilling counter-bores

Note that the counter-bore set-up was followed according to the description above but due to issues encountered during machining, see Notes Taken on Testing for a full explanation, this process had to be altered. The revised method of machining the counter-bores still utilizes the soft jaws but in a different orientation. The jaws are secured in the same way as in Figure 52 but the part is rotated within the groove such that the mating surface is perpendicular to the ground. Using a ¾” carbide end mill, two paths are machined out of the segment at a depth and width such that the head of the screws can fit. See Figure 54 for a visual of the set up, and Figure 55 for the final results from this method. Note that a clamp was used to help secure the part in the soft jaws since most of the material was not resting within the groove. This increased the rigidity of the fixture, which could have been an issue.

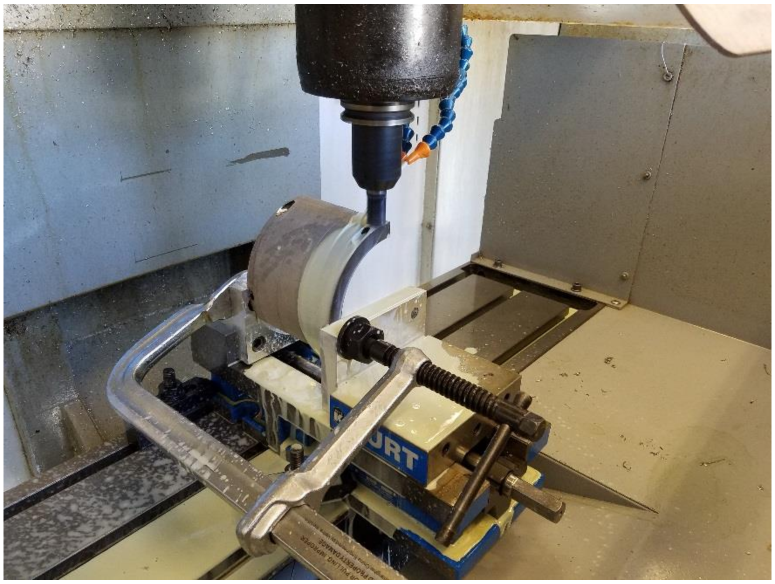


Figure 54. Milling counter-bore, second attempt

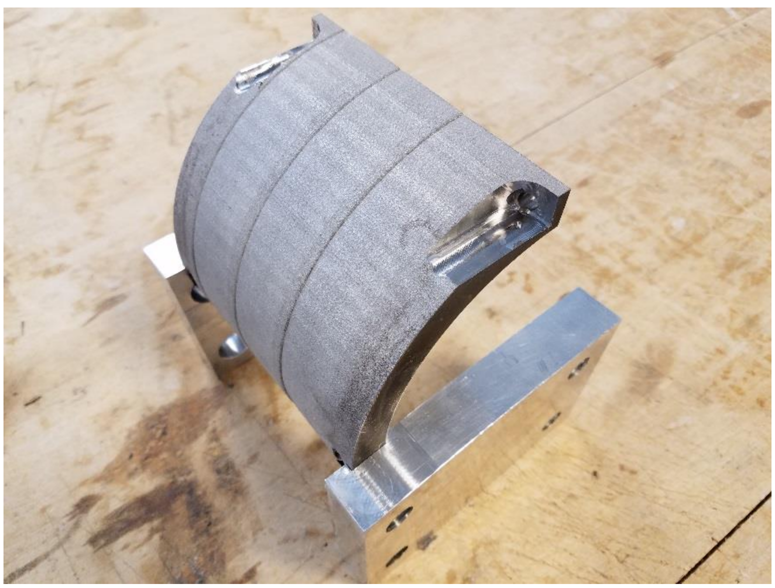


Figure 55. Final results from counter-boring using second method

M3: Step 14

Load the final assembly of outer band, printed parts, and inner band into the lathe and turn to the final diameter of 165 ± 0.15mm (6.490 ± .006in). Before removing the part from the lathe, part off the collar on the end and face the surface until the lattice is exposed.

M3: Step 15

Flip the part around in the lathe such that the second collars are not held by the jaws, and bore the inner diameter of the inner band to 135 ± 0.15mm (5.310 ± .006in). Part off the second collar and face until the lattice is exposed, achieving the desired axial length of 90 ± 0.10mm (3.540 ± .004in).

Notes Taken on Manufacturing

Soft Jaw Assembly

4/27 – All soft jaw parts were machined on a CNC mill (Haas Tool Room Mill) using just a Kurt Vise and parallel bars.

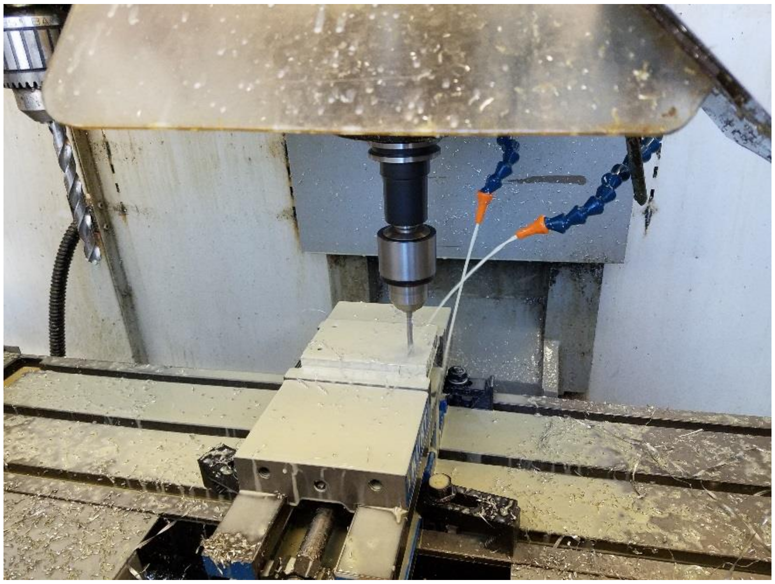


Figure 56. Drilling thru-holes into soft jaws

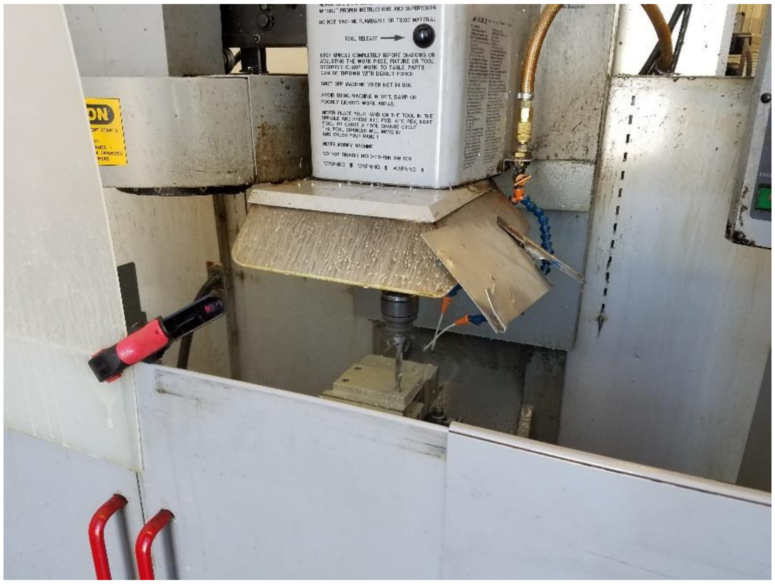


Figure 57. Drilling counter-bores into soft jaws

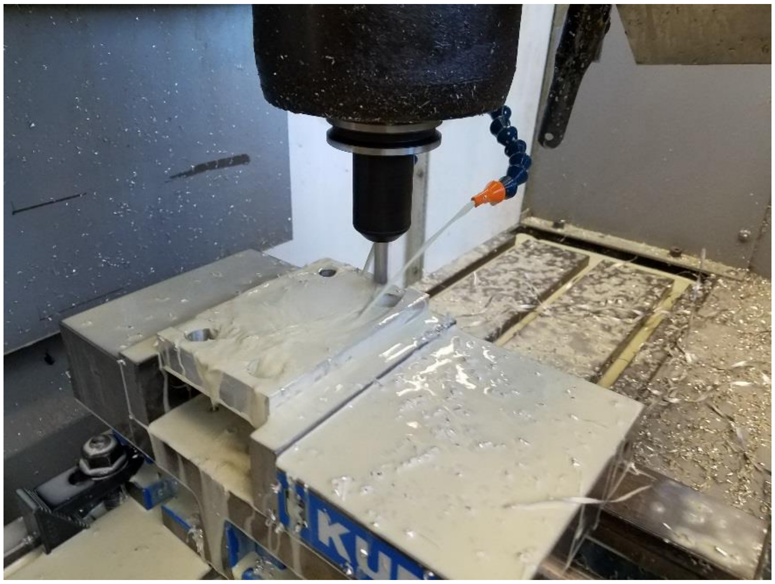


Figure 58. Milling arc into soft jaws

Testing Fixture

4/15 – A band saw was used to cut off first hemi-cylinder from stock, but the band saw was not suitable to cut the second hemi-cylinder from the rest of the stock because there was not enough material for the band saw clamp to hold onto. Then AMPP tried parting the cylinder, but the parting tool broke due to a dull parting tool and an insufficiently rigid lathe. The only other option was to face the rest of the stock off the back side to get axial height of second hemi-cylinder.

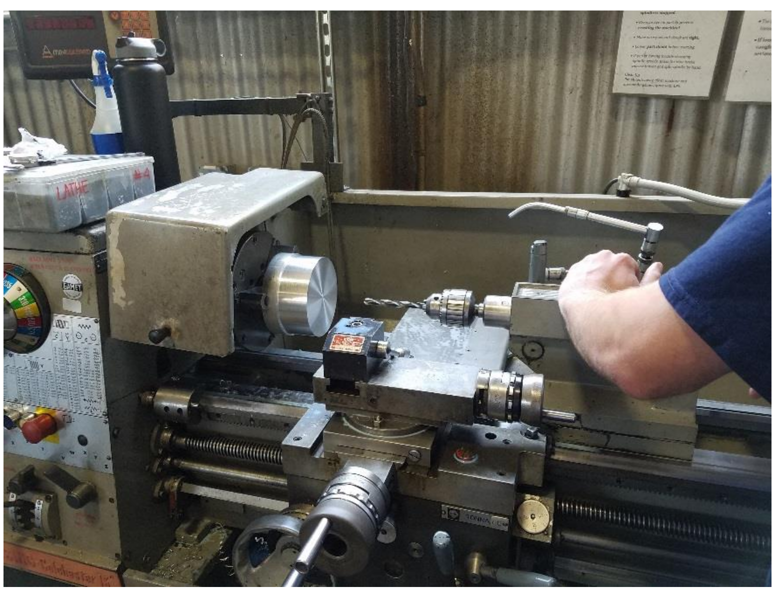


Figure 59. Turning OD of both hemi-cylinders to 5.318".

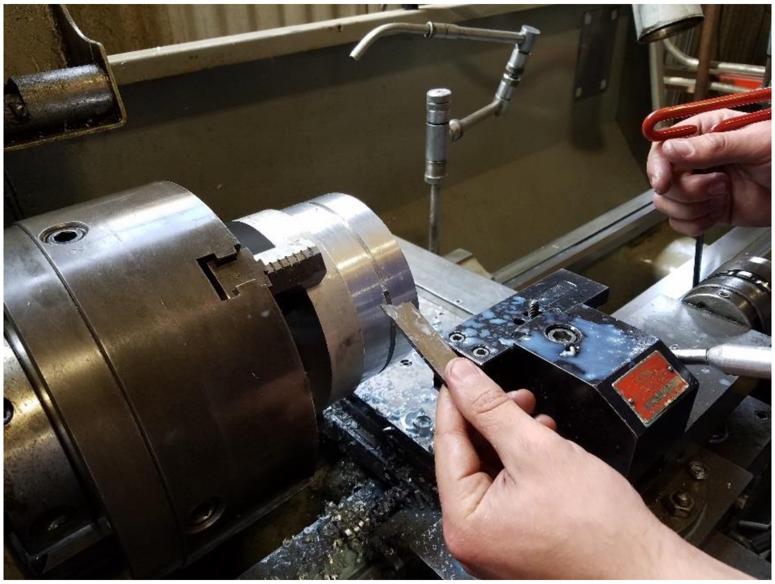


Figure 60. Attempt at parting off first hemi-cylinder but breaking the parting tool

Figure 61. Hemi-cylinders cut to axial height but still in need of cutting into hemi-circles

4/20 – The side arms were milled and drilled to the proper dimensions on the CNC, but the edge finder offset was not accounted for. This resulted in the side arms looking offset from each other. This resulted in the side arms being too long and this did not allow the hemi-cylinders to meet face to face. In response, the ends of the side arms were cut on the band saw instead of the mill because the band saw was faster.

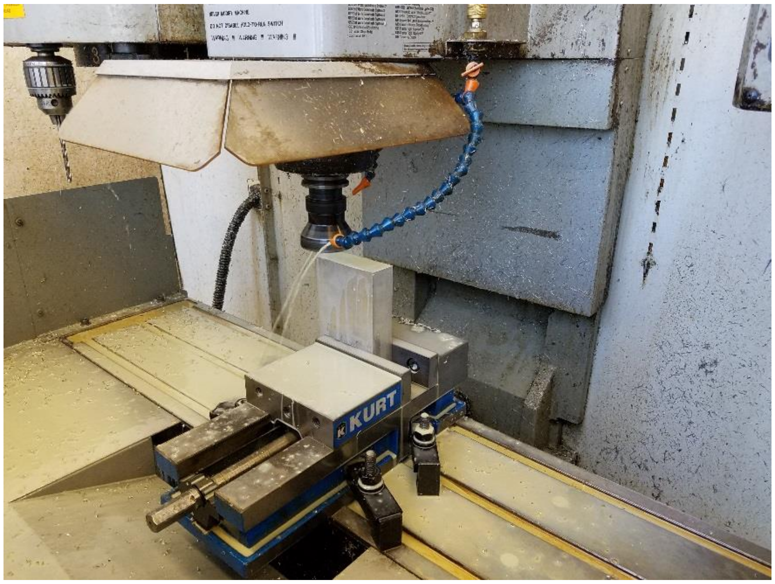


Figure 62. Facing text fixture side arms

4/27 – The saw-cut edges on the hemi-cylinders were milled to achieve half-circles and then through holes were drilled.

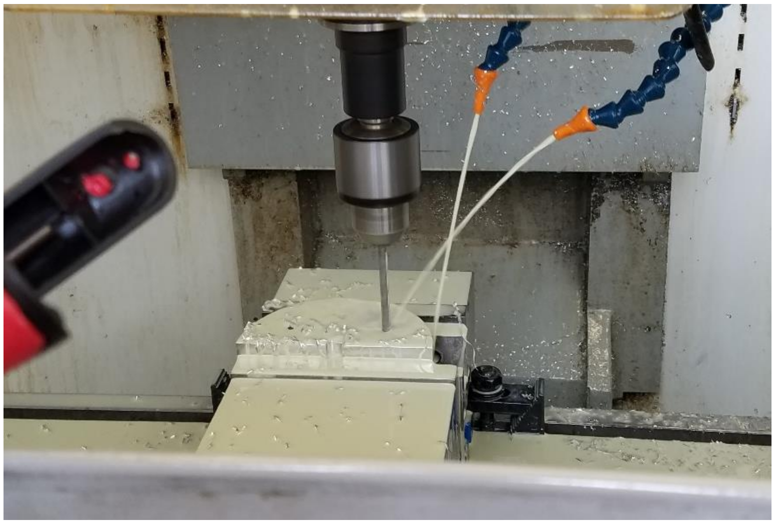


Figure 63. Drilling thru-holes into hemi-cylinders

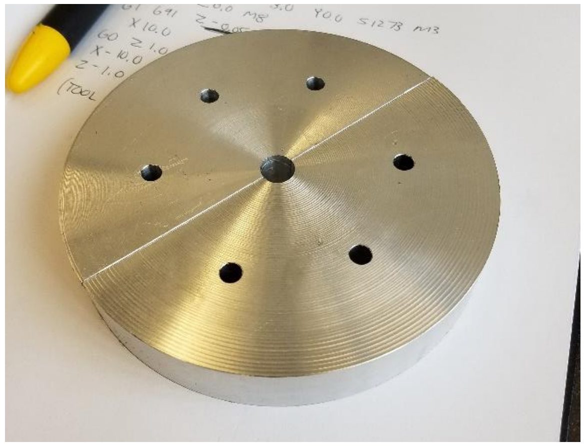


Figure 64. Completed hemi-cylinders

Band Fabrication

5/4 – Since the band saw teeth were dull, AMPP needed to replace the band saw with a different blade. Each cut took over 30 minutes with the other blade that was somewhat sharp. AMPP noticed that band cut starts to angle once the blade was 1/3 - ½ way through tube. This cause AMPP to need to rotate once approximately half way through cut so that cut is somewhat flat.

Figure 65. Cutting outer band with horizontal band saw

5/9 – The final 6” band was cut on this day. The band saw began to bend, and then broke. Without another band saw blade, AMPP had to TIG weld the blade back together. Initially, the blade was welded in reverse direction, which caused the teeth to cut in the opposite direction. Once the blade was re-broken and re-welded back together, the duration of each 1/3 of a cut was about 30 minutes long.

Testing

The plan was to create three inner and three outer bands at varying thickness as previously explained in the Test Piece Assembly section. The joining process was to be completed using multiple outer and inner bands and then each completed part would be tested in the testing fixture to determine the minimum possible band thickness, but since the printed parts took a few weeks longer to arrive, the testing plans have been shortened such that the joining process can still be attempted and well-documented. The test part assembly will no longer be used to perform the band thickness tests and the corresponding bands which were pre-fabricated will not be used. The final joining process will be conducted at full scale using the nominal band thickness of 1.7mm.

Notes Taken on Testing

5/9 – When the four side arms (part #510) were machined, the offset of the edge finder was not taken into account. Even though the holes were in the correct position compared to each other, the location of the holes cause the side arms interfere when each half of the testing fixture (part #500) was put together. Since the part that was interfering was not structural or functional, it was quickly cut off on the band saw. This allowed the hemi-cylinders to sit flush with one another as the design intended. Unfortunately, the cut is not completely straight, but the quality of the cut will not affect the function of the test fixture.

5/25 – The soft jaws were machined before the printed parts were received. AMPP estimated that 0.002” of clearance on either side of the inner and outer diameter would be sufficient to allow the printed parts to fit within the curved slots of the soft jaws. Once the parts arrived, they did not fit within the curved slots. The soft jaws’ important dimensions, including the curved slots, were measured to be within 0.001” of the intended dimensions. This meant that the printed parts were not within tolerance. Neither end of the printed parts (top or bottom) fit into the soft jaws, which meant that the problem was not due to warpage of the printed parts. The inner diameter, outer diameter, and arc angle of the printed parts were measured in the IME Department’s metrology lab and the results are plotted below in Figure 66. All of the final parts’ inner diameters were much smaller than expected. Therefore, AMPP re-machined the soft jaws by widening the curved slots. The outer radius of the slot was changed to 0.002” plus the largest radius of the printed parts, and the inner radius was changed to the smallest radius minus 0.004”. This provided an excellent fit between the soft jaws and the printed parts that allowed them to fit together with minimal force and no noticeable clearance.

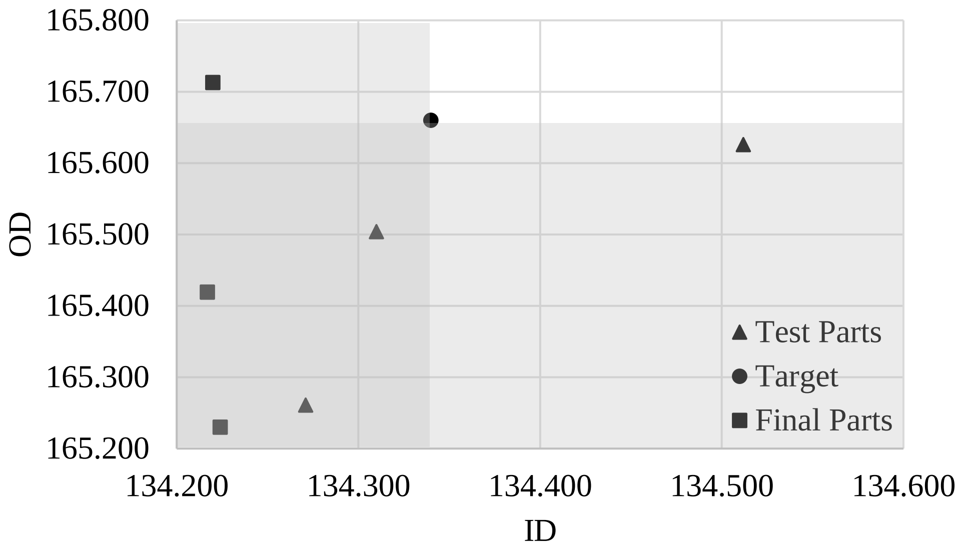


Figure 66. Distribution of printed part inner and outer diameters

5/26 – The clearances on the soft jaws' bolt holes were too small when attempting to install the soft jaws into the vise. This was likely due to the incorrect drill bit being used, or a drill bit with excessive wear being used, when the soft jaws were initially machined. To fix this, the through holes for the mounting screws were drilled out to ½" on drill press. A great tip for anyone trying to drill out preexisting holes with a larger drill bit is to fold a piece of paper towel and place it above the hole to prevent chattering and allow for a smooth hole widening. Once the soft jaws were installed in the vise, the mounting screws did not sit flush with bottom of the soft jaws' curved slots. To fix this, the heads needed to be ground down so parts can be clamped in the soft jaw without interfering with the bolt head since the bolt head was in the same location as the slot. The counter bore's depth was sufficiently sized for the CAD version of the screw, but the actual screw had a taller head.

The first operations of facing and drilling the pilot holes encountered a couple of issues. The first issue was that the facing operation did not cut the lattice, instead it deformed the lattice. No immediate fix was found, but suggestions on how to fix this are in the Future Works section. The other issue that was encountered was that the drill bit would become dull after just a few holes. The source of this problem is most likely due to the geometry of the end of the drilled hole. The drill bit breaks through the part on a surface that is at a steep angle. As the drill bit breaks through, there are uneven cutting forces which cause the drill bit to deflect against the hole it has already drilled. This caused excessive heat and wear on the drill bit due to rotating bending forces. Tool life could be prolonged if the holes are not drilled through completely, but this could cause the counter bore machining operation to change. AMPP managed to drill all of the holes completely through, but it is not recommended. Another reason not to drill through holes in this case is because the holes were very close to the soft jaw as seen in

Figure 67. The drill bit began rubbing against the face of the soft jaw, cutting a slight groove into it, which is circled in Figure 68. However, the depth of the groove was not as deep as it should have been, meaning that the drill bit may have been deflecting away from the face of the soft jaw. This deflection is the same previously-mentioned reason why the drill bit became dull. A shallower curved slot or additional printed material may fix this, but the best option would be to not drill through holes.

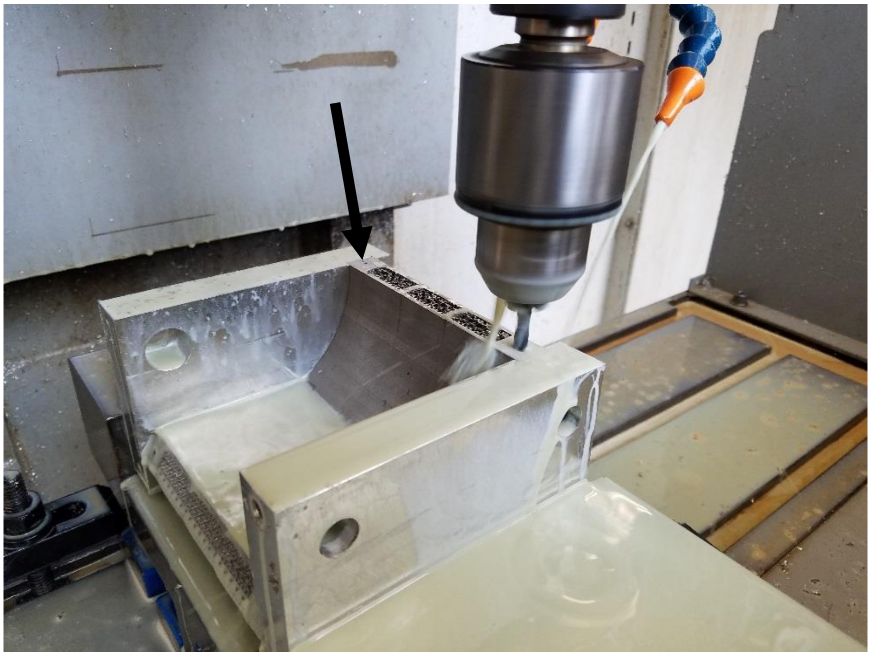


Figure 67. Drilling of through holes on the segment's mating surface

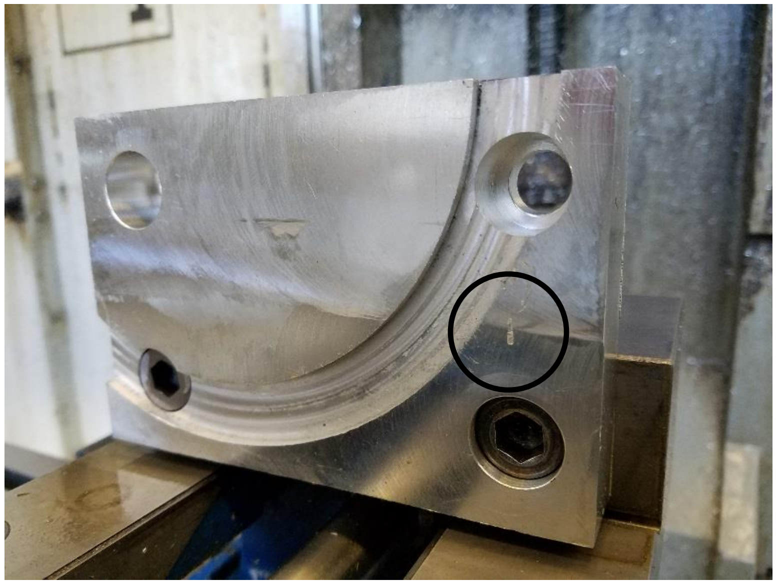


Figure 68. The circled area is where the drill bit began cutting into the soft jaw. This groove depth should be deeper, meaning that the drill bit was deflecting away from the face of the soft jaw, causing extra wear

Future Works

Due to a delay in receiving the printed parts, the final joining process was not fully completed. Therefore, AMPP's major suggestion for future work is to complete the joining process with the parts that are stored in the IME Department. Currently, the parts are midway through Step 6, and require counter bores. The time restraint, cost of tooling, and incorrect speeds and feeds caused AMPP to leave five of the six parts without counter bores. This section will cover the actions that would have been taken by the team if given extra time as well as tips about what was manufactured and how those parts/processes could have been completed with fewer troubles.

Printed Part Geometry

One issue that was encountered before Step 6 was that the dimensions of the printed parts were not within the tolerance of the curved slot in the soft jaws. The inner and outer diameters could be measured at each end of the part to quantify the dimensional variation due to warpage in the axial direction. If enough printed parts were measured, it could be possible to estimate the necessary dimensions of the curved slot in the soft jaws so that the soft jaws may be machined before the parts are printed. Otherwise, the soft jaws must be dimensioned and machined after the parts are printed and measured.

Another opportunity to explore would be to attempt to print the counter bore into the printed parts. If a larger diameter part was desired, boring the through holes in the collar would be more difficult

due to the longer tool stick out, which would cause excessive tool deflection. Holes do not print well with a horizontal axis, but the small diameter may be worth trying. If the counter bores are not feasible, the pilot holes are essentially pointless. Otherwise, AMPP recommends holding the parts in the soft jaws as seen in Figure 54 or to machine other soft jaws that hold the part in the same orientation. This would allow a tool with less stick out to machine the parts faster, but it undoubtedly weakens the structure an unknown amount.

Also, the design of the soft jaws could be changed slightly to improve the accuracy of the arc length of the parts after machining in step 6. AMPP did not add additional material to the printed parts in the direction of the circumference. Specifically, AMPP printed 120° segments even though the parts needed to be 120° after machining. Since only light facing of about 0.004" was performed on the ends of the printed parts, the angle of the segment was reduced by about 0.07° on each side, which is essentially negligible. The problem exists that the printed parts vary around their nominal dimension. Ideally, the segments would be printed to a larger nominal arc angle, which will allow for the machining process to reduce the angle to within tolerance of the nominal value. AMPP recommends printing segments of this diameter with an arc angle of about 122°. The extra 2° is more than AMPP's printed parts varied and it increases the arc length of the nominal outer diameter by 0.113". This allows for more material to be taken off during the machining operation which would prevent tool wear by facing with too small of a depth of cut. If it is not possible to achieve the desirable finish on the lattice, AMPP recommends cutting the arc angle with wire EDM instead of facing.

Soft Jaw Geometry

Since the arc length of the printed segment would increase, the soft jaw ends would have to be shimmed to accommodate. In theory, the soft jaw ends could be shimmed a certain amount such that only 1° of the segment was machined on one end of the printed part. Once the soft jaws are turned around and the printed part is loaded in the other orientation, the remaining material (nominally 1°) could be removed to reduce the arc angle to approximately 120°. The purpose of this is to provide a better fit once the parts are screwed together, which will better achieve the no change in step density requirement.

Heating Considerations

The time that the parts should soak in the furnace was not calculated. This was partly due to the complexity of the heat transfer analysis and the unknown heat transfer coefficient inside the furnace. There was concern that an uneven heat distribution within the part may cause the part to crack. This may be mitigated by inserting the parts or bands into the furnace and ramping the set point temperature to the suggested temperature. Heating the parts up slowly would reduce the temperature gradient within the part. Also, the suggested temperatures should provide enough clearance to perform the heat shrink, but it has not been tested. AMPP recommends attempting the heat shrink procedure on a test part before the final part.

Final Part Strength Analysis

The only strength calculations that were performed in the scope of the project were the strength calculations based on area and certified yield stress. Additional calculations were attempted to quantify the internal forces due to the heat shrink procedure, but the lattice complicated the assumptions. AMPP advises that a computational model be developed to account for the significant change in lattice strength and stiffness. AMPP hypothesized that the inner and outer band would not equally share the load produced by the load testing fixture or any load on the inner band. Additional calculations should quantify the amount that the bands share loads and the relationship between different band thicknesses and residual stresses from the heat shrink. AMPP did not complete the tests in the Instron with the test fixture. Thus, AMPP also recommends completing the planned Instron tests on the test parts in addition to developing an analytical model.

Management Plan

Both team members have a specific role in order to eliminate confusion within the group in terms of who will be the one responsible for each part of the project. These roles do not restrict the other team member from assisting in these areas of the project. They are designed to create order so that the team may work together to solve problems concerning the project and have a designated individual responsible for completing the task at hand. There are two main categories of responsibilities with three separate roles within each category. Both members are in charge of a total of three major roles.

The first category is overhead and these roles are created to maintain the logistical framework of the team. The first role, held by Andrew is communications; this individual is to be the main point of contact with the project sponsor, will initiate new topics of discussion with the sponsor, and facilitate team meetings with the sponsor. The second role, held by Nathan, is economics; this individual is responsible for maintaining the teams travel budget, materials budget, and scanning all corresponding receipts to the One Drive folder. The third role, held by Andrew, is the archivist, this individual is responsible for maintaining physical copies of all materials, including items relevant to the project that are scanned to the One Drive.

The second category is engineering and contains all responsibilities that will be necessary to determine the best joining method. The first role, held by Nathan, is the analyst; this individual is in charge of performing the final hand calculation checks of the teams joining method calculated analysis. The second role, held by Andrew, is the manufacturer; this person is in charge of the manufacturing of the part (including being trained to work with the student technician in charge of the SLM machine) and analyzes dimensions and tolerances. The final role, held by Nathan, is the tester; this individual is in charge of the testing methods and procedures once a joining method has been selected as well as fabricating any necessary fixtures to perform these tests.

There are milestones that must be completed along the way and are presented in Table 5. Senior Project Milestones below.

Table 5. Senior Project Milestones

Deliverable Title	Date
Project Proposal	10/25/16
Preliminary Design Review	11/15/16
Critical Design Review	02/07/16
Manufacturing & Test Review	03/16/17
Hardware Safety Demo	05/02/17
Final Design Review (Report & Expo)	06/02/17

In order to ensure that each milestone is achieved with the highest level of quality a Gantt chart will be used to clarify the timeline of when things will be completed. The preliminary design review will have a rough draft completed no later than four days prior to the presentation date to allow for revisions and presentation preparation. This same requirement holds true for the critical design review but may be increased to a two-week preparation phase depending on the status of the project. The bulk of the writing for these two reviews will build off of previous milestones. For example, the preliminary design review will build off of the project proposal and will be compiled incrementally as the project progresses.

Gantt Chart

Project progression is aided by the use of proper scheduling. A Gantt chart was created to estimate the allotted duration of each projected task. Since the parts were received late, the joining process was not completed and therefore the Gantt chart was not strictly followed. For this reason, two Gantt charts can be found in Appendix 7: Gantt Chart. The first Gantt chart is the one which would have been followed if everything had run exactly on schedule. The second Gantt chart reflects the actual timeline of the project with several tasks planned for after the final due date of the project. Both charts start from the project proposal (November 4, 2016) and progress up until the senior project expo (June 2, 2017)

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Appendices

Appendix 1: Patents

Patent 1 (19)

United States Patent [11] **3,584,187**

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[73] Assignee **The United States Steel Corporation**

[54] **METHOD OF WELDING STAINLESS STEEL**
9 Claims, No Drawings

[52] **U.S. Cl.** **219/137,** 29/492, 219/118
[51] **Int. Cl.** **B23k 9/00**
[50] **Field of Search** 219/137, 118; 29/492

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ABSTRACT: A method for improving the weldability of stainless steels wherein, prior to welding by conventional processes, the steel surface is provided with a coating of at least one oxide selected from the group consisting of the oxides of iron, chromium, silicon, titanium, manganese, nickel, cobalt, molybdenum and calcium. The oxide coating may be applied by physically depositing a slurry of the oxide onto the steel surface, or by oxidizing the stainless steel surface by subjecting it to an elevated temperature in an oxidizing environment.

METHOD OF WELDING STAINLESS STEEL

BACKGROUND OF THE INVENTION

This invention relates generally to the welding of stainless steel and, more specifically, to a method for improving the weldability of stainless steel by the conventional gas shielded welding processes.

The best known prior art methods for welding stainless steels are the automated plasma or gas tungsten-arc welding processes using a shielding gas of argon, helium, hydrogen or mixtures thereof. For example, a considerable amount of stainless steel tubing is made from coiled strip, about 0.1 inch thick, by automated equipment that uncoils the strip, forms it into a tube and joins the seam by a single-pass gas tungsten-arc (GTA) or plasma weld. Such welds are generally made without the application of flux or the addition of filler metal.

Stainless steels, when welded by any known process, frequently exhibit varying degrees of poor weldability, which is characterized by insufficient weld penetration at the conventional welding speed. That is to say, some stainless steel heats can be satisfactorily welded without complications, while others will yield satisfactory welds only if the welding speed is reduced, thus making the operation less economical. In extreme cases, even greatly reduced welding speeds still do not result in full penetration. Hence, the problems encountered may not only be severe, but sometimes insurmountable.

Although there have been many recent research studies in attempts to determine the factors which affect the weldability of stainless steel, the causes of poor weldability are not understood. Some experts have theorized that the concentration ranges of the alloy constituents should be more narrowly limited to assure good weldability. Yet, even with closer more limited concentration ranges, the weldability of stainless steel is still poor in many heats. Others have suggested that small amounts of residual refractory elements may cause the formation of refractory oxides that combine to produce refractory slags upon welding. Although such slags do of course influence the welding arc, it has become apparent that they alone are not responsible for poor weldability of stainless steel, since poor weldability is frequently encountered in heats being virtually free of the refractory residuals considered menacing.

SUMMARY OF THE INVENTION

This invention is predicated upon our unexpected discovery that the weldability of all stainless steels can be substantially improved if, prior to welding by gas shielded welding processes, the steel surface is first provided with a suitable oxide coating. The oxide coating will permit full penetration welding at substantially increased welding speeds. Although the oxides of iron and chromium are preferred for optimum results, the oxides of silicon, titanium, manganese, nickel, cobalt, molybdenum and calcium will serve to improve weldability of stainless steels an appreciable degree.

Accordingly, it is an object of this invention to provide a method of improving the weldability of stainless steels whereby a suitable oxide coating is provided on the surface of the steel prior to welding by conventional gas-shielded welding processes.

It is another object of this invention to provide a process for improving the weldability of stainless steels whereby, prior to welding by conventional gas-shielded welding processes, an oxide slurry is applied onto the steel surface and allowed to dry.

It is still another object of this invention to provide a method for improving the weldability of stainless steels whereby, prior to welding by conventional gas-shielded welding processes, the steel is heated sufficiently in an oxidizing environment to provide an oxide coating thereon.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

As noted above, the crux of this invention resides in the provision of a suitable oxide coating on the surface of stainless

steel which will improve the steel's weldability. That is to say, the oxide coating will promote full penetration welding at substantially enhanced welding speeds. The oxide coating should comprise one or more of the oxides selected from the group consisting of the oxides of iron, chromium, silicon, titanium, manganese, nickel, molybdenum and calcium. For optimum results, the oxides of iron and chromium are preferred. Of the oxides remaining, those of silicon, titanium and manganese are preferred over the oxides of nickel, cobalt, molybdenum and calcium. Practically any conceivable method for applying oxide coating will suffice.

According to one practice of our invention, powders of the selected oxide or oxides are mixed with a volatile liquid to form a slurry. The slurry is then brushed, painted or sprayed onto the stainless steel surface along the weld path and allowed to dry. The oxide powder will of course remain adhering to the steel surface after the volatile liquid has evaporated. Since the bond between the oxide and metal substrate is obviously not very strong, precautions must be taken to avoid wiping the oxide powder off of the steel surface prior to welding.

Although any volatile liquid, such as water for example, will suffice for the slurry matrix, we have preferred to use acetone because of its fast drying characteristic. In applying a silicon oxide coating, however, we have found water-glass (i.e. an aqueous solution of sodium silicate, $NaO\text{-}SiO_2$) to be most effective. This of course provides an oxide of sodium as well as silicon, but the sodium oxide is not detrimental.

Neither the concentration of the slurry nor the particle size of the oxide in the slurry is of critical significance. It should be sufficient to say that the concentration is preferably heavy to yield a thick or pasty slurry so that the required amount of coating, as noted below, can be deposited with a minimum number of applications. The particle size of the oxide should be fine enough to remain in suspension within the slurry while the slurry is being applied. Accordingly, we have preferred commercially available powders of minus 300 mesh or finer, although larger particle sizes such as minus 100 mesh will suffice.

The extent of the oxide coating is critical since either too little or too much coating will not yield an improvement in weldability, and may even adversely affect weldability. With the exception of calcium oxide, CaO, the effective amount of oxide coating is roughly within the range established by the empirical formula: 0.4 to 2.0 multiplied by the specific gravity of the oxide applied, the product expressed in milligrams per square inch. For example, Fe_2O_3 has a specific gravity of 5.24, and following the above formula, the effective range for an Fe_2O_3 coating would roughly be 0.4 (5.24) to 2.0 (5.24) mg./sq. in., or 2.096 to 10.48 mg./sq. in. Expressed more generally, the effective range for Fe_2O_3 is indeed from about 2 to about 10 mg./sq. in. As noted above, however, CaO does not follow the empirical formula. Rather, to be effective for the purposes of this invention, CaO should be applied within the range 20 to 40 mg./sq. in.

When the stainless steel surface has been coated with an oxide as described above, it may be welded using any of the conventional gas-shielded welding processes, and a substantial improvement in weldability will be realized. That is, full penetration welding can be achieved at greater welding speed than is possible without the oxide coating. In addition a narrower, smoother weld bead will result when using the oxide coating giving further evidence of improved weldability.

Since all stainless steels essentially comprise iron and chromium, the oxide coating may consist of oxides of iron and chromium derived from the steel itself. Hence, another method for applying the oxide coating is to heat the stainless steel or the surface thereof to a temperature in excess of about 1400° F. and subject it to an oxidizing environment for a sufficient time to allow the formation of the required oxide coating. A sufficient oxide coating is usually characterized by a visible blue coating upon cooling. Periods of from 2 to 15 minutes should be sufficient for most stainless steels.

To exemplify the detailed characteristics of this invention, the two tables below contrast the prior art with the improved weldability of stainless steel according to this invention. Table I illustrates the improved penetration at a constant high welding speed, while table II illustrates the increased welding speed for a constant full penetration weld.

Specifically, table I illustrated typical results of some of the tests which were made to determine the influence of the oxide coating thickness. All welds in table I were performed on a single heat of AISI Type 316 stainless steel 0.120 inch thick using identical welding conditions at a rather fast welding speed of 17.5 inches per minute.

TABLE I

Influence of Coating Thickness on Weldability Response of Several Applied Powders

Coating	Weight, mg./in.^{2}	Penetration
None		None
Fe_2O_3	3.0	Full
	4.6	Do.
	9.4	Do.
	10.7	Slight.
	17.3	None.
CaO	4.7	Do.
	8.2	Do.
	9.1	Do.
	22.4	Full.
	27.0	Do.
	30.8	Do.
SiO_2	3.3	Do.
	10.2	None.
	10.8	Do.
Water-glass	6.9	Full.
	17.4	None.
	24.4	Do.
Al_2O_3	1.2	Do.
	2.8	Do.
	11.8	Do.
	22.1	Do.
	33.7	Do.
MgO	0.9	Do.
	4.1	Do.
	4.7	Do.
	8.1	Do.
	10.7	Do.

From table I above, it is apparent that a welding speed of 17.5 inches per minute was too fast for the uncoated test sample in that no measurable amount of full penetration could be achieved at the test speed. In a like manner, oxide coating falling outside the scope of this invention, namely Al_2O_3 and MgO, did not improve the weldability of the steel. However, oxide coatings in accordance with this invention greatly improved the weldability of this heat of steel to such an extent that full penetration of the weld was realized when the effective amount of oxide was present. Similar results have been obtained with other oxide coatings of this invention, namely Fe_3O_4 and oxides of chromium, titanium, manganese, nickel, cobalt and molybdenum.

TABLE II

Effect of "Paint-On" Coating with Fe_2O_3-Acetone Slurry on Penetration for Different Types and Thicknesses of Austenitic Stainless Steel

AISI type	Thickness, inch	Maximum travel speed resulting in full penetration, i.p.m. — Uncoated	Coated	Percent improvement
304	0.125	10	17.5	75
316	0.120	7.5–10	17.5	(1)
316	0.083	5	22.5	350
316	0.095	7.5	15.0	100
321	0.120	12.5	17.5	40

[1] 75 min.

Table II contrasts the effect of a "painted-on" coating of Fe_2O_3 on six different stainless steel heats. Each weld was performed using identical procedures between the coated and uncoated samples. In each test the travel speed was increased in increments of 2½ inches per minute until the maximum welding speed for full penetration was reached.

It is readily apparent from the above table II that the "painted-on" Fe_2O_3 coating does indeed substantially improve the weldability of various stainless steels. For some samples, the improvement was as much as 350 percent. Similar tests with the other coatings of this invention showed similar improvements.

In all of the tests exemplified in the above tables, the same standard welding procedures were used. For each test, gas tungsten-arc welding was used with an argon shielding gas at a flow rate of 15 CFH. On samples from 0.060 to 0.089 inch thick, a three thirty-seconds inch electrode was used at a welding current of 200/210 amp. On samples 0.090 to 0.129 inch thick, a one-eighth inch electrode was used at a welding current of 300/310 amp. For all samples, a 1 percent thoriated tungsten electrode was used at a workpiece distance of 0.045 inch and a tip configuration of 120° vertex angle. A water cooled copper backup bar was always used.

We claim:

1. A method of welding stainless steel along a predetermined weld path comprising, coating the steel at least along the weld path with at least one oxide selected from the group consisting of oxides of iron, chromium, silicon, titanium, manganese, nickel, cobalt, molybdenum and calcium; said coatings of the group consisting of the oxides of iron, chromium, silicon, titanium, manganese, nickel, cobalt and molybdenum applied in an amount sufficient to fall within the range of about 0.4 to about 2.0 multiplied by the specific gravity of the oxide, the product expressed in milligrams per square inch, and said oxide of calcium applied in an amount sufficient to fall within the range of from 20 to 40 milligrams per square inch; and welding said stainless steel along the oxide-coated weld path utilizing conventional gas-shielded welding techniques.

2. The method of claim 1 in which said coating step includes applying water-glass onto said stainless steel surface, and allowing said water-glass to dry depositing an oxide coating including silicon dioxide.

3. The method of claim 1 wherein said coating step includes heating said stainless steel to a temperature in excess of 1400° F., and subjecting said heated steel to an oxidizing atmosphere for a time sufficient to allow the formation of an iron and chromium oxide coating.

4. The method of claim 3 wherein said heated steel is maintained in the oxidizing atmosphere for a period of from 2 to 15 minutes.

5. The method of claim 1 wherein said coating step includes forming a slurry consisting of a volatile liquid and a powdered form of said oxide, applying the slurry onto said stainless steel, and allowing the volatile liquid to evaporate depositing the oxide onto the steel surface.

6. The method of claim 5 wherein said applying step includes brushing the slurry onto the stainless steel surface.

7. The method of claim 5 wherein said applying step includes spraying said slurry onto the stainless steel surface.

8. The method of claim 5 wherein said volatile liquid is acetone.

9. The method of claim 5 wherein said oxide powder is finer than 100 mesh.

Patent 2 (18)

United States Patent Office 3,336,657
Patented Aug. 22, 1967

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3,336,657

SCARFING TOOL AND METHOD FOR JOINING METAL BANDS

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6 Claims. (Cl. 29—482)

This invention relates to an apparatus for treating the cross-sectional area of metal belts and to a method of joining two such treated cross sectional areas. In one aspect, this invention relates to a tool for scarfing the end of a thin metal band. In another aspect, it relates to a method of overlapping two such scarfed ends and joining them so that the resulting joint displays qualities and characteristics comparable to those of the metal band itself.

Continuous metal belts for use in conjunction with high speed pulley drive systems have found numerous applications in contemporary industry. The high tensile strength of metals such as steel is one of the principal characteristics which promote use of such materials in fabrication of the belts. This high tensile strength permits the use of very small cross sectional areas in the belt design for transfer of the pulley system forces. This small cross sectional area eliminates a number of otherwise significant engineering problems in pulley systems such as gravity effect and system imbalances caused by inertia. Other properties of metal belts which have recently added appreciably to their utility are their excellent heat and electrical conductivities. For example, thin metal bands are finding increasing application in mechanisms designed to package manufactured articles in air-tight containers of heat sensitive thermoplastic resins. Operating requirements of the metal bands in these mechanisms often require cyclic heating and cooling and simultaneous high speed flexing. This combination of actions required of the metal band, namely cyclic heating and cooling and high speed flexing, are extremely detrimental to the fabricated points of juncture by which the metal bands are made continuous. Presently known methods of joining the opposing ends of steel bands are not capable of producing a joint with a satisfactory life span under the prescribed operating conditions.

It is an object of this invention to provide a method of joining the ends of steel bands which will result in a joint of superior strength and durability.

It is another object of this invention to provide a tool to be used in preparing the ends of steel bands for joining.

It is still another object of this invention to provide a joint for steel bands which lends itself to repeated heating and cooling and to rapid and continuous flexing.

Other objects of this invention will become apparent to those skilled in the art from reading this specification.

It is shown in the art that the ends of metal bands may be joined by overlapping the scarfed edges of two such ends and applying adhesive to the opposing contact surfaces. I have found that in joining the ends of metal bands having a thickness between 0.001 inch and 0.05 inch the resulting joint will display increased strength when the opposing overlapping ends have certain geometrical characteristics. My experimentation and study have shown that the steel band joint of greatest strength is obtained when the hypotenuse dimension of the right triangle seen when viewing the scarfed edge from either side is equal in length to approximately 10 times the thickness of the bands to be joined. In other words, the most desirable scarf is equal in cross sectional area to very nearly 10 times the cross sectional area of the band. The scarfed end having this geometry has a most desirable combination of qualities, among which are a surface area

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greatly multiplied over the band cross sectional area for applying adhesive material to effect the joint together with a protruding edge of the scarf which is not so thin as to be delicate or brittle. After arriving at this scarf geometry, there is a need for a means of expediently reproducing the desired scarfed edge with suitable properties for immediate joining. Means designed to effect such a reproduction simply and effectively are further aspects to be disclosed in this invention.

The tool designed to effect the scarfing of the steel band end consists primarily of a shearing or mashing head whose forward surface is a chisel-like edge. The shearing edge slides in an enclosed channel and is confronted at its forward surface by a transverse, stationary, flat plate. A slot of suitable dimensions is provided by which the metal band to be scarfed may be inserted in the proper position in relation to the channel and flat plate members mentioned above. The chisel-like edge of the shearing head is then advanced to contact the surface of the metal band and slow, continuous force sufficient to push the chisel edge of the mashing head through the metal band is applied longitudinally to the shearing member. The chisel-like edge "mashes" the metal band apart and a scarfed surface results both at the end of the remaining metal belt and the end of the opposing waste material which may be discarded. The fresh surface produced by this mashing has a number of qualities which lend the surface to immediate treatment for joining, among which are the practically total absence of metal oxides which normally inhibit surface bonding. Since the mechanism described to this point has no characteristics which definitely insure that the length of the scarfed edge will equal about 10 times the band thickness, the required characteristics of the chisel-like edge will now be disclosed.

I have found that the apex angle of the mashing edge must be within a certain range of obtuse angles, and it is further limited by definite and distinguishable ranges of values for the band side angle and for the waste side angle. The scarfing tool may best be described and understood by referring to the accompanying drawings.

FIGURE 1 is a view of the scarfing tool from the top.

FIGURE 2 is a cross sectional view of the scarfing tool as seen when viewed along section **2** of FIGURE 1.

FIGURE 3 is a three-dimensional perspective view of the scarfing tool showing a possible design of the stationary members, the sliding mashing head, and the slot for insertion of the metal band.

FIGURE 4 shows a perspective view of a scarfed band end made according to this invention in which L equals about 10*t*.

FIGURE 5 is a side view of two over-lapped scarfed band ends with the thin strip of silver solder **9** inserted.

FIGURE 6 is a side view of a simply designed clamping, pressing, and heating apparatus for joining band ends according to this invention.

The critical geometry of the chisel-head surface as described above may be seen in FIGURE 2. The angle referred to above as the band side angle is angle A and the angle referred to above as the waste side angle is angle B. My experimentation has shown that in order to accomplish reproduction of the desirable scarfed edge on steel bands, angle A of the chisel-head surface must lie in the range of 6–10° and angle B must lie in the range of 25–30°. The shearing head member should be fabricated of a material of sufficient hardness to retain this specific geometry at its chisel-head surface while being used repeatedly in the mashing operation. Should angle B be made greater than 30° it would cause a resultant force during the mashing operation in the longitudinal direction of the band which would tend to break the band by a tensile fracture before the chisel edge is able to effect

a smooth, scarfed surface across the thickness of the band. Should angle B be made less than 25° it would contribute an unnecessary retarding force during the shearing operation. As for angle A, the smaller angle is needed to "mash" and cold-form the scarfed surface during the operation, and to yield the scarfed end of proper geometry.

If angle A is greater than 10°, the scarfed surface will not be as wide as ten times the band thickness. Neither will the band end be cold-formed as is desirable. If angle A is made smaller than 6°, the band end is cold-formed to too great an extent, and flaws of thinness and brittleness develop in the scarf protrusion.

The force which is to be applied to the shearing head to effect the parting and scarfing of the steel band should be sufficient to accomplish the operation expediently. However, it should be noted that according to the best manner of practicing this invention the applied force should not be one of rapid impact. The most apt description of the force to be applied would be that exerted by the jaws of a substantial vice advanced by a deliberate mechanical means.

The method of joining the ends of the steel bands consists of the following procedure. Two opposing scarfed edges as shown in FIGURE 5 are each gripped rigidly by clamping means **6** as shown in FIGURE 6. A thin strip of silver solder, for example about 0.003 inch thick when the band thickness is about 0.005 inch, is placed between the opposing contact surfaces, and two opposing members **7** are advanced to contact either side of the juncture. The two opposing members **7** are capable of compressing the joint and assuring intimate contact of all surfaces while at the same time each member **7** is electrically wired **8** and supplies heat to the juncture sufficient to melt the silver solder and effect the brazing of the surfaces. When the brazing of the joint is complete and the heating and compressing members are retracted, the jointed band **3** is removed from the clamping means **6**, and the joint is placed between opposing flat surfaces which apply high pressure to the juncture, sufficient to reduce the thickness of the juncture to the uniform dimensions of the band. When this compressing operation is complete any excess material is trimmed away so that the resulting joint is clean and smooth. The joint is now ready for service.

The advantages offered by this invention are numerous and will be apparent to those skilled in the art. This scarfing tool gives a means for preparing band ends for joining which is exact and uniform in producing a high quality joint. The entire joining process is both simple and expedient in operation. Continuous metal bands with joints prepared according to techniques disclosed by this invention have displayed surprisingly long service lives when run at high speeds on heat sealing machines being used in conjunction with polyethylene packaging machines. Steel bands joined according to the previously best known method had service lives on such machines of no more than 3–4 days. Similar bands joined according to the method of this invention serve under similar operating conditions for periods exceeding one month.

I claim as my invention:

1. An apparatus for scarfing the ends of thin metal bands which comprises a sturdy metal member having its forward cross sectional surface machined or shaped to form a wedge or chisel-head, said chisel-head surface being of such a design that sloping sides meet in a straight line crest, said crest being of geometrical proportions such that one side of said crest slopes at an angle of 6–10° and on the opposite side of said crest the surface slopes at an angle of between 25–30° from the surface of the cross section of said chisel-head, means for advancing and retracting said member along its longitudinal axis through rigid channel guides to contact said wedge point or chisel-head surface with the broad surface of a transversely oriented metal band, and means to transmit force and direct the chisel-head surface against the metal band with said force so that the metal band is parted by said chisel-head and the resulting sheared end of said metal band has a smooth scarfed or chamfered surface.

2. An apparatus for scarfing the ends of thin metal bands comprising an enclosed channel, a sturdy metal member capable of advancing and retracting in and being guided by said enclosed channel, a wedge-like or chisel-head surface on the forward, cross sectional face of said metal member, said chisel-head surface being of such design that the sloping sides meet in a straight-line crest which runs squarely with the shanks of said metal member, said crest or apex angle being of geometrical proportions such that to one side of said crest the surface slopes at an angle of 6–10° and on the opposite side of said crest the surface slopes at an angle between 25–30° from the surface of the cross section, a flat plate at the forward end of said channel which squarely and rigidly impedes the further advance of said chisel-head surface, slots positioned in opposite sides of said channel directly above and parallel to said flat plate which allow insertion of a metal band across the channel and flush against the surface of said flat plate, said metal band being oriented in such a direction by the slot that said chisel-head surface when contacted with the surface of said metal band spans the width of said metal band squarely, and means to transmit a force through said metal member so that said chisel-head surface presses said metal band against said flat plate in such a manner that said metal band is sheared and a smooth uniform scarfed surface whose area closely approximates ten times the cross sectional area of said metal band results on the end of said metal band.

3. A method for scarfing the end of a thin metal band which comprises pressing said thin metal band against a rigid back-up surface with a wedge-like, chisel-head surface, said wedge-like surface being sloped toward one extremity at an angle of 6–10° and sloped toward the opposite extremity at an angle of 25–30°, in such a manner that said thin metal band is sheared squarely relative to its width extremities and the resulting fresh surface on the end of said thin metal band is scarfed at such a slope that the area of said fresh surface closely approximates ten times the cross-sectional area of said thin metal band.

4. A method of effecting a joint between the ends of thin metal bands which comprises scarfing the two ends to be joined by means of pressing each of said bands against a rigid surface with a chisel-head surface in such a manner that said bands are sheared and a scarfed surface results, the area of said scarfed surface being approximately ten times the cross-sectional area of said bands, then overlapping two such scarfed ends in such a manner that said scarfed surfaces are parallel and abutted, placing a thin strip of silver solder between the scarfed surfaces, then subjecting this juncture to sufficient heat to melt said silver solder and simultaneously to sufficient pressure to insure intimate contact of said silver solder with said scarfed surfaces, removing said heat and pressure, then compressing the resulting joint between opposing flat surfaces so that said joint is cold-formed and reduced in size to the dimensions of the joined bands, and finally trimming away any excess material at said joint.

5. A method of effecting a joint between the ends of thin metal bands which comprises scarfing the two ends to be joined by means of an apparatus which consists of an enclosed channel, a sturdy metal member capable of advancing and retracting in and being guided by said enclosed channel, a wedge-like or chisel-head surface on the forward face of said metal member, said chisel-head surface being of such design that the sloping sides meet in a straight-line crest which runs squarely with the shanks of said metal member, said crest or apex angle being of geometrical proportions such that to one side of said crest the surface slopes at an angle of 6–10° and on the opposite side of said crest the surface slopes at an angle

between 25–30° from the surface of the cross section, a flat plate at the forward end of said channel which squarely and rigidly impedes the further advance of said chisel-head surface, slots positioned in opposite sides of said channel directly above and parallel to said flat plate which allow insertion of the metal band across the channel and flush against the surface of said flat plate, said metal band being oriented in such a direction by the slots that said chisel-head surface when contacted with the surface of said metal band spans the width of said metal band squarely, by transmitting a force through said metal member so that said chisel-head surface presses said metal band against said flat plate and shears the metal band so that a smooth, uniform, scarfed surface whose area closely approximates ten times the cross sectional area of said metal band results on the end of said metal band; then overlapping two such scarfed ends in such a manner that said scarfed surfaces are parallel and abutted; placing a strip of silver solder 0.003 inch thick between the scarfed surfaces; then subjecting this juncture to sufficient heat to melt said surface solder and simultaneously subjecting the juncture to sufficient pressure to insure intimate contact of said silver solder with said scarfed surfaces; removing said heat and pressure; then compressing the resulting joint between opposing flat surfaces so that said joint is cold-formed and reduced in size to the dimensions of the joined bands; and then trimming away any excess material at said joint.

6. A method of effecting a joint between the ends of thin metal bands which comprises scarfing the two ends

to be joined by means of pressing each of said bands against a rigid surface with a chisel head surface in such a manner that said bands are sheared and a scarfed surface results, the area of said scarfed surface being approximately ten times the cross-sectional area of said bands, then overlapping two such scarfed ends in such a manner that said scarfed surfaces are parallel and abutted, placing a thin strip of fusible metal bonding material between the scarfed surfaces, then subjecting this juncture to sufficient heat to fuse said bonding material and simultaneously to sufficient pressure to insure intimate contact of said bonding material with said scarfed surfaces, removing said heat and pressure, and compressing the resulting joint between opposing flat surfaces so that said joint is cold formed and reduced in size to dimensions of the joined bands.

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JOHN F. CAMPBELL, *Primary Examiner.*

L. J. WESTFALL, *Assistant Examiner.*

Aug. 22, 1967 E. H. FLAMING 3,336,657

SCARFING TOOL AND METHOD FOR JOINING METAL BANDS

Filed Sept. 14, 1964

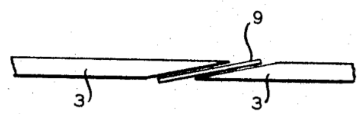


FIG. 5

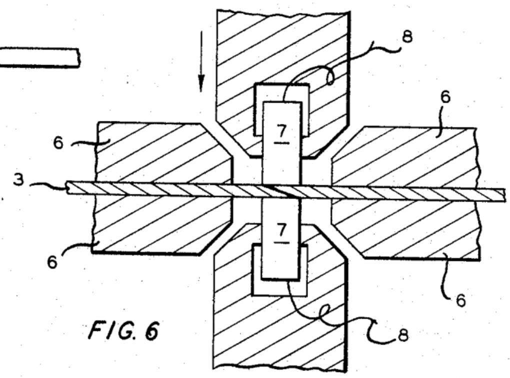


FIG. 6

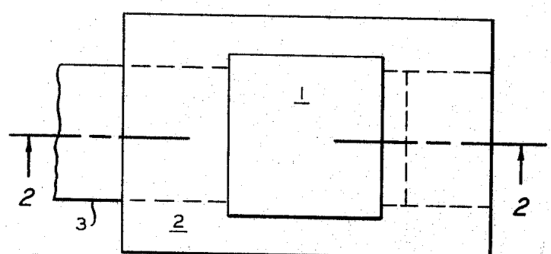


FIG. 1

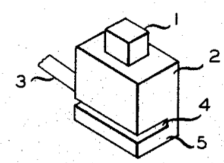


FIG. 3

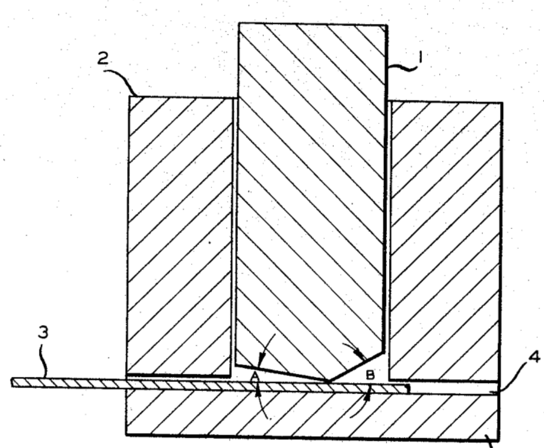


FIG. 2

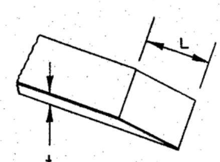


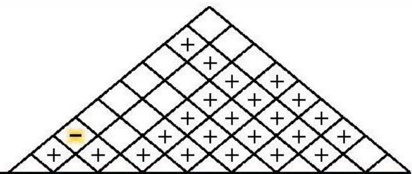
FIG. 4

INVENTOR.
E. H. FLAMING

BY

Young + Grigg
ATTORNEYS

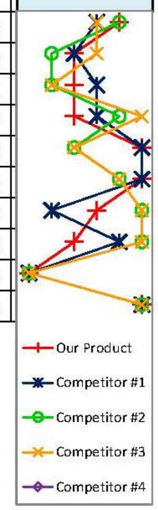
Appendix 2: QFD

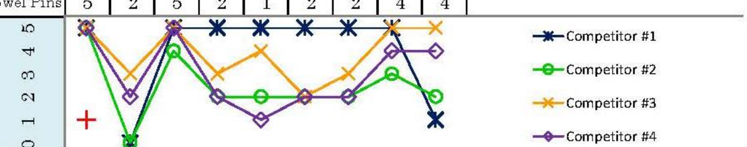


Row #	Weight Chart	Relative Weight	Machine Operators	Post-Processor	LLNL Design Engineers	Metrologist	Other AM Factories	Maximum Relationship	WHAT: Customer Requirements (explicit & implicit) / HOW: Engineering Specifications	1 Parts printed per print cycle	2 Print time	3 Wall Thickness	4 Max allowable radial forces	5 Max allowable axial forces	6 Max allowable bending forces	7 Max allowable Torque	8 Mass	9 Number of fixtures to make	Welding	Gluing	Puzzle Piece	Dowel Pins
									Direction of Improvement	▲	▼	◇	▲	▲	▲	▲	◇	▼	NOW: Current Product Assesment - Customer Requirements			
1		15%	3	4	5	5	4	9	GD&T Specified in Part Drawing	▽	▽	●	▽	▽	▽	▽	▽	○	4	3	4	3
2		8%	2	2	5	2	1	9	No Lumped Masses in Theta and Z	▽	▽	●	○	○	○	●	●	▽	2	2	1	3
3		8%	2	2	5	2	1	9	No Step Change in Density in Theta and Z	▽	▽	●	○	○	○	●	●	▽	2	3	1	1
4		11%	1	5	5	3	3	3	Look like a fully printed part	○	▽	▽	▽	▽	▽	▽	▽	▽	2	3	4	5
5		7%	1	1	3	2	3	3	Temperature Requirements	▽	▽	○	○	○	○	○	▽	▽	5	5	2	2
6		9%	1	4	5	1	3	9	Approach strength of a fully printed part	▽	▽	○	●	●	●	●	○	▽	5	5	4	4
7		10%	2	5	3	1	4	9	Quick post processing time	●	●	○	▽	▽	▽	▽	●	●	3	1	5	5
8		9%	1	3	4	1	5	9	Cheap post processing	●	●	○	▽	▽	▽	▽	○	●	2	4	5	5
9		10%	1	4	5	3	2	3	No Bolts/Fasteners	▽	▽	▽	▽	▽	▽	▽	○	○	0	0	0	0
10		13%	4	5	4	2	3	9	Splitting of part	●	●	▽	●	○	●	●	▽	●	5	5	5	5

WHO: Customers

Column #	1	2	3	4	5	6	7	8	9
HOW MUCH: Target	3	3 adys	2m m	TBD	TBD	TBD	TBD	2.54 kg	10
Max Relationship	9	9	9	9	9	9	9	9	9
Technical Importance Rating	379	357	421	320	242	320	417	366	407
Relative Weight	12%	11%	13%	10%	7%	10%	13%	11%	13%
Weight Chart									
Current Product Assesment - Engineering Specifications: Welding	5	0	5	5	5	5	5	5	1
Gluing	5	0	4	2	2	2	2	3	2
Puzzle Piece	5	3	5	3	4	2	3	5	5
Dowel Pins	5	2	5	2	1	2	2	4	4





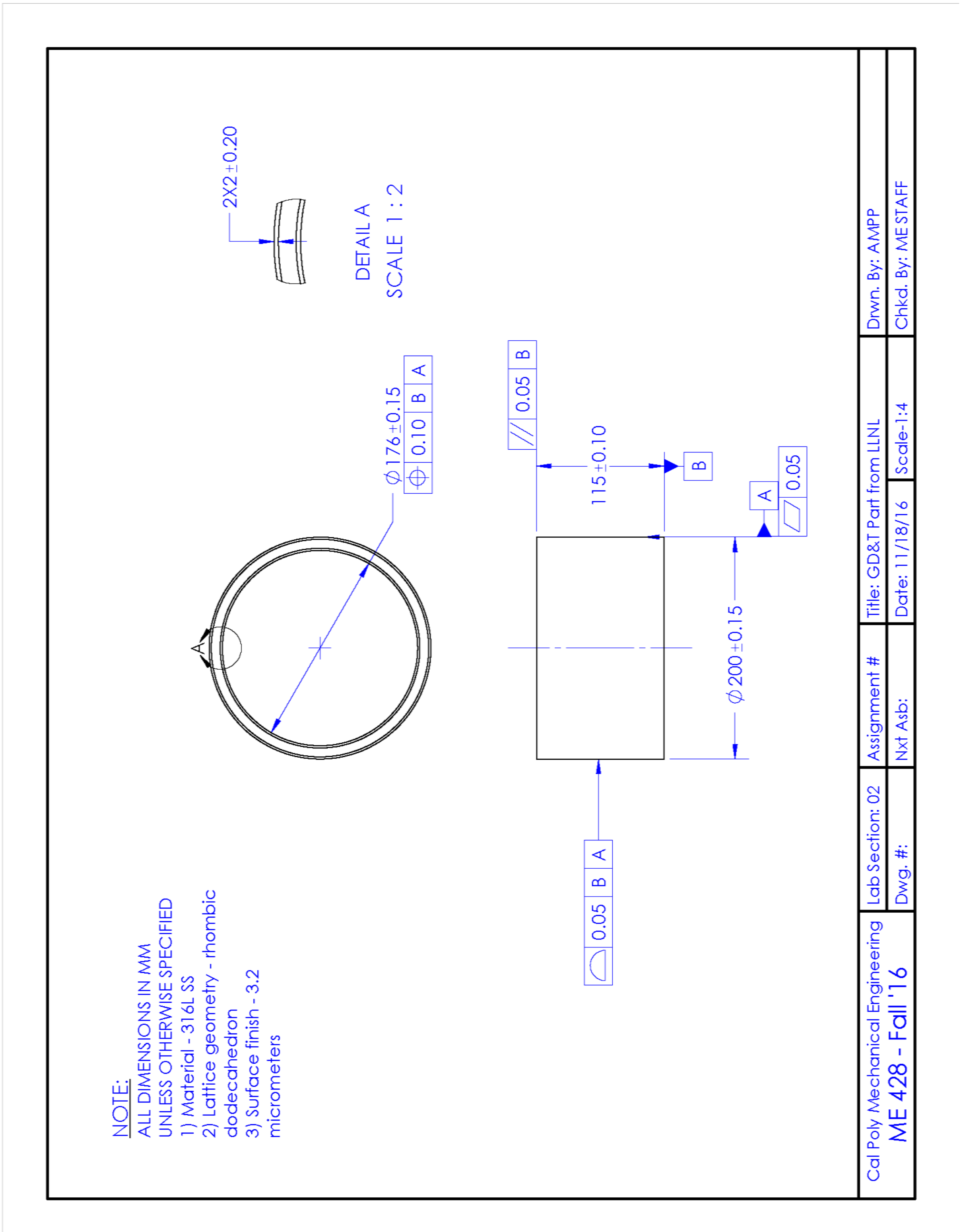
Column #	1	2	3	4	5	6	7	8	9

Correlations
- Positive +
- Negative −
- No Correlation

Relationships
- Strong ●
- Moderate ○
- Weak ▽

Section of Improvement
- Maximize ▲
- Target ◇
- Minimize ▼

Appendix 3: Part with GD&T



Appendix 4: Pugh Matrix

Adhesion type	Weld	Weld	Heat shrink	Heat shrink	Heat shrink	Heat shrink	Weld	Weld	Weld	Weld	Weld
Joint geometry	Straight joint	Puzzle piece	Full thickness outer shell	Partial thickness outer shell	Full thickness outer band on each end	Partial thickness outer band on each end	Hook Joint	Button	Threaded cap band inside and outside	Internal band	Dowel pins
Criteria\Concept	**1a**	**2a**	**3a**	**3b**	**4a**	**4b**	**5a**	**6a**	**7a**	**8a**	**9a**
Amount of parts	Datum	S	-	-	-	-	S	S	-	-	-
Post processing difficulty		+	+	+	+	+	S	S	-	-	S
Post processing time		S	+	+	+	+	+	+	S	-	S
Tangential strength		S	+	+	-	-	+	+	+	-	S
Post processing safety		S	+	+	+	+	S	S	S	s	S
Part cost		S	-	-	-	-	S	S	-	-	S
Quality of joined part		S	+	+	+	+	S	S	+	s	S
Temperature resistivity		S	S	S	S	S	S	S	S	s	S
Σ +		1	5	5	4	4	2	2	2	0	0
Σ -		0	2	2	3	3	0	0	3	5	1
Σ S		7	1	1	1	1	6	6	3	3	7

Adhesion type	Adhesive	Adhesive	Adhesive	Adhesive	Adhesive	Adhesive	Adhesive
Joint geometry	Straight joint	Puzzle piece	Hook Joint	Button	Threaded cap band inside and outside	Internal band	Dowel pins
Criteria\Concept	**1b**	**2b**	**5b**	**6b**	**7b**	**8b**	**9b**
Amount of parts	S	S	S	S	-	-	-
Post processing difficulty	+	+	+	+	+	-	+
Post processing time	-	-	-	-	-	-	-
Tangential strength	-	-	-	S	s	-	-
Post processing safety	+	+	+	+	+	+	+
Part cost	+	+	+	+	-	-	+
Quality of joined part	-	-	-	-	-	-	-
Temperature resistivity	-	-	-	-	-	-	-
Σ +	3	3	3	3	2	1	3
Σ -	4	4	4	3	5	7	5
Σ S	1	1	1	2	1	0	0

Legend
(+) = Better Than
(-) = Worse Than
S = Same

Appendix 5: Weighted Decision Matrix

			Amount of parts	Post processing difficulty	Post processing time	Tangential strength	Post processing safety	Part cost	Quality of joined part	Temperature resistivity	
		Weight	2	6	4	10	3	4	9	8	46
		Weight (%)	4.35%	13.04%	8.70%	21.74%	6.52%	8.70%	19.57%	17.39%	100.00%
1	Straight Joint - Weld	Rating	10.0	3.0	7.0	5.0	4.0	4.0	8.0	10.0	6.4
		Wgt Rtg	0.4	0.4	0.6	1.1	0.3	0.3	1.6	1.7	
2	Straight Joint - Adhesive	Rating	10.0	5.0	4.0	3.0	8.0	9.0	5.0	4.0	5.1
		Wgt Rtg	0.4	0.7	0.3	0.7	0.5	0.8	1.0	0.7	
3	Puzzle Piece - Weld	Rating	10.0	4.0	8.0	6.0	5.0	4.0	8.0	10.0	6.9
		Wgt Rtg	0.4	0.5	0.7	1.3	0.3	0.3	1.6	1.7	
4	Puzzle Piece - Adhesive	Rating	10.0	5.0	5.0	4.0	8.0	9.0	4.0	4.0	5.2
		Wgt Rtg	0.4	0.7	0.4	0.9	0.5	0.8	0.8	0.7	
5	Full Thickness Outer Shell - Heat Shrink	Rating	7.0	8.0	8.0	10.0	7.0	4.0	10.0	10.0	8.7
		Wgt Rtg	0.3	1.0	0.7	2.2	0.5	0.3	2.0	1.7	
6	Partial Thickness Outter Shell - Heat Shrink	Rating	7.0	8.0	8.0	9.0	7.0	4.0	10.0	10.0	8.5
		Wgt Rtg	0.3	1.0	0.7	2.0	0.5	0.3	2.0	1.7	
7	Full Thickness Outer Band on Each End	Rating	5.0	7.0	6.0	7.0	7.0	5.0	4.0	10.0	6.6
		Wgt Rtg	0.2	0.9	0.5	1.5	0.5	0.4	0.8	1.7	
8	Partial Thickness Outer Band on Each End	Rating	5.0	7.0	6.0	5.0	7.0	5.0	4.0	10.0	6.2
		Wgt Rtg	0.2	0.9	0.5	1.1	0.5	0.4	0.8	1.7	
9	Hook Joint - Weld	Rating	10.0	2.0	6.0	7.0	5.0	4.0	8.0	10.0	6.7
		Wgt Rtg	0.4	0.3	0.5	1.5	0.3	0.3	1.6	1.7	
10	Hook Joint - Adhesive	Rating	10.0	4.0	3.0	5.0	8.0	9.0	5.0	4.0	5.3
		Wgt Rtg	0.4	0.5	0.3	1.1	0.5	0.8	1.0	0.7	
11	Button - Weld	Rating	10.0	5.0	9.0	7.0	4.0	5.0	8.0	10.0	7.4
		Wgt Rtg	0.4	0.7	0.8	1.5	0.3	0.4	1.6	1.7	
12	Button - Adhesive	Rating	10.0	7.0	5.0	6.0	8.0	9.0	4.0	4.0	5.9
		Wgt Rtg	0.4	0.9	0.4	1.3	0.5	0.8	0.8	0.7	
13	Threaded Cap Band Inside and Outside - Weld	Rating	5.0	2.0	7.0	4.0	4.0	2.0	8.0	10.0	5.7
		Wgt Rtg	0.2	0.3	0.6	0.9	0.3	0.2	1.6	1.7	
14	Threaded Cap Band Inside and Outside - Adhesive	Rating	5.0	5.0	5.0	3.0	8.0	4.0	3.0	4.0	4.1
		Wgt Rtg	0.2	0.7	0.4	0.7	0.5	0.3	0.6	0.7	
15	Internal Band - Weld	Rating	1.0	1.0	5.0	5.0	4.0	2.0	8.0	10.0	5.4
		Wgt Rtg	0.0	0.1	0.4	1.1	0.3	0.2	1.6	1.7	
16	Internal Band - Adhesive	Rating	1.0	4.0	3.0	3.0	8.0	4.0	4.0	4.0	3.8
		Wgt Rtg	0.0	0.5	0.3	0.7	0.5	0.3	0.8	0.7	
17	Dowel Pin - Weld	Rating	6.0	4.0	8.0	4.0	5.0	4.0	8.0	10.0	6.3
		Wgt Rtg	0.3	0.5	0.7	0.9	0.3	0.3	1.6	1.7	
18	Dowel Pin - Adhesive	Rating	6.0	5.0	5.0	2.0	8.0	9.0	4.0	4.0	4.6
		Wgt Rtg	0.3	0.7	0.4	0.4	0.5	0.8	0.8	0.7	

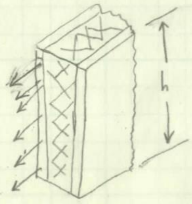
Appendix 6: Hand Calculations

Safety Factors for PDR Methods

316L

	AK STEEL	LINCOLN ELECTRIC	
σ_y	42	30	ksi
σ_u	81	78	ksi

FULL THICKNESS OUTER BAND



ALL LOAD CARRIED BY OUTER BAND

$\sum \rightarrow = 5000\ lbf$ mh

$t = 0.002\ m = 0.0787\ in$

$h = 115\ mm = 4.5276\ in$

$A = th = 4.5276\ in\ (0.0787\ in) = 0.3563\ in^2$

$\sigma_{yeld} = 4200\ \frac{lbf}{in^2}$

$F_{max} = \sigma_{yeild} A = 42000\ \frac{lbf}{in^2}\ (0.3563\ in^2)$

$F_{max} = 14964.6\ lbf$

$F_{design} = 5000\ lbf$

$\frac{F_{max}}{F_{design}} = \boxed{SF = 2.993}$

PARTIAL THICKNESS OUTER BAND

$A = \frac{3}{4} t h = \left(\frac{3}{4}\right)(0.3563\ in^2)$

$F_{MAX} = 42000\ \frac{lbf}{in^2}\left(\frac{3}{4}\right)(0.3563\ in^2)$

$F_{MAX} = 11223.5$

$SF = \frac{11223.5\ lbf}{5000\ lbf}$

$\boxed{SF = 2.245}$

BUTTON METHOD

FOR A BUTTON 1 mm OR 0.4528 in TALL, 0.1683 in LONG

FOR PERFECTLY DISTRIBUTED SHEAR LOAD ON BUTTONS:

$A = (2)(5)(0.4528)(0.1683) = 0.762\ in^2$

$FS = \frac{(1500\ psi)(0.762\ in^2)}{5000\ lbf} = \boxed{2.286}$

FOR TENSILE STRESS IN MALE SIDE OF JOINT

$A = 2\left[0.1783 - (5)(0.178)\right]$

$A = 0.1786\ in^2$

$SF = \frac{(3000)(0.1786)}{5000}$

$\boxed{SF = 1.1}$

Button Method Deflection

BEAM EQUATIONS TO RULE OUT BUTTON METHOD

STRAIGHT BEAM APPROXIMATION UNDERESTIMATES FAILURE

$$\delta_{MAX} = \frac{P\ell^3}{3EI}$$

$$\sigma = \frac{t\,m}{I} \;;\; m = P\ell \;,\; I = \frac{1}{2} b t^3$$

$$\sigma = \frac{t\,P\ell}{I}$$

$$\frac{P\ell}{I} = \frac{\sigma}{t}$$

$$\delta_{MAX} = \frac{P\ell}{I} \cdot \frac{\ell^2}{3E}$$

$$\delta_{MAX} = \frac{\sigma \ell^2}{t\,3E}$$

$$\sigma = \frac{\delta_{MAX}\, t\, 3E}{\ell^2}$$

$\delta_{MAX} = 1mm$ — THIS IS THE THICKNESS OF THE BUTTON THAT THE ENDS HAVE TO DEFLECT AROUND
$= 0.039 in$

$t = 1mm$ — SO THAT 1mm COULD BE PRINTED AS SKIN ON THE PRINTED PARTS, TOTALING A 2mm WALL THICKNESS

$E = 28 \times 10^6 \ \frac{lb_f}{in^2}$

$\ell = 34 mm$ — DISTANCE FROM BUTTON TO LATTICE (EFFECTIVE "BEAM" LENGTH)
$= 1.338 in$

$$\sigma = \frac{(0.039 in)(0.039 in)\, 3 \left(28 \times 10^6 \ \frac{lb_f}{in^2}\right)}{(1.338 in)^2}$$

$\sigma = 71366.8 \ psi$

σ_Y = MAX ALLOWABLE STRESS

$\sigma_Y = 25 \ KSI$

$\sigma > \sigma_Y$

PART WILL YIELD

Minimum Band Thickness

NATHAN GOODWIN — SENIOR PROJECT — 1/17/17

MINIMUM BAND THICKNESS CALCULATIONS

$$S.F. = \frac{F_{MAX}}{F_{DESIGN}} \; ; \; S.F. \geq 3 \, , \; F_{DESIGN} = 5000 \text{ lb}_f$$

$$3 \leq \frac{F_{MAX}}{5000 \text{ lb}_f}$$

$$F_{MAX} \geq 15000 \text{ lb}_f$$

$$F_{MAX} = \sigma_{YIELD} A \; ; \quad \sigma_{YIELD} = 25 \text{ KSI}$$

$$A = t_T h \quad ; h = 115 \text{ mm} = 4.53 \text{ in}$$

$$\left(25000 \frac{\text{lb}_f}{\text{in}^2}\right)(4.53 \text{ in})\, t \geq 15000 \text{ lb}_f$$

$$t_T \geq 0.1325 \text{ in}$$
$$t_T \geq 3.366 \text{ mm}$$

't_T' IS TOTAL BAND THICKNESS

∴ EACH BAND MUST BE GREATER THAN 1.68 mm

$$t \geq 1.68 \text{ mm}$$

Interference Fit and Heating Ranges

BULK MODULUS OF LATTICE CALCULATION

TEST 1:

$$K_{P_1} = \frac{6.2\ MPa}{0.02\varepsilon} = 310\ MPa \cdot \frac{145.038\ PSI}{1\ MPa} = 44.96\ KSI$$

$$K_{P_2} = \frac{5\ MPa}{0.02\varepsilon} = 250\ MPa \cdot \frac{145.038\ PSI}{1\ MPa} = 36.26\ KSI$$

$$\boxed{K_P = 40.6\ KSI}$$

$E_{316L} = 27.56 \times 10^6\ PSI$ } AZO MATERIALS

$K_{316L} = 19.44 \times 10^6\ PSI$

$$\frac{E_{316L}}{K_P} = \boxed{678.8} \qquad \frac{K_{316L}}{K_P} = \boxed{478.8}$$

SOLVING FOR PRESSURES AT THE INNER & OUTER INTERFACES OF THE PRINTED PART

$P_o \equiv$ OUTER INTERFACE PRESSURE

$P_i \equiv$ INNER INTERFACE PRESSURE

MAX STRAIN: $\varepsilon = 0.01 \frac{mm}{mm}$ OR 1%

$$\varepsilon = \frac{\delta_r}{t_{LATTICE}}$$

$$\varepsilon \cdot K_P = \sigma_r$$

$$\sigma_r = \left(\frac{a^2 p_i - b^2 p_o}{b^2 - a^2}\right) - \left(\frac{a^2 b^2 (p_i - p_o)}{b^2 - a^2}\right)\frac{1}{r^2}$$

$$\delta_r = \left(\frac{1-v}{K_P}\right)\left(\frac{a^2 p_i - b^2 p_o}{b^2 - a^2}\right) r + \left(\frac{1+v}{K_P}\right)\left(\frac{a^2 b^2 (p_i - p_o)}{b^2 - a^2}\right)\frac{1}{r}$$

$V = 0.265$ → AZO MATERIALS

$\delta_r = 0.00215$ IN @ a

$a = 2.722$ IN

$b = 3.183$ IN

$r = a$

$K = 40600$ PSI

$t_{LATTICE} = 11mm$

AFTER SOLVING SYSTEM OF EQUATIONS IN CALCULATO

$p_i = 265.6$ PSI

$p_o = 243.6$ PSI

$\sigma_r = 406$ PSI

TO FIND SEPARATION FORCE, MULTIPLY TIMES AREA OF INTERFACE AND μ_s

$$F_{INNER} = 265.6 \text{ PSI} \cdot 2\pi \cdot a \cdot 115mm \cdot \frac{1in}{25.4mm}$$

$$= 12000 \text{ lbf}$$

$$F_{OUTER} = 243.6 \text{ PSI} \cdot 2\pi\, b \cdot 115mm \cdot \frac{1in}{25.4mm}$$

$$= 12800 \text{ lbf}$$

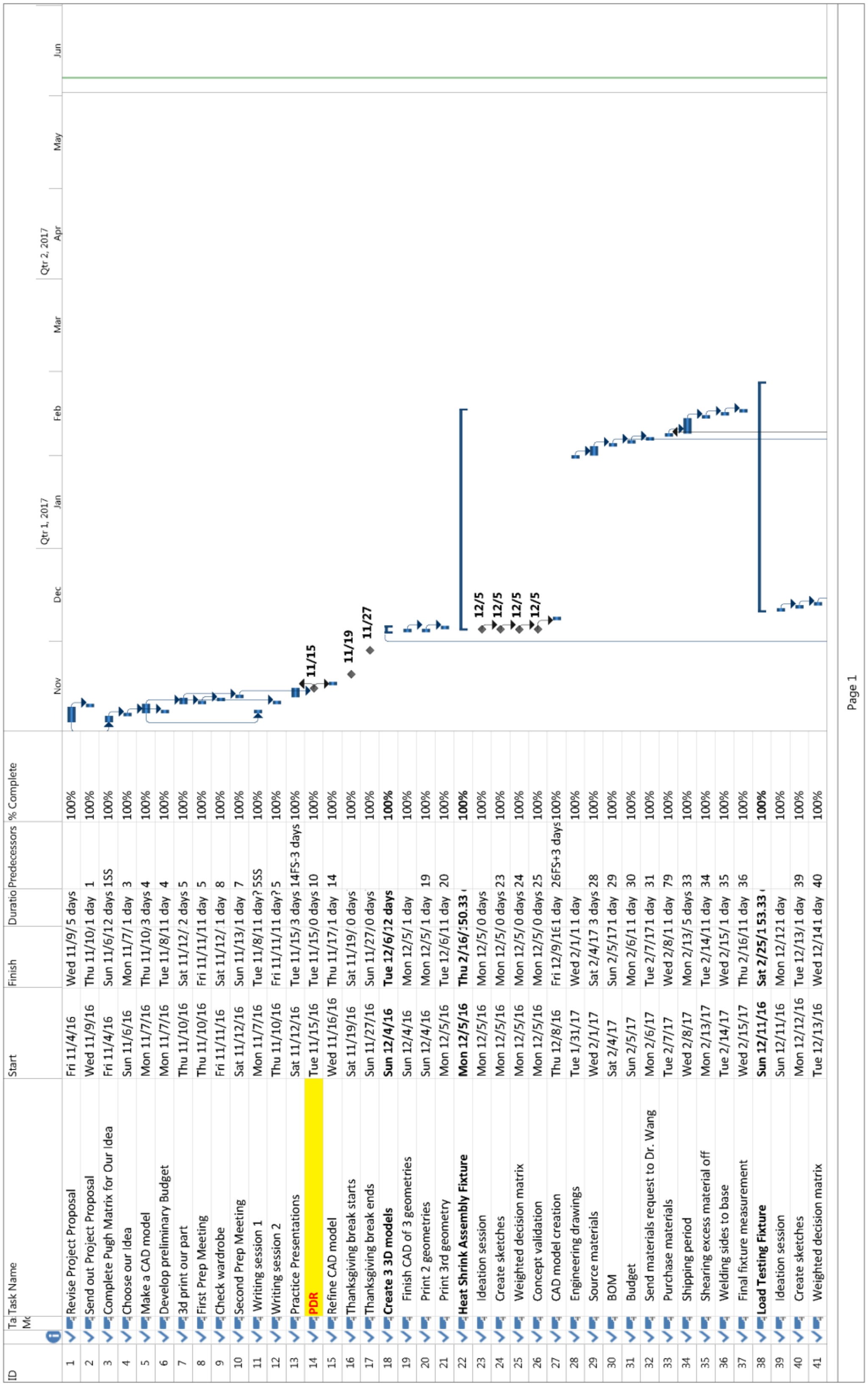
HEAT SHRINK TEMP RANGES

$$d_i = d_o(\Delta T \alpha + 1)$$

$$\alpha = 15 \times 10^{-6} K^{-1}$$

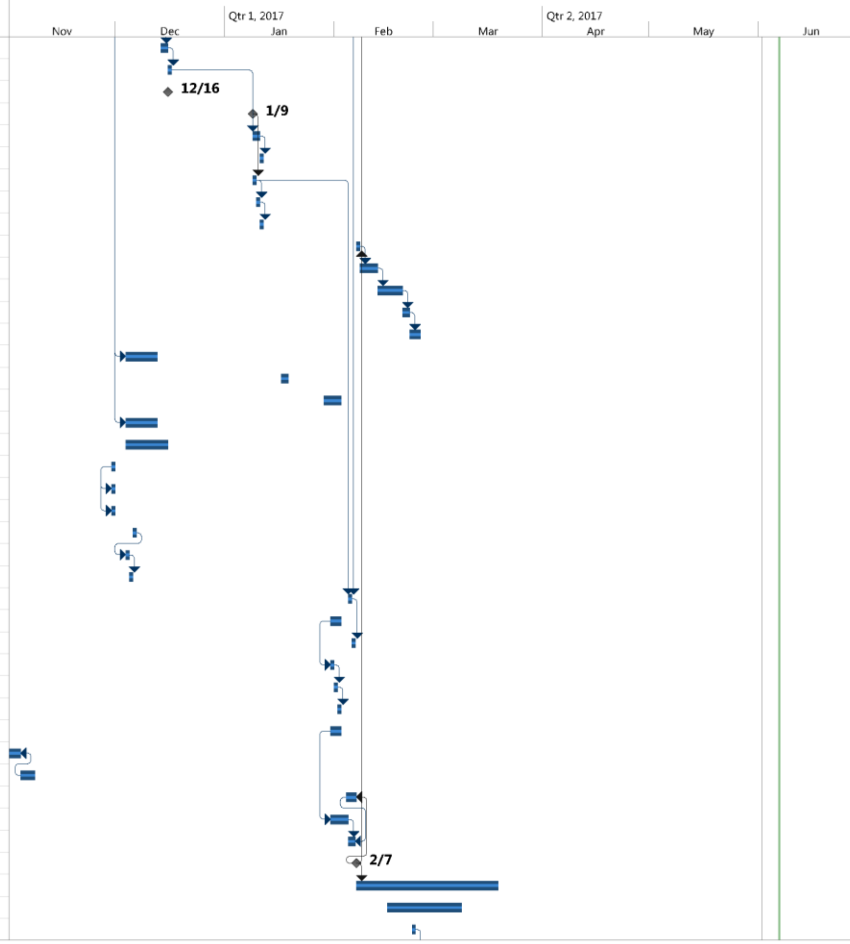
$$\frac{\frac{2.72415 in}{2.722 in} - 1}{\alpha} = \Delta T = 52.7°C$$

Appendix 7: Gantt Chart

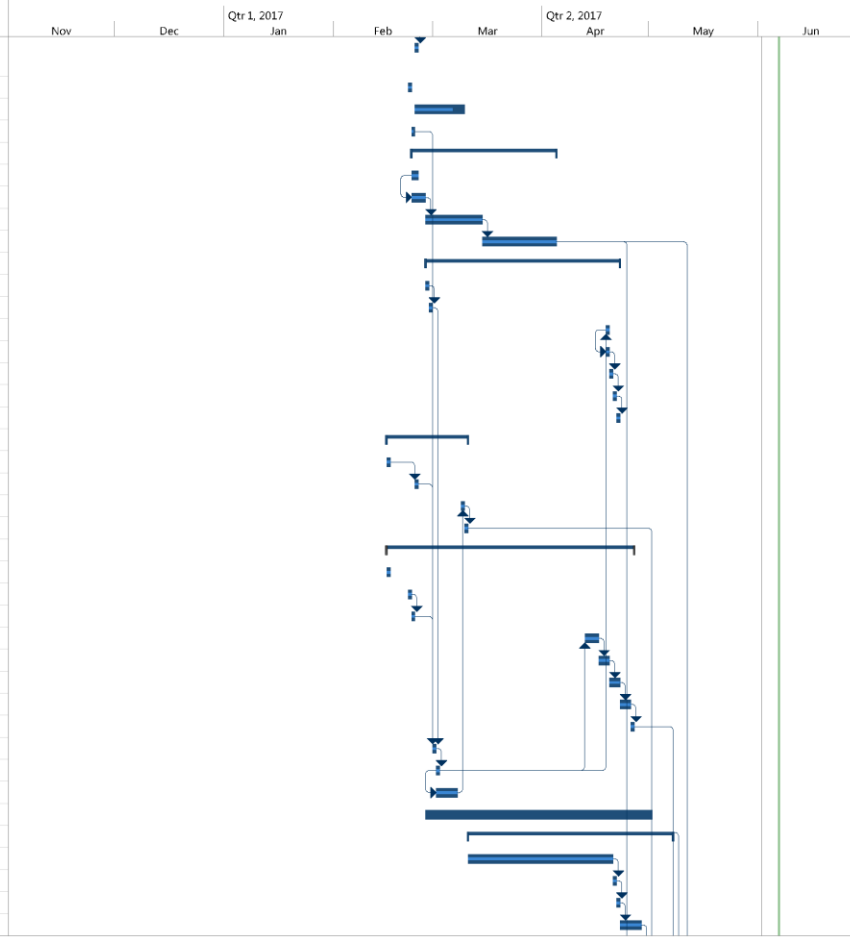


ID	Task Mode	Task Name	Start	Finish	Duration	Predecessors	% Complete
1		Revise Project Proposal	Fri 11/4/16	Wed 11/9/	5 days		100%
2		Send out Project Proposal	Wed 11/9/16	Thu 11/10/	1 day	1	100%
3		Complete Pugh Matrix for Our Idea	Fri 11/4/16	Sun 11/6/1	2 days	1SS	100%
4		Choose our Idea	Sun 11/6/16	Mon 11/7/1	1 day	3	100%
5		Make a CAD model	Mon 11/7/16	Thu 11/10/	3 days	4	100%
6		Develop preliminary Budget	Mon 11/7/16	Tue 11/8/1	1 day	4	100%
7		3d print our part	Thu 11/10/16	Sat 11/12/	2 days	5	100%
8		First Prep Meeting	Thu 11/10/16	Fri 11/11/1	1 day	5	100%
9		Check wardrobe	Fri 11/11/16	Sat 11/12/	1 day	8	100%
10		Second Prep Meeting	Sat 11/12/16	Sun 11/13/	1 day	7	100%
11		Writing session 1	Mon 11/7/16	Tue 11/8/1	1 day?	5SS	100%
12		Writing session 2	Thu 11/10/16	Fri 11/11/1	1 day?	5	100%
13		Practice Presentations	Sat 11/12/16	Tue 11/15/	3 days	14FS-3 days	100%
14		PDR	Tue 11/15/16	Tue 11/15/	0 days	10	100%
15		Refine CAD model	Wed 11/16/16	Thu 11/17/	1 day	14	100%
16		Thanksgiving break starts	Sat 11/19/16	Sat 11/19/	0 days		100%
17		Thanksgiving break ends	Sun 11/27/16	Sun 11/27/	0 days		100%
18		**Create 3 3D models**	**Sun 12/4/16**	**Tue 12/6/1**	**2 days**		**100%**
19		Finish CAD of 3 geometries	Sun 12/4/16	Mon 12/5/	1 day		100%
20		Print 2 geometries	Sun 12/4/16	Mon 12/5/	1 day	19	100%
21		Print 3rd geometry	Mon 12/5/16	Tue 12/6/1	1 day	20	100%
22		**Heat Shrink Assembly Fixture**	**Mon 12/5/16**	**Thu 2/16/1**	**50.33**		**100%**
23		Ideation session	Mon 12/5/16	Mon 12/5/	0 days		100%
24		Create sketches	Mon 12/5/16	Mon 12/5/	0 days	23	100%
25		Weighted decision matrix	Mon 12/5/16	Mon 12/5/	0 days	24	100%
26		Concept validation	Mon 12/5/16	Mon 12/5/	0 days	25	100%
27		CAD model creation	Thu 12/8/16	Fri 12/9/16	1 day	26FS+3 days	100%
28		Engineering drawings	Tue 1/31/17	Wed 2/1/1	1 day		100%
29		Source materials	Wed 2/1/17	Sat 2/4/17	3 days	28	100%
30		BOM	Sat 2/4/17	Sun 2/5/17	1 day	29	100%
31		Budget	Sun 2/5/17	Mon 2/6/1	1 day	30	100%
32		Send materials request to Dr. Wang	Mon 2/6/17	Tue 2/7/17	1 day	31	100%
33		Purchase materials	Tue 2/7/17	Wed 2/8/1	1 day	79	100%
34		Shipping period	Wed 2/8/17	Mon 2/13/	5 days	33	100%
35		Shearing excess material off	Mon 2/13/17	Tue 2/14/1	1 day	34	100%
36		Welding sides to base	Tue 2/14/17	Wed 2/15/	1 day	35	100%
37		Final fixture measurement	Wed 2/15/17	Thu 2/16/1	1 day	36	100%
38		**Load Testing Fixture**	**Sun 12/11/16**	**Sat 2/25/1**	**53.33**		**100%**
39		Ideation session	Sun 12/11/16	Mon 12/12	1 day		100%
40		Create sketches	Mon 12/12/16	Tue 12/13/	1 day	39	100%
41		Weighted decision matrix	Tue 12/13/16	Wed 12/14	1 day	40	100%

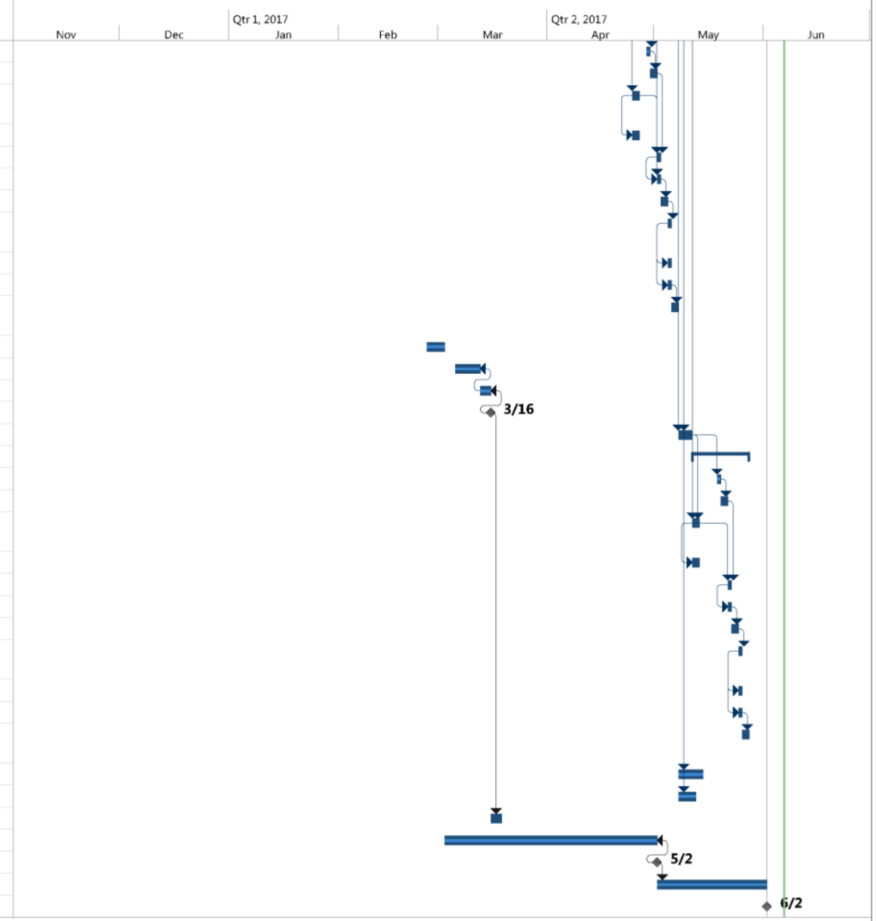
ID	Task Mode	Task Name	Start	Finish	Duration	Predecessors	% Complete
42	✓	Concept validation	Wed 12/14/16	Fri 12/16/1	2 days	41	100%
43	✓	CAD model creation	Fri 12/16/16	Sat 12/17/1	1 day	42	100%
44	✓	Winter break begins	Fri 12/16/16	Fri 12/16/1	0 days		100%
45	✓	Return from winter break	Mon 1/9/17	Mon 1/9/1	0 days		100%
46	✓	Engineering drawings	Mon 1/9/17	Wed 1/11/	2 days	43	100%
47	✓	Source materials	Wed 1/11/17	Thu 1/12/1	1 day	46	100%
48	✓	BOM	Mon 1/9/17	Tue 1/10/1	1 day	45	100%
49	✓	Budget	Tue 1/10/17	Wed 1/11/	1 day	48	100%
50	✓	Send materials request to Dr. Wang	Wed 1/11/17	Thu 1/12/1	1 day	49	100%
51	✓	Purchase materials	Tue 2/7/17	Wed 2/8/1	1 day	79	100%
52	✓	Shipping period	Wed 2/8/17	Mon 2/13/	5 days	51	100%
53	✓	Machining individual components	Mon 2/13/17	Mon 2/20/	7 days	52	100%
54	✓	Assembly	Mon 2/20/17	Wed 2/22/	2 days	53	100%
55	✓	Final fixture measurement	Wed 2/22/17	Sat 2/25/1	3 days	54	100%
56	✓	Curved beam in bending hand calcs	Sun 12/4/16	Tue 12/13/	9 days	18SS	100%
57	✓	Minimal band thickness calculation	Tue 1/17/17	Wed 1/18/	1.98 d		100%
58	✓	Thermal expansion equations	Sun 1/29/17	Fri 2/3/17	5 days		100%
59	✓	Create request for extrusion material	Sun 12/4/16	Tue 12/13/	9 days	18SS	100%
60	✓	Revise PDR report	Sun 12/4/16	Fri 12/16/1	12 day		100%
61	✓	Initial FMEA	Wed 11/30/16	Thu 12/1/1	1 day		100%
62	✓	Initial DVP Matrix	Wed 11/30/16	Thu 12/1/1	1 day	61SS	100%
63	✓	Initial Analysis plan	Wed 11/30/16	Thu 12/1/1	1 day	61SS	100%
64	✓	Final FMEA	Tue 12/6/16	Wed 12/7/	1 day		100%
65	✓	Final Analysis plan	Sun 12/4/16	Mon 12/5/	1 day	64	100%
66	✓	Final DVP Matrix	Mon 12/5/16	Tue 12/6/1	1 day	65	100%
67	✓	Develop total BOM	Sun 2/5/17	Mon 2/6/1	1 day	30,48	100%
68	✓	Complete detailed report outline	Tue 1/31/17	Fri 2/3/17	3 days		100%
69	✓	Cost analysis	Mon 2/6/17	Tue 2/7/17	1 day	67	100%
70	✓	Final CAD final joint design renders	Tue 1/31/17	Wed 2/1/1	1 day	68SS	100%
71	✓	Final CAD assembly fixture renders	Wed 2/1/17	Thu 2/2/17	1 day	70	100%
72	✓	Final CAD testing fixture renders	Thu 2/2/17	Fri 2/3/17	1 day	71	100%
73	✓	Write Geometry, Component Selection	Tue 1/31/17	Fri 2/3/17	3 days		100%
74	✓	Write Design For Mfg	Mon 10/31/16	Fri 11/4/1	4 days	75SF	100%
75	✓	Write Design For Safety	Fri 11/4/16	Tue 11/8/1	4 days		100%
76	✓	Practice Present and peer review	Sat 2/4/17	Tue 2/7/17	3 days	79SF	100%
77	✓	Presentation Storyboard	Tue 1/31/17	Sun 2/5/17	5 days	73SS	100%
78	✓	Writing information to slides	Sun 2/5/17	Tue 2/7/17	2 days	77,76SF	100%
79	✓	CDR	Tue 2/7/17	Tue 2/7/17	0 days		100%
80	✓	Review CDR feedback	Tue 2/7/17	Sun 3/19/1	40 day	79	100%
81	✓	Organize OneDrive folders	Thu 2/16/17	Thu 3/9/17	21 day		100%
82	✓	Adjust press fit calculations	Thu 2/23/17	Fri 2/24/17	1 day		100%



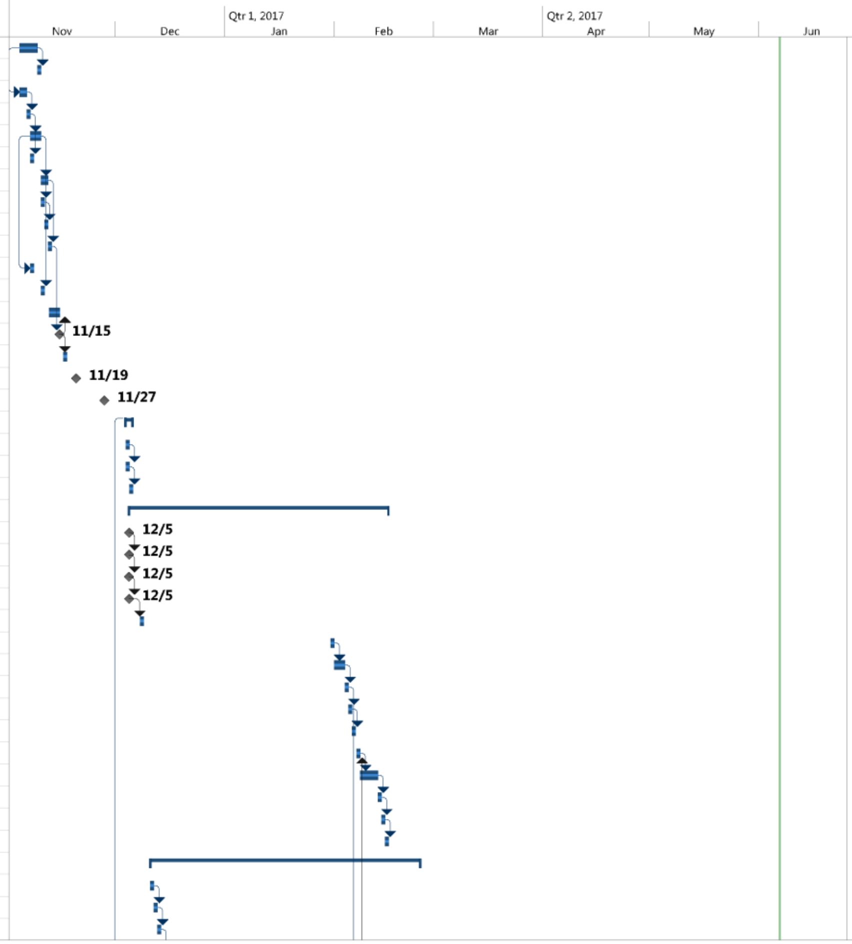
ID	Task Mode	Task Name	Start	Finish	Duratio	Predecessors	% Complete
83	✓	Create table for final dimensions + tolerances	Fri 2/24/17	Sat 2/25/17	1 day	82	100%
84	✓	Confirm purchasing with Stephen	Wed 2/22/17	Thu 2/23/1	1 day		100%
85		Compile owners manual	Fri 2/24/17	Fri 3/10/17	14 day		75%
86		Talk to shop tech about tooling	Thu 2/23/17	Fri 2/24/17	1 day		50%
87	✓	**Bands**	**Thu 2/23/17**	**Wed 4/5/1**	**27 day**		**100%**
88	✓	Email Penn Stainless	Thu 2/23/17	Sat 2/25/1	2 days		100%
89	✓	Create request to Wang for Bands	Thu 2/23/17	Mon 2/27/	4 days	88SS	100%
90	✓	Purchase band materials	Mon 2/27/17	Wed 3/15/	16 day	89	100%
91	✓	Shipping period	Wed 3/15/17	Wed 4/5/1	7 days	90	100%
92	✓	**Soft Jaws**	**Mon 2/27/17**	**Sun 4/23/1**	**41 day**		**100%**
93	✓	Finalize CAD	Mon 2/27/17	Tue 2/28/1	1 day		100%
94	✓	Create request to Wang for soft jaws	Tue 2/28/17	Wed 3/1/1	1 day	93	100%
95	✓	Drill pilot holes	Wed 4/19/17	Thu 4/20/1	1 day	115FS+33 d	100%
96	✓	Cut into 4 pieces	Wed 4/19/17	Thu 4/20/1	1 day	95SS	100%
97	✓	Mill pieces square	Thu 4/20/17	Fri 4/21/17	1 day	96	100%
98	✓	Drill counter bore holes for vise jaw bolts	Fri 4/21/17	Sat 4/22/1	1 day	97	100%
99	✓	Machine arc on rotary table	Sat 4/22/17	Sun 4/23/1	1 day	98	100%
100	✓	**Assembly Fixture**	**Thu 2/16/17**	**Sat 3/11/1**	**23 day**		**100%**
101	✓	Source materials for assembly fixture	Thu 2/16/17	Fri 2/17/17	1 day		100%
102	✓	Create request to Wang for assembly fixt	Fri 2/24/17	Sat 2/25/1	1 day	101	100%
103	✓	Shear metal	Thu 3/9/17	Fri 3/10/17	1 day	116FS+1 day	100%
104	✓	Weld sheared parts together	Fri 3/10/17	Sat 3/11/1	1 day	103	100%
105	✓	**Test Fixture**	**Thu 2/16/17**	**Thu 4/27/1**	**56 day**		**100%**
106	✓	Create CAD models for test fixture	Thu 2/16/17	Fri 2/17/17	1 day		100%
107	✓	Source materials for test fixture	Wed 2/22/17	Thu 2/23/1	1 day		100%
108	✓	Create request to Wang for test fixture	Thu 2/23/17	Fri 2/24/17	1 day	107	100%
109	✓	Turn cylinder	Thu 4/13/17	Mon 4/17/	4 days	115FS+27 d	100%
110	✓	Mill hemicylinders	Mon 4/17/17	Thu 4/20/1	3 days	109	100%
111	✓	Mill T blocks	Thu 4/20/17	Sun 4/23/1	3 days	110	100%
112	✓	Mill tabs	Sun 4/23/17	Wed 4/26/	3 days	111	100%
113	✓	Assemble test fixture	Wed 4/26/17	Thu 4/27/1	1 day	112	100%
114	✓	McMaster Order	Wed 3/1/17	Thu 3/2/17	1 day	108,102,94,	100%
115	✓	McMaster Shipping	Thu 3/2/17	Fri 3/3/17	1 day	114	100%
116	✓	Speedy Metals Shipping	Thu 3/2/17	Wed 3/8/1	6 days	115SS	100%
117		AM training on SLM 125HL	Mon 2/27/17	Tue 5/2/17	50 day		0%
118		**Test Part Joining process**	**Fri 3/10/17**	**Sun 5/7/1**	**44 day**		**70%**
119	✓	Step 1: Segmented part print at LLNL	Fri 3/10/17	Thu 4/20/1	27 day		100%
120	✓	Step 4: Cut part off build plate	Thu 4/20/17	Fri 4/21/17	1 day	119	100%
121	✓	Step 5: Heat Treatment at LLNL	Fri 4/21/17	Sat 4/22/1	1 day	120	100%
122	✓	Shipping from LLNL	Sat 4/22/17	Fri 4/28/17	6 days	121	100%



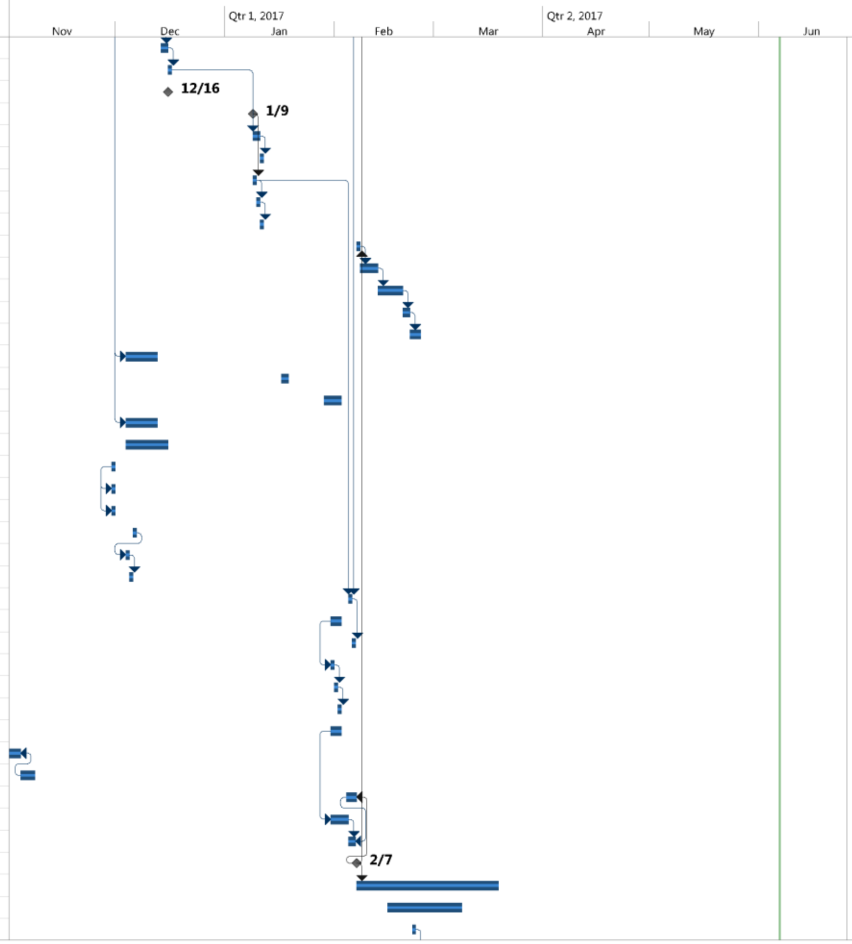
ID	Task Mode	Task Name	Start	Finish	Duration	Predecessors	% Complete
123		Step 6: Drill holes/machine/assemble	Fri 4/28/17	Sat 4/29/1'	1 day	122	75%
124		Step 7: Lathe outer shell clean	Sat 4/29/17	Mon 5/1/1	2 days	123	0%
125		Step 2: Lathe outer band ID to pre-HS dim	Tue 4/25/17	Thu 4/27/17	2 days	91FS+20 days	0%
126		Step 3: Lathe IB to pre-HS OD	Tue 4/25/17	Thu 4/27/1	2 days	125SS	0%
127		Step 8: Heat outer bands	Mon 5/1/17	Tue 5/2/17	1 day	125,124	0%
128		Step 9: Perform first heat shrink	Mon 5/1/17	Tue 5/2/17	1 day	127SS,104	0%
129		Step 10: Lathe inner shell	Tue 5/2/17	Thu 5/4/17	2 days	128	0%
130		Step 11: Heat printed parts and outer band	Thu 5/4/17	Fri 5/5/17	1 day	129	0%
131		Step 12: Cool inner band	Thu 5/4/17	Fri 5/5/17	1 day	130SS	0%
132		Step 13: Perform second HS	Thu 5/4/17	Fri 5/5/17	1 day	130SS	0%
133		Step 14: Lathe outer band to final OD and ID	Fri 5/5/17	Sun 5/7/17	2 days	132	0%
134	✓	Create safety checklist	Sun 2/26/17	Fri 3/3/17	5 days		100%
135	✓	**Update test plan**	Mon 3/6/17	Mon 3/13/	7 days	136SF	100%
136	✓	Practice Presentations and peer review	Mon 3/13/17	Thu 3/16/1	3 days	137SF	100%
137	✓	**Manufacturing and Test Review**	Thu 3/16/17	Thu 3/16/1	0 days		100%
138		Instron testing	Sun 5/7/17	Thu 5/11/1	4 days	118,113	0%
139		**Final Part Joining process**	**Thu 5/11/17**	**Sat 5/27/1**	**16 day**		**5%**
140		Step 6: Drill holes/machine/assemble	Thu 5/18/17	Fri 5/19/17	1 day	138FS+7 day	75%
141		Step 7: Lathe outer shell clean	Fri 5/19/17	Sun 5/21/1	2 days	140	0%
142		Step 2: Lathe outer band ID to pre-HS dim	Thu 5/11/17	Sat 5/13/17	2 days	91,138	0%
143		Step 3: Lathe IB to pre-HS OD	Thu 5/11/17	Sat 5/13/1'	2 days	142SS	0%
144		Step 8: Heat outer bands	Sun 5/21/17	Mon 5/22/	1 day	141,142	0%
145		Step 9: Perform first heat shrink	Sun 5/21/17	Mon 5/22/	1 day	144SS	0%
146		Step 10: Lathe inner shell	Mon 5/22/17	Wed 5/24/	2 days	145	0%
147		Step 11: Heat printed parts and outer band	Wed 5/24/17	Thu 5/25/17	1 day	146	0%
148		Step 12: Cool inner band	Wed 5/24/17	Thu 5/25/1	1 day	147SS	0%
149		Step 13: Perform second HS	Wed 5/24/17	Thu 5/25/1	1 day	147SS	0%
150		Step 14: Lathe outer band to final OD and ID	Thu 5/25/17	Sat 5/27/17	2 days	149	0%
151	✓	Compile owners manual	Sun 5/7/17	Sun 5/14/1	7 days	118	100%
152	✓	Edit owners manual	Sun 5/7/17	Fri 5/12/1	5 days	118	100%
153		Develop Instron testing schedule	Thu 3/16/17	Sun 3/19/1	3 days	137	0%
154	✓	**Practice Presentations and peer review**	Fri 3/3/17	Tue 5/2/17	46 day	155SF	100%
155	✓	**Hardware Safety Demo**	Tue 5/2/17	Tue 5/2/17	0 days		100%
156	✓	**Prep for Final Design Review**	Tue 5/2/17	Fri 6/2/17	31 day	155	100%
157	✓	**Final Design Review (Report & Expo)**	Fri 6/2/17	Fri 6/2/17	0 days		100%



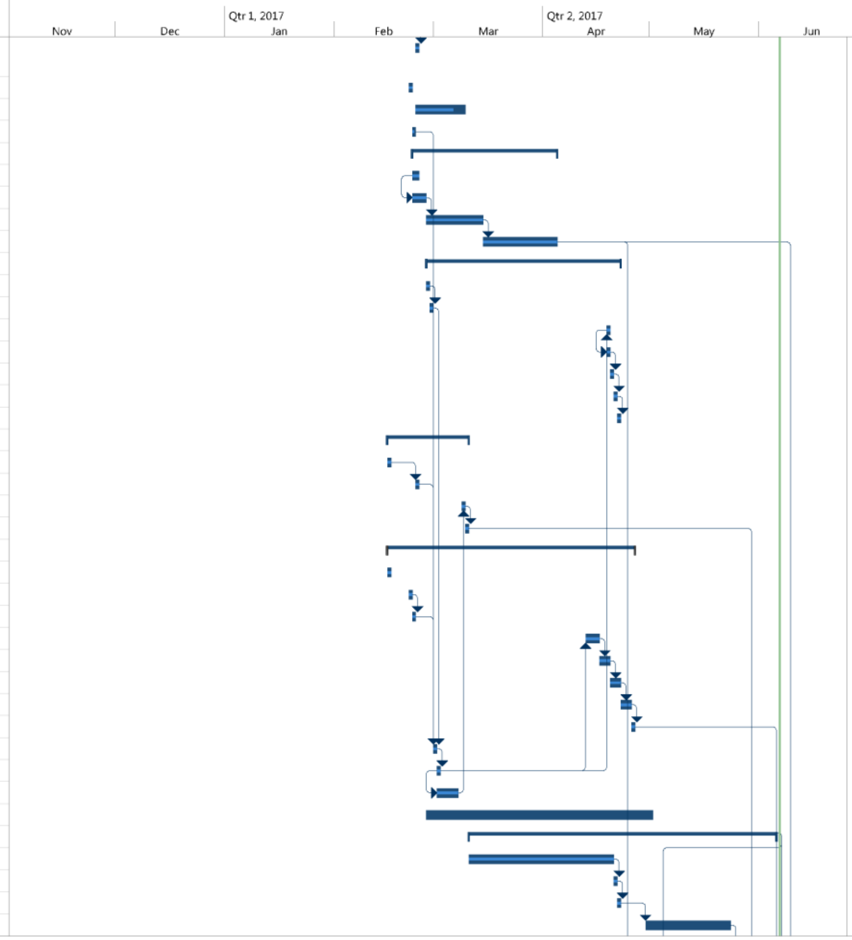
ID	Task Mode	Task Name	Start	Finish	Duration	Predecessors	% Complete
1	✓	Revise Project Proposal	Fri 11/4/16	Wed 11/9/	5 days		100%
2	✓	Send out Project Proposal	Wed 11/9/16	Thu 11/10/	1 day	1	100%
3	✓	Complete Pugh Matrix for Our Idea	Fri 11/4/16	Sun 11/6/1	2 days	1SS	100%
4	✓	Choose our Idea	Sun 11/6/16	Mon 11/7/	1 day	3	100%
5	✓	Make a CAD model	Mon 11/7/16	Thu 11/10/	3 days	4	100%
6	✓	Develop preliminary Budget	Mon 11/7/16	Tue 11/8/1	1 day	4	100%
7	✓	3d print our part	Thu 11/10/16	Sat 11/12/	2 days	5	100%
8	✓	First Prep Meeting	Thu 11/10/16	Fri 11/11/1	1 day	5	100%
9	✓	Check wardrobe	Fri 11/11/16	Sat 11/12/	1 day	8	100%
10	✓	Second Prep Meeting	Sat 11/12/16	Sun 11/13/	1 day	7	100%
11	✓	Writing session 1	Mon 11/7/16	Tue 11/8/1	1 day?	5SS	100%
12	✓	Writing session 2	Thu 11/10/16	Fri 11/11/1	1 day?	5	100%
13	✓	Practice Presentations	Sat 11/12/16	Tue 11/15/	3 days	14FS-3 days	100%
14	✓	PDR	Tue 11/15/16	Tue 11/15/	0 days	10	100%
15	✓	Refine CAD model	Wed 11/16/16	Thu 11/17/	1 day	14	100%
16	✓	Thanksgiving break starts	Sat 11/19/16	Sat 11/19/	0 days		100%
17	✓	Thanksgiving break ends	Sun 11/27/16	Sun 11/27/	0 days		100%
18	✓	**Create 3 3D models**	**Sun 12/4/16**	**Tue 12/6/1**	**2 days**		**100%**
19	✓	Finish CAD of 3 geometries	Sun 12/4/16	Mon 12/5/	1 day		100%
20	✓	Print 2 geometries	Sun 12/4/16	Mon 12/5/	1 day	19	100%
21	✓	Print 3rd geometry	Mon 12/5/16	Tue 12/6/1	1 day	20	100%
22	✓	**Heat Shrink Assembly Fixture**	**Mon 12/5/16**	**Thu 2/16/1**	**50.33 (**		**100%**
23	✓	Ideation session	Mon 12/5/16	Mon 12/5/	0 days		100%
24	✓	Create sketches	Mon 12/5/16	Mon 12/5/	0 days	23	100%
25	✓	Weighted decision matrix	Mon 12/5/16	Mon 12/5/	0 days	24	100%
26	✓	Concept validation	Mon 12/5/16	Mon 12/5/	0 days	25	100%
27	✓	CAD model creation	Thu 12/8/16	Fri 12/9/16	1 day	26FS+3 days	100%
28	✓	Engineering drawings	Tue 1/31/17	Wed 2/1/1	1 day		100%
29	✓	Source materials	Wed 2/1/17	Sat 2/4/17	3 days	28	100%
30	✓	BOM	Sat 2/4/17	Sun 2/5/17	1 day	29	100%
31	✓	Budget	Sun 2/5/17	Mon 2/6/1	1 day	30	100%
32	✓	Send materials request to Dr. Wang	Mon 2/6/17	Tue 2/7/17	1 day	31	100%
33	✓	Purchase materials	Tue 2/7/17	Wed 2/8/1	1 day	79	100%
34	✓	Shipping period	Wed 2/8/17	Mon 2/13/	5 days	33	100%
35	✓	Shearing excess material off	Mon 2/13/17	Tue 2/14/1	1 day	34	100%
36	✓	Welding sides to base	Tue 2/14/17	Wed 2/15/	1 day	35	100%
37	✓	Final fixture measurement	Wed 2/15/17	Thu 2/16/1	1 day	36	100%
38	✓	**Load Testing Fixture**	**Sun 12/11/16**	**Sat 2/25/1**	**53.33 (**		**100%**
39	✓	Ideation session	Sun 12/11/16	Mon 12/12/	1 day		100%
40	✓	Create sketches	Mon 12/12/16	Tue 12/13/	1 day	39	100%
41	✓	Weighted decision matrix	Tue 12/13/16	Wed 12/14/	1 day	40	100%



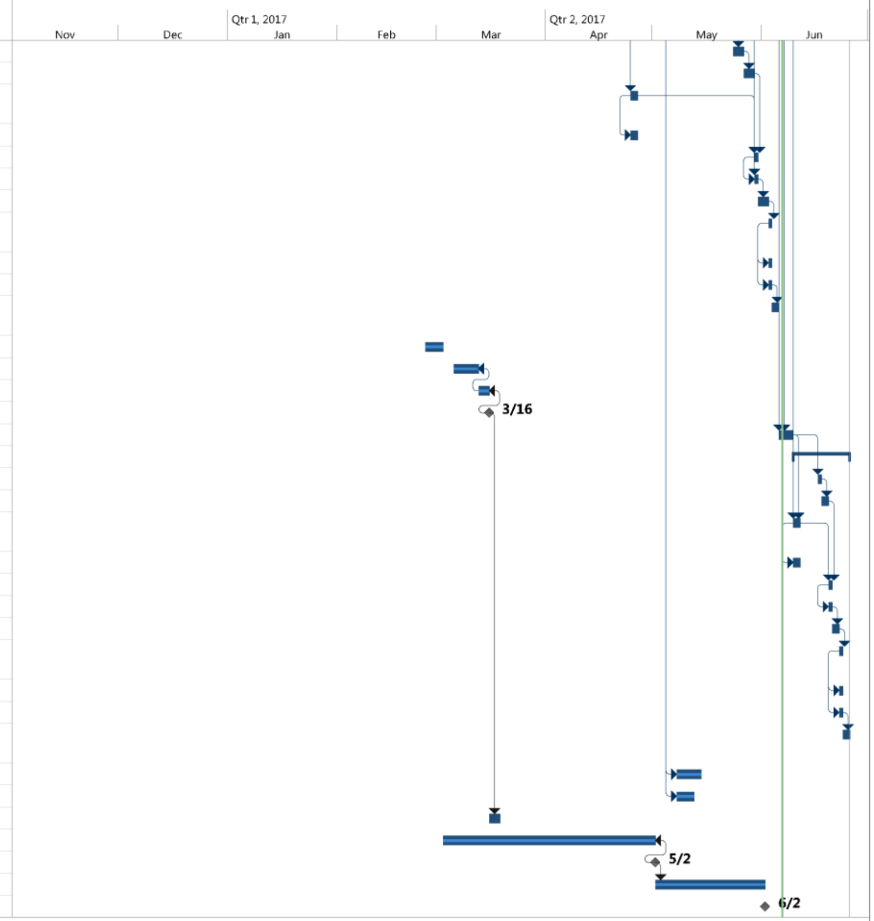
ID	Task Mode	Task Name	Start	Finish	Duration	Predecessors	% Complete
42	✓	Concept validation	Wed 12/14/16	Fri 12/16/1	2 days	41	100%
43	✓	CAD model creation	Fri 12/16/16	Sat 12/17/'	1 day	42	100%
44	✓	Winter break begins	Fri 12/16/16	Fri 12/16/1	0 days		100%
45	✓	Return from winter break	Mon 1/9/17	Mon 1/9/1	0 days		100%
46	✓	Engineering drawings	Mon 1/9/17	Wed 1/11/	2 days	43	100%
47	✓	Source materials	Wed 1/11/17	Thu 1/12/1	1 day	46	100%
48	✓	BOM	Mon 1/9/17	Tue 1/10/1	1 day	45	100%
49	✓	Budget	Tue 1/10/17	Wed 1/11/	1 day	48	100%
50	✓	Send materials request to Dr. Wang	Wed 1/11/17	Thu 1/12/1	1 day	49	100%
51	✓	Purchase materials	Tue 2/7/17	Wed 2/8/1	1 day	79	100%
52	✓	Shipping period	Wed 2/8/17	Mon 2/13/	5 days	51	100%
53	✓	Machining individual components	Mon 2/13/17	Mon 2/20/	7 days	52	100%
54	✓	Assembly	Mon 2/20/17	Wed 2/22/	2 days	53	100%
55	✓	Final fixture measurement	Wed 2/22/17	Sat 2/25/1'	3 days	54	100%
56	✓	Curved beam in bending hand calcs	Sun 12/4/16	Tue 12/13/	9 days	18SS	100%
57	✓	Minimal band thickness calculation	Tue 1/17/17	Wed 1/18/	1.98 d		100%
58	✓	Thermal expansion equations	Sun 1/29/17	Fri 2/3/17	5 days		100%
59	✓	Create request for extrusion material	Sun 12/4/16	Tue 12/13/	9 days	18SS	100%
60	✓	Revise PDR report	Sun 12/4/16	Fri 12/16/1	12 day		100%
61	✓	Initial FMEA	Wed 11/30/16	Thu 12/1/1	1 day		100%
62	✓	Initial DVP Matrix	Wed 11/30/16	Thu 12/1/1	1 day	61SS	100%
63	✓	Initial Analysis plan	Wed 11/30/16	Thu 12/1/1	1 day	61SS	100%
64	✓	Final FMEA	Tue 12/6/16	Wed 12/7/	1 day		100%
65	✓	Final Analysis plan	Sun 12/4/16	Mon 12/5/	1 day	64	100%
66	✓	Final DVP Matrix	Mon 12/5/16	Tue 12/6/1	1 day	65	100%
67	✓	Develop total BOM	Sun 2/5/17	Mon 2/6/1	1 day	30,48	100%
68	✓	Complete detailed report outline	Tue 1/31/17	Fri 2/3/17	3 days		100%
69	✓	Cost analysis	Mon 2/6/17	Tue 2/7/17	1 day	67	100%
70	✓	Final CAD final joint design renders	Tue 1/31/17	Wed 2/1/1	1 day	68SS	100%
71	✓	Final CAD assembly fixture renders	Wed 2/1/17	Thu 2/2/17	1 day	70	100%
72	✓	Final CAD testing fixture renders	Thu 2/2/17	Fri 2/3/17	1 day	71	100%
73	✓	Write Geometry, Component Selection	Tue 1/31/17	Fri 2/3/17	3 days		100%
74	✓	Write Design For Mfg	Mon 10/31/16	Fri 11/4/1	4 days	75SF	100%
75	✓	Write Design For Safety	Fri 11/4/16	Tue 11/8/1	4 days		100%
76	✓	Practice Present and peer review	Sat 2/4/17	Tue 2/7/17	3 days	79SF	100%
77	✓	Presentation Storyboard	Tue 1/31/17	Sun 2/5/17	5 days	73SS	100%
78	✓	Writing information to slides	Sun 2/5/17	Tue 2/7/17	2 days	77,76SF	100%
79	✓	**CDR**	Tue 2/7/17	Tue 2/7/17	0 days		100%
80	✓	Review CDR feedback	Tue 2/7/17	Sun 3/19/1	40 day	79	100%
81	✓	Organize OneDrive folders	Thu 2/16/17	Thu 3/9/17	21 day		100%
82	✓	Adjust press fit calculations	Thu 2/23/17	Fri 2/24/17	1 day		100%



ID	Task Mode	Task Name	Start	Finish	Duration	Predecessors	% Complete
83		Create table for final dimensions + tolerances	Fri 2/24/17	Sat 2/25/17	1 day	82	100%
84		Confirm purchasing with Stephen	Wed 2/22/17	Thu 2/23/1	1 day		100%
85		Compile owners manual	Fri 2/24/17	Fri 3/10/17	14 day		75%
86		Talk to shop tech about tooling	Thu 2/23/17	Fri 2/24/17	1 day		50%
87		**Bands**	**Thu 2/23/17**	**Wed 4/5/1**	**27 day**		**100%**
88		Email Penn Stainless	Thu 2/23/17	Sat 2/25/1	2 days		100%
89		Create request to Wang for Bands	Thu 2/23/17	Mon 2/27/	4 days	88SS	100%
90		Purchase band materials	Mon 2/27/17	Wed 3/15/	16 day	89	100%
91		Shipping period	Wed 3/15/17	Wed 4/5/1	7 days	90	100%
92		**Soft Jaws**	**Mon 2/27/17**	**Sun 4/23/1**	**41 day**		**100%**
93		Finalize CAD	Mon 2/27/17	Tue 2/28/1	1 day		100%
94		Create request to Wang for soft jaws	Tue 2/28/17	Wed 3/1/1	1 day	93	100%
95		Drill pilot holes	Wed 4/19/17	Thu 4/20/1	1 day	115FS+33 d	100%
96		Cut into 4 pieces	Wed 4/19/17	Thu 4/20/1	1 day	95SS	100%
97		Mill pieces square	Thu 4/20/17	Fri 4/21/17	1 day	96	100%
98		Drill counter bore holes for vise jaw bolts	Fri 4/21/17	Sat 4/22/1	1 day	97	100%
99		Machine arc on rotary table	Sat 4/22/17	Sun 4/23/1	1 day	98	100%
100		**Assembly Fixture**	**Thu 2/16/17**	**Sat 3/11/1**	**23 day**		**100%**
101		Source materials for assembly fixture	Thu 2/16/17	Fri 2/17/17	1 day		100%
102		Create request to Wang for assembly fixt	Fri 2/24/17	Sat 2/25/1	1 day	101	100%
103		Shear metal	Thu 3/9/17	Fri 3/10/17	1 day	116FS+1 day	100%
104		Weld sheared parts together	Fri 3/10/17	Sat 3/11/1	1 day	103	100%
105		**Test Fixture**	**Thu 2/16/17**	**Thu 4/27/1**	**56 day**		**100%**
106		Create CAD models for test fixture	Thu 2/16/17	Fri 2/17/17	1 day		100%
107		Source materials for test fixture	Wed 2/22/17	Thu 2/23/1	1 day		100%
108		Create request to Wang for test fixture	Thu 2/23/17	Fri 2/24/17	1 day	107	100%
109		Turn cylinder	Thu 4/13/17	Mon 4/17/	4 days	115FS+27 d	100%
110		Mill hemicylinders	Mon 4/17/17	Thu 4/20/1	3 days	109	100%
111		Mill T blocks	Thu 4/20/17	Sun 4/23/1	3 days	110	100%
112		Mill tabs	Sun 4/23/17	Wed 4/26/	3 days	111	100%
113		Assemble test fixture	Wed 4/26/17	Thu 4/27/1	1 day	112	100%
114		McMaster Order	Wed 3/1/17	Thu 3/2/17	1 day	108,102,94,	100%
115		McMaster Shipping	Thu 3/2/17	Fri 3/3/17	1 day	114	100%
116		Speedy Metals Shipping	Thu 3/2/17	Wed 3/8/1	6 days	115SS	100%
117		AM training on SLM 125HL	Mon 2/27/17	Tue 5/2/17	50 day		0%
118		**Test Part Joining process**	**Fri 3/10/17**	**Mon 6/5/17**	**73 day**		**40%**
119		Step 1: Segmented part print at LLNL	Fri 3/10/17	Thu 4/20/1	27 day		100%
120		Step 4: Cut part off build plate	Thu 4/20/17	Fri 4/21/17	1 day	119	100%
121		Step 5: Heat Treatment at LLNL	Fri 4/21/17	Sat 4/22/1	1 day	120	100%
122		Shipping from LLNL	Sat 4/29/17	Tue 5/23/1	24 day	121	0%



ID	Task Mode	Task Name	Start	Finish	Duration	Predecessors	% Complete
123		Step 6: Drill holes/machine/assemble	Tue 5/23/17	Fri 5/26/17	3 days	122	0%
124		Step 7: Lathe outer shell clean	Fri 5/26/17	Mon 5/29/	3 days	123	0%
125		Step 2: Lathe outer band ID to pre-HS dim	Tue 4/25/17	Thu 4/27/17	2 days	91FS+20 days	0%
126		Step 3: Lathe IB to pre-HS OD	Tue 4/25/17	Thu 4/27/1	2 days	125SS	0%
127		Step 8: Heat outer bands	Mon 5/29/17	Tue 5/30/1	1 day	125,124	0%
128		Step 9: Perform first heat shrink	Mon 5/29/17	Tue 5/30/1	1 day	127SS,104	0%
129		Step 10: Lathe inner shell	Tue 5/30/17	Fri 6/2/17	3 days	128	0%
130		Step 11: Heat printed parts and outer band	Fri 6/2/17	Sat 6/3/17	1 day	129	0%
131		Step 12: Cool inner band	Fri 6/2/17	Sat 6/3/17	1 day	130SS	0%
132		Step 13: Perform second HS	Fri 6/2/17	Sat 6/3/17	1 day	130SS	0%
133		Step 14: Lathe outer band to final OD and ID	Sat 6/3/17	Mon 6/5/17	2 days	132	0%
134	✓	Create safety checklist	Sun 2/26/17	Fri 3/3/17	5 days		100%
135	✓	**Update test plan**	Mon 3/6/17	Mon 3/13/	7 days	136SF	100%
136	✓	Practice Presentations and peer review	Mon 3/13/17	Thu 3/16/1	3 days	137SF	100%
137	✓	**Manufacturing and Test Review**	Thu 3/16/17	Thu 3/16/1	0 days		100%
138		Instron testing	Mon 6/5/17	Fri 6/9/17	4 days	118,113	0%
139		**Final Part Joining process**	**Fri 6/9/17**	**Sun 6/25/1**	**16 day**		**0%**
140		Step 6: Drill holes/machine/assemble	Fri 6/16/17	Sat 6/17/1	1 day	138FS+7 day	0%
141		Step 7: Lathe outer shell clean	Sat 6/17/17	Mon 6/19/	2 days	140	0%
142		Step 2: Lathe outer band ID to pre-HS dim	Fri 6/9/17	Sun 6/11/17	2 days	91,138	0%
143		Step 3: Lathe IB to pre-HS OD	Fri 6/9/17	Sun 6/11/1	2 days	142SS	0%
144		Step 8: Heat outer bands	Mon 6/19/17	Tue 6/20/1	1 day	141,142	0%
145		Step 9: Perform first heat shrink	Mon 6/19/17	Tue 6/20/1	1 day	144SS	0%
146		Step 10: Lathe inner shell	Tue 6/20/17	Thu 6/22/1	2 days	145	0%
147		Step 11: Heat printed parts and outer band	Thu 6/22/17	Fri 6/23/17	1 day	146	0%
148		Step 12: Cool inner band	Thu 6/22/17	Fri 6/23/17	1 day	147SS	0%
149		Step 13: Perform second HS	Thu 6/22/17	Fri 6/23/17	1 day	147SS	0%
150		Step 14: Lathe outer band to final OD and ID	Fri 6/23/17	Sun 6/25/17	2 days	149	0%
151	✓	Compile owners manual	Sun 5/7/17	Sun 5/14/1	7 days	118	100%
152	✓	Edit owners manual	Sun 5/7/17	Fri 5/12/17	5 days	118	100%
153		Develop Instron testing schedule	Thu 3/16/17	Sun 3/19/1	3 days	137	0%
154	✓	**Practice Presentations and peer review**	Fri 3/3/17	Tue 5/2/17	46 day	155SF	100%
155	✓	**Hardware Safety Demo**	Tue 5/2/17	Tue 5/2/17	0 days		100%
156	✓	**Prep for Final Design Review**	Tue 5/2/17	Fri 6/2/17	31 day	155	100%
157	✓	**Final Design Review (Report & Expo)**	Fri 6/2/17	Fri 6/2/17	0 days		100%



Appendix 8: Drawing List and Part Drawings

100 – Final Part Assembly
- **110** – Final Print Segment
- **120** – Hex Bolt Data Sheet
- **130** – Outer Shell Heat Shrink Band
- **140** – Inner Shell Heat Shrink Band

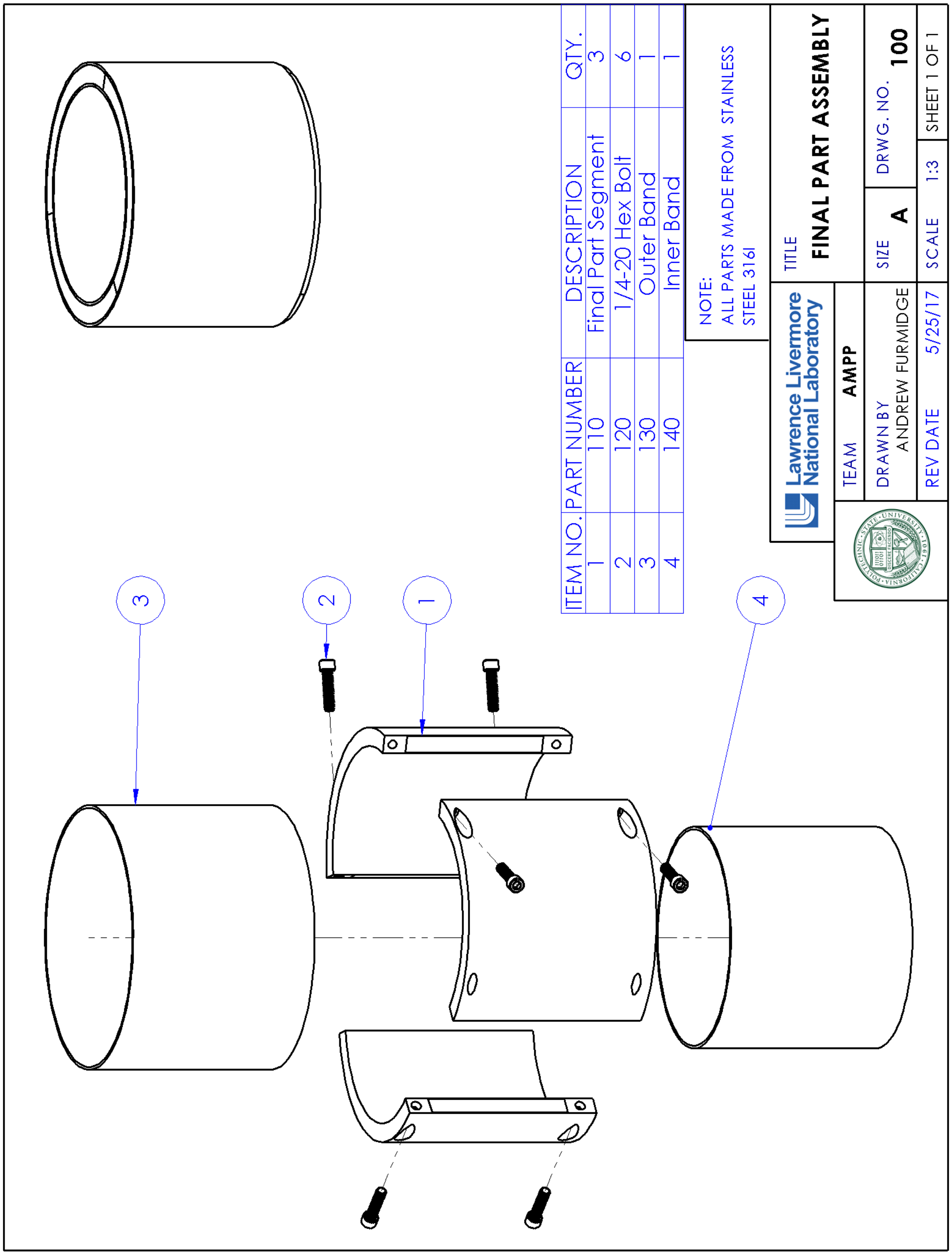
200 – Total Test Part Assembly
- **210** – Large Outer Band
- **220** – Nominal Outer Band
- **230** – Small Outer Band
- **240** – Large Inner Band
- **250** – Nominal Inner Band
- **260** – Small Inner Band
- **270** – Test Part
- **280** – Hex Bolt Data Sheet

300 – Assembly Fixture
- **310** – Assembly Fixture Base
- **320** – Assembly Fixture Walls

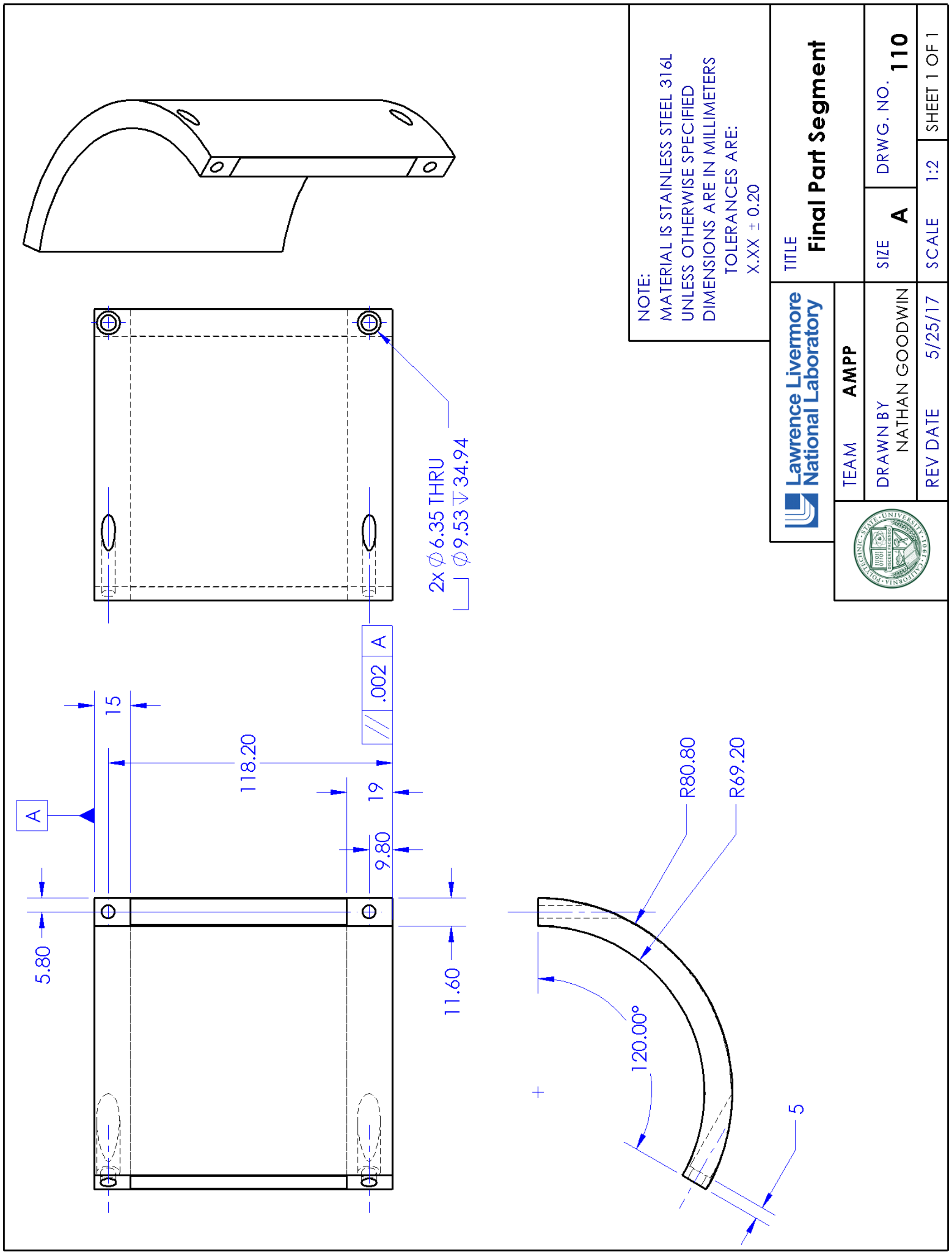
400 – Soft Jaw Assembly
- **410** – Soft Jaw – L
- **420** – Soft Jaw – R
- **430** – Soft Jaw End
- **440** – Hex Bolt Data Sheet

500 – Testing Fixture
- **510** – Test Fixture Side Arms
- **520** – Hemi-cylinder
- **530** – Instron Clamp
- **540** – Hex Bolt Data Sheet
- **550** – Hex Nut Data Sheet

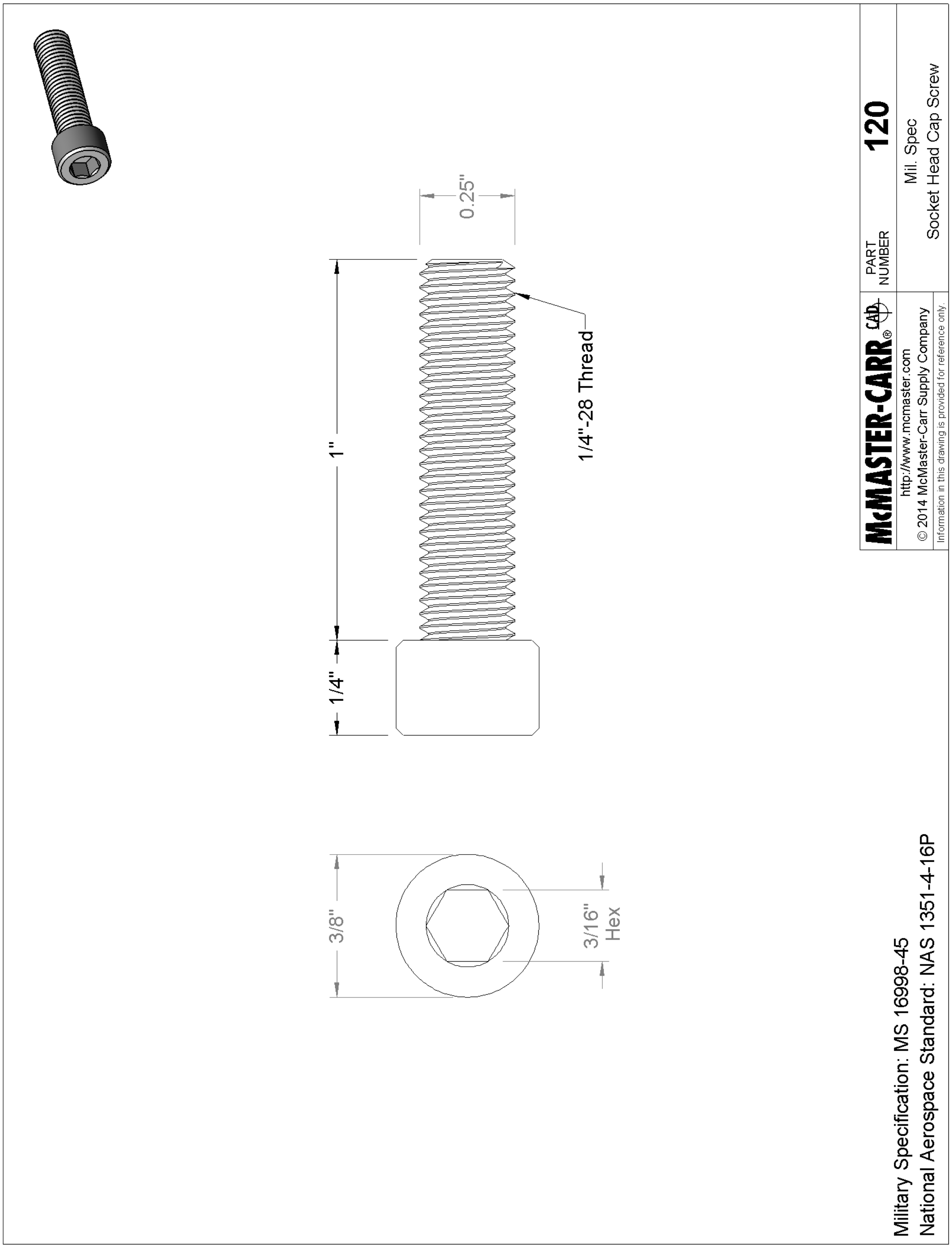
100 – Final Part Assembly



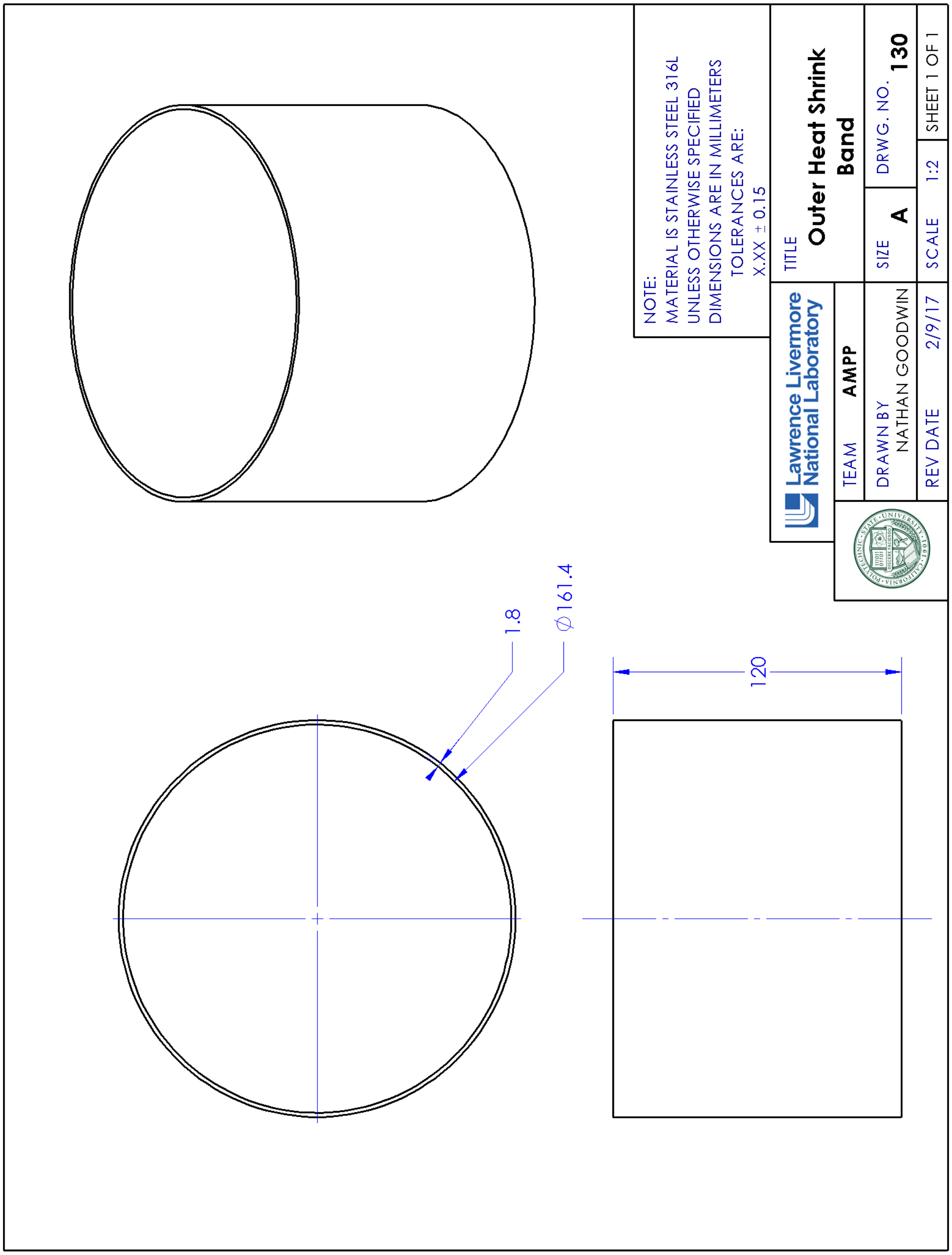
110 – Final Part Segment



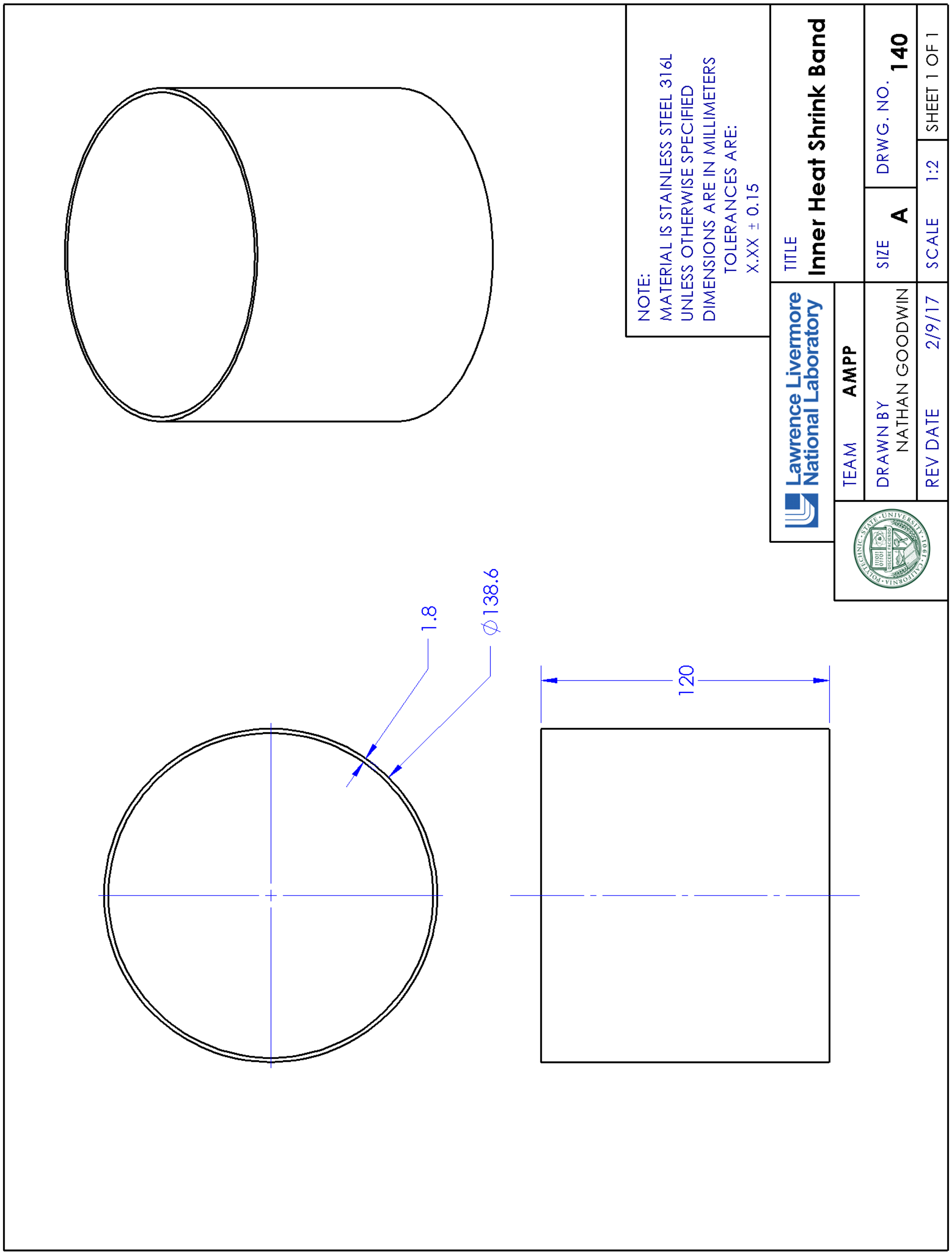
120 – Hex Bolt Data Sheet



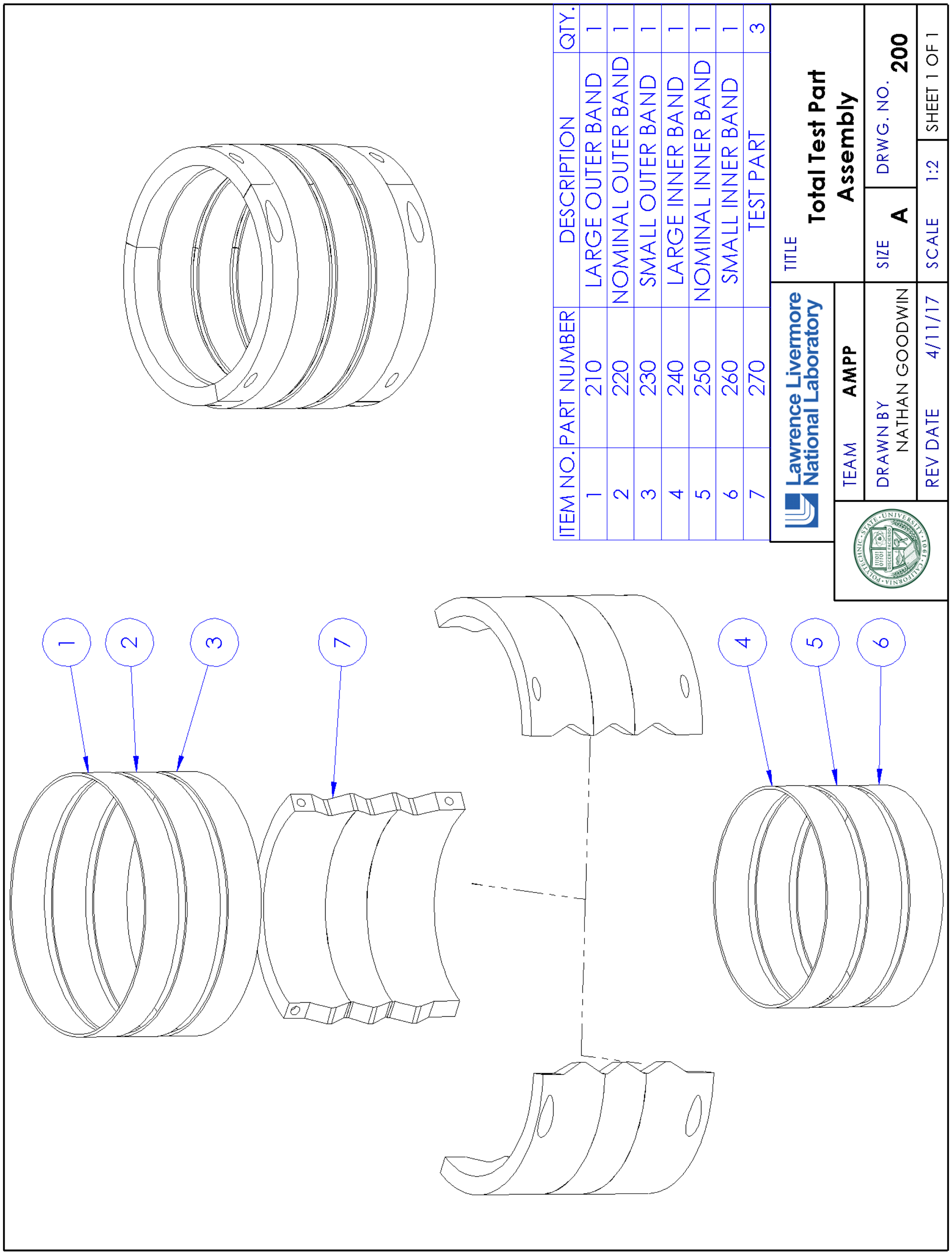
130 – Outer Heat Shrink Band



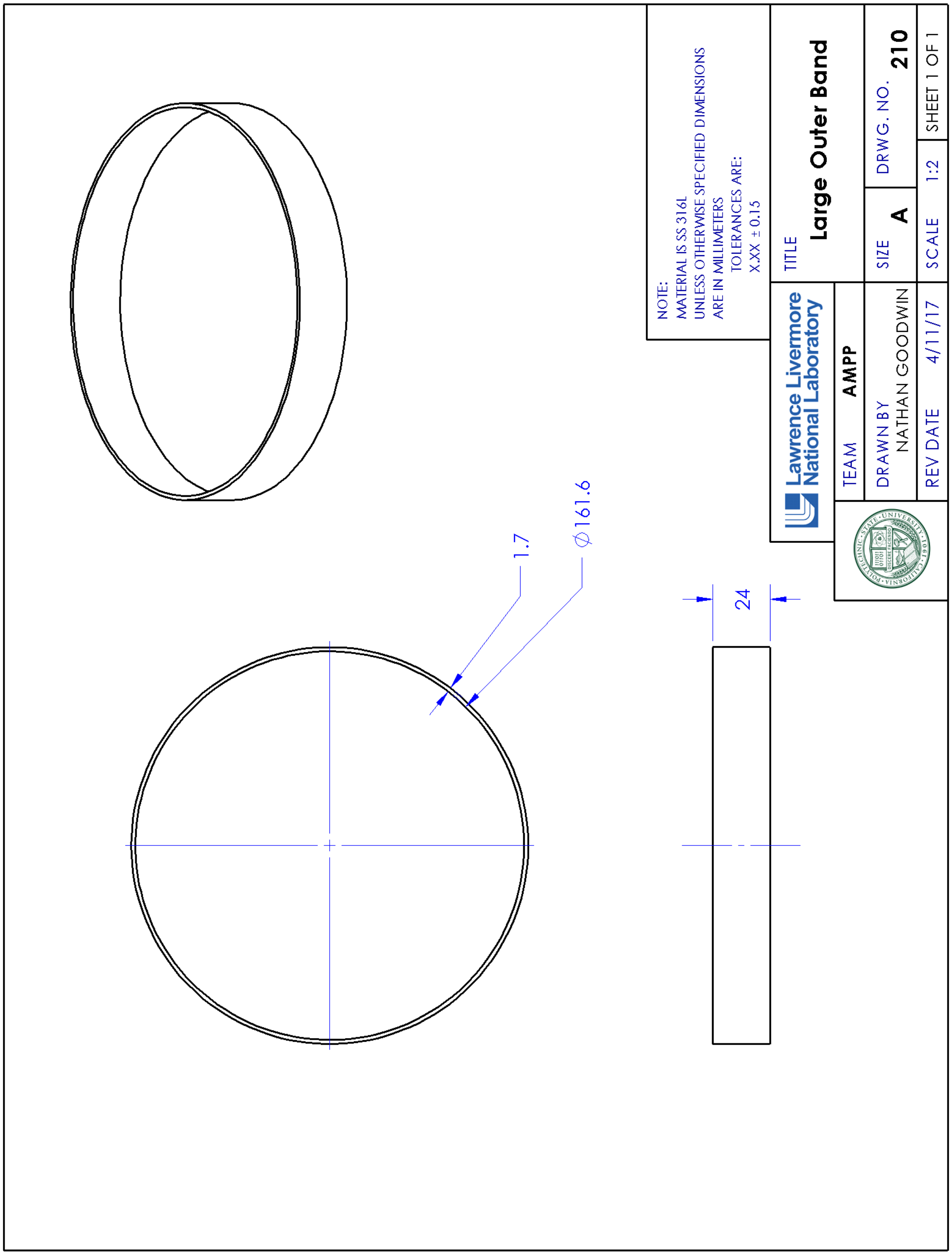
140 – Inner Heat Shrink Band



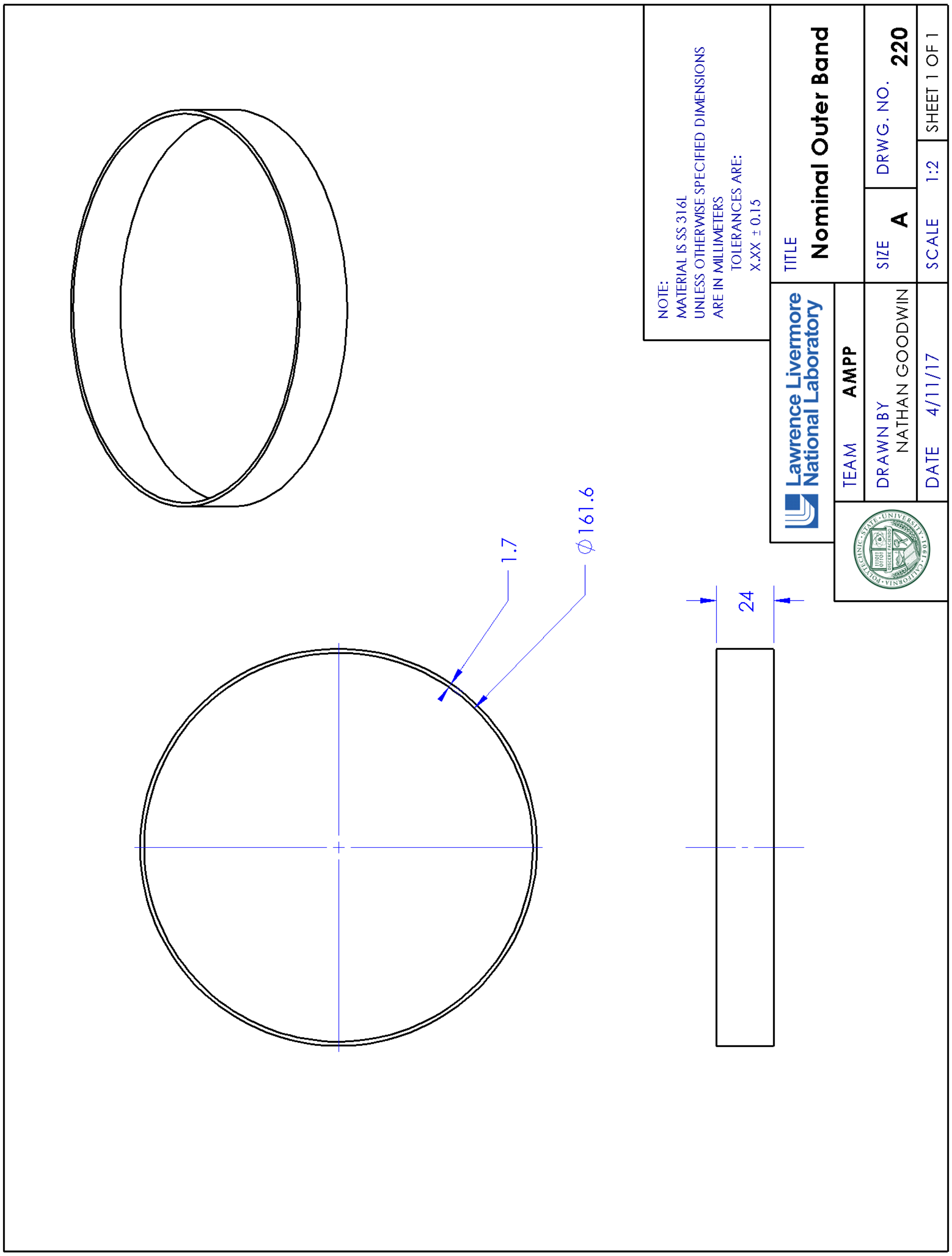
200 – Total Test Part Assembly



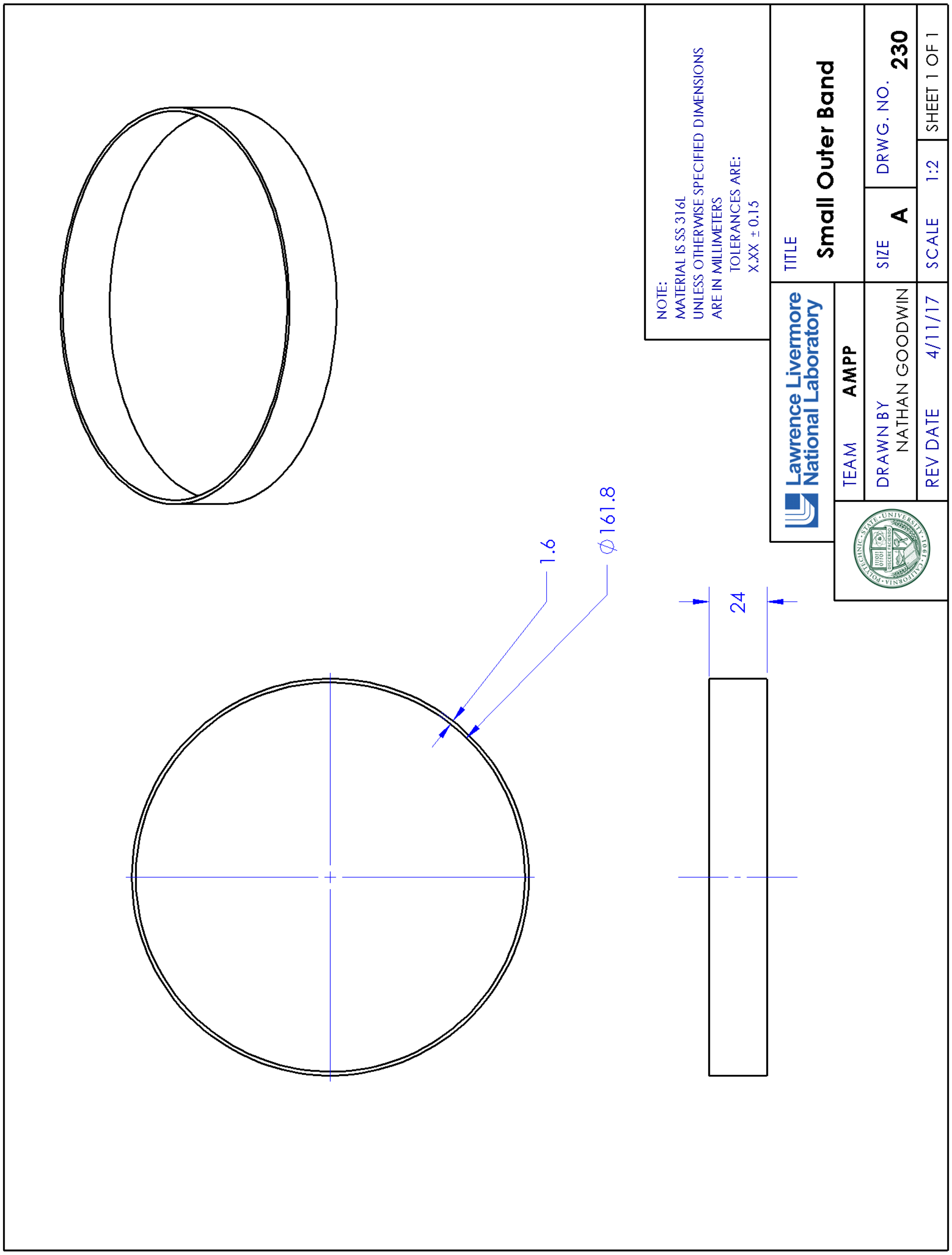
210 – Large Outer Band



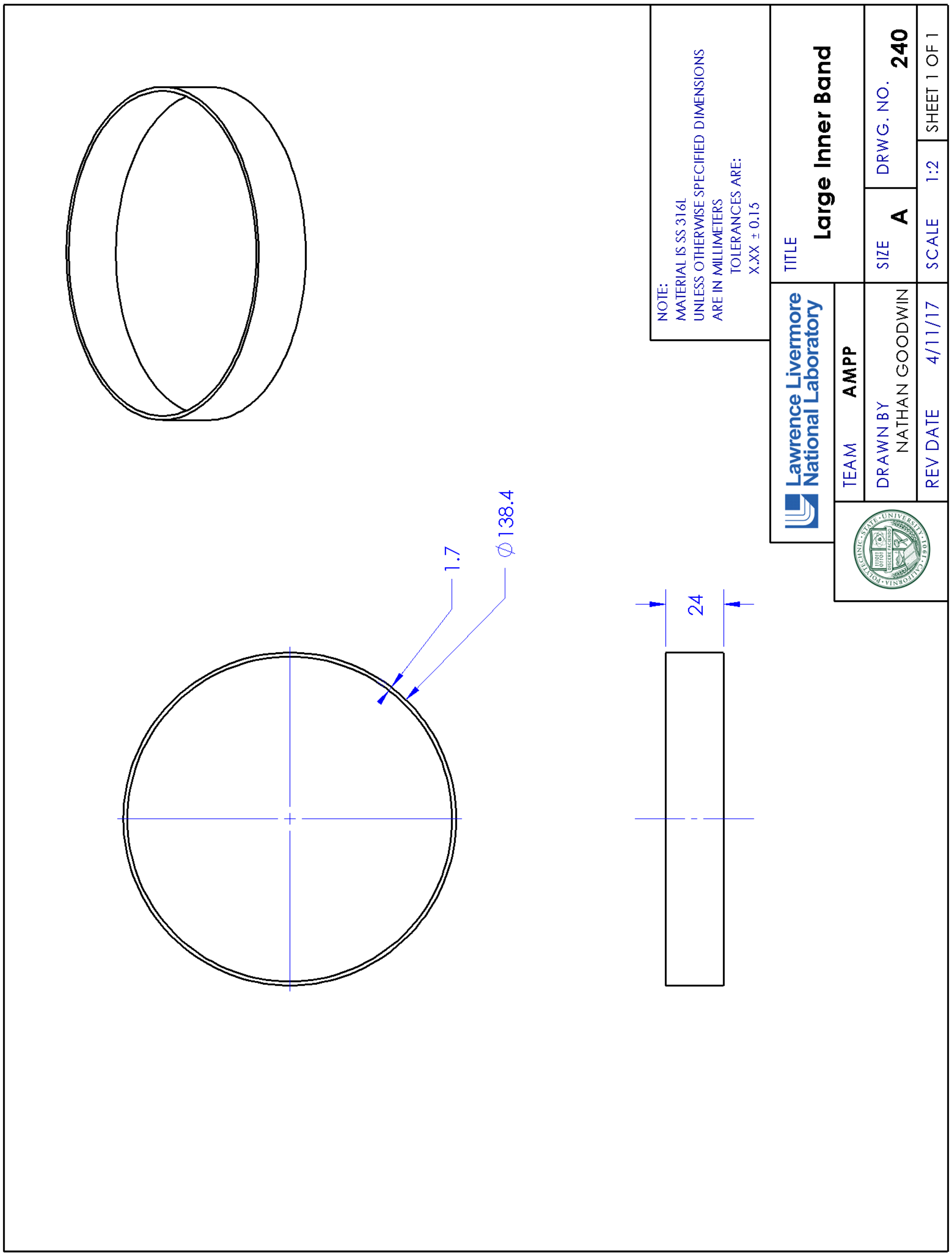
220 – Nominal Outer Band



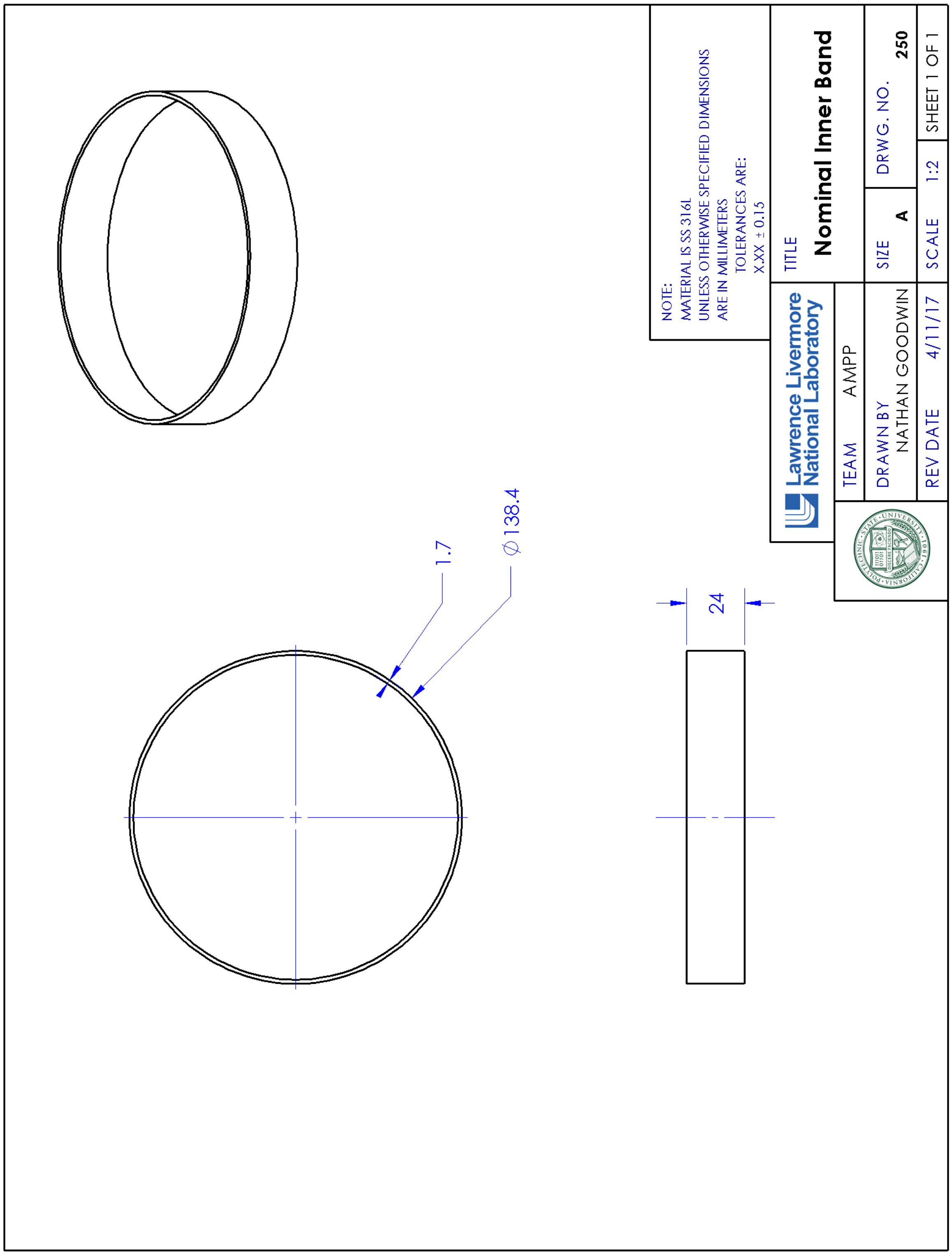
230 – Small Outer Band



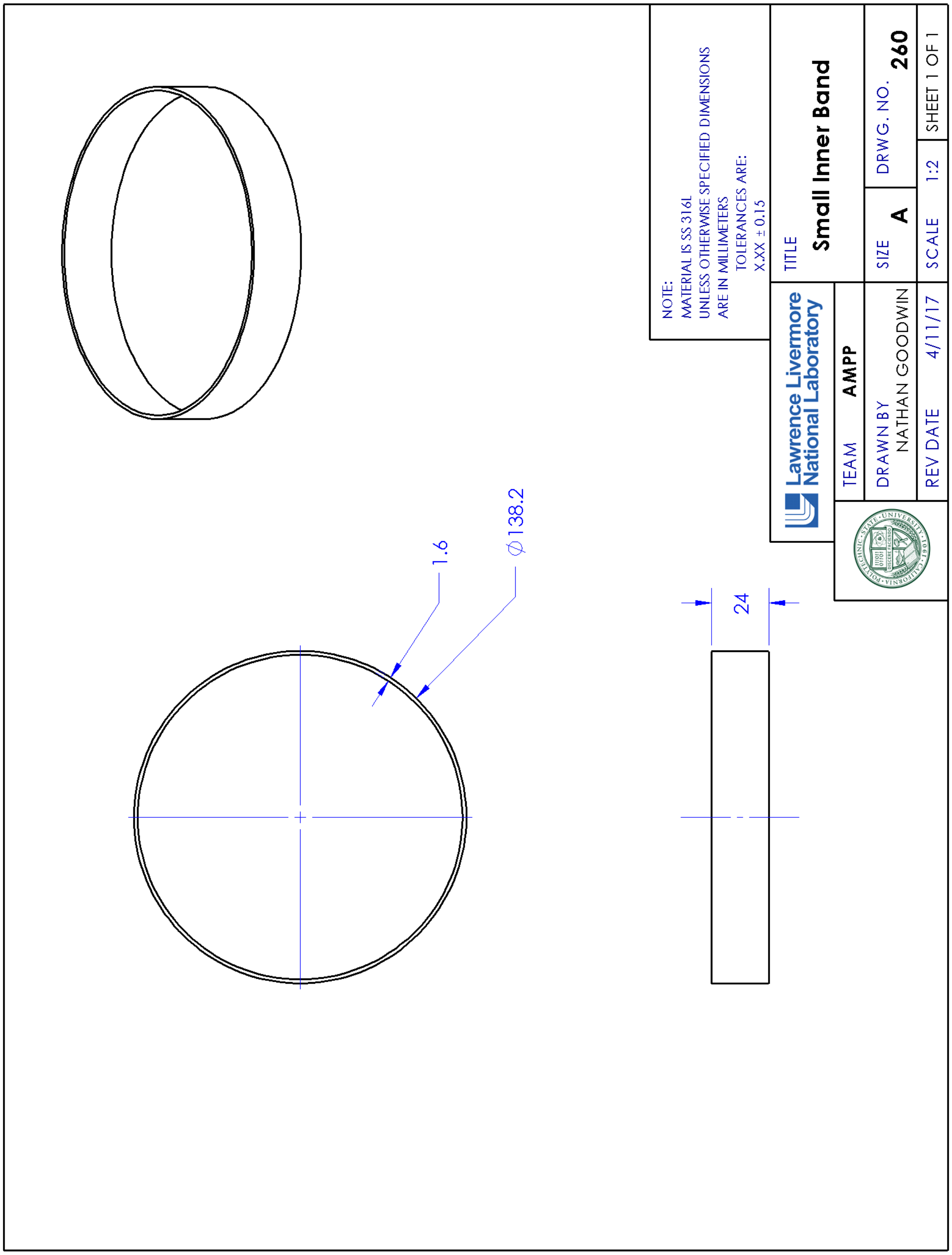
240 – Large Inner Band



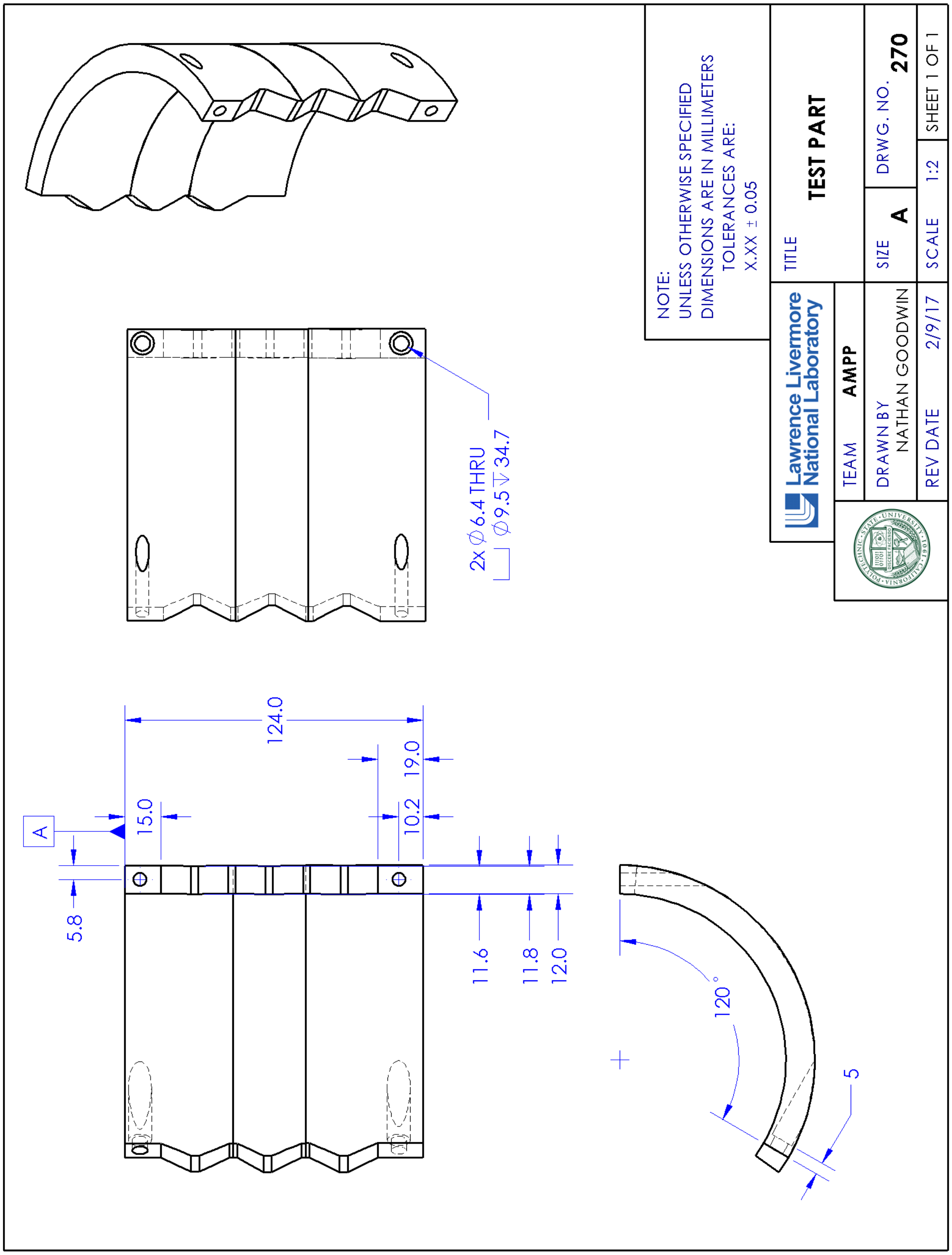
250 – Nominal Inner Band



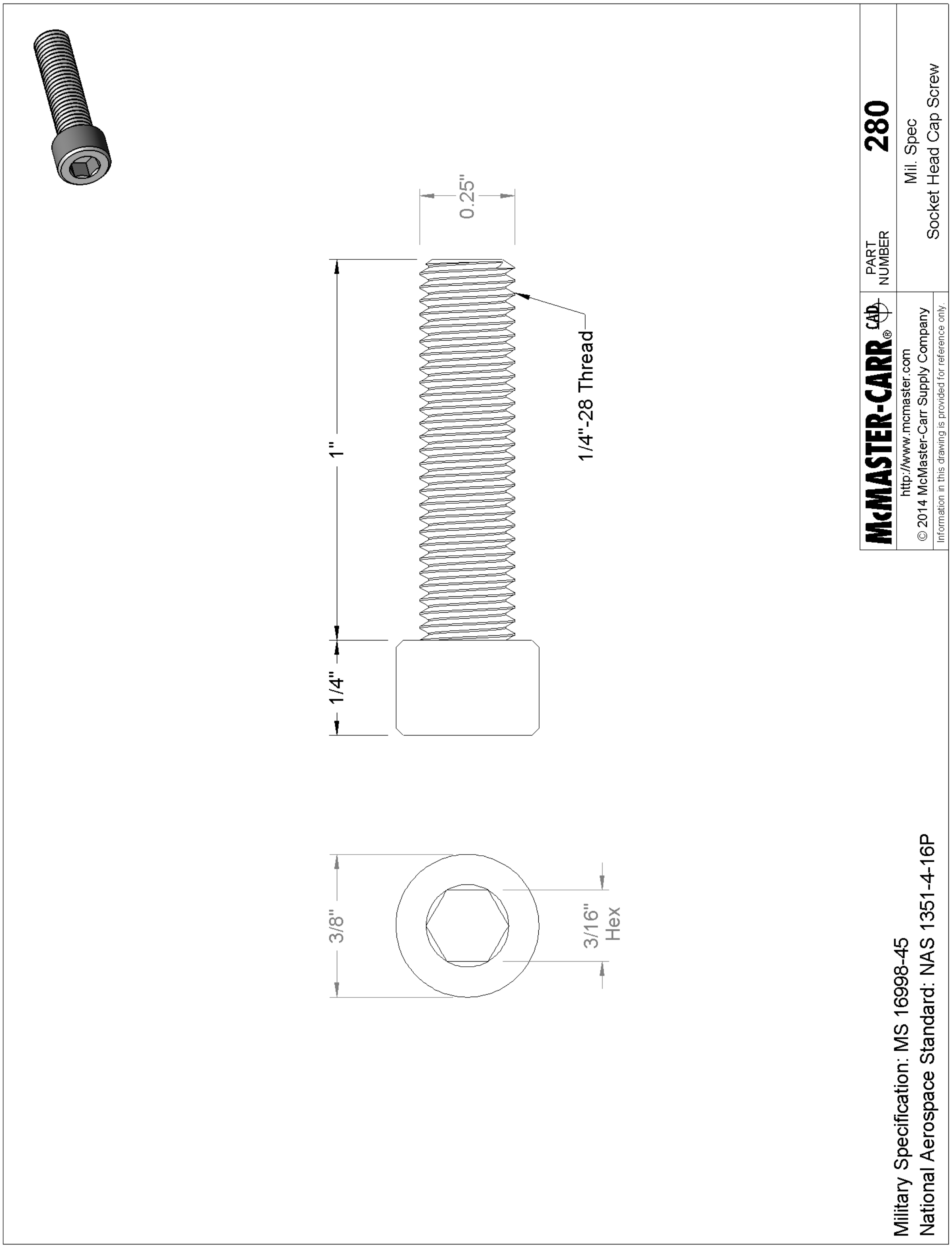
260 – Small Inner Band



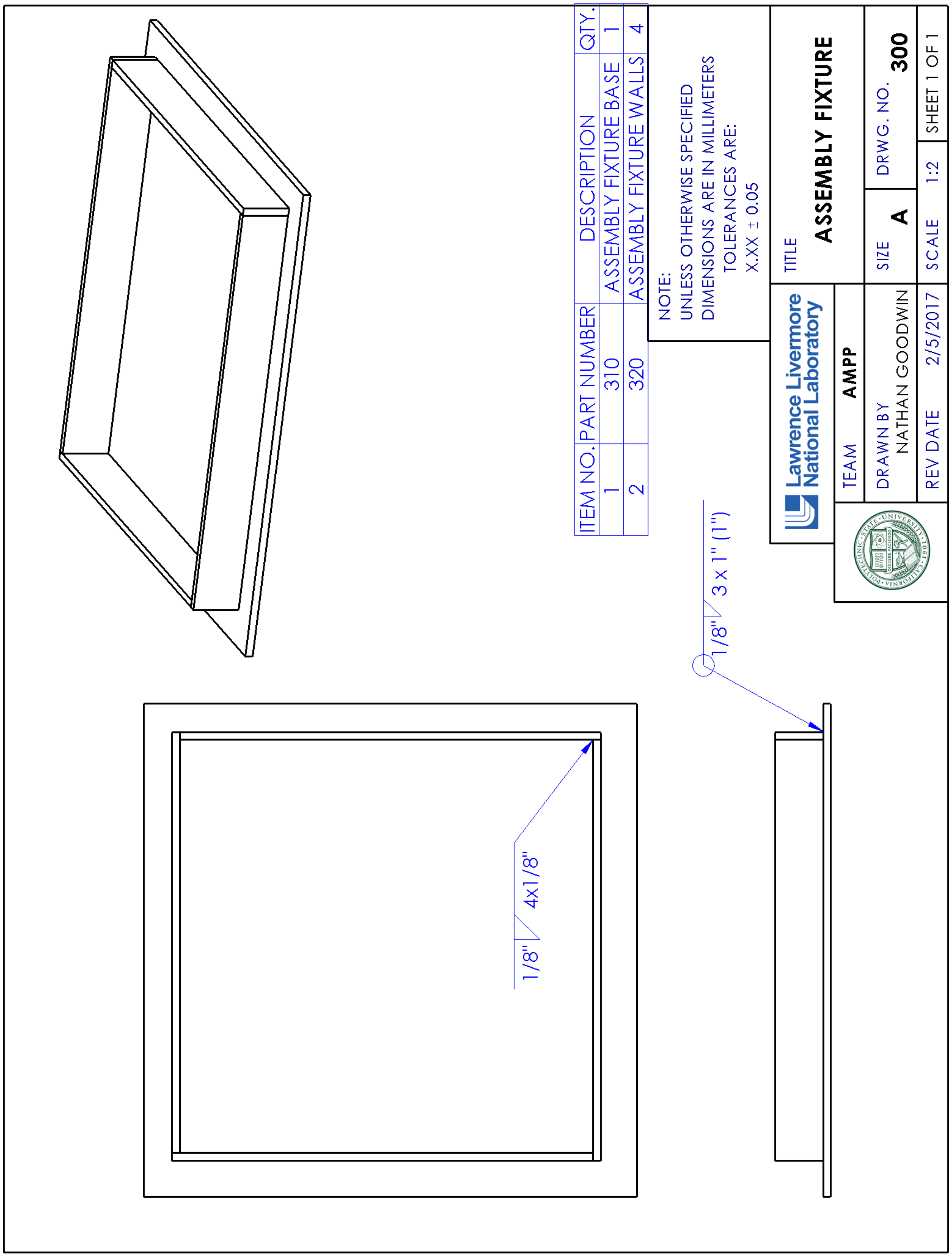
270 – Test Part



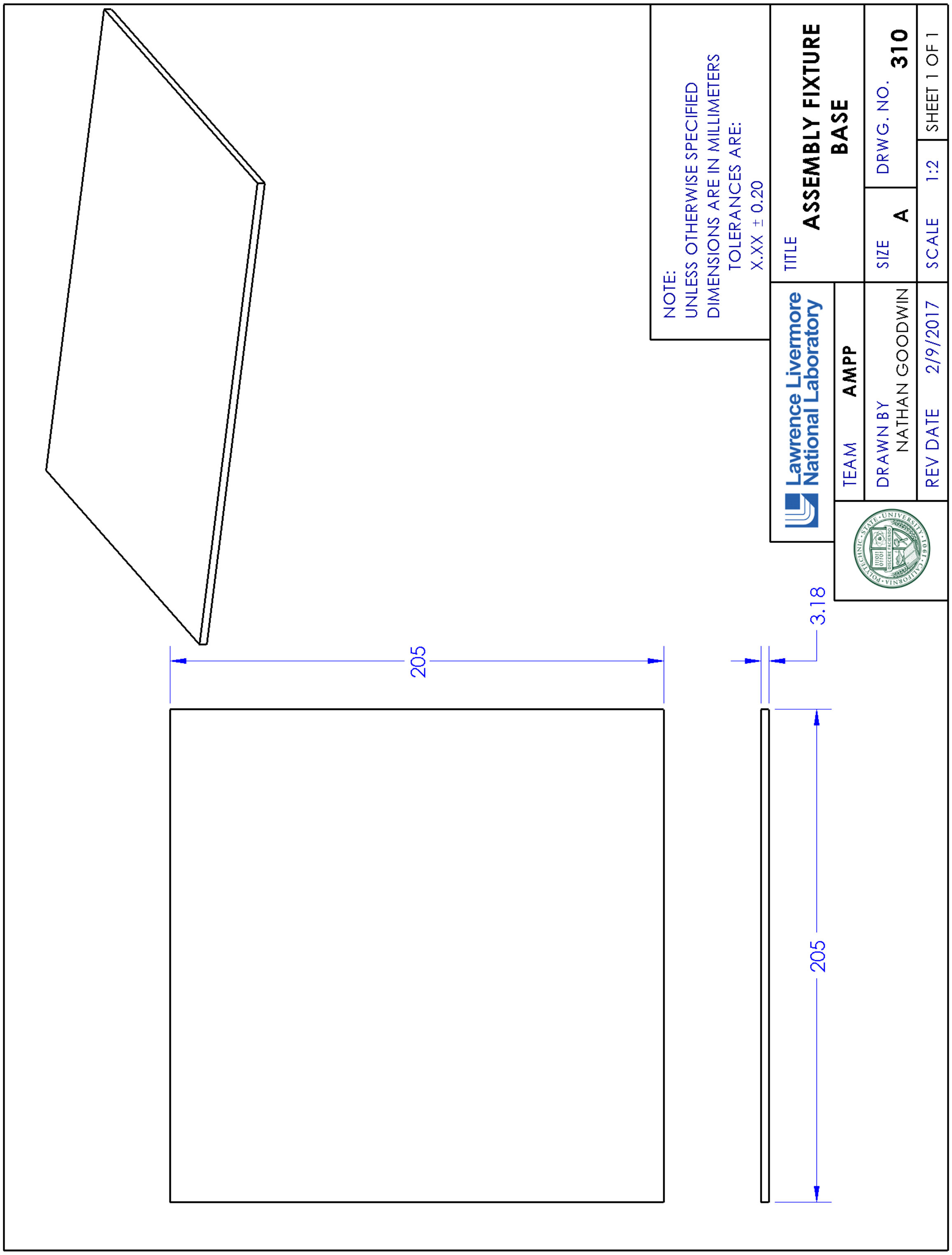
280 – Hex Bolt Data Sheet



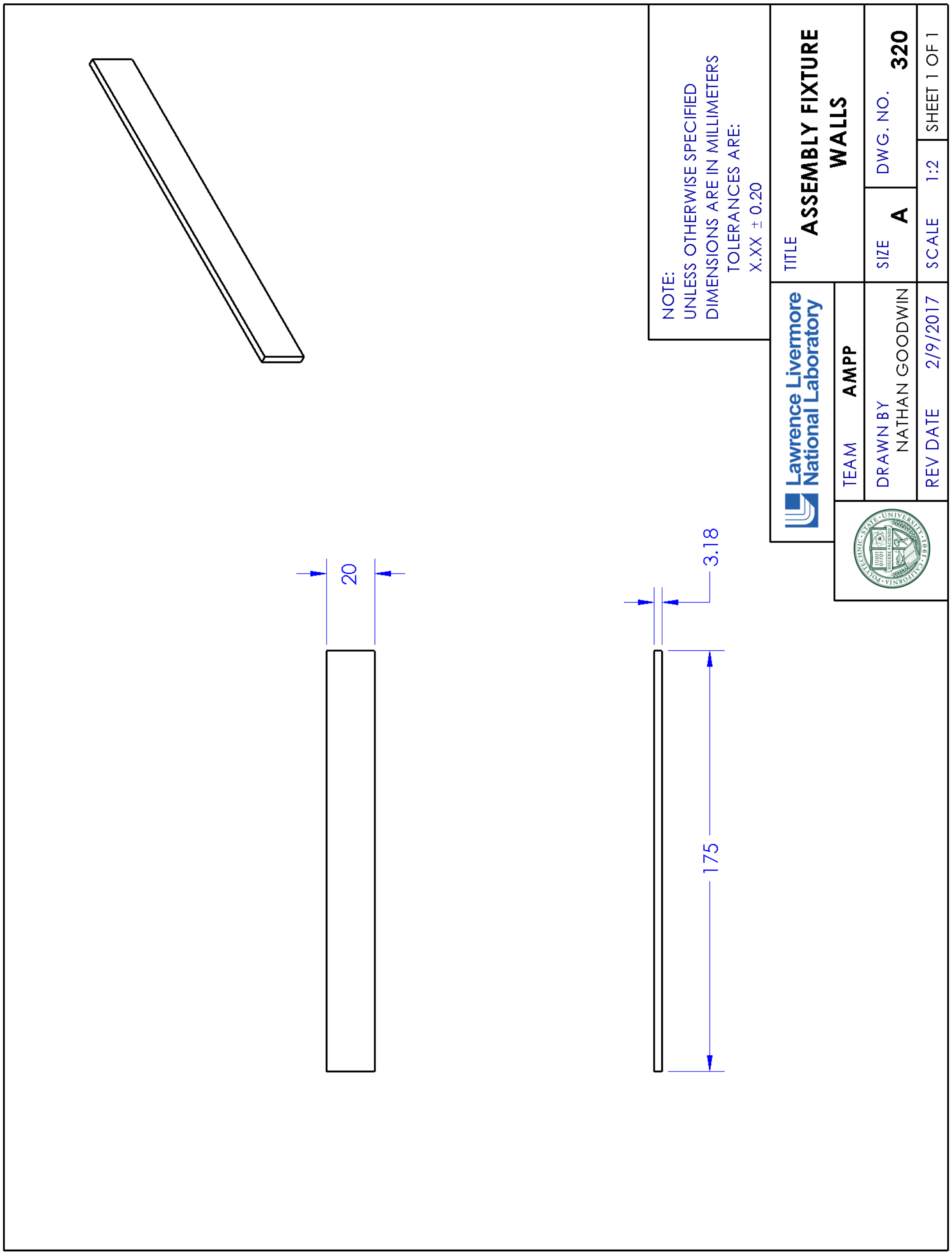
300 – Assembly Fixture



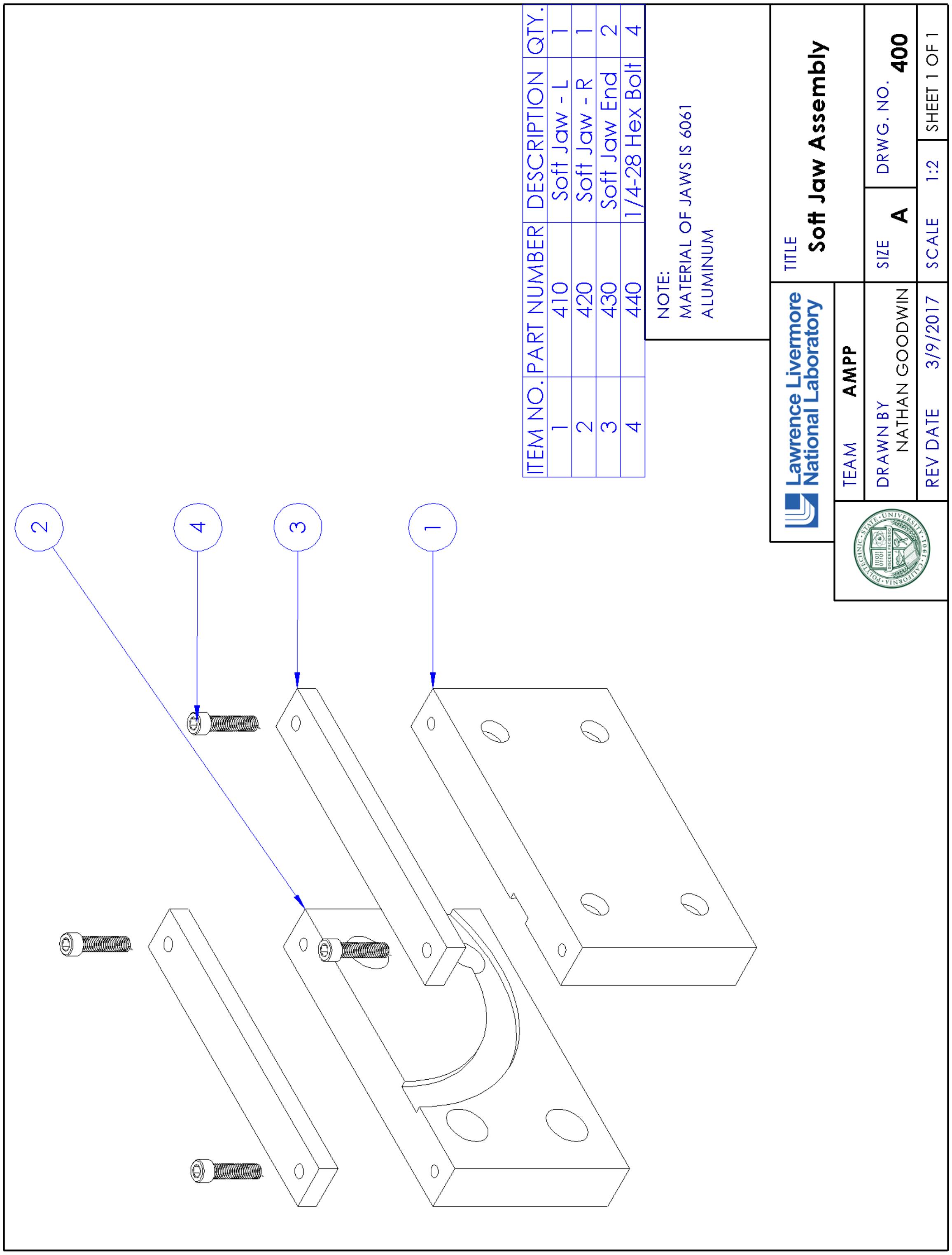
310 – Assembly Fixture Base



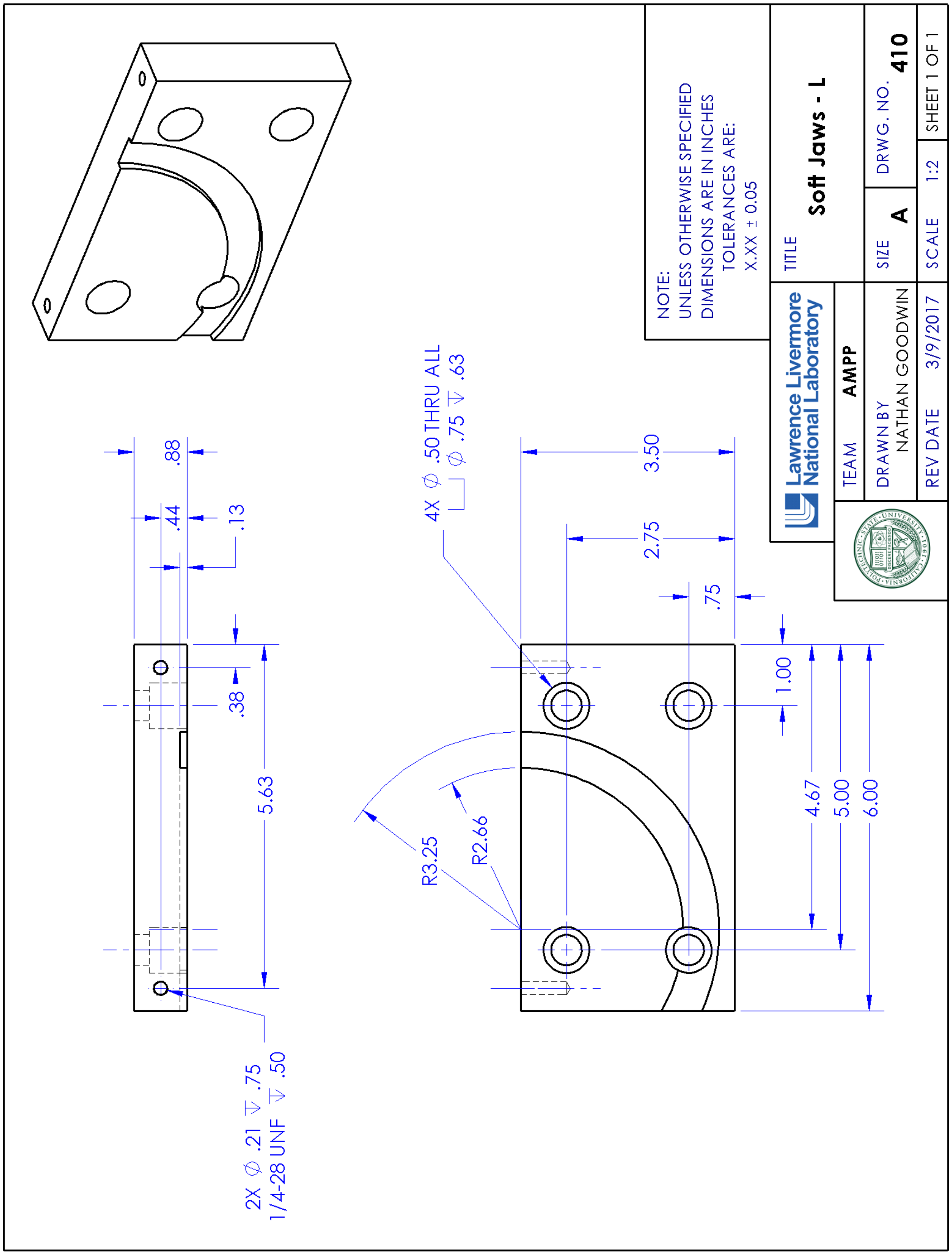
320 – Assembly Fixture Walls



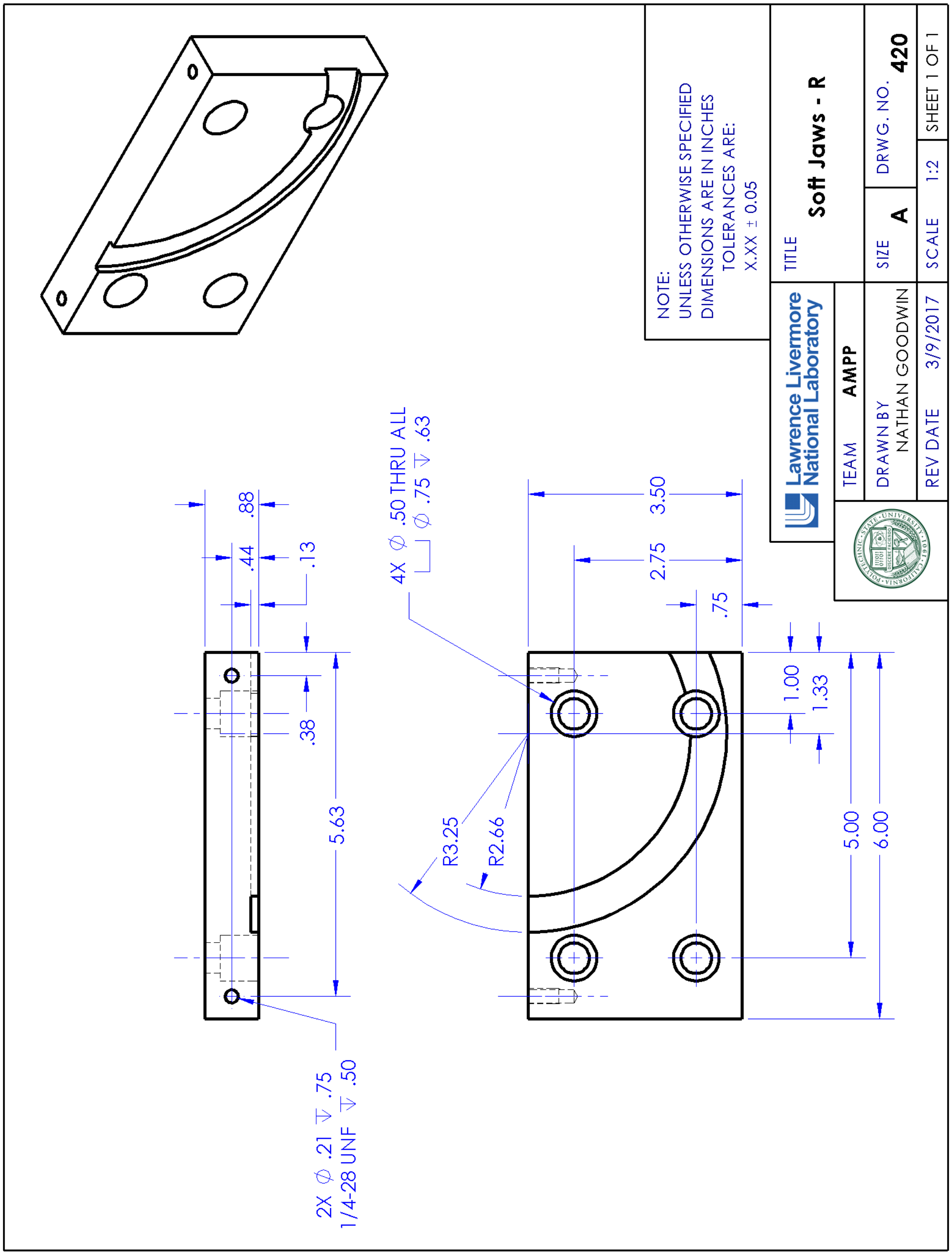
400 – Soft Jaw Assembly



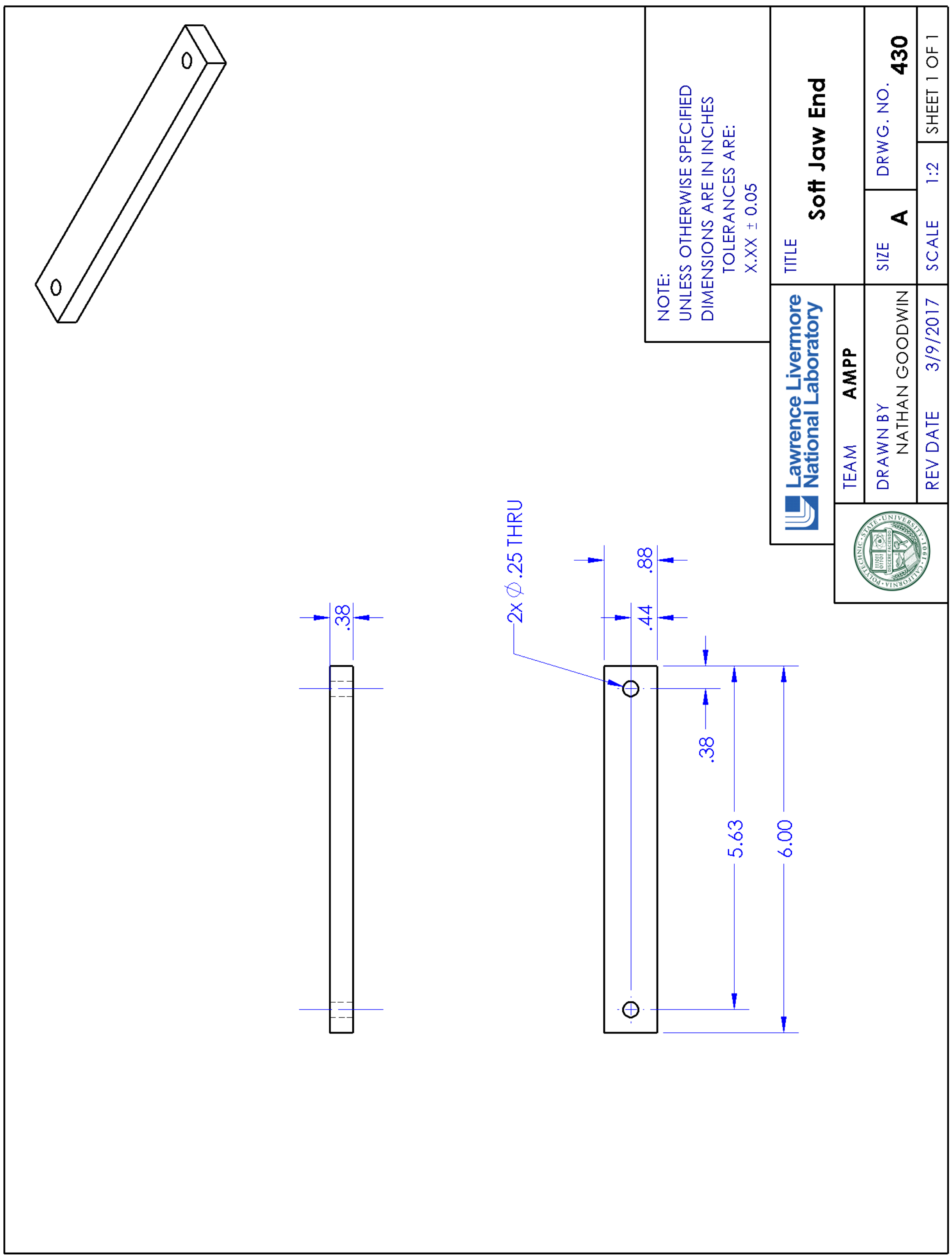
410 – Soft Jaw – L



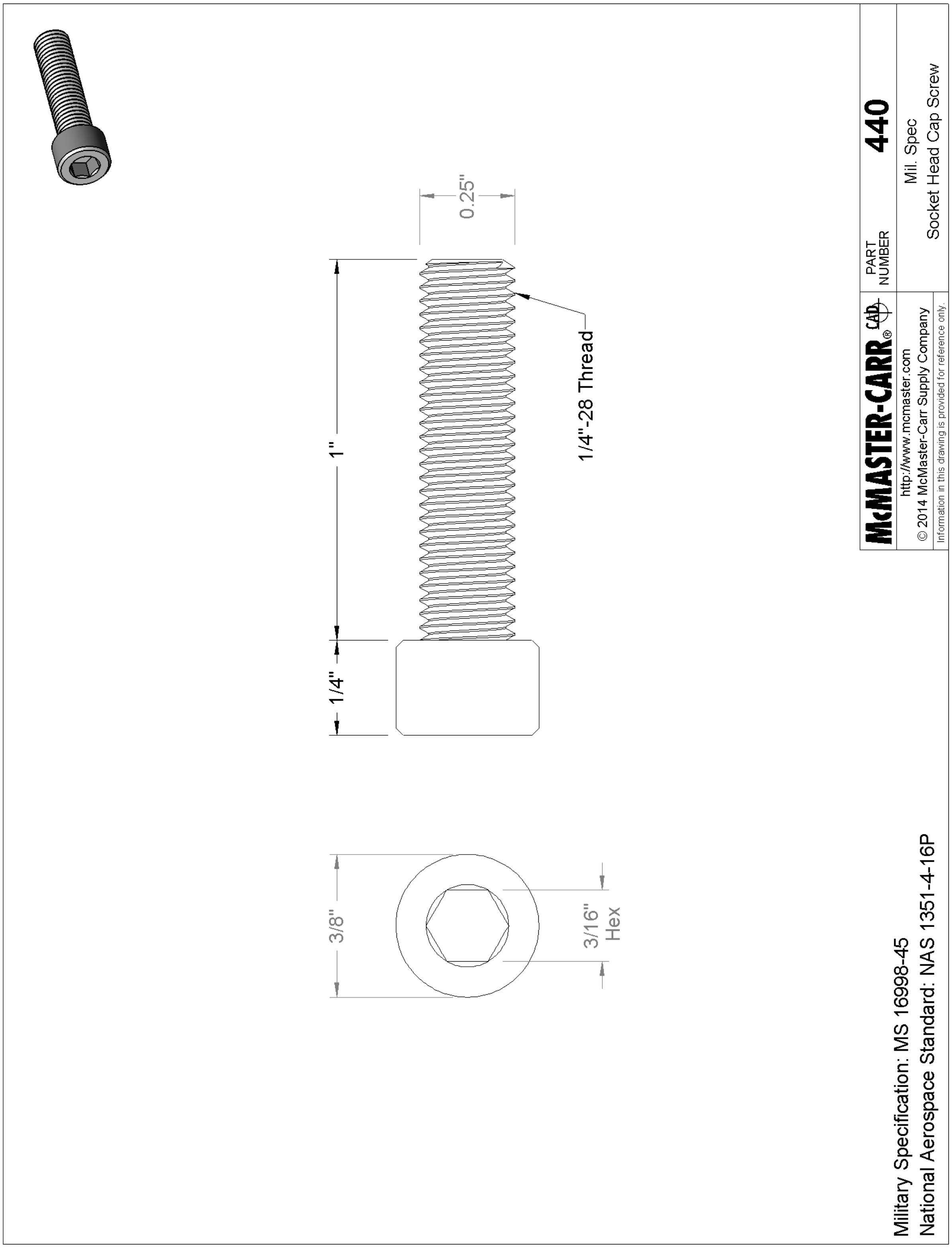
420 – Soft Jaw – R



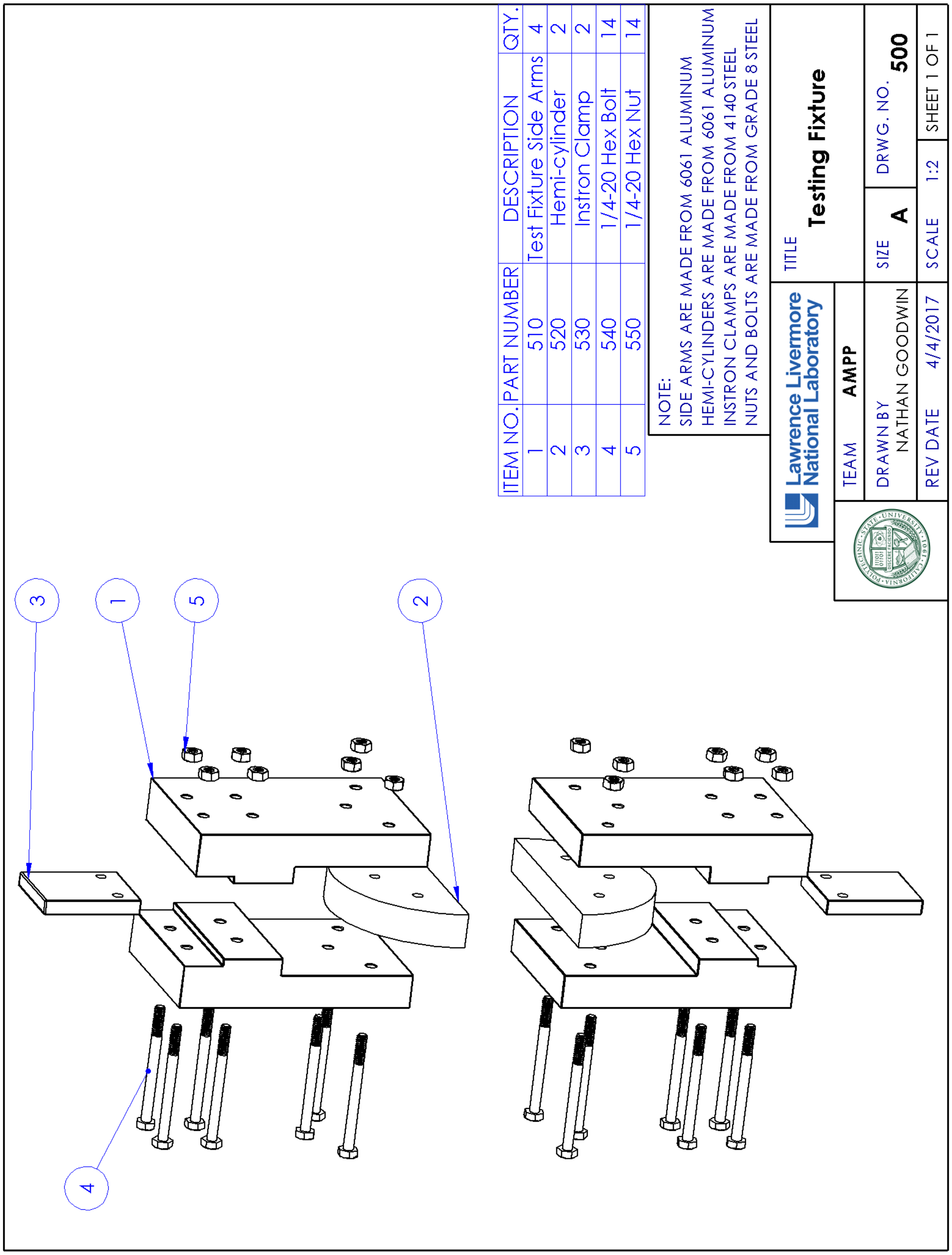
430 – Soft Jaw End



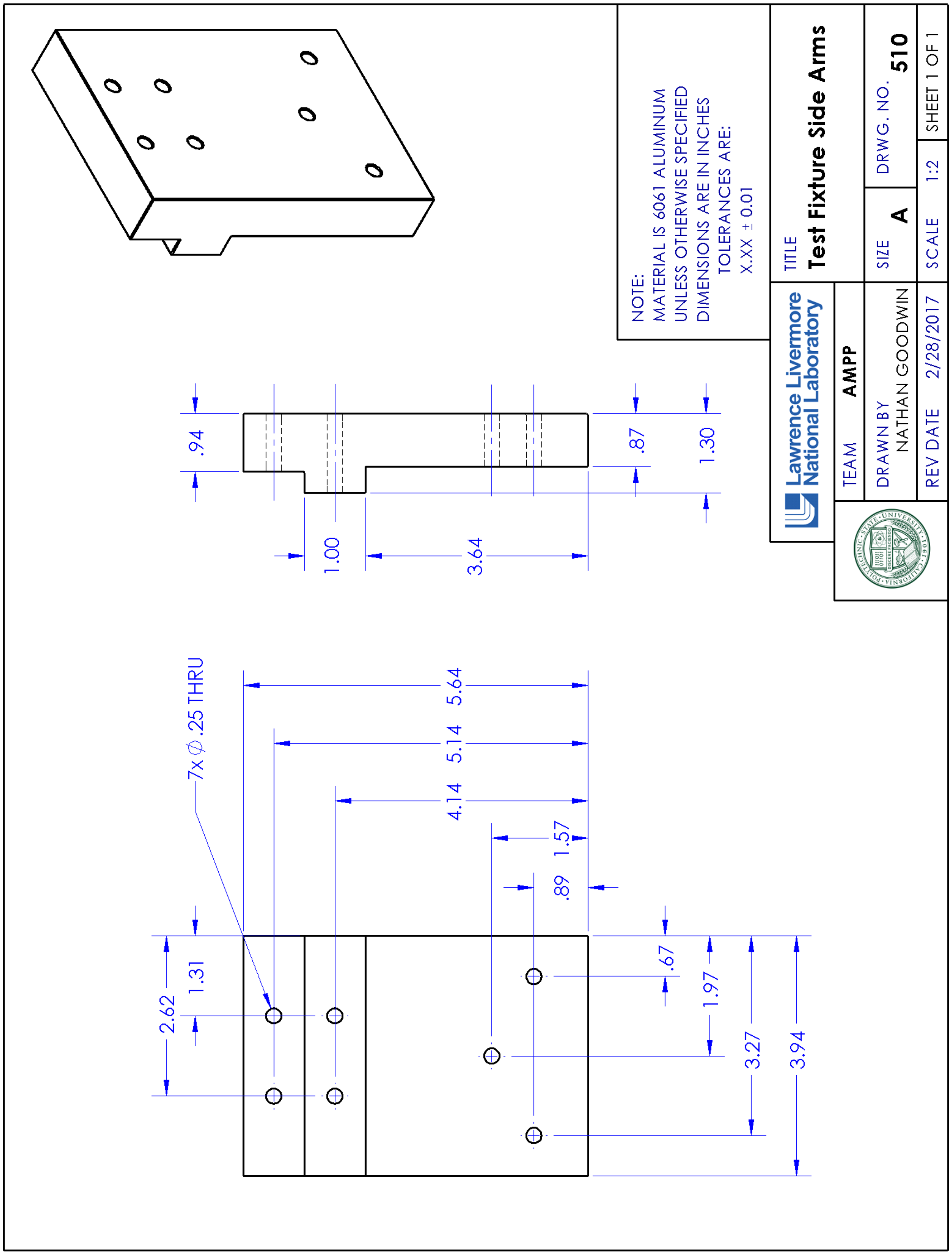
440 – Hex Bolt Data Sheet



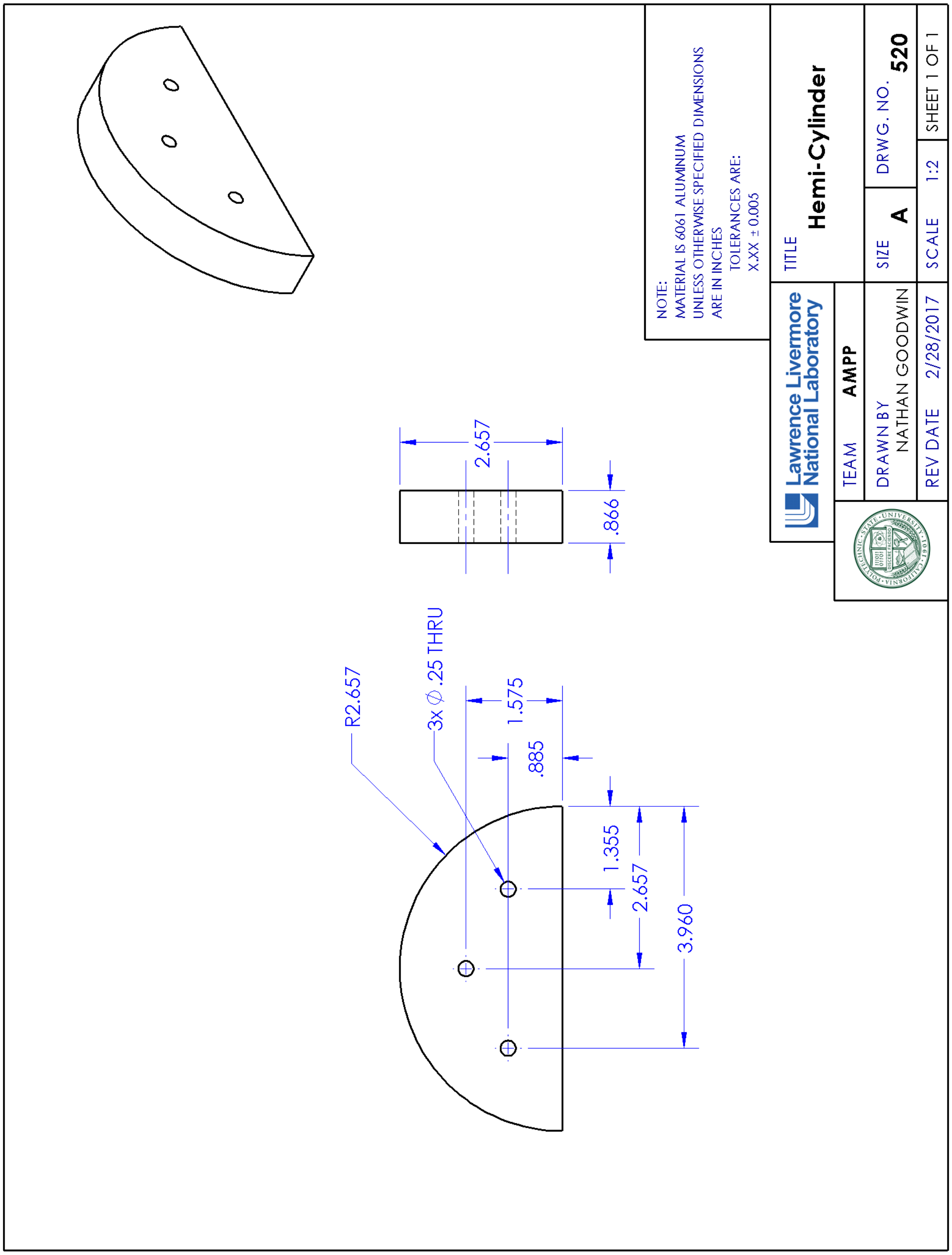
500 – Testing Fixture



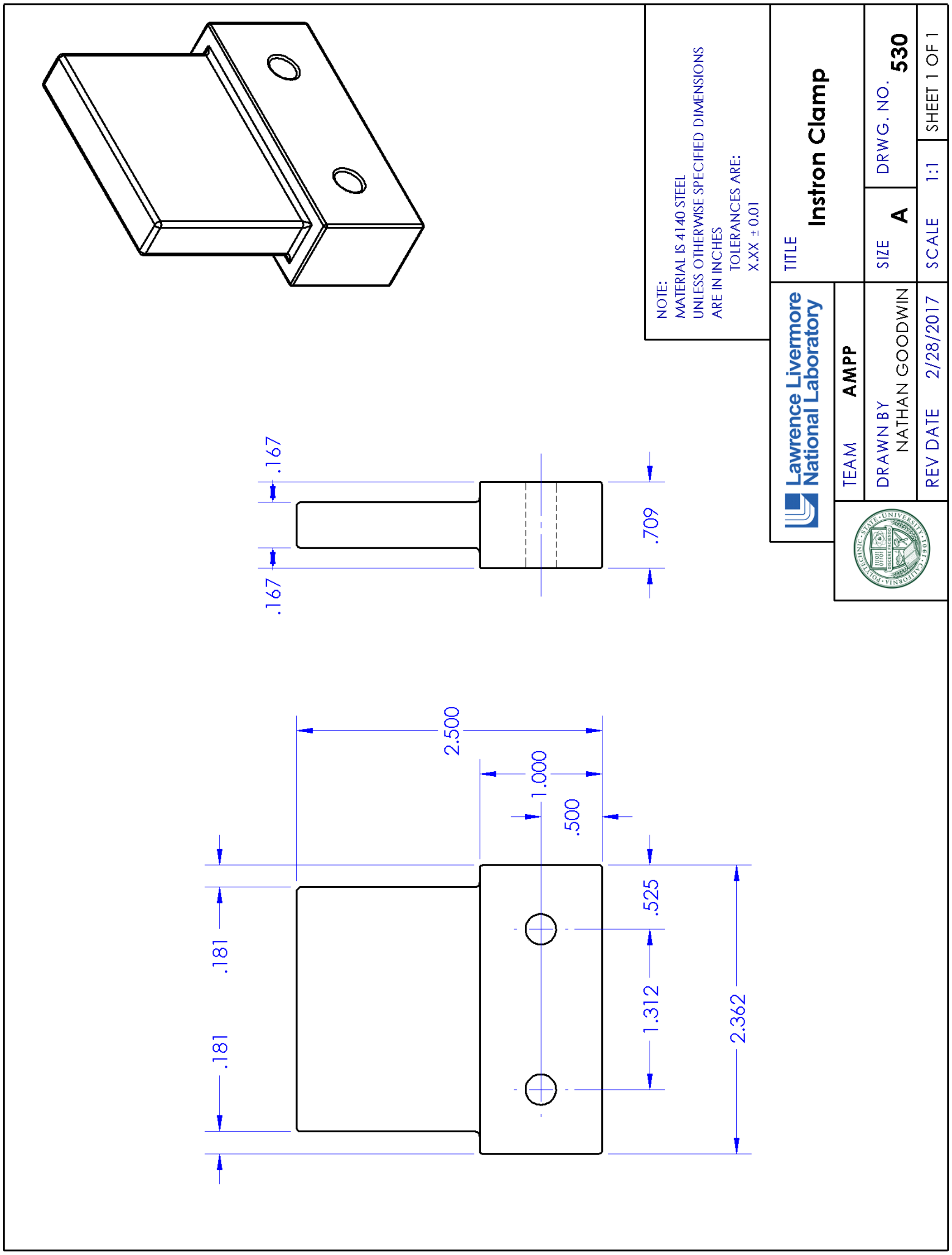
510 – Test Fixture Side Arms



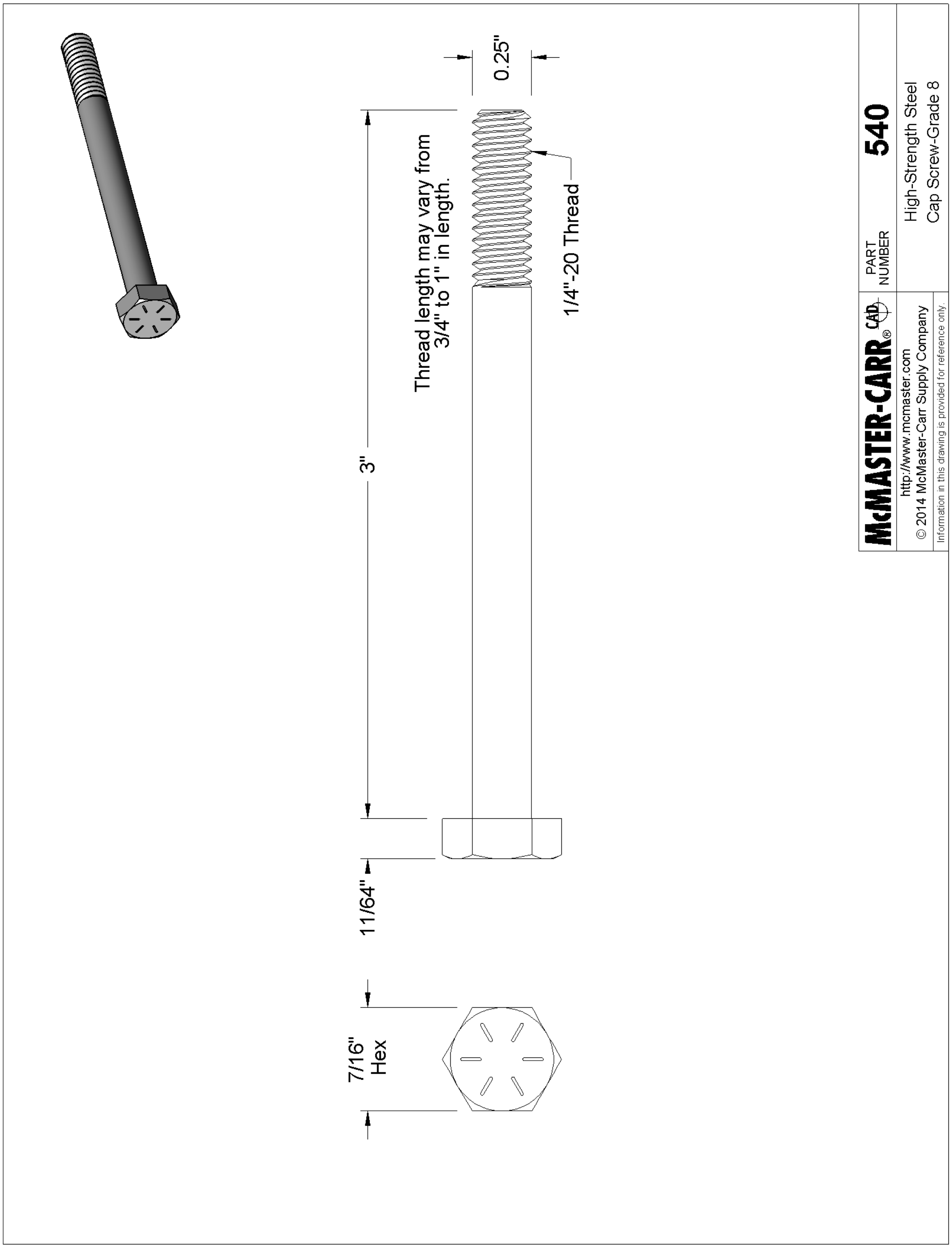
520 – Hemi-cylinder



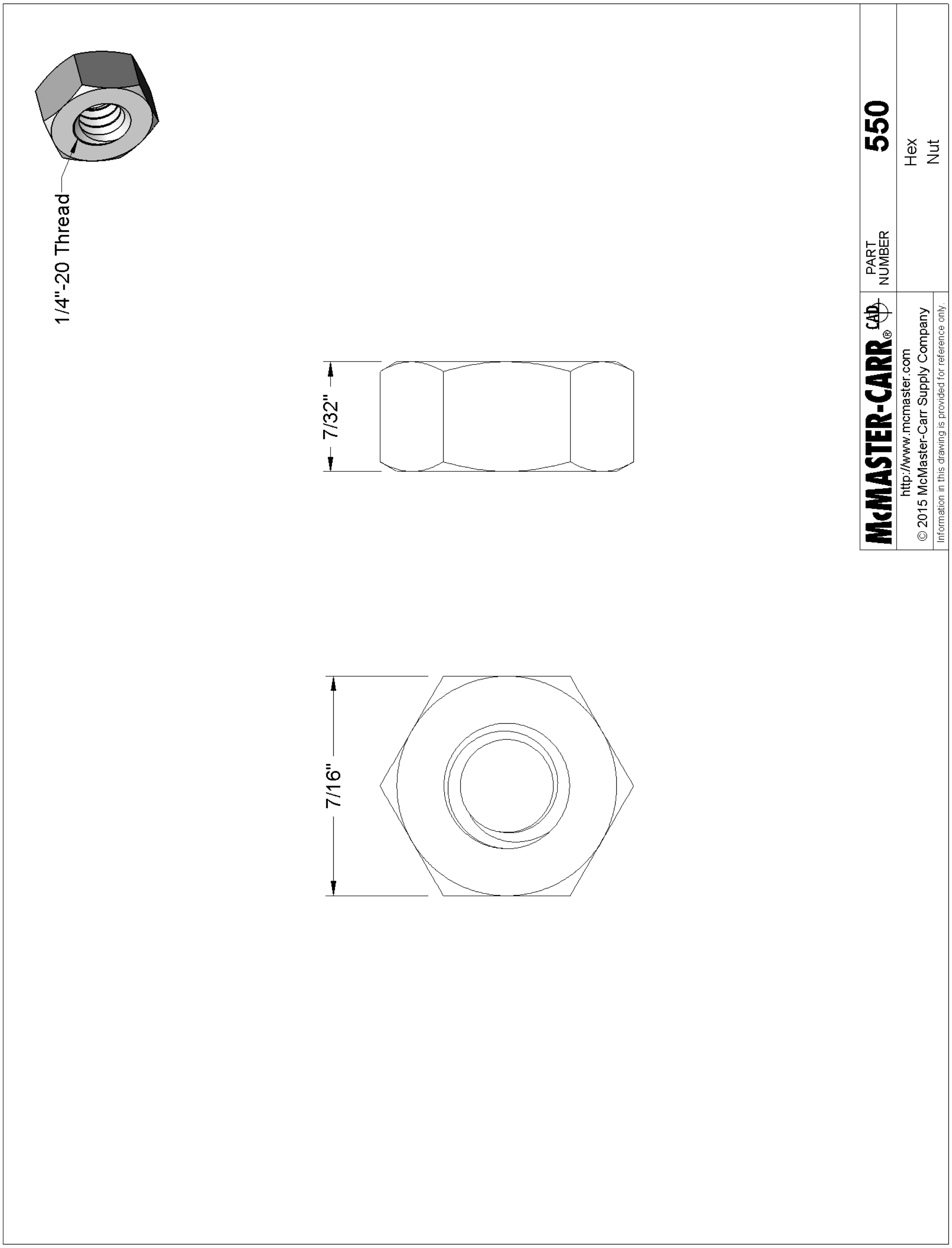
530 – Instron Clamp



540 – Hex Bolt Data Sheet



550 – Hex Nut Data Sheet



Appendix 9: BOM

Final BOM										
Assembly Level	Part Number	Description								
		Lvl 0	Lvl 1	Matl	Vendor	Qty	Cost	Tax	Ship	Ttl Cost
0	100	Final Part Assembly								
1	110		Segment of Printed Part	SS 316L Powder						
1	120		Socket Head Screw [1/4"-28 x 1"]	Alloy Steel	McMaster Carr	1	$ 6.06	$ 0.42	$ 8.46	$ 14.94
1	130		Outer Heat Shrink Band	SS 316L	Atlantic Stainless	1	$ 499.00	$ 39.92	$ 32.48	$ 571.40
1	140		Inner Heat Shrink Band	SS 316L	Atlantic Stainless	1	$ 470.00	$ 37.60	$ -	$ 507.60
0	200	Total Test Part Assembly								
1	210		Thick Outer Heat Shrink Band	SS 316L	Atlantic Stainless					
1	220		Nominal Outer Heat Shrink Band	SS 316L	Atlantic Stainless					
1	230		Thin Outer Heat Shrink Band	SS 316L	Atlantic Stainless					
1	240		Thick Inner Heat Shrink Band	SS 316L	Atlantic Stainless					
1	250		Nominal Inner Heat Shrink Band	SS 316L	Atlantic Stainless					
1	260		Thin Inner Heat Shrink Band	SS 316L	Atlantic Stainless					
1	270		Test Part	SS 316L Powder						
1	280		Socket Head Screw [1/4"-28 x 1"]	Alloy Steel	McMaster Carr					
0	300	Assembly Fixture								
1	310		Assembly Fixture Base	1018 Steel	SpeedyMetals	1	$ 8.73	$ 0.70	$ 30.00	$ 39.43
1	320		Assembly Fixture Walls	1018 Steel	SpeedyMetals					
0	400	Soft Jaw Assembly								
1	410		Soft Jaw - L							
1	420		Soft Jaw - R	6061 Aluminum	McMaster Carr	1	$ 48.00	$ 3.36	$ -	$ 51.36
1	430		Soft Jaw End							
1	440		Socket Head Screw [1/4"-28 x 1"]	Alloy Steel	McMaster Carr					
0	500	Testing Fixture								
1	510		Test Fixture Side Arms	6061 Aluminum	Speedy Metals	1	$ 66.38	$ 5.31	$ -	$ 71.69
1	520		Hemi-cylinder	6061 Aluminum	McMaster Carr	1	$ 43.50	$ 3.05	$ -	$ 46.55
1	530		Instron Clamp	4140 Steel	McMaster Carr	1	$ 21.99	$ 1.54	$ -	$ 23.53
1	540		Hex Head Screws [1/4"-20 x 3" long]	Grade 8 Steel	McMaster Carr	1	$ 9.79	$ 0.69	$ -	$ 10.48
1	550		Hex Nut [1/4"-20]	Grade 8 Steel	McMaster Carr	1	$ 2.90	$ 0.23	$ -	$ 3.13
		Tooling								
0	N/A	3/4" X 1" X 3" 5 Flute Square End mill		Solid Carbide	MSC	1	$ 165.40	$ 16.43	$ 11.60	$ 193.43
0	N/A	1/4"X 1-1/2" X 4" 2 Flute Ball End Mill		Solid Carbide	MSC	1	$ 40.82	$ -	$ -	$ 40.82
0	N/A	#3 X 3-3/4" Oxide Coated Jobber Drill		High Speed Steel	MSC	1	$ 2.38	$ -	$ -	$ 2.38
	Total Parts Cost									**$ 1,576.73**

Appendix 10: DVP

ME430 DVP&R			Test #	1	2	3	4
	Project:	TEST PLAN	Specification	Preliminary Band Load Test	Maximum Tangential Load	Dimensions	Geometry
	Cal Poly Senior Project		Test Description	Apply tangential load on just the inner band using the testing fixture to test if it can carry all of the required load	Apply maximum tangential load on final part such that force is distributed equally at two opposing radial locations along the axis	Confirm that the final dimensions are within the specified tolerance range	Confirm that the surface finish of the part meets specificiation
	Team:		Test Location	Dr. Mello's lab	Dr. Mello's lab	IME Metrology Lab	IME Metrology Lab
	Additive Manufacturing for Post Processing		Test Equipment	Instron	Instron	Optical Comparitor	Micro Vu
			Parts Needed	Test parts (all variations), final part	Test parts (all variations), final part	Test parts (all variations), final part	Test parts (all variations), final part
	Sponsor:		Acceptance Criteria	>4500 lbf	>2500 lbf	Given GD&T	Given GD&T
	Lawrence Livermore National Lab		Test Responsibility	Nathan	Nathan	Nathan	Nathan
			TIMING: Start date	N/A	N/A	5/25/2017	N/A
			TIMING: Finish date	N/A	N/A	5/25/2017	N/A
		TEST REPORT	Numerical Results	N/A	N/A	Outer diameter: Inner Diameter:	N/A
			Notes on Testing	Not completed because parts were received late and unable to be turned to final dimensions. Inner band was to be dimensioned from received parts and machined concurrently with all other inner and outer bands	Joining process was not completed due to complications in receving pritned parts	All parts were dimensioned using Optical Comparator once received from LLNL to confirm print accuracy	Joining process was not completed due to complications in receving pritned parts

Appendix 11: Owner's Manual

Joining Process Owner's Manual

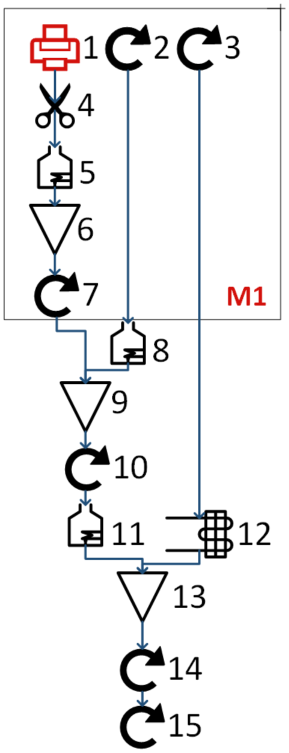
Produced by Cal Poly Senior Project Team:

Additive Manufacturing for Post Processing (AMPP)

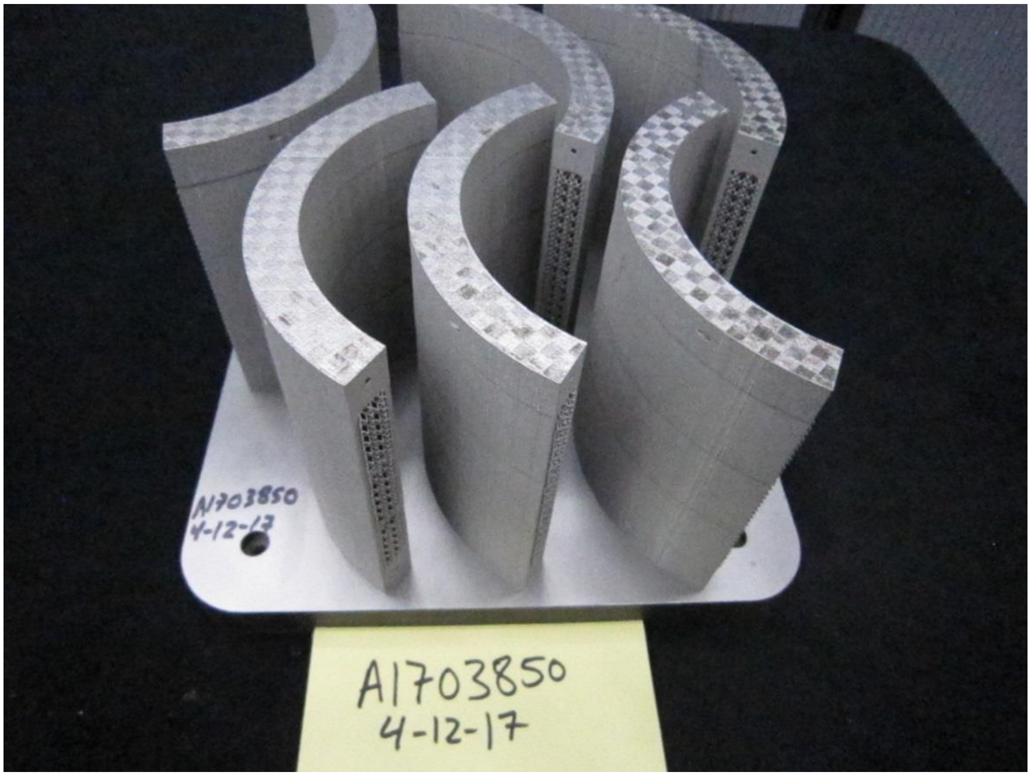
For the project sponsor:

Lawrence Livermore National Laboratory

Step 1: Print

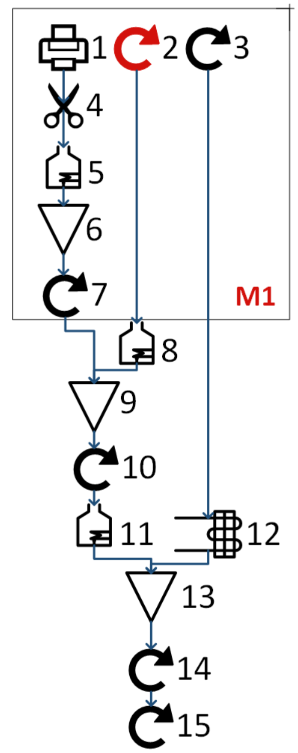


- Print parts on SLM machine



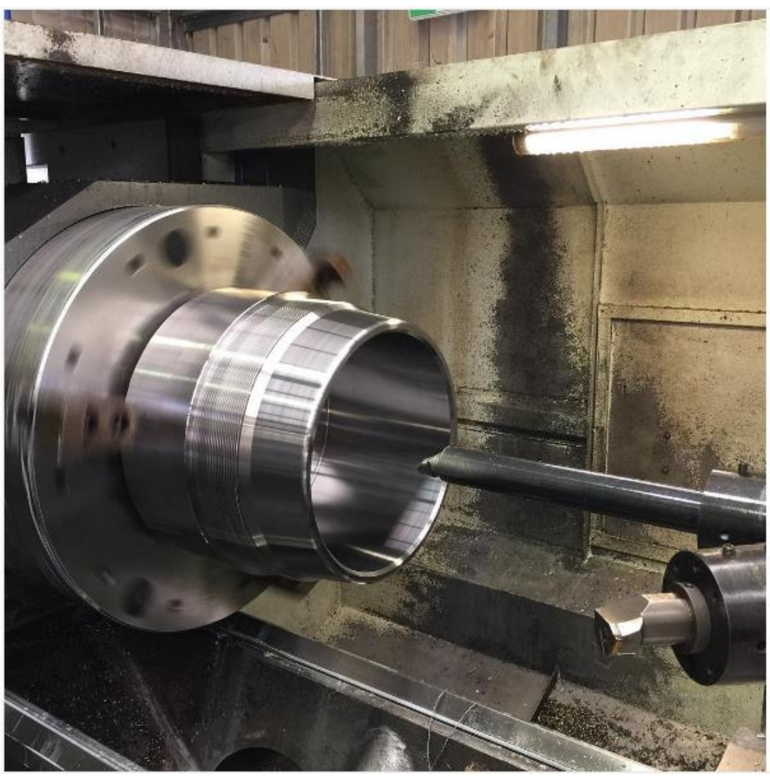
NOTE: Periodically check on machine to ensure print is running smooth

Step 2: Bore



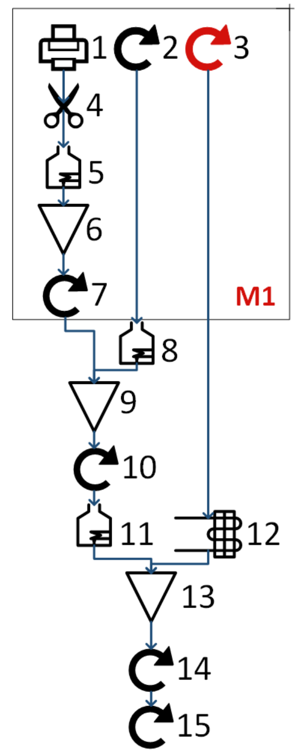
- Set outer band into lathe jaws, secure externally

Initial Inner Diameter
6.00 in
(152.4 mm)
Final Inner Diameter
6.3622 ± 0.006 in
(161.6 ± 0.15mm)



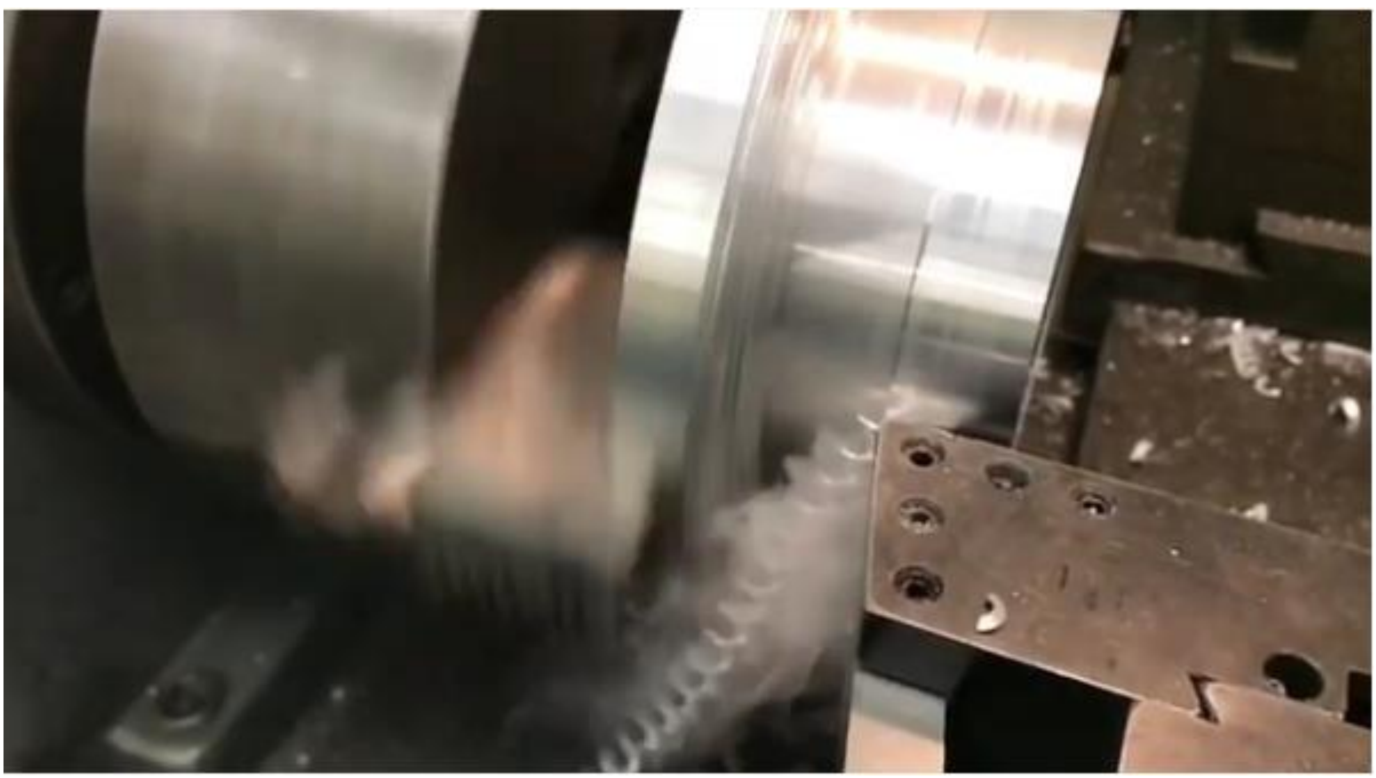
NOTE: Follow machine shop safety protocols when operating lathe

Step 3: Turn



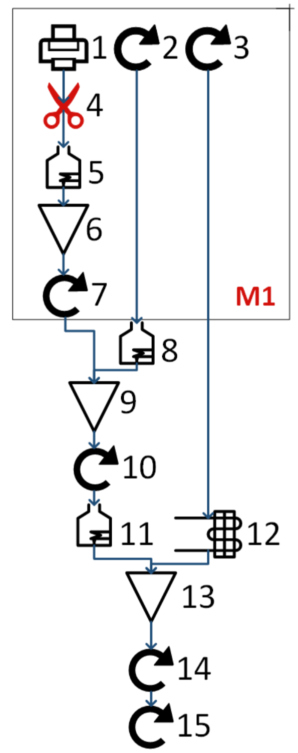
- Set inner band into lathe jaws, secure internally

Initial Outer Diameter
5.75 in
(146.05 mm)
Final Outer Diameter
5.4488 ± 0.006 in
(138.4 ± 0.15mm)

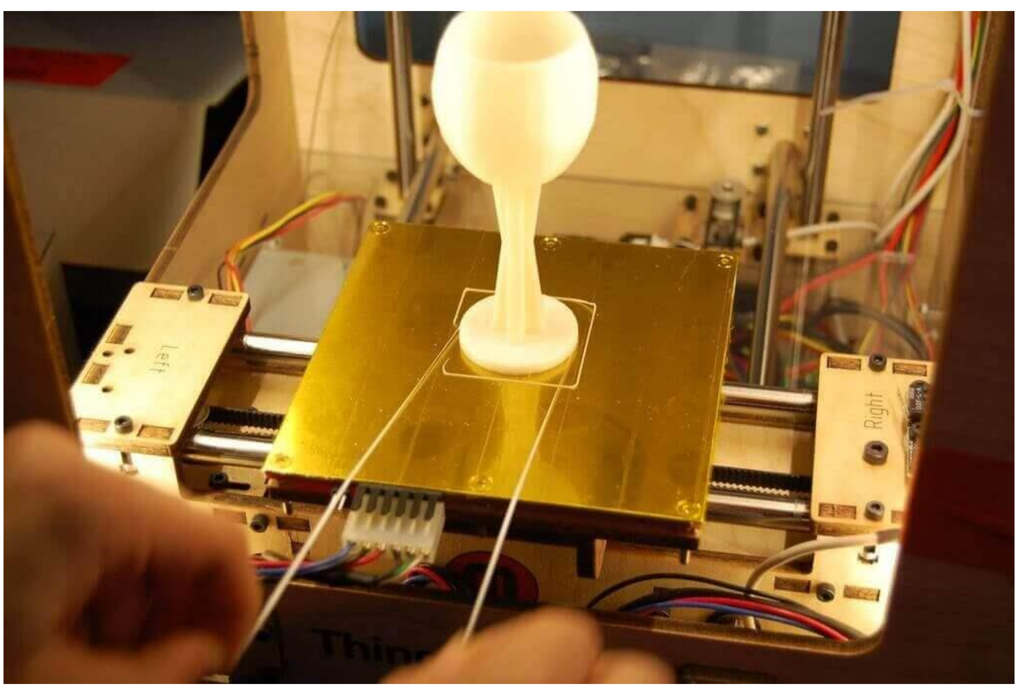


NOTE: Follow machine shop safety protocols when operating lathe

Step 4: Cut



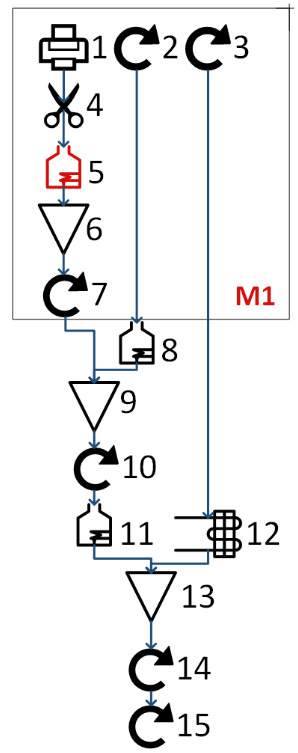
- Remove part (with build plate attached) from SLM machine
- Use a band saw (or wire EDM) to separate part from build plate



Note: above image is not an example of wire EDM or removal of 3d printed stainless steel parts

NOTE: Follow machine shop safety protocols when operating band saw

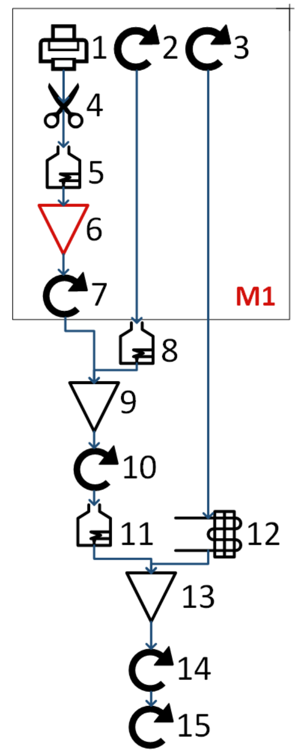
Step 5: Heat Treat



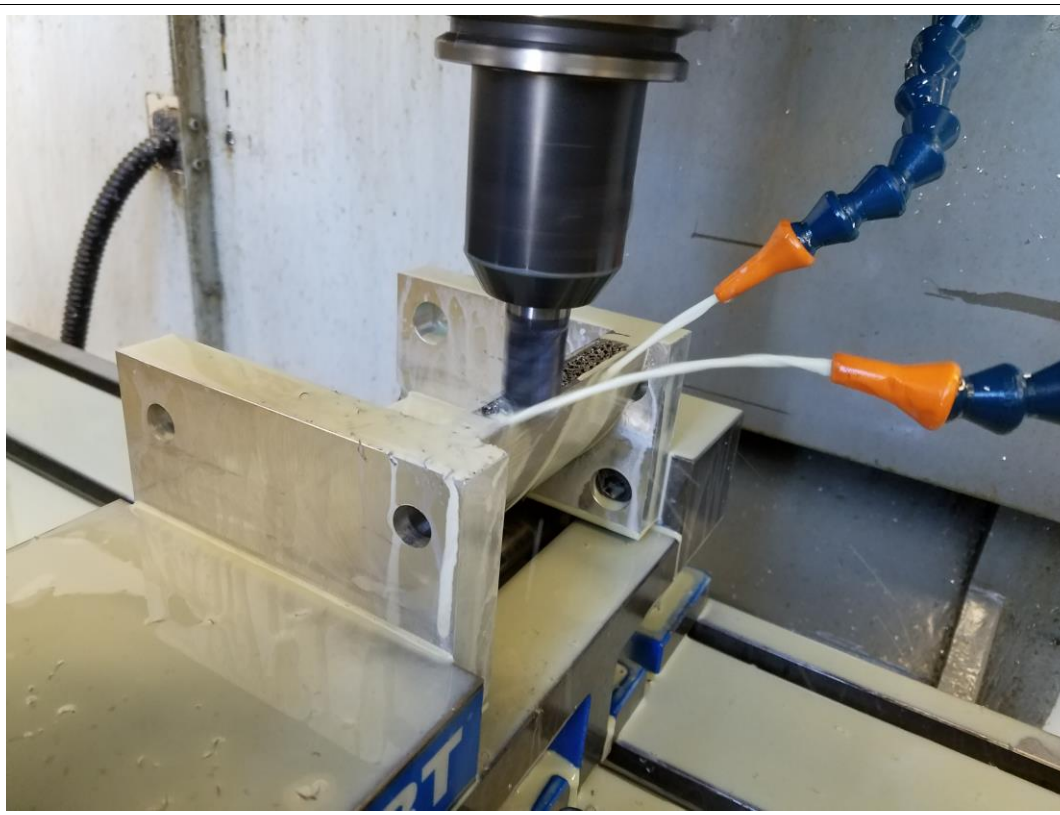
- Place printed parts into the IME furnace and heat to 1900°F

NOTE: Wear proper PPE while operating furnace including: high temp. gloves, face shield, long pants, closed toed shoes

Step 6a: Facing

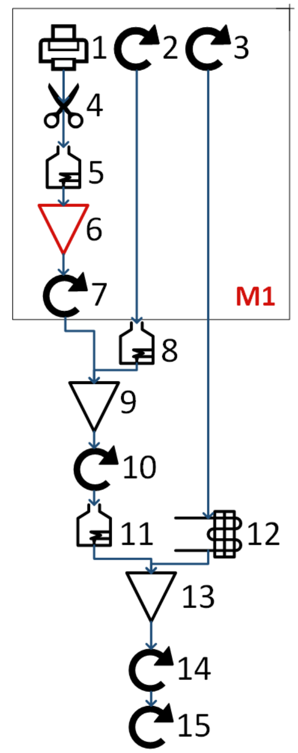


- Set soft jaws in vise, groove concave up
- Secure end plates on both soft jaws
- Slide segment into groove and set face flush with end plate
- Tighten vise
- Mill face until lattice is exposed
- Repeat for each segment



NOTE: Follow machine shop safety protocols when operating mill

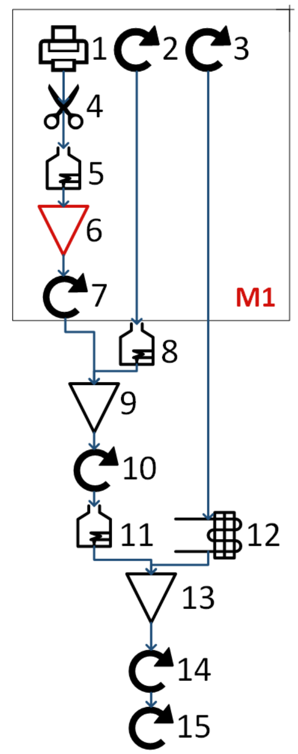
Step 6b: Machine



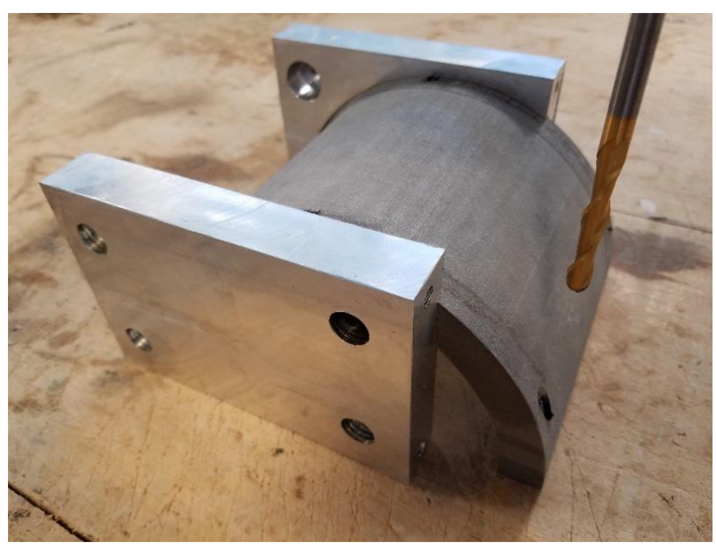
- Set segment in soft jaw concave up using previous procedure
- Mill two holes using a #3 drill bit
- Thread holes using a ¼-28 tap
- Repeat for each segment

NOTE: Follow machine shop safety protocols when operating mill

Step 6c: Machine

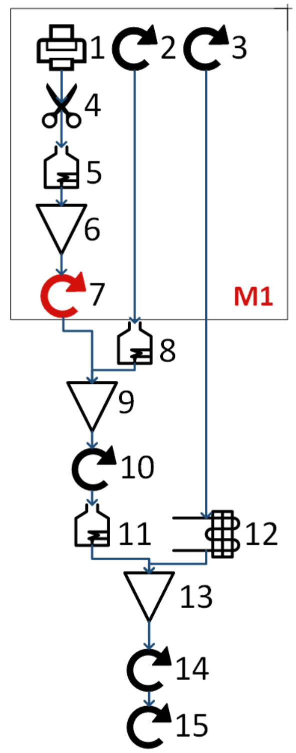


- Set segment in soft jaw concave up using procedure 6a
- Mill two 0.21 in (5.4 mm) holes
- Flip soft jaws concave down with face of part flush with face of bottom of soft jaw
- Mill two 0.25 in (6.4 mm) ⌴ 0.37 in (9.5 mm) ↧ 1.37 in (34.7 mm) counter bores
- Repeat for each segment
- Combine segments using screws



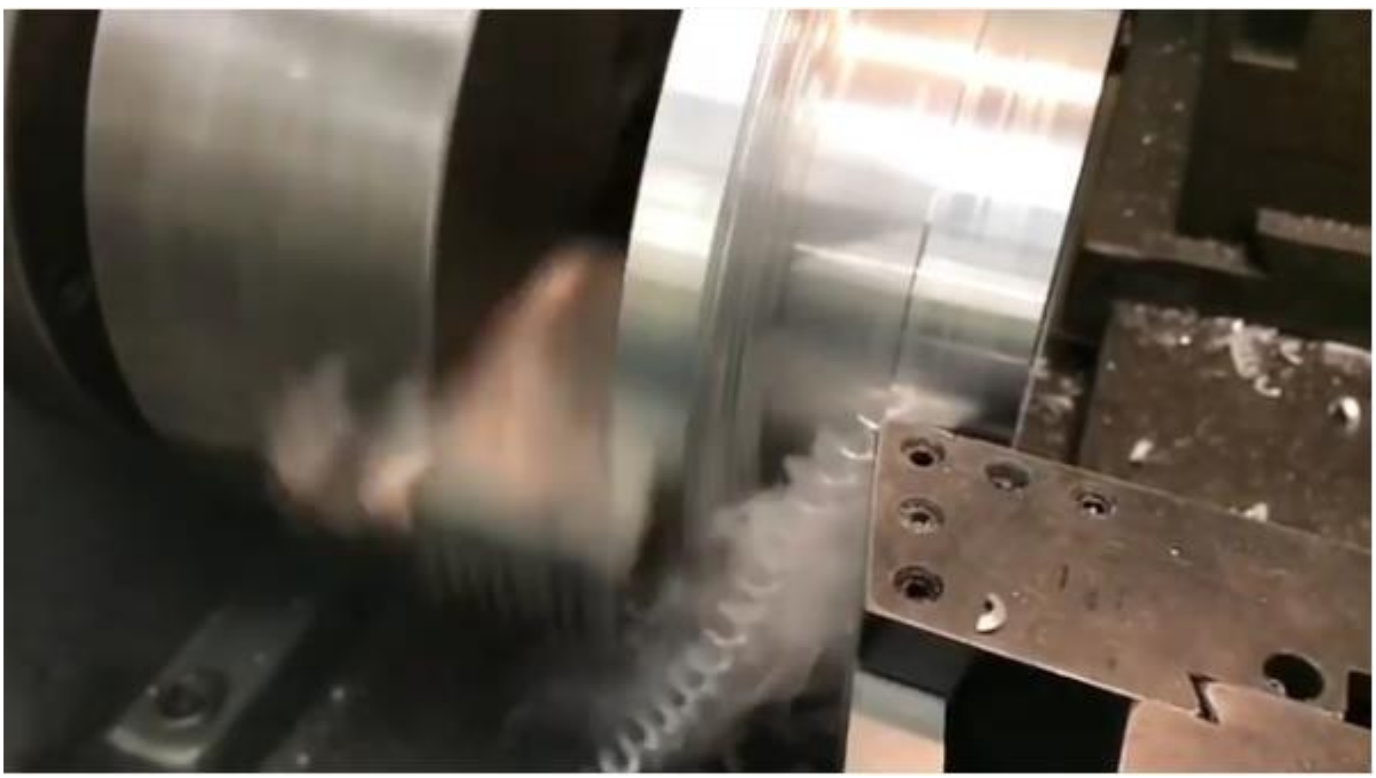
NOTE: Follow machine shop safety protocols when operating mill

Step 7: Turn



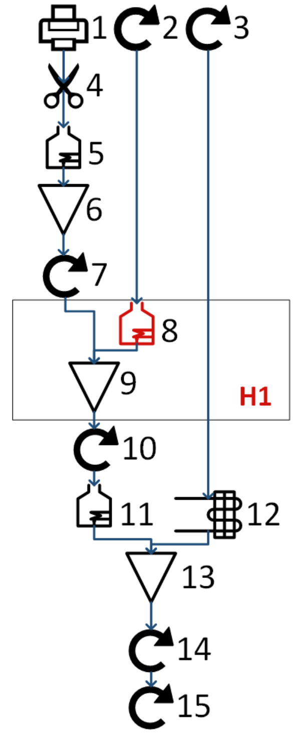
- Set printed part into jaws, secure from the inside

Approximate Initial Outer Diameter
6.52 in
(165.6 mm)
Final Outer Diameter
6.36 ± 0.006 in
(161.66 ± 0.15 mm)



NOTE: Follow machine shop safety protocols when operating lathe

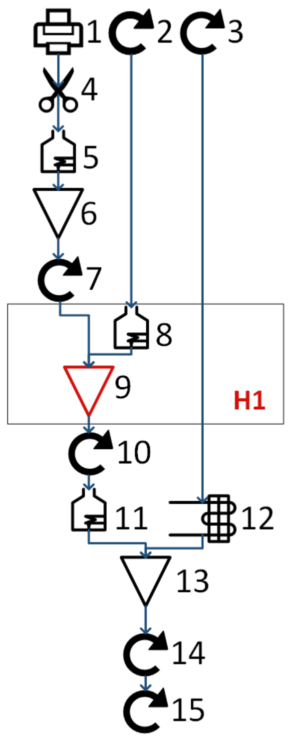
Step 8: Heat



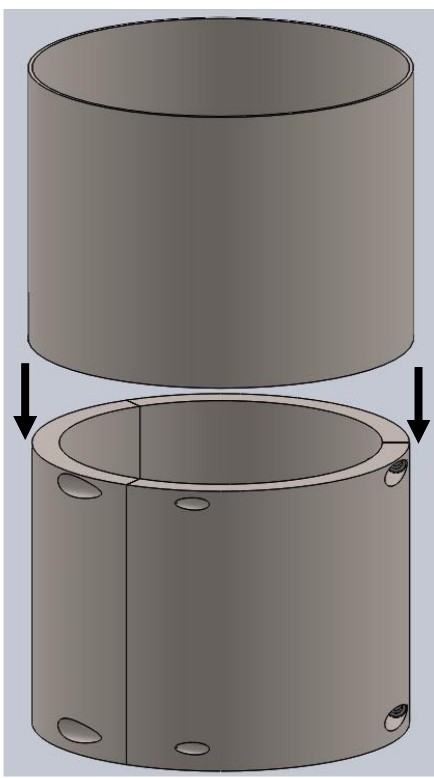
- Place outer band inside IME furnace and heat to 325°C at least one hour, soak time will vary due to convection coefficient of furnace

NOTE: Wear proper PPE while operating furnace including: high temp. gloves, face shield, long pants, closed toed shoes

Step 9: Insert

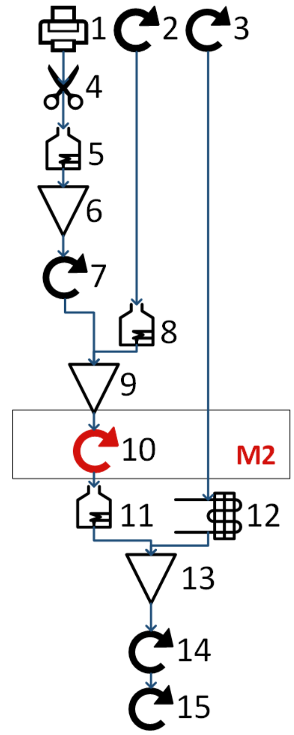


- Remove outer band from the furnace and place into assembly fixture
- Lower printed parts assembly into outer band
- Let everything reach equilibrium temperature



NOTE: Wear proper PPE while operating furnace including: high temp. gloves, face shield, long pants, closed toed shoes

Step 10: Bore

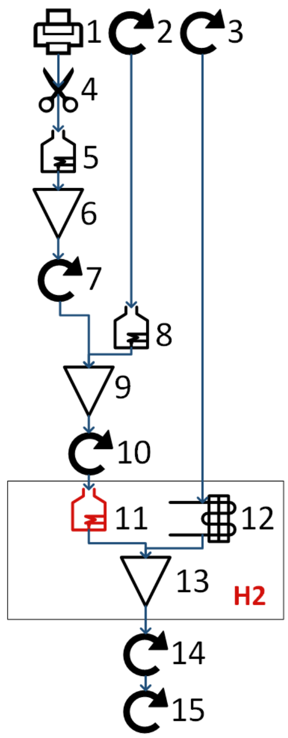


- Set printed parts/outer band assembly into jaws, secure externally

Approximate Initial Inner Diameter
5.29 in
(134.4 mm)
Final Inner Diameter
5.450 ± 0.006 in
(138.34 ± 0.15 mm)

NOTE: Follow machine shop safety protocols when operating lathe

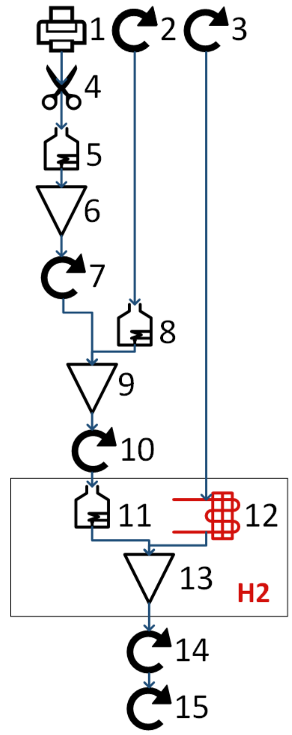
Step 11: Heat



- Place printed parts and outer band assembly into furnace and heat to 325°C for at least one hour, soak time will vary due to convection coefficient of furnace

NOTE: Wear proper PPE while operating furnace including: high temp. gloves, face shield, long pants, closed toed shoes

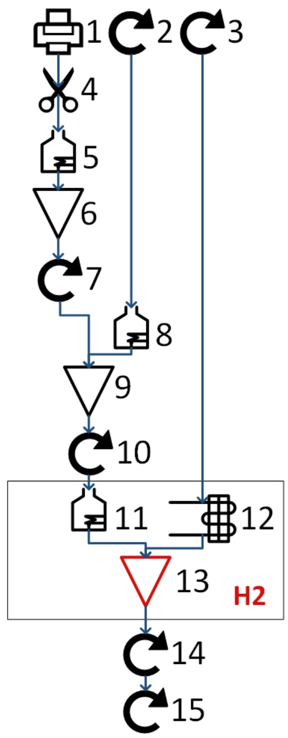
Step 12: Cool



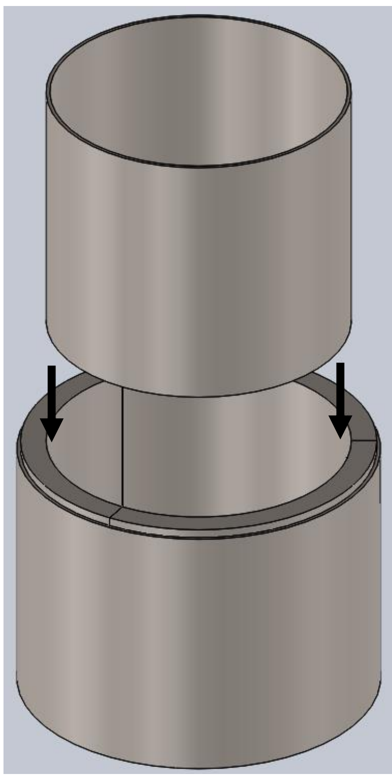
- Place inner band into IME freezer and cool to 0°C for at least one hour

NOTE: Follow IME safety protocols when operating freezer

Step 13: Insert

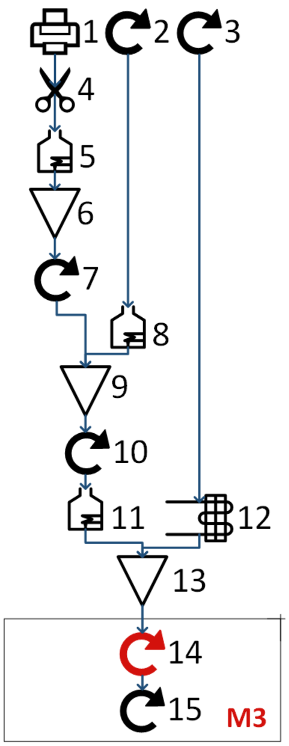


- Remove printed parts/outer band assembly from the furnace and place inside assembly fixture
- Remove inner band from freezer and insert inside printed parts
- Let everything reach equilibrium temperature



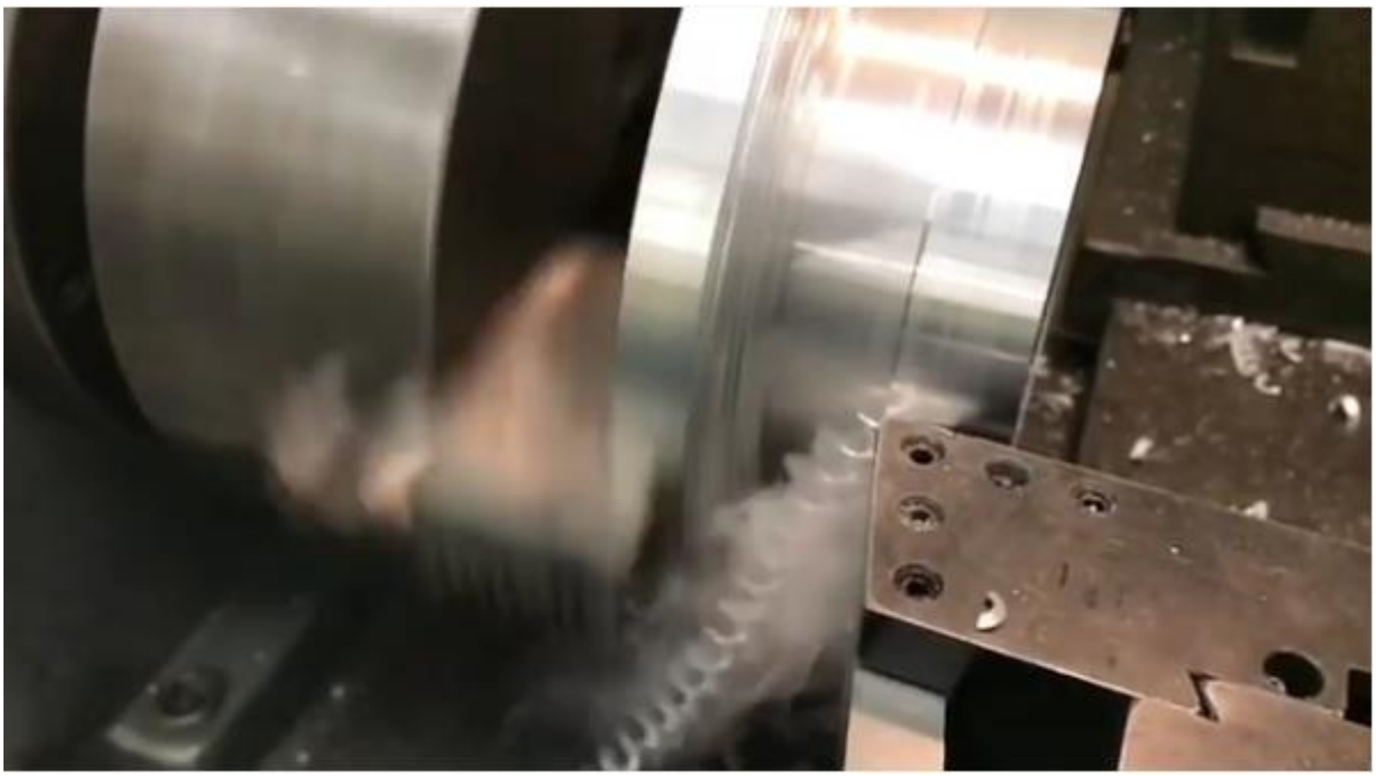
NOTE: Wear proper PPE while operating furnace including: high temp. gloves, face shield, long pants, closed toed shoes

Step 14a: Turn



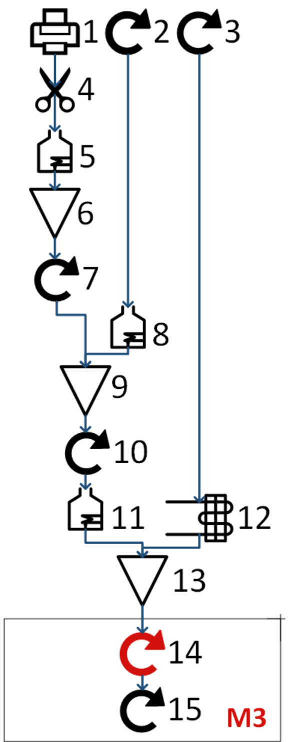
- Set final assembly into jaws, secure internally

Initial Outer Diameter
6.75 in
(171.45 mm)
Final Outer Diameter
6.49 in ± 0.0010 in
(165 mm ± 0.02 mm)

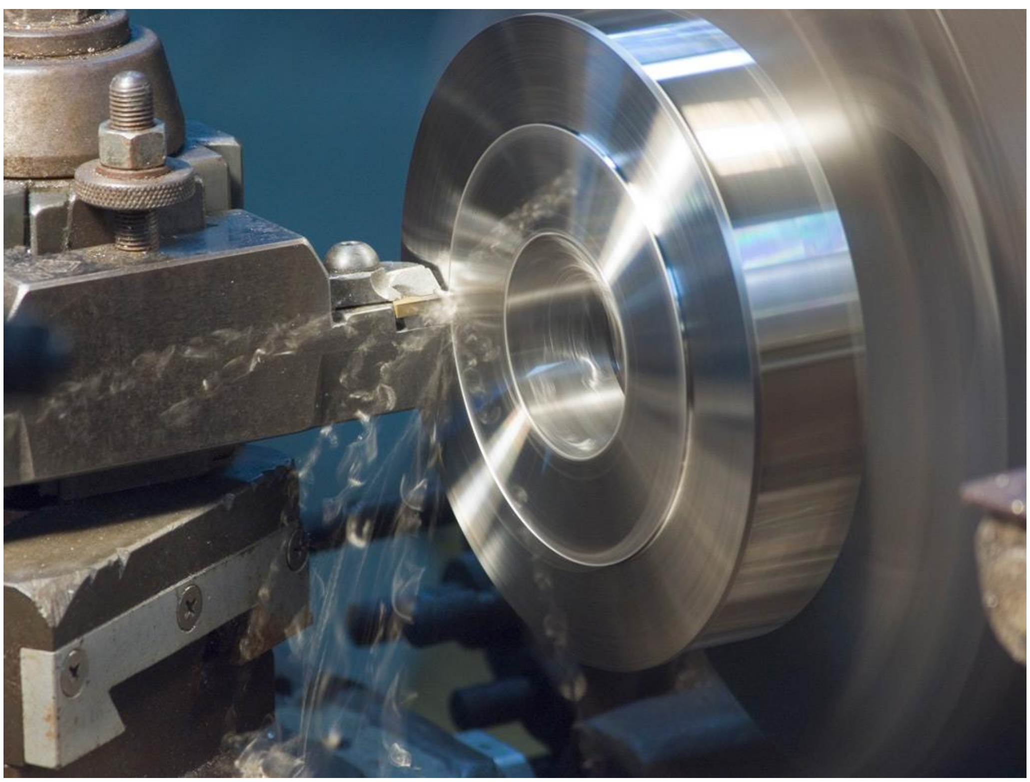


NOTE: Follow machine shop safety protocols when operating lathe

Step 14b: Face

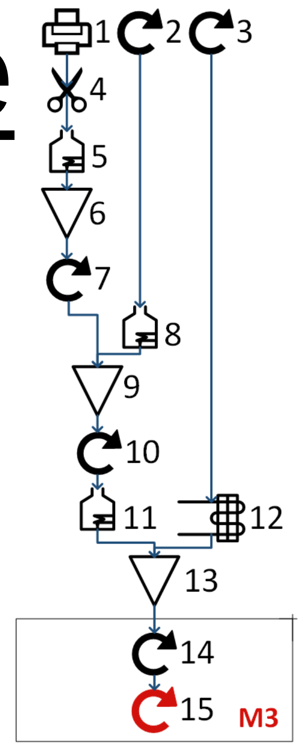


- After turning, part off collar
- Face surface until lattice is exposed



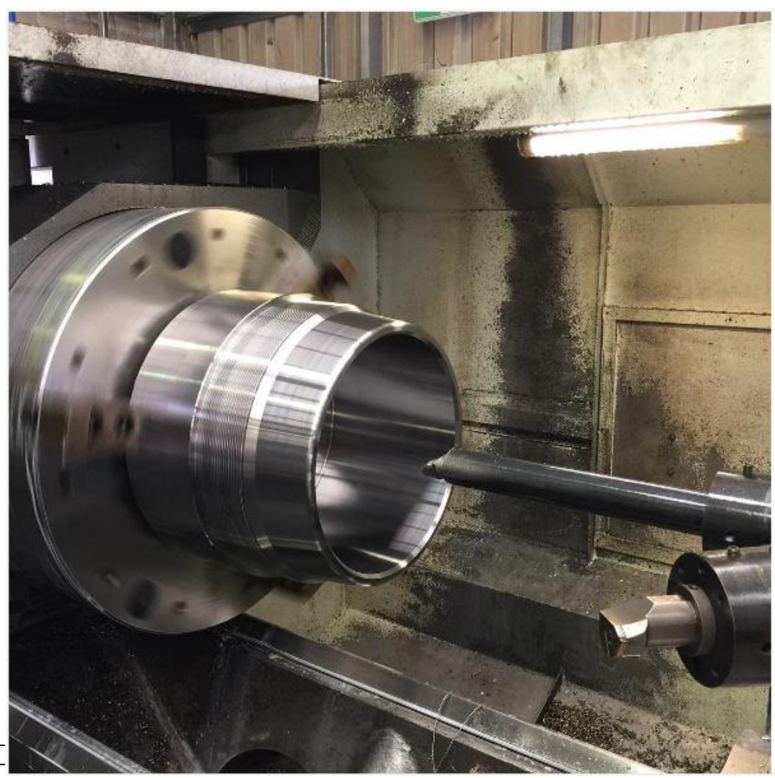
NOTE: Follow machine shop safety protocols when operating lathe

Step 15a: Bore



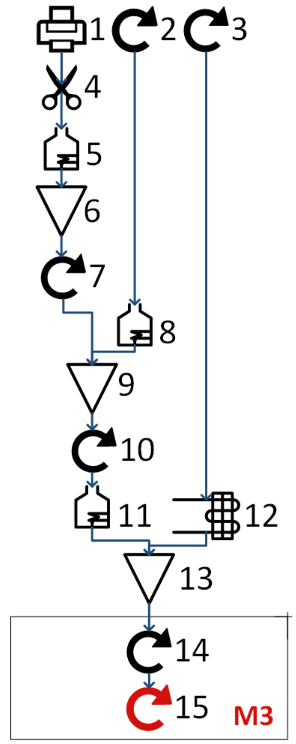
- Remove part from lathe and reset with the second collar exposed, secure externally

Initial Inner Diameter
5.00 in
(127 mm)
Final Inner Diameter
5.31 in ± 0.0010 in
(135 mm ± 0.02 mm)

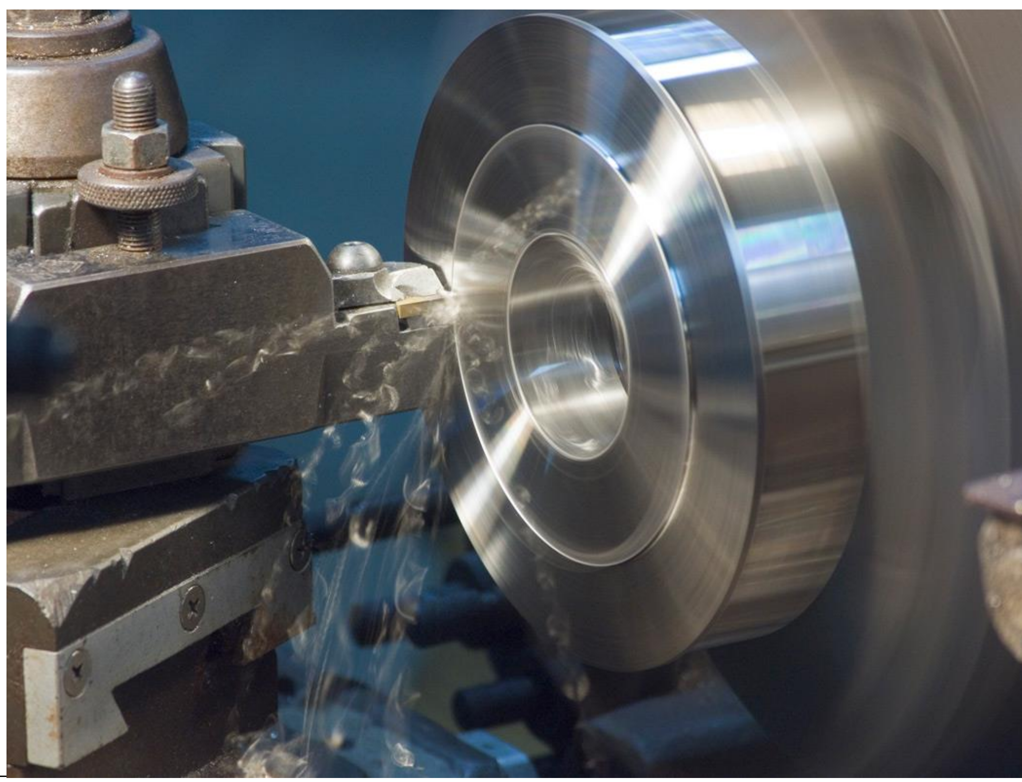


NOTE: Follow machine shop safety protocols when operating lathe

Step 15b: Face



- After turning, part off collar
- Face surface until lattice is exposed



NOTE: Follow machine shop safety protocols when operating lathe