MANUFACTURING COMPLEX SURFACES TO RECREATE THE DESIGN INTENT OF LEGACY ARTIFACTS

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Presented in Partial Fulfillment of the Requirements for the
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with a
Major in Mechanical Engineering
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University of Idaho
by
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Authorization to Submit Thesis

This thesis of Coleton Bailey, submitted for the degree of Master of Science with a Major in Mechanical Engineering and titled "Manufacturing Complex Surfaces to Recreate the Design Intent of Legacy Artifacts," has been reviewed in final form. Permission as indicated by the signatures and dates below, is now granted to submit final copies to the College of Graduate Studies for approval.

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Abstract

Manufacturing processes and techniques have changed throughout history. When designing a product for manufacturing, knowledge and availability of these processes greatly influences design even though the intent remains the same. To evaluate and compare the effects of these manufacturing processes on design two legacy artifacts were recreated using manufacturing methods that differed from the original product. These artifacts were an early 1900’s sand casted infill mallet head from the Studley Tool Cabinet, and a 1950‘s Hydro-electric dam scroll cage at 1/80th scale created using vacuum forming. [This analysis resulted in seven different pieces of finished hardware using five different manufacturing methods.] Three of these processes belonged to the infill mallet, and two to the scroll cage. Using these different manufacturing methods we were able to produce similar geometries of the original design while maintaining the intent of the design.

Acknowledgements

The first person that I need to thank for guiding me through my studies at the University of Idaho would be my major professor Dr. Edwin Odom. Through multiple classes, my undergraduate senior project, and all of my graduate studies Dr. Odom has guided me to be a better engineer. He has shown me what can be achieved when you have a vision, and on multiple occasions has inspired me to work harder toward my goals. I have learned many lessons about leadership and humility from Dr. Odom, and his philosophy of “getting the people right,” will be one that I will always look back on and carry with me. Since I have met Dr. Odom, he has taught me much about life. I have never had a person with the capability to motivate people in the ways that Dr. Odom has.

The Mechanical Engineering Department Chair Dr. Steven Beyerlein has been a great mentor of mine. Through our conversations about projects to philosophy, he has caused me to contemplate the important things. I appreciate the time that we have shared over my time at the University of Idaho.

The University of Idaho Mechanical Engineering Shop Manager Bill Magnie has been an invaluable resource during this thesis. He has taught me a great amount about machining, and helped me to gain experience in manufacturing. It was under his guidance that the products in this thesis were created, and we couldn’t have done it without him.

It would not be fitting to talk about my time in graduate studies without talking about the members of Idaho Engineering Works. The people in this office are some of the brightest, nicest and hardest working people I have ever met. Through the stresses of crunch time to the laughs we share I always love coming to work with these people. We will always share the load of one another and try to build each other up. I will always remember my time working here and I am proud that to be a part of its legacy.

Never underestimate the trouble that an undergraduate engineering student can get themselves into. Working with the students has greatly challenged my ability to think outside the box and to help solve some of the most interesting problems. The experiences I have had working with the students here have been some of the most challenging and rewarding. I thank all the students I have worked with for their hard work and interesting problems.

Our neighbors in Pullman, WA, at Schweitzer Engineering Laboratories have been exceedingly helpful during this project and my master’s program. In addition to donating the

HAAS Tool Room Mill in 2003 in which most of the work described in this document was manufactured with, they offered their equipment to produce the sand casting patterns discussed in this paper. I am appreciative of all their help in making this possible.

Travis Pattern and Foundry in Spokane, WA, were kind enough to cast the infill mallet presented in chapter 2. Without their assistance that data point may not have been achieved. They did a terrific job and I appreciate their contribution to our program and this thesis.

Meghann Hester deserves a special thanks for her work in designing a version of the initial 2.5 dimensional infill mallet. Meghann used standard prismatic modeling to develop the model that was used to define the 2.5-axis machined hammer head presented in chapter 2.

Alex Olson and the “Intolerables,” senior design team are the shoulders in which my success with vacuum forming stands. Their work created the path that I was able to finish. Thank you for your hard work and dedication.

Dedication

I first would like to thank my parents Deborah Moon and Brett Peterson for their love and support while I have been attending school. They kept me encouraged when I was down and humble when I was full of myself. The lessons that they have taught me are foundation on which I now stand. My parents set the golden standard of hard work, and have taught me by example. I am thankful for how they taught me that hard work is nothing to be afraid of. They have shown me what you can accomplish with a little time and dedication and that has given me the resolve to keep pushing even when I was at my limit. I wouldn’t be here now without them.

I would then like to thank my younger brother Cheston. Growing up our comradery and our rivalry taught me how to work well with people and build fulfilling relationships. Our relationship also taught me to push myself to do better whenever I could. Growing up with you gave me the competitive spirt that allowed me to rise up to the occasion and never settle for “good enough.” I owe much of my success to you.

Throughout my time here at the University of Idaho I have had many struggles and triumphs. My closest friends were there for me every step of the way. When I succeed they were by me and when I failed they were there to pick me up. I have formed some amazing friendships here at the University of Idaho that I hope preserve these relationships for the rest of my life.

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Chapter 1: Introduction to Design

1.1 Timeless Design

Engineers solve problems. We use what we have learned and our past experience to develop a solution to the current challenge. Engineers design mechanisms, structures, devices, control systems, circuits, or whatever to create an adequate solution. For mechanical solutions I believe that design exists on the intersection of theory, creativity, and manufacturability.

In this context what is referred to as theory is the solution to the problem that needs to be implemented. In the form of structures, it would be the area of beams to support a load; in thermo-fluids it would be the amount of heat needed to be transported from a working fluid. Physics and science provide the theory, and design is the implementation of governing principal into the physical world.

Creativity is the word chosen to describe the development of what the solution would look like. It is the choices made based off physics, math and past experiences. When properly performed it also includes the artistic decisions and clever choices to produce a product just as beautiful as it is functional. This is the most subjective area of design, but it is that portion of the design that makes it timeless.

Manufacturability answers the question of “can it be made.” There is little value in designing a product if it cannot be produced under reasonable methods. If designed well, a mechanical design should be able to function properly and maintain beauty, while being possible to create. Knowledge of the manufacturing methods available to the user can greatly influence the design.

A combination of physics, science, creativity and manufacturing like shown in Figure 1.1, is what leads to a great and timeless design. A design with these attributes works in a clever way that is easy to make and appeasing to look at.

1.2 The Evaluation of Design Concepts

This thesis focuses on the manufacturability of complex surfaces of two legacy designs. The first legacy design was the infill mallet from the Studley Tool Cabinet presented in chapter 2. The infill mallet was used as the subject to evaluate manufacturability of complex curves. The final legacy design studied was the water turbine of the Noxon Rapids Hydroelectric Dam in Montana which is presented in chapter 3. The principals of design and the lessons learned from the infill mallet were applied to the design and creation of a 1/80th scale model of the scroll cage. In both legacy designs the emphasis is on the aesthetics and functional aspects of the surfaces. In one instance the aesthetics are crucial to the fabrication of the design and the other to the physical function. These legacy designs were created long before computer based solid modeling and its ability to create any surface, practical or not. However, these legacy artifacts were fabricated without the use of modern modeling and manufacturing capabilities. It is the goal of this thesis to examine the intent of these legacy designs and their manufacturing or best estimate thereof, then apply just enough modern technology in order to recreate them.

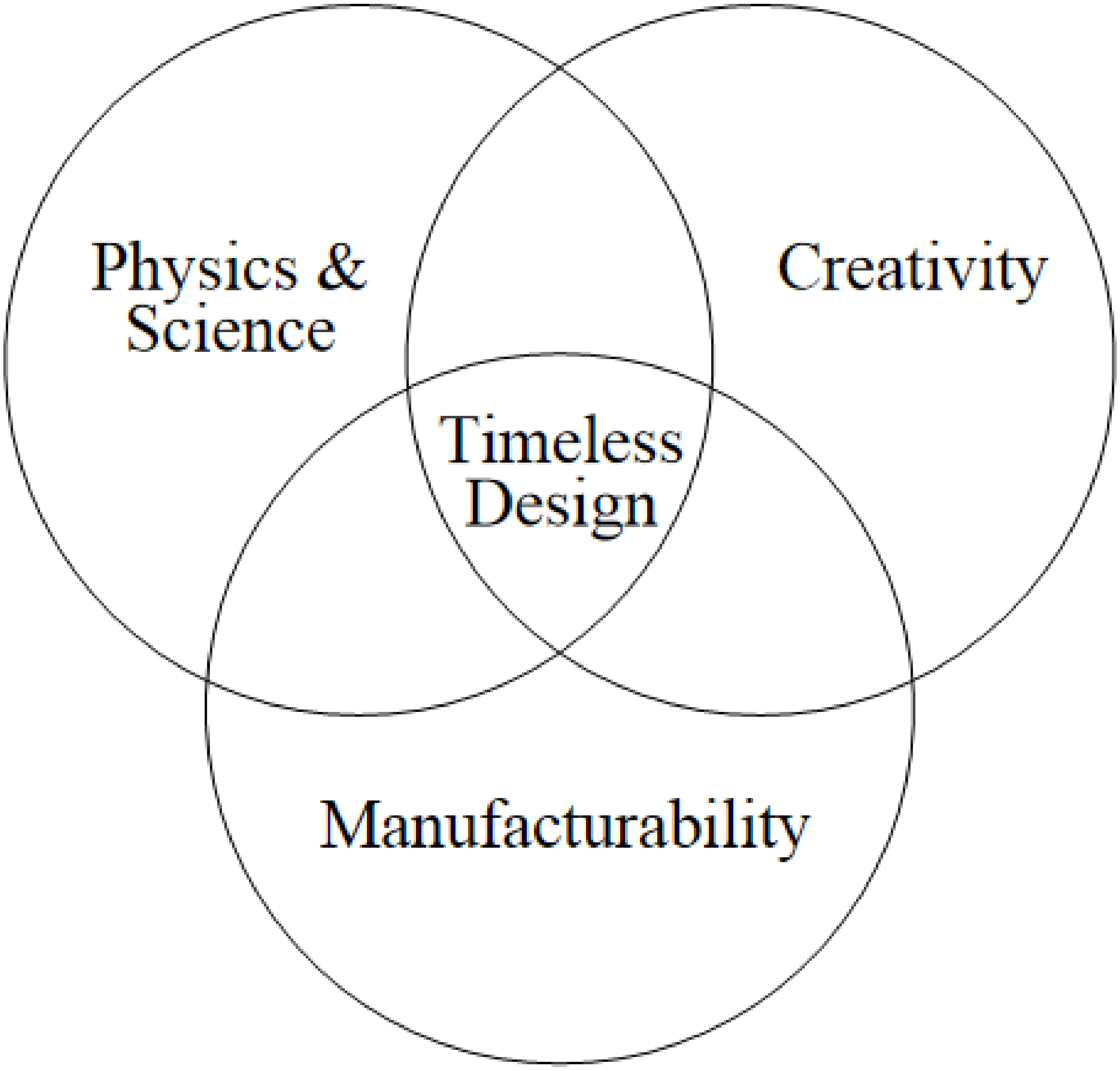


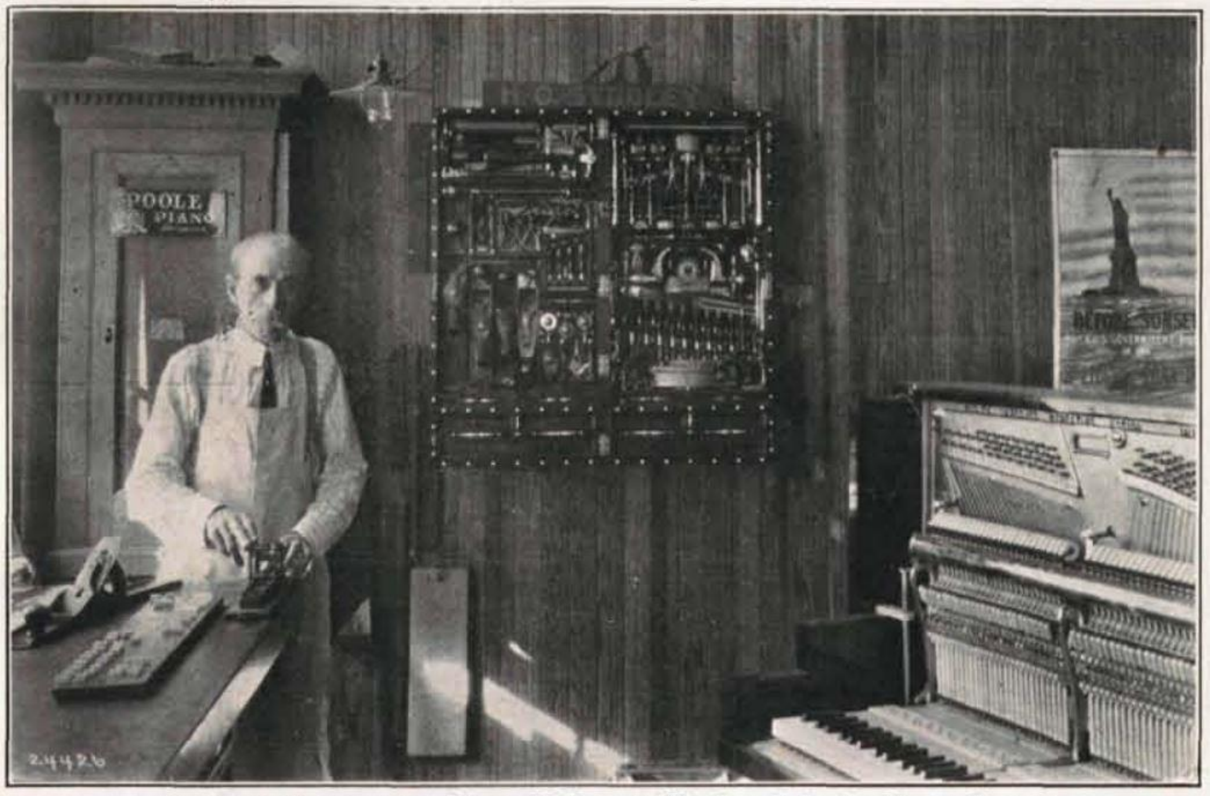
Figure 1.1: The combination that forms a timeless design.

Chapter 2: Modeling and Manufacturing of the Studley Tool Cabinet Brass Infill Mallet

2.1 Background of the Studley Tool Cabinet

A man who had mastered the attributes of great design was Henry O. Studley. Mr. Studley lived between the years of 1838 to 1925. He was a civil war veteran, master mason, and expert wood worker. At the end of his career Studley was a piano and organ maker for the Poole Piano Company in Boston, Massachusetts, until he retired in 1919. Studley was truly a master of his craft and his work is still famous among woodworkers and craftsmen. The capstone of his achievements, an intricate tool cabinet, has even been featured in the Smithsonian Institution’s National Museum of American History.

Near the end of his career Studley put together an amazing piece of fine wood working which is now commonly called the Studley Tool Cabinet. This Tool cabinet measuring just 39 x 19-1/2 x 9-15/16 inches houses over 240 tools. The cabinet served as a piece of art as much



H. O. Studley, Veteran Piano Maker, at His Bench in the Poole Factory

Figure 2.1: The only known photo of Henry Studley that exist. He is standing at his workbench with the tool cabinet behind him at the Poole Piano Company. This photo was taken from “The Music Trade Review,” March 30, 1918, on page 27.

as it was a functioning tool storage location. The tool cabinet was made from materials that were commonly available to Studley while he worked at the Poole Piano Company. The primary wood that was used was mahogany with Gabon ebony details. The outside edges as well as the areas around the draws were inlaid with mother of pearl accents. Without the tools the cabinet is just as pleasing to look at. Each detail of the cabinet was created with ultimate craftsmanship and precision. The piece seems as if Studley created the cabinet largely to show off his immense skill at his trade.

The interest with the cabinet at the University of Idaho started with my major Professor Dr. Edwin M. Odom. It was his goal to add the chest to his “Advanced SolidWorks and Manufacturing” course. It was his vision to see the tool cabinet modeled in SolidWorks and ultimately have an assembly video of the all the tools in the cabinet flying into their custom fabricated mounts as Mr. Studley would have placed them himself. The tool cabinet became a project that we were unable to let go of. During the “Design Intent” course the following semester, the first semester of my graduate program, the focus was narrowed to one tool in the chest, a brass and beech infill mallet.

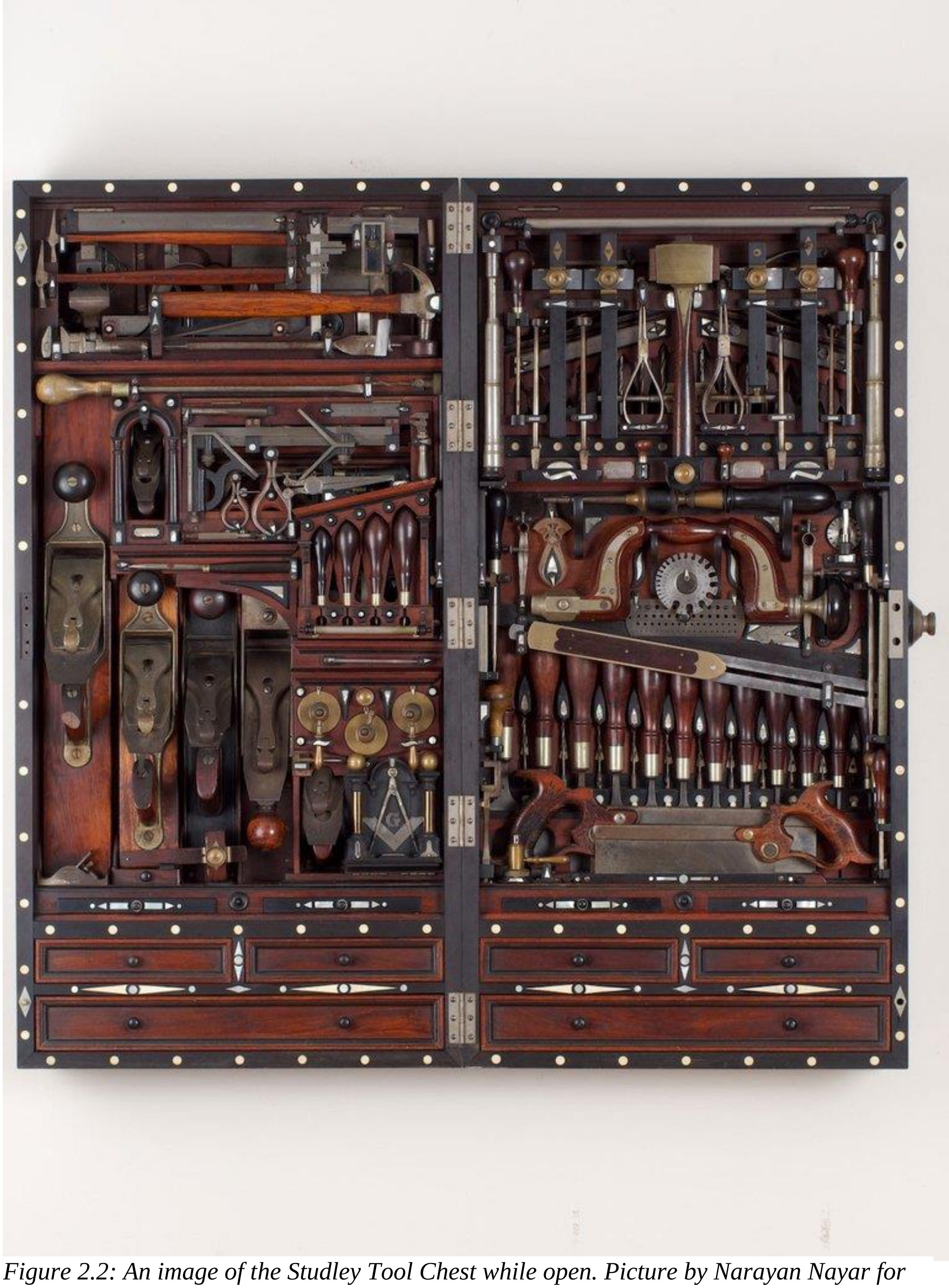


Figure 2.2: An image of the Studley Tool Chest while open. Picture by Narayan Nayar for use in Williams' book (Williams D. C., 2015).

In the upper right-hand corner of Mr. Studley's Cabinet there is an infill mallet. The mallet tends to catch the eye of anyone who looks at the open cabinet. As seen in Figure 2.2 the upper right portion of this assembled tool cabinet is section off by lines of the compartments as well as a few outlining tools. The bodies of the tools in this section all hang vertically giving an ordered impression, while the blocks on the ebony marking gauges bring your eyes to center. The tools are arranged in a symmetric pattern with the most prominent tool, the infill mallet, as the line of symmetry and vanishing point. Behind the first layer of tools the lines in the chest all point to the bottom of the brass inset of the hammer. The gothic arches at the top of the drill bits in the second layer appear to be the pillars holding up the structure of the cabinet all pointing toward the mallet. It is as if Studley chose the tool for us.

The mallet itself is a piece of beauty. The handle is rosewood with inset brass triangle that holds together the brass outer shell and the infill beech block. The mechanical purpose of this mallet is to have a high mass hammer with a non-marring surface. This style of mallet would be used for joining work or anything that needs extra motivation, without damaging the striking surface. The original hammer that Mr. Studley produced is shown in Figure 2.3.

Figure 2.3: Mr. Studley's brass and beech infill mallet. The picture is by Narayan Nayar for use in Williams' book (Williams D. C., 2015).

2.2 Introduction to the Infill Mallet

The initial project was to create a replica of Mr. Studley's infill mallet at the University of Idaho using our in house machine shop. However, this project transformed into a thesis of complex surface manufacturing. A solid model of the hammer head was created in SolidWorks using the following two paragraph description from Donald C Williams' book, "Virtuoso: The Tool Cabinet and Workbench of Henry O. Studley." It read as follows:

"Infill Mallet

Dimensions: The mallet's overall length is 11" with a weigh of 17 ounces. The distance of the handle to the coved shoulder is 8-3/4", and the head overall with coved details is 2" on the tool's long axis. The length of the shell at the bottom of the head is 2-7/16"; at top it is 2-5/8". The head width at the bottom and top outer dimension is 1-3/8", the inside dimension at the same points is 1-7/32", and the infill block is 3-1/16" long from end to end the major cross-section axis of the handle is 15/16" and the minor axis is 3/4".

Notes: Studley-made or modified. The mallet has a rosewood handle with a brass triangle inset on either face where the handle meets the head, plus a brass button on the end of the handle. The head is a sand-cast shell with a beech infill. The shell has the same coved edge detail as the ends of the marking gauges; the face of the head shell is slightly declined toward the handle-about 1/16" taper – and the head is slightly bombé on both axes. At the entry and exit points for handle the head has a cove detail as a shoulder fillet, and there is a nail and wedge arrangement at the top that protrudes ¼" from the head." (Williams D. C., 2015)

Using the description from Williams' book and a few other images of the infill mallet from Williams' website "The Barn on White Run," we began to create SolidWorks models for the brass portion of the infill mallet to manufacture in our machine shop. It was at this stage that the project truly began.

It is important now to talk about how the original mallet was made. The brass outer shell of the mallet was most definitely sand cast as was stated by Williams. Sand casting is the obvious method of choice considering the surface geometry and the time-period that it was created. Attaining all the curves and features on the mallet would be difficult with any other method. When the mallet is observed close up, a few sand pitting marks can be seen in the metal further proving this technique. At the time of this mallet's manufacturing and the likelihood that it was Mr. Studley that created it, it was assumed that the pattern for the hammer was most likely hand carved to produce the geometries that were desired.

The geometry of the infill mallet was not only for the aesthetic appeal. In Williams' description the infill mallet is "bombé on both axis." Bombé refers to a curvature on the hammer head; on both axis means that the surfaces are not just rounded around a single axis of rotation, but curved in two directions. These features although pleasing to look at, are included to allow release of the pattern from the sand during the casting process. In the case of the infill mallet these surfaces were necessary for manufacturing.

Using the Studley Tool Cabinet Infill Mallet as a subject, this chapter will compare and contrast three different manufacturing methods to achieve the mallet's complex geometry. The first method is that of sand casting and finishing work done with hand tools. This method of manufacturing is the most similar to the process that Mr. Studley would have conducted to produce the original infill mallet. The sand casting process that was conducted for this thesis is presented in section 2.3. To prove the concept of manufacturing the infill mallet using subtractive manufacturing methods, the second manufacturing of the infill mallet is presented in section 2.4. This proof of concept is a 2.5 axis machining using linear and planar geometry. Finally to reproduce the full curved surfaces of the infill mallet using subtractive methods a virtual 5-axis version of the infill mallet was created. The different manufacturing methods of the infill mallet are compared and contrast on the basis of the quality of the manufacturing method and the production cost per unit.

2.3 Sand Casting Manufacturing

2.3.1 Introduction

To understand what the challenges Mr. Studley encountered in manufacturing the original infill mallet and features used in his design, creating a sand casting was pursued. 100 years later Mr. Studley cannot be asked why he made the choices he did when creating the mallet during the synthesizing stages of his design. As explained by Jon Kolko the synthesis of a design can occur privately without pen and paper (Kolko, 2010). Using abduction also described by Jon Kolko "as the argument to the best explanation," inferences as to why the infill mallet took the form it did could be made. Knowing the manufacturing method of the original infill mallet and the mallet's design intent this section explains our pursuit into understanding the synthesis of the form Mr. Studley created.

In sand casting the molten metal is poured into a mold and fills an empty cavity. Once the metal has been allowed to cool and harden the metal retains the shape of the cavity it was poured into. The cavity is formed by compressed green sand. Simply put, green sand is a mixture of materials like sand, pulverized coal, bentonite clay and water that compresses and retains shape easily (Reliance Foundry, 2017). The sand is compressed by around a pattern that is of the shape of the final product. A flat surface or line of symmetry is needed to base the draft of the pattern to allow for removal after the sand had been packed around it. The manufacturing method of casting is beneficial as the desired geometry can be made from an easy to manipulate material such as wax, clay or plastic. Casting is also an efficient use of material as very little is wasted during pouring and scrap material can typically be reused (Reliance Foundry, 2017). Sand casting allows for the use of the 3D printing to create the patterns, but became challenging to create a hollow shell like that of the infill mallet. The pattern would leave an indent in the sand, but to create the hollow shape that allows for the handle and beech infill, a core would be needed as well. With these challenges in mind the process of design began.

2.3.2 CAD Design

The creation of the solid model for this sand cast infill mallet would challenge the skills of most prismatic solid modeling program users. The manufacturing method that was to be used created a need for consideration on how the hammer was going to pull out of the sand. Manufacturing the hammer head by this method allows for simple manufacturing of complex surfaces as long as they are all draft from the same direction of pull. Mr. Studley used curves to hide his draft angles leaving an aesthetically pleasing shape. The curves were imitated in the sand cast version of the infill mallet that was designed at the University of Idaho. Typically, in casting it is safe to have three degrees of draft on all surfaces that would otherwise be straight. A smaller draft angle can yield success, for example, two degrees or less can also be used with non-complex shapes. For small features even zero degrees of draft may be successful. In the design of the sand cast infill mallet replica, the curves were tangent to the direction of pull at the parting surface leaving an instantaneous zero degree of draft. The dimensions of the curves were altered to ensure that the bulk of the surface would remain above 2 degrees of draft while still resembling the original mallet. To maintain the aesthetics of the hammer and to create the bombé surfaces that were described by Williams, swept circles and arcs were used to create the hammer’s curved surfaces. The dimensions of these curves used to create the hammer are shown in Figure 2.4.

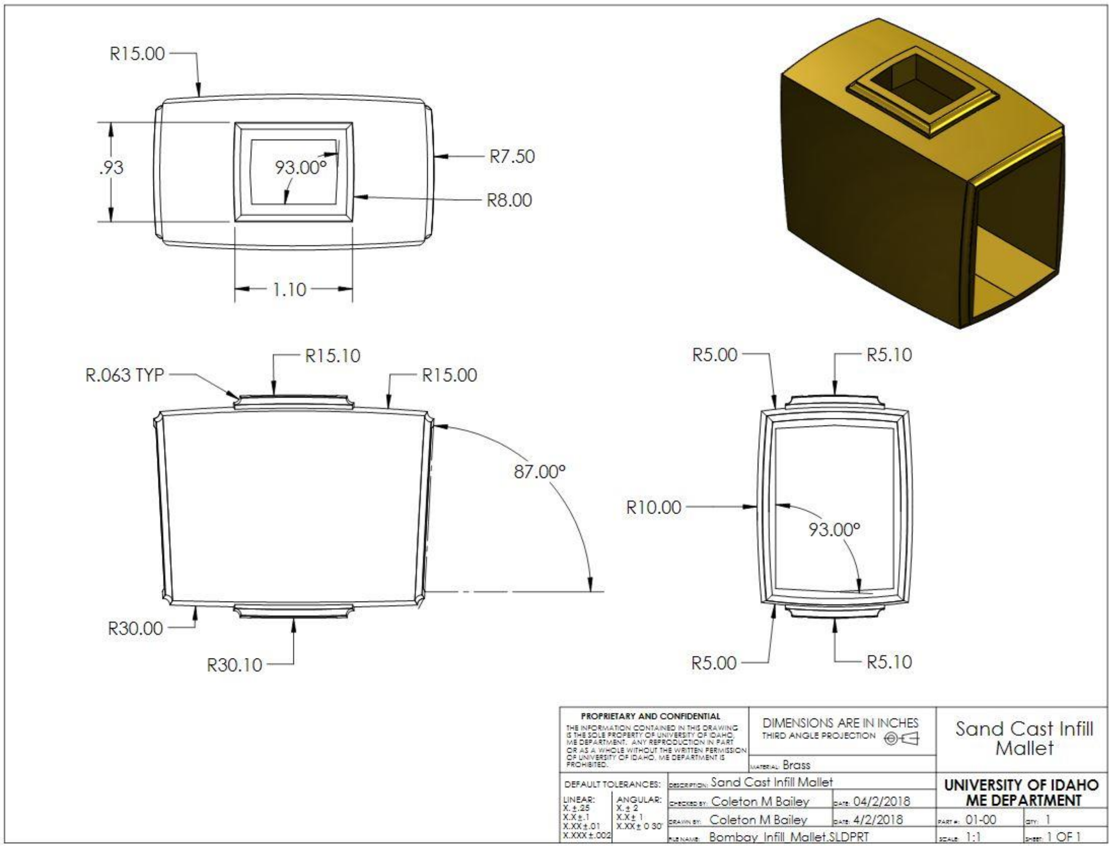


Figure 2.4: A drawing showing the curvature on the faces, and the draft angles inside the hollow shape of the sand cast infill mallet.

The infill mallet with the curved surfaces was modeled using the prismatic modeling tools in the “Features” bar in SolidWorks. First an extruded block was created around the origin of the workspace to make symmetrical features easy to model. Modifiable variables were added to govern the curves of the hammer. With these variables the curvature of the hammer could be changed to better match the aesthetics in the images from the original infill mallet after the modeling was complete. The main curves of the hammer were created by using swept cuts in a giant arcs where the profile of the cut were circles. This action created the two directions of curvature on a single surface of the infill mallet. This process was repeated with all sides of the hammer until the geometry resembled that of the original.
The process of creating these shapes can be seen in Figure 2.5. The result of this work can be seen in the rendered image in Figure 2.6.

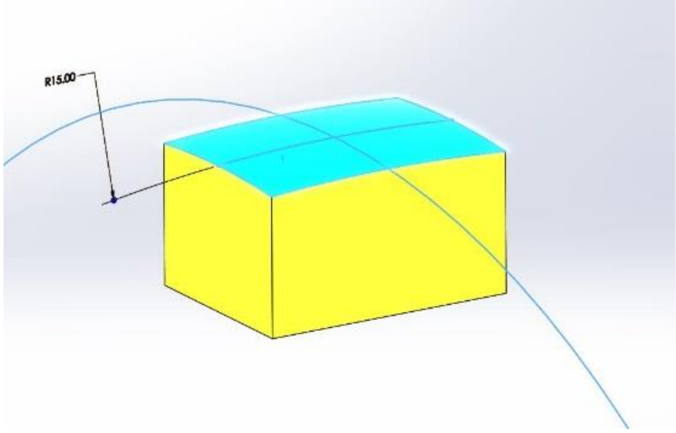


Figure 2.5: An image showing the process of creating one of the curved sides of the bombé mallet.

With the general shape of the infill mallet completed the next step was to add the through holes for the infill and the handle. The two through holes on the mallet were surrounded by a cove detail on both the start and end of the hole. The through hole of the handle also had bosses surrounding the entry and exit. All of these features would need to have a draft angle away from the direction of pull, or in the case of this sand casting curvature. The curvature of the bosses was projected off of the curvature of the top and bottom surfaces to be consistent. Referring to the drawing in Figure 2.4, the change in radius on these surfaces can be seen. This change in dimension is due to the concentric center of the arches. The sides of the bosses whose normal would be perpendicular to the normal of the

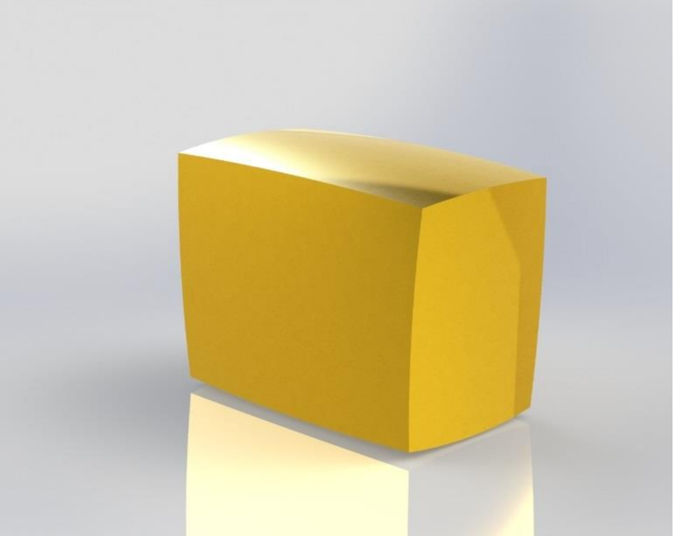


Figure 2.6: An image of the CAD model after adding curvatures.

parting plane were curved to angle from the direction of pull. The result of this process was a curve with an axis of rotation that exists in three dimensions. Bosses were created that extended out to the end of the part body around the through holes and fillets were added into the corners to create the cove detail.

The holes through the part proposed their own challenges. The core described in 2.3.3, required 3° draft from the direction of pull. This resulted in the inside surfaces of the infill mallet retaining the same draft from the parting surface. The effects of this internal draft angle can be seen in the final rendering of the infill mallet in Figure 2.7, and in the drawing in Figure 2.4.

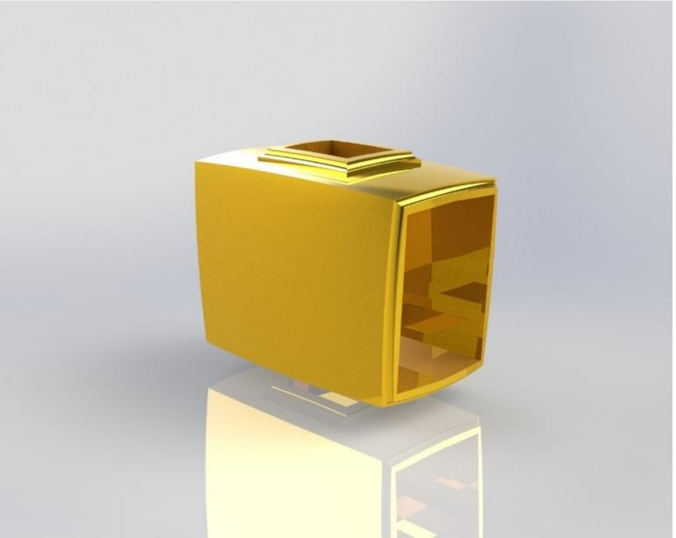


Figure 2.7: Image of the finished sandcast model.

2.3.3 Pattern and Core

With a finished model complete the next step was the design of the pattern and core for the sand casting. In sand casting, green sand is packed around the pattern on to create an indentation in the sand. The pattern is then removed and the core is placed inside the created cavity. Gates and sprues are added into the sand to allow the molten metal to flow through the cavity and harden. Once the metal has cooled it is removed from the sand and the gates and sprues are cut off and ground flush with the rest of the surface. A pattern and core for this version of the infill mallet was designed with this process in mind.

As discussed in the previous subsection 2.3.2 the pattern of the infill mallet was to be 3D printed. This was to eliminate the material and geometry constraints of other manufacturing methods. The core however, needed to be present in the sand during the casting process and could not be made of plastic. To solve problems like hollow shapes it is common in the casting industry to use a hardened sand core. To make a hardened sand core, green sand mixed with a hardener is molded into shape and hardened with CO_2 or temperature. Hardened sand is more capable than green sand in handling the stresses from bridging gaps, the flow of metal and the buoyancy forces during the casting process. For the sand to retain its shape while hardening, a mold needed to be created that could be baked with the sand. To allow for the release of the core once hardened a 3° draft angle was added to all vertical sides of the mold. A drawing of this mold is shown in Figure 2.8.

The pattern and the core must be designed together as they interact with one another during the casting process. To create the pattern for this design the model was cut in half along the center of the beech insert cavity. Doing so reduced the modeling time and can be advantageous during the sand casting process explained later in this section. Ledges were then created that extended out of all the holes to create an indent in the sand for the core to rest on. The corners of these corners were curved so that a mold for the core could be created

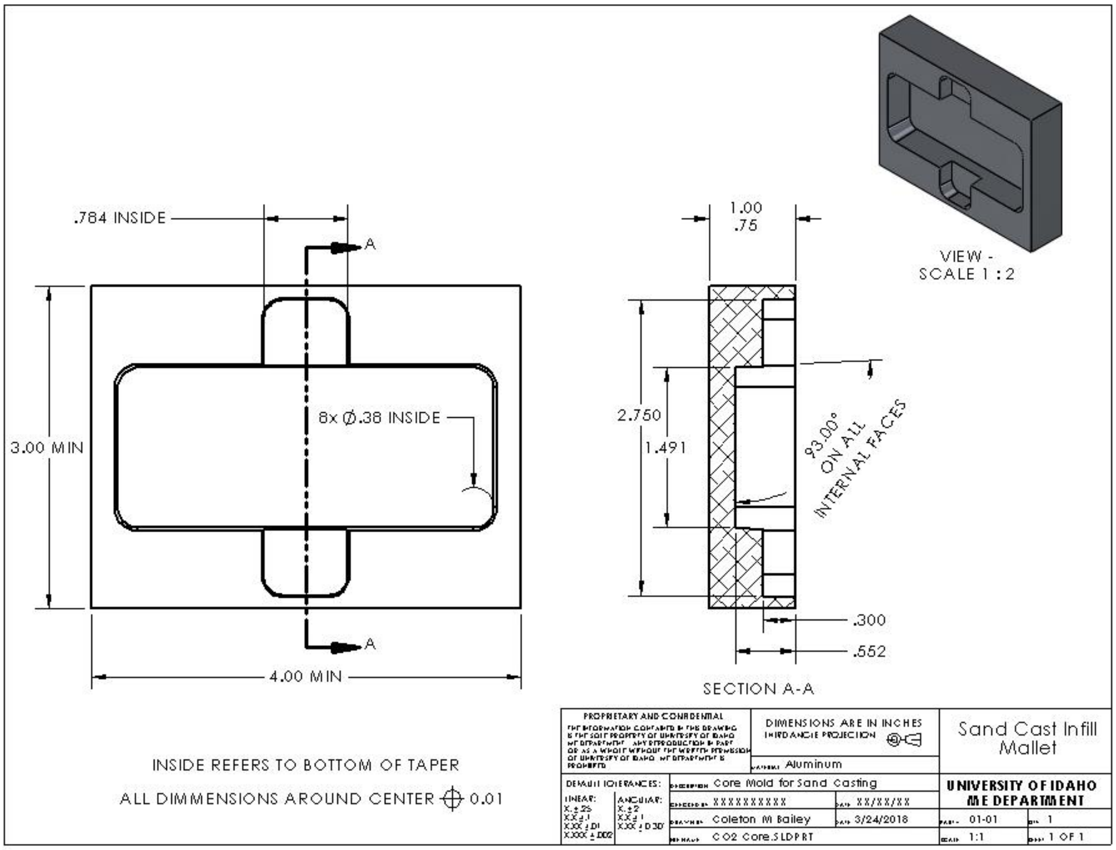


Figure 2.8: Drawing of the mold used to make the core for the sand casting manufacturing method.

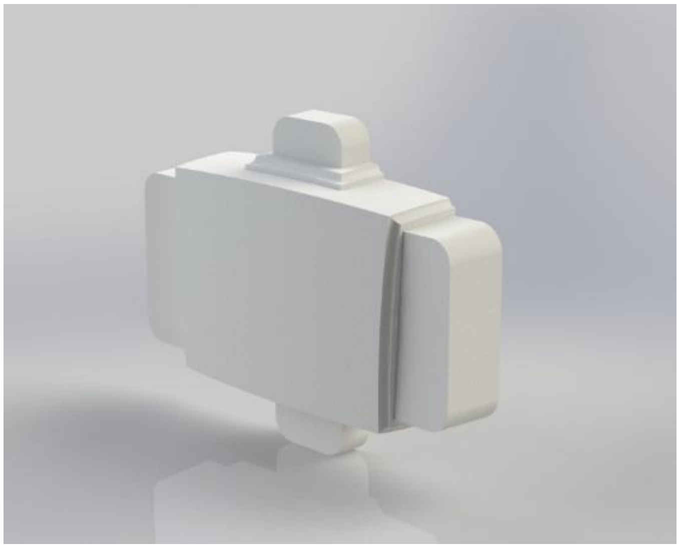


Figure 2.9: An image of a single halve of the pattern used to create the sand cast infill mallet.

in house on a three axis mill and a tapered endmill. One side of the resulting pattern can be seen in Figure 2.9. The back side of the pattern was hollow. This design choice was made to reduce the amount of material needed for 3D printing. To ensure alignment of the two halves during the sand indentation process holes were added to the back side of the pattern halves intended for 1/4-inch dowel pins. The model of the infill mallet like the original, was not symmetric over a plane normal to the axis that runs through the center of the handle. If the

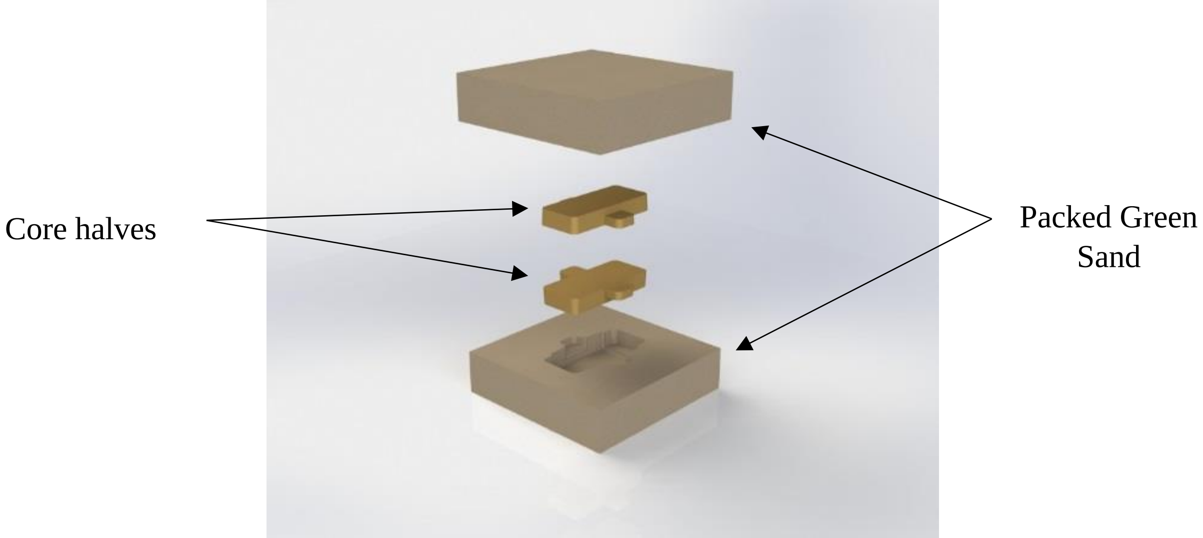


Figure 2.10: The concept assembly of the sand casting used. The top and bottom blocks are the formed green sand while the lighter colored center is the hardened core halves made from the mold in Figure 2.8 that rest on the shelfs made by the pattern in Figure 2.9.

hardened sand core extended the same distance out of both sides of the infill mallet, the orientation of core would need to be specified. To prevent this the core was centered on the infill and handle holes and designed to be symmetric. As a result of this difference in geometry, one ledge extended further out of the body than the other. The sides of the ledges also had to be tapered to match the taper on the core mold. The combination of the core and pattern would create a cavity in the sand in the final shape of the infill mallet. A rendered image of the idealized assembly is shown in Figure 2.10.

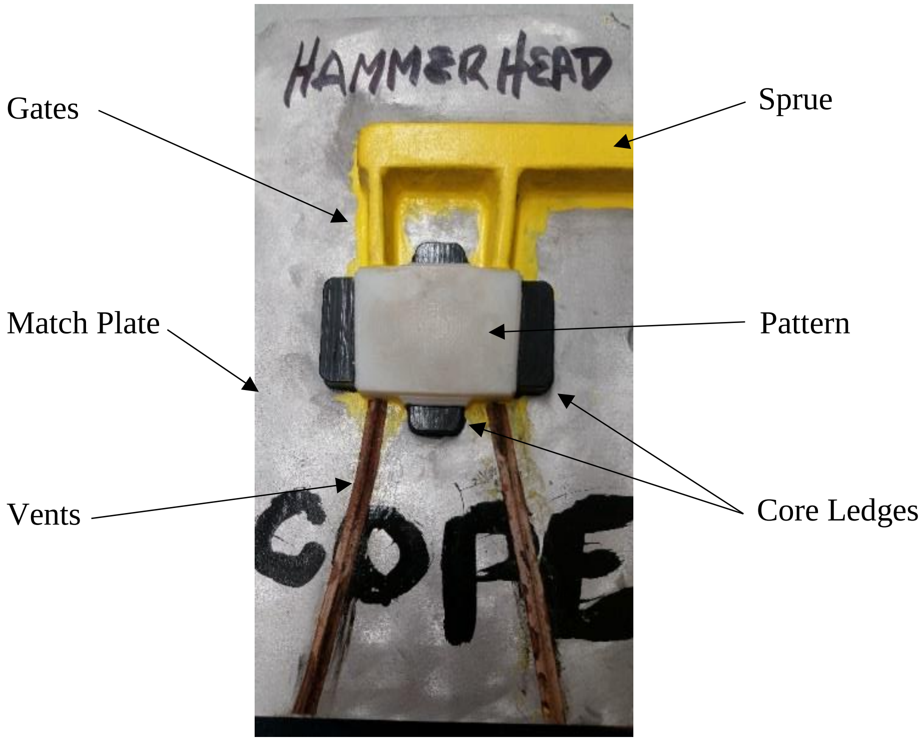


Figure 2.11: An image of the SEL printed pattern attached to the match plate that was used to sand cast the hammer head. The gates and risers are already added.

With the concept of the pattern and core designed, the process of manufacturing began. The size, geometry, and intended use of the pattern made 3D printing the obvious choice. The complex surfaces and square corners would make it difficult to machine or manufacture by other methods. In this application the strength provided by a 3D printed material would be more than adequate. In the Mechanical Engineering Department at the University of Idaho printers with the capability to print PLA and ABS plastics were available in house. PLA plastic is easier to print and holds up well mechanically. ABS plastic requires a heated printing bed and enclosure and has a preferred impact resistance. ABS however, has the added feature of dissolving when subjected to acetone in a process called vapor smoothing. To properly release from the sand the surface of the pattern had to be smooth. Whatever defect or indentation on the pattern would also show up in the final product. For this reason patterns were printed out of both materials in order to determine which would give the best surface finish and be used as the pattern. This process is described in the appendix.

As explained in the appendix neither material was capable of achieving our goals while using standard desktop 3D printers. To solve this problem we reached out to Schweitzer Engineering Laboratories (SEL). The pattern for this hammer head became a test piece to refine their 3D printing process. SEL used a high accuracy 3D printer to print PLA with a greater precision than the desktop printers previously used. The layer height of these prints significantly decreased the layer height of the pattern to the extent that no post processing was

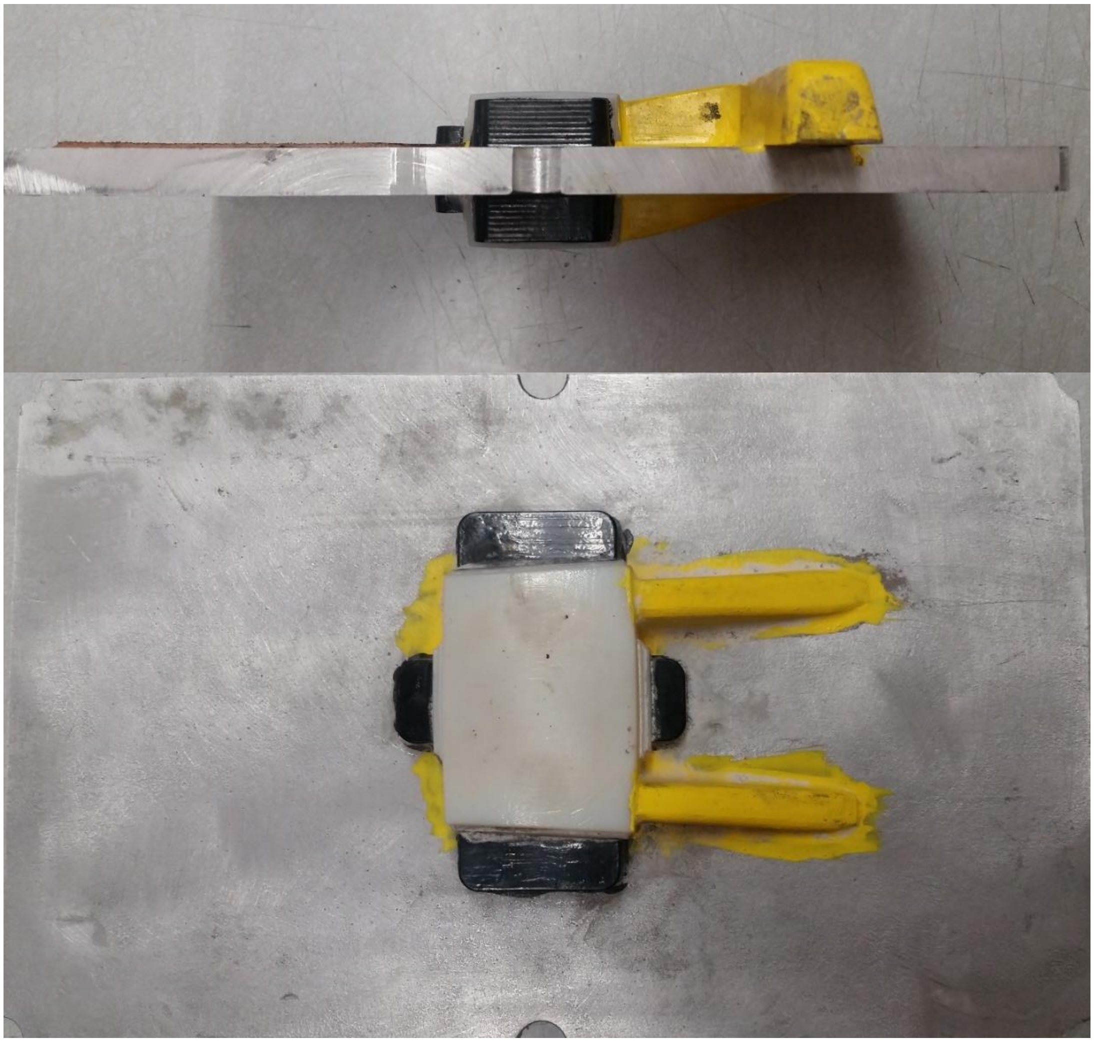


Figure 2.12: Images of the side and back of the pattern mounted to the match plate from Travis Pattern.

required. This print without modification became the print that we used for the sand cast pattern. The final print can be observed in Figure 2.11.

Sand casting is no longer a manufacturing method practiced at the University of Idaho. As a result we sought help from a local foundry in Spokane, WA, “Travis Pattern & Foundry Inc.” The foundry volunteered to help us in this endeavored and took control of the casting process from this point on. The staff at Travis Pattern mounted the 3D printed pattern to a match plate and added the gates and sprues. In match plate casting two halves of a pattern are mounted to a plate that acts as the base for the sand to be packed around. After the indentation of the pattern is made the entire plate is removed and the cores are put into place. The match plate that was returned with the final pattern can be seen in Figure 2.11 with alternate views in Figure 2.12.

2.3.4 Results

The sand casting of the hammer head was a success. About two weeks after dropping off the pattern and the core mold to Travis Pattern the finished product was returned. The surface finish was rough, and there was evidence of rotation of the pattern, but the overall shape and appearance of the hammer was well achieved and ready for post processing. It was apparent that a significant amount of post casting work was required to make the surface shine like the original mallet that Mr. Studley had in his tool cabinet. It is interesting to note that Mr. Studley 100 years ago and the University of Idaho today completes the final finish in the same way: file, sand paper, polish.

With a Dremel Micro, small flat file, and round file the process of reshaping the cove details and finishing the surfaces of the infill mallet began. The Dremel was used in order to quickly sand down the surfaces until the general roughness of the sand casting was removed. This gave a base point to file down the brass to remove as many sand pits as possible and create a continuous surface. The round file was used to recreate the cove detail which was almost all lost during casting. The inside holes were remade by attaching sand paper to a thin board and running the hammer back and forth to ensure that the holes would be lines up properly on the top and bottom. Pictures of the refinishing process can be seen below.

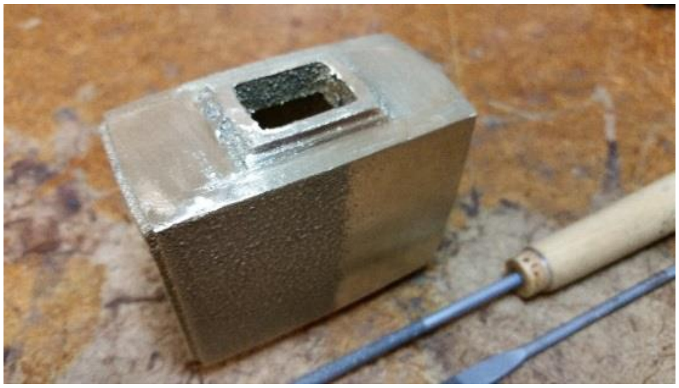


Figure 2.13: Recreating the top boss using a round file and a flat file.

Figure 2.14: Smoothing out have of the first face using a Dremel Micro with a sanding attachment and wire brush.

Figure 2.15: A raw hammer head delivered by Travis Pattern and Foundry.

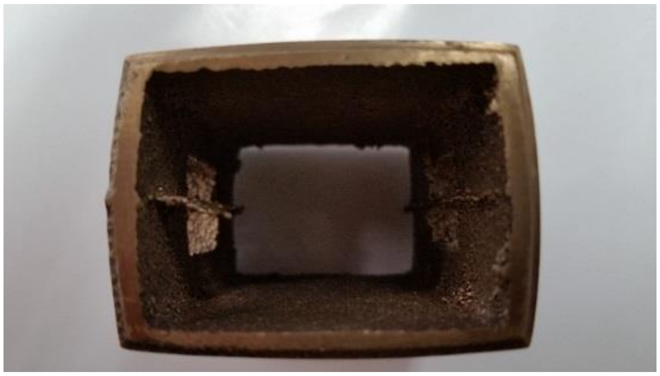


Figure 2.16: Inside the center of the sand cast hammer before post processing.

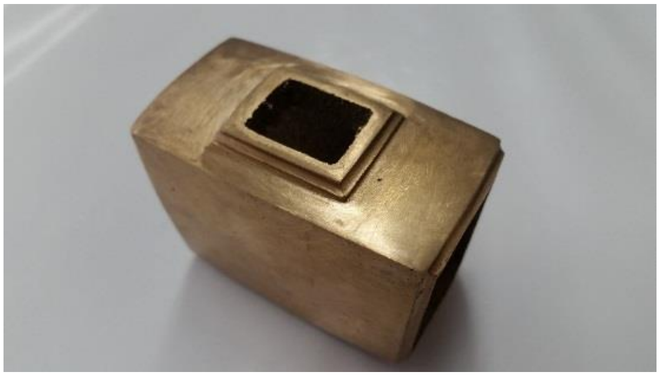


Figure 2.17: The sand cast hammer after the reformation of the top and side cove detail and the top and side surfaces.

2.3.5 Discussion and Conclusion

This version of the Studley Tool Cabinet infill mallet is as close to the original version as can be reasonably produced. This infill mallet was manufactured in the same way that Mr. Studley would have produced his all those years ago. The addition of the 3D printing technology made the processes easier and more reproducible, but the results would be very much near the same. With more iterations of this pattern the gates and risers could be adjusted in order to reduce the amount of sand pitting and improve upon the initial finish leading to less post casting work. This form of manufacturing the infill mallet is the most simple and repeatable. Once all the upfront work of creating the pattern and core is completed it is a reasonably quick and easy process to increase the production scale of the infill mallet. More patterns could be made and added to the same match plate to increase the number of hammer heads with each pouring, or the pattern could be used to make multiple indentations. The surface finish of the hammer will always be rough as the forming medium is sand. With the additional work of cutting and grinding off the gates and risers, this infill mallet has the largest amount of post manufacturing work that needs to be done to make a finished product. The surface finish however does not affect the function of the hammer. A rough looking infill mallet will still transfer energy to whatever the infill is coming in contact with.

The geometry this manufacturing method of the infill mallet is not ideal. Because of the casting process the infill had tapered sides on the internal holes. A regrettable detail that seemed to be mostly avoided in the original infill mallet design. It is likely that a different method of creating the core, or a lesser degree of draft was used by Mr. Studley. Although a slight angle on the inside of the shell will more than likely not affect the performance of the hammer, it is still a visible feature that if removed would make the form more aesthetically pleasing.

Overall this is a fine way of reproducing the Studley Tool Cabinet Infill Mallet. Costing only $70 to pour each casting, this method of manufacturing is the most economical out of the manufacturing methods with the worst surface finish, and the second best geometry.

2.4 Manufacturing using 2.5-Axis Control

The sand casting of the infill mallet provided a better understanding of what Mr. Studley was thinking during the design and creation of his original version. The next step in the exploration of this topic was to recreate a similar infill mallet using alternative manufacturing methods. The method that was chosen to be explored was manufacturing using 2.5-axis control of a CNC mill. This method was chosen because it was knowingly achievable with our initial knowledge and familiarity of the manufacturing process. This is not the first reproduction of Mr. Studley's infill mallet that had been created using this method. A Mr. Jim Moon assembled a replica of the Studley Tool Cabinet in which he also created an infill mallet head using subtractive methods (Moon, 2016). The geometry of his infill mallet was simplified from the original version. Judging by the images presented in the "American Period Furniture" journal, Mr. Moon was able to reproduce single axis curves on the top and bottom faces of the infill mallet. The 2.5-axis mallet created at the University of Idaho has geometry achieved that differed from Mr. Moon's mallet. From the start we knew that it would be extremely difficult to retain all the geometry of the original sand casting while being able to easily align the mallet after repositioning. The simplified version of the infill mallet retained the cove detail and a few single direction curves of the original infill mallet. The geometry of the 2.5-axis version did not contain any complex curves like that of the sand casting. The manufacturing of this mallet provided lessons needed for the virtual 5-axis infill mallet discussed in in section 2.5 to be achieved.

2.4.1 CAD Design

The mallet that was created utilizing the 2.5-axis control of a HAAS Tool Room CNC mill was based off a version of the infill mallet originally drawn by undergraduate student Meghann Hester. Meghann modeled that mallet as a part the University of Idaho's "Design Intent" course. The final production of the mallet varied from her original model to produce using standard tooling. The curves that were included on this hammer only existed on the top, front, and back faces of the mallet. All curves that were included in the model were around an axis of rotation that was parallel to a coordinal direction. The bosses on the top and bottom of

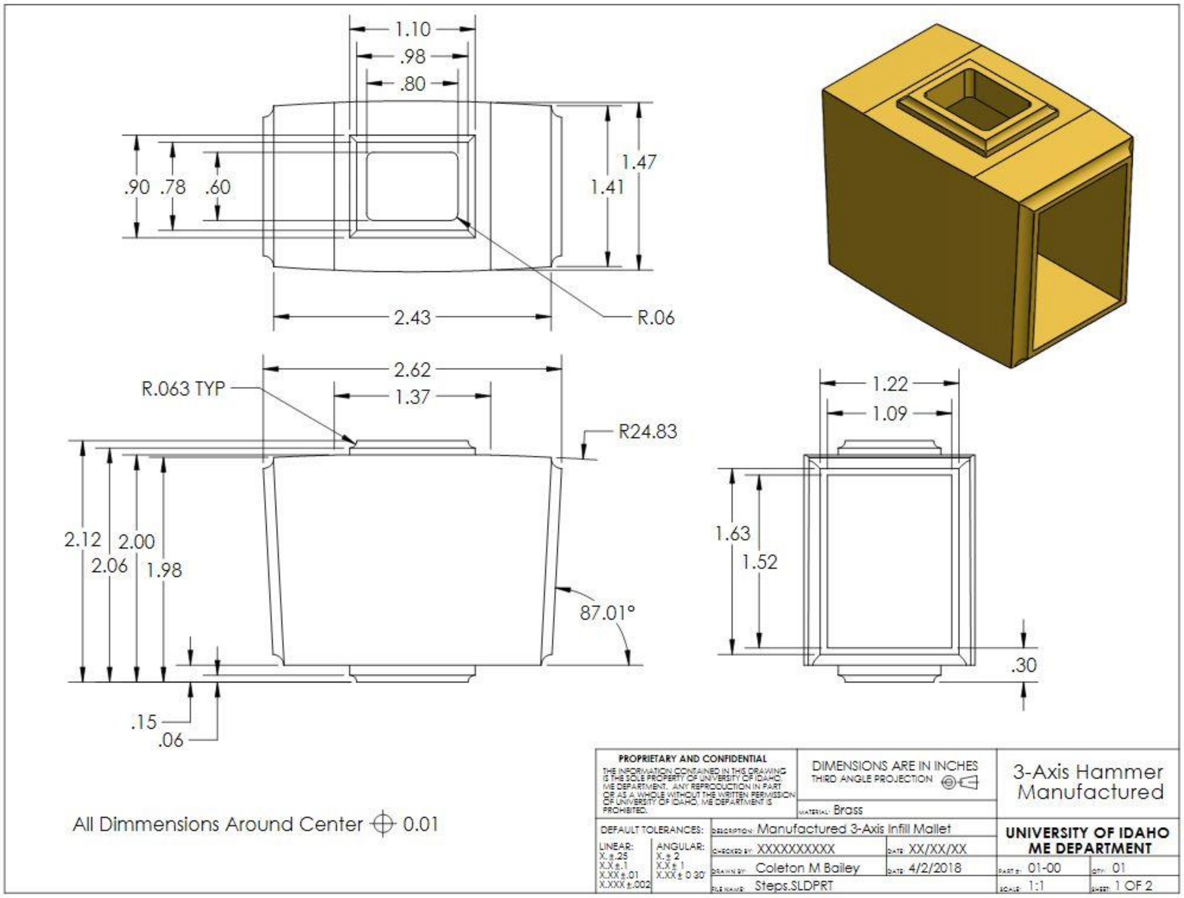


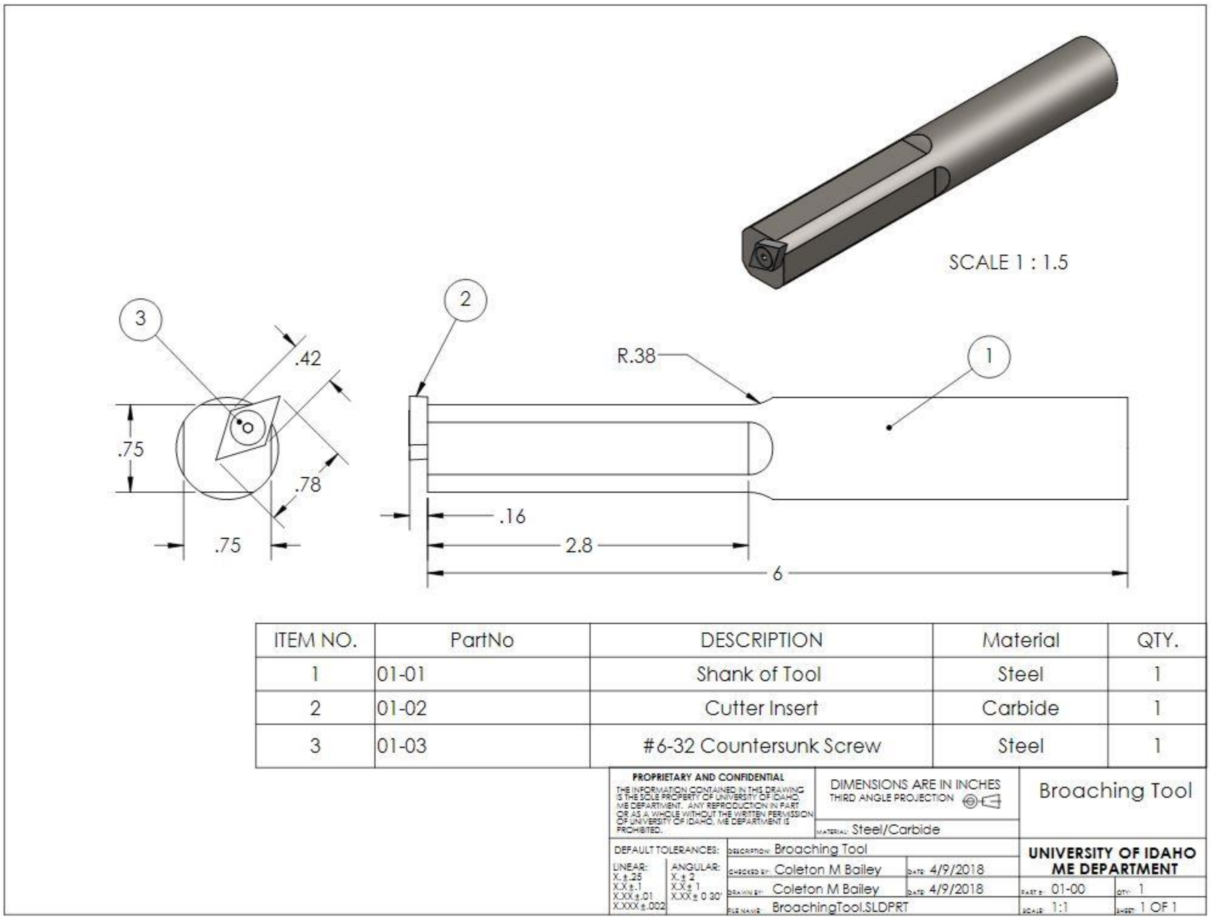
Figure 2.18: A drawing of the 2.5-axis hammer head that was manufactured to prove the concept of manufacturing the infill mallet with subtractive methods.

the hammer were kept to be prismatic, and the bottom face was made to be flat. The ends of the mallet where the beech infill would protrude were angled, but not rounded like that of the sand casting. These design choices allowed for the infill mallet to be produced and fixtured using standard methods and 2.5-axis control. The geometry of the hammer modeled can be seen in the drawing in Figure 2.18.

2.4.2 Machining Process

2.4.2.1 Operation 1

The first operation of the 2.5-axis machining process was to create the through hole for the beech infill. This operation is the first in which the difficulties of using subtractive manufacturing to create the infill mallet were encountered. For a square block to fit through the hollow center of the mallet the internal corners of the brass had to be square. To accomplish this 1/8-inch holes were drilled at the center of each corner to remove as much material as possible. Then using a long 3/8-inch endmill the majority of the hollow shape was milled out from both sides. The length of the mallet created a depth that was greater than our longest available 3/8-inch endmill and 1/8-inch drill bit thus this operation was performed on both sides of the block. The final operation was to broach the corners of the through hole to make them square. The broach was a custom tool made from a section of 7/8-inch diameter steel round stock. The sides of the shaft were milled to allow for the body of the broach to fit inside the already milled hole. A carbide insert was attached to the end of the steel shaft to act as the cutter. The broaching tool created is pictured in Figure 2.20. Using manually written G-Code the 2.5-axis control was used to plunge the cutter through the depth of the hole in .002-inch increments repeatedly to create a sharp inside corner. This was repeated for every corner of the beech through hole. The top hole was not subjected to the square corner broaching as the broaching tool was too large. With how the handle of the infill mallet would wedged against the sides of the brass and beech insert upon assembly, the square hole was deemed unnecessary for the effort needed to complete the operation. A rendered image of the infill mallet after this operation is shown in Figure 2.21.



ITEM NO.	PartNo	DESCRIPTION	Material	QTY.
1	01-01	Shank of Tool	Steel	1
2	01-02	Cutter Insert	Carbide	1
3	01-03	#6-32 Countersunk Screw	Steel	1

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DIMENSIONS ARE IN INCHES
THIRD ANGLE PROJECTION

MATERIAL: Steel/Carbide

Broaching Tool

DEFAULT TOLERANCES:
LINEAR:
X. ±.25
X.X ±.1
X.XX ±.01
X.XXX ±.002
ANGULAR:
X. ± 2
X.X ± 1
X.XX ± 0 30'

DESCRIPTION: Broaching Tool
CHECKED BY: Coleton M Bailey
DATE: 4/9/2018
DRAWN BY: Coleton M Bailey
DATE: 4/9/2018
FILE NAME: BroachingTool.SLDPRT

UNIVERSITY OF IDAHO
ME DEPARTMENT

PART #: 01-00
QTY: 1
SCALE: 1:1
SHEET: 1 OF 1

Figure 2.19: Drawing of the broaching tool that was designed to create the internal square corners of the infill mallet.

Figure 2.20: Broaching tool used on the internal

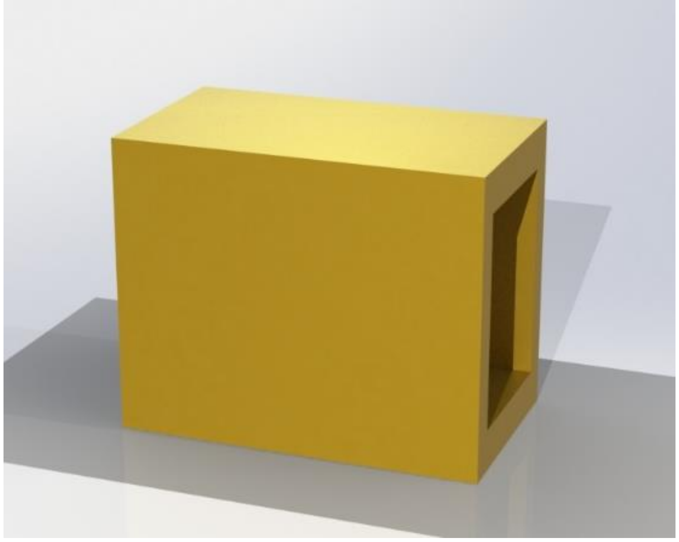

Figure 2.21: A rendered image of the hammer head after the second operation was complete.

2.4.2.2 Operation 2

As a result of the similarities in shape and operation, the creation of the top and bottom bosses and their cove details will be considered as one. This operation used an endmill to create the bosses on the top and bottom of the mallet, and the sharp corners where these features meet the main body. The level of the bottom of the boss was machined across the entirety of the surface as pictured in the drawing in Figure 2.18. The hole for the handle through the top and bottom bosses were also milled at this time. With the bosses created and the surfaced leveled a 1/8-inch ball endmill was used to create the cove detail around the top and bottom boss as well as the top and of the angled cut.

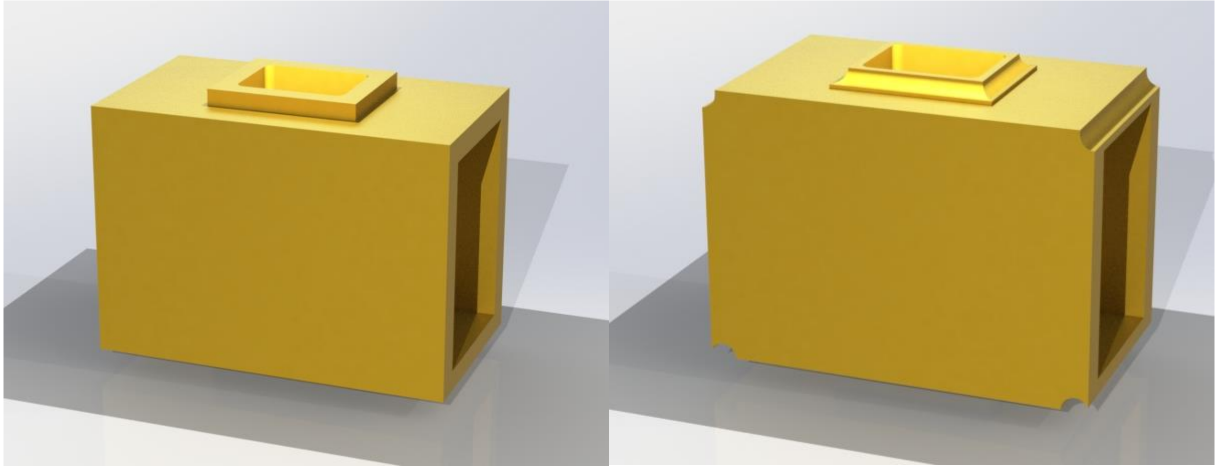

Figure 2.22: Rendered images of the process taken in Operation 3.

2.4.2.3 Operation 3

Operation 3 was to add the curvature to the sides of the mallet. With two flat faces on either end of the infill hole and the bosses on the top and bottom of the mallet having a flat plane, this operation was relatively straight forward. The mallet was clamped on either side of the large through hole and the bottom boss set on the base of the vice with the front face of the infill mallet extending to the side. Using a large endmill a curve was added to the large front face. This process was repeated to the opposite side to achieve the barreling shown in Figure 2.23.

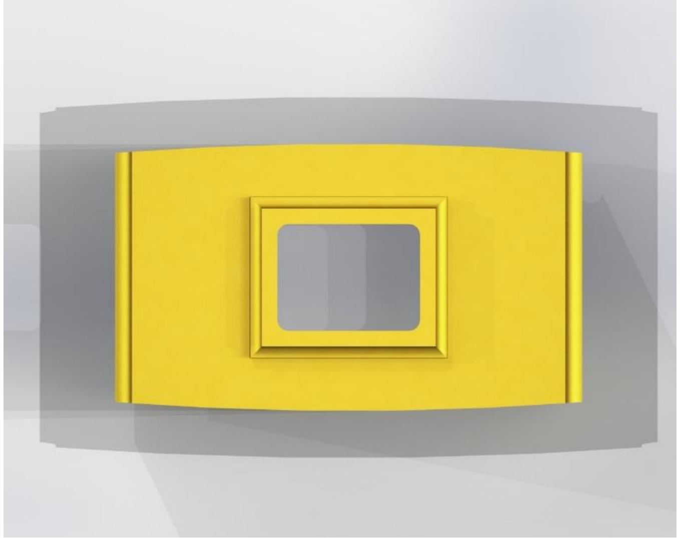

Figure 2.23: The resulting hammer after Operation 3 as viewed from the top.

2.4.2.4 Operation 4

This operation is the last operation to manufacture the geometry of the 2.5-axis hammer head. It was the intent of this operation to add the curvature to the top of the mallet as well as the cove details on the sides of the beech infill hole. Because the surfaces on the top and bottom of the mallet's bosses were flat, those were used to align the hammer and clamp the vice. The rotation of the infill mallet was restricted by using a parallel through the center hole. The fixturing setup for this operation is shown in Figure 2.24. Using a ball endmill the cove details were added on both sides of the infill mallet. A large endmill was used to apply the chamfer on the end of the beech infill hole and round one side of the top surface. The mallet was then flipped and the same operation conducted. The result of this is the competed hammer head form shown in the rendered image in Figure 2.25, and the assembled 2.5-axis hammer in Figure 2.26.

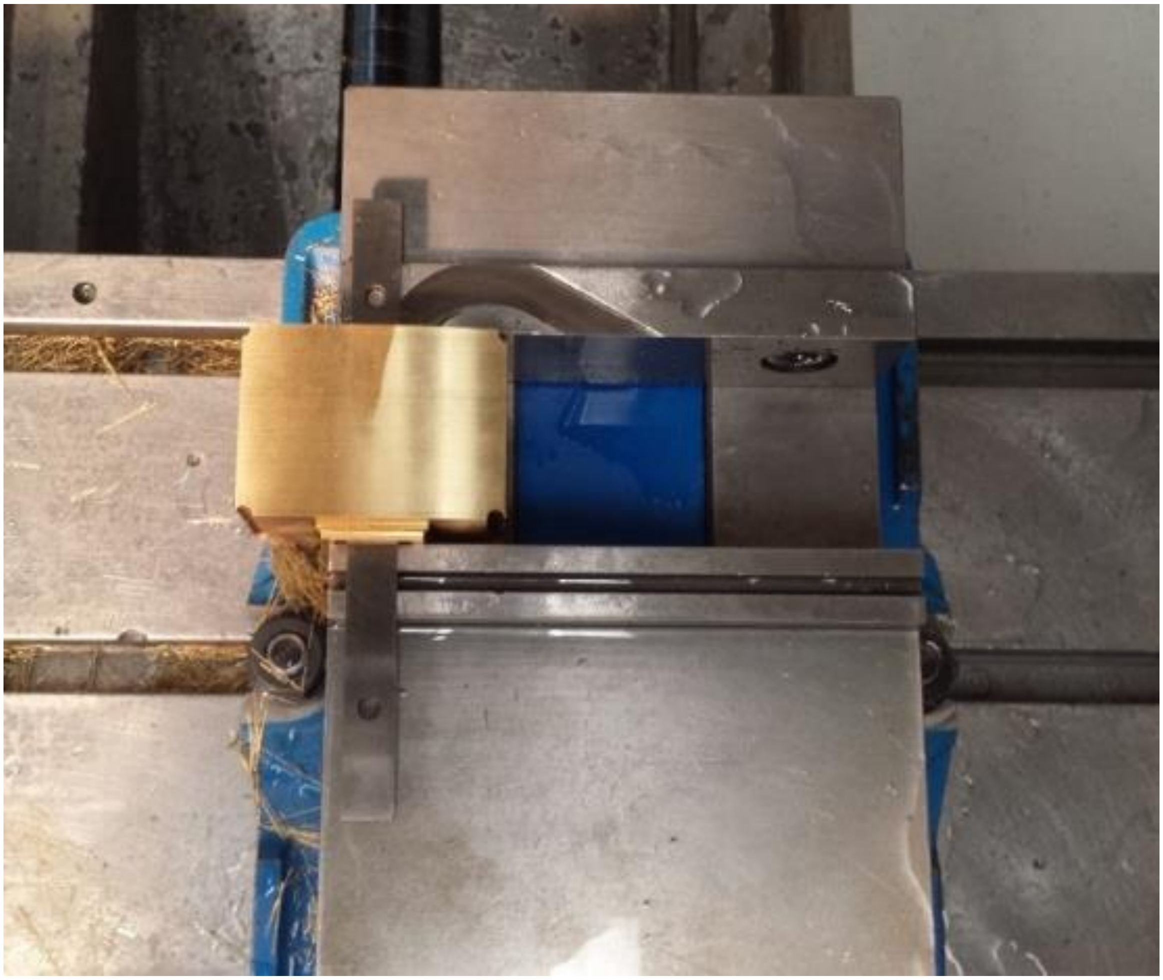

Figure 2.24: An image of the last fixturing of the hammer head to cut the angled sides and the rounded top.

Figure 2.25: Rendered image of the 2.5-Axis hammer head after the final operation.

2.4.3 Discussion and Conclusion

The making of the infill mallet using the 2.5-axis CNC control proved that using subtractive manufacturing methods that we could achieve a simplified version of Mr. Studley's original mallet. Using a 2.5-axis mill we could keep much of the sand casting geometry while making one major improvement on the design. By using a broaching tool the main infill through hole had square corners and flat surfaces, unlike the taper holes on the sand cast version. The final version of the 2.5-axis infill mallet had two complete curves on the front and back, and one intermitted curve on the top surface. It is not lost that in hindsight that the process could be improved to include more curvature while still using 2.5-axis machining. Like Mr. Moon a continuous curve on the top surface and bottom surface could also be achieved while adding the additional feature of barreling to the sides. If the flat plane in operation 2 was not created, the curvature of the top and bottom could have been machined in the orientation shown in Figure 2.24 as a part of operation 4. This improvement would result in four continuous curves on the top, bottom, front, and back sides of the mallet. This infill mallet is an important step in the progression of manufacturing of Mr. Studley's tool. The version presented in this section has a better surface finish than that of the sand cast hammer. This is largely due to the accuracy of the machine and the lack of sand pitting in the brass. With the increased surface finish comes an increased cost. Calculated at $100 per hour to machine and using the operation times predicted in the CAM software SolidCAM, and 10 min to change each orientation and find the origin, the total cost of this 2.5-axis infill mallet per unit was $462.67. These calculations are shown in Table 2.1. The lessons that were learned from this infill mallet were well worth the expense.

Figure 2.26: Images of the completed 2.5-axis infill mallet with a hardwood infill and handle.

Table 2.1: The calculation table for the 2.5-axis infill mallet.

3Axis	Machine Time (min)	Change Time (min)	Fixture Changes	Total Time	Machinist Cost Per hour	Machine Time Cost per Hour	Operation Cost
Facing Block to Size	60	10	0	60	50	50	$ 100.00
Operation 2	26	10	2	46	50	50	$ 76.67
Broaching	57.6	5	4	77.6	50	50	$ 129.33
Operation 3	20	10	2	40	50	50	$ 66.67
Operation 4	7	10	2	27	50	50	$ 45.00
Operation 5	7	10	2	27	50	50	$ 45.00
			Total Time (hrs)	**4.63**		**Total Cost**	**$ 462.67**

2.5 Virtual 5-Axis Manufacturing

2.5.1 Introduction

Examining the differences between the 2.5-axis and the sand cast infill mallets it was hard not to wonder if the geometry of the sand casting could be reproduced using subtractive manufacturing. Machining the complex curves would increase the surface finish and dimensional accuracy of the sand cast version with the added benefit of the aesthetics from its geometry. The combination of the two designs from the different manufacturing methods is what made this process possible. The design for the sand cast version of the infill mallet had only 4 straight lines on the external surfaces, located at the bottom of each boss. With the sides of the bosses being curves it was unlikely that these could be used for fixturing. The only other straight lines on the model were on the interior where the brass infill and handle met. On the sand cast version of the mallet these surfaces were tapered making it difficult to index off of, but using the technique utilized in the 2.5-axis version a new possibility arose. The solution to this problem was the rectangular hole through the center of the mallet. Using custom made fixturing it was possible to hold onto the inside of the infill mallet once the center hole was created. With this style of fixture it was possible to machine the mallet from any angle regardless of surface curvature. The complex curves of the sand cast mallet could be machined using surface machining techniques and a ball endmill. However, further evaluation of the geometry and the machining process revealed that this would not be enough in order attain all the geometry that was desired. The sharp corners around the bosses on the top and bottom of the mallet would not be achievable without rotating the infill mallet and changing the tool height simultaneously. For this reason the use of the 4th axis on our HAAS Tool Room CNC mill would be required to create a virtual axis of rotation to achieve all desired geometry.

2.5.2 CAD Design

The CAD design for the 4-axis infill mallet would not change from that of the sand cast version other than the through holes for the handle and infill. Like that of the 2.5-axis mallet the previously tapered holes could be squared off. The hole for the handle through the top and bottom bosses would again have rounded corners as the broaching tool would not fit inside the center hole. The cove detail at the ends of the hammer were to be made with a 1/8-inch ball endmill in order to more closely resemble the sand cast hammer and the original

Studley Infill mallet. With the exception of these small changes the model was kept the same as seen in Figure 2.27.

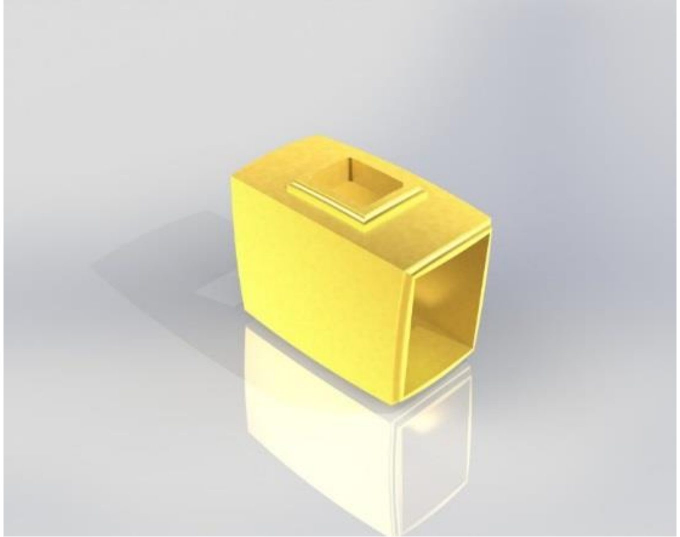

Figure 2.27: A rendered image of the cad model for the 4th axis version of the hammer head.

With this manufacturing method an internal fixture needed to be designed. The fixture was required to attach to the fourth axis of our CNC machine (a three jaw chuck), be able to rotate around the x-axis, prevent translation or rotation along or around all other axes, and be capable of aligning with our CNC Mill. After a few design iterations and assistance from the machine shop manager Bill Magnie, the final design was set as shown in Figure 2.28. The fixture was in three pieces that were machined .005-inch less than the infill hole in both directions. This was done to create a slip fit of the hammer head over the fixture. A lip was added to each of the outer blocks for gasket material to rest. The concept of the fixture was to force gaskets to expand towards the inside of the infill mallet by tightening the cap screws that extended through the three sections. This would apply enough force to hold the infill

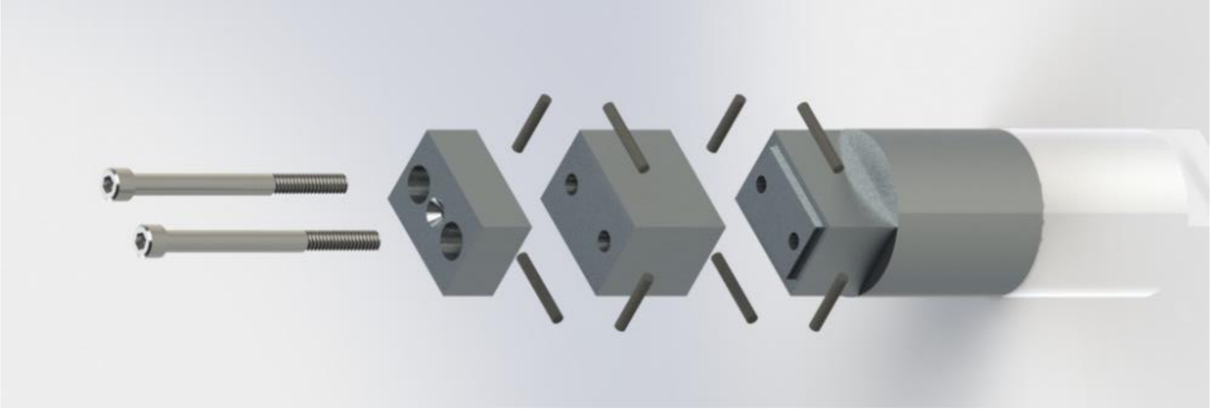

Figure 2.28: An exploded view of all the metal components that made up the fixture.

mallet in place during machining. The block on the right of the image would be centered using the three jaw chuck. The block on the left side of the image would be centered using a dead center. The center block would act as a spacer between the other two components.

2.5.3 Machining Process

2.5.3.1 Fixture

Before the machining of the virtual 5-axis infill mallet, the fixture had to be manufactured. The manufacturing process of the fixturing was designed to mitigate misalignment in the three individual pieces as shown in Figure 2.28. The assembly began as one piece of aluminum round stock. Using a lathe a center hole was drilled and the sections of the fixture were parted and refaced to make parallel planes. The sections were then taken to a mill and the through holes were drilled in the two discs, and tapped holes in the base cylinder. The three components of the fixture were assembled mounted in the three jaw chuck of the fourth axis. The largest cylinder was aligned in the jaws of the 4th axis and then used to align the 4th axis with the x-axis of the CNC machine. A dead center was used to support the center-

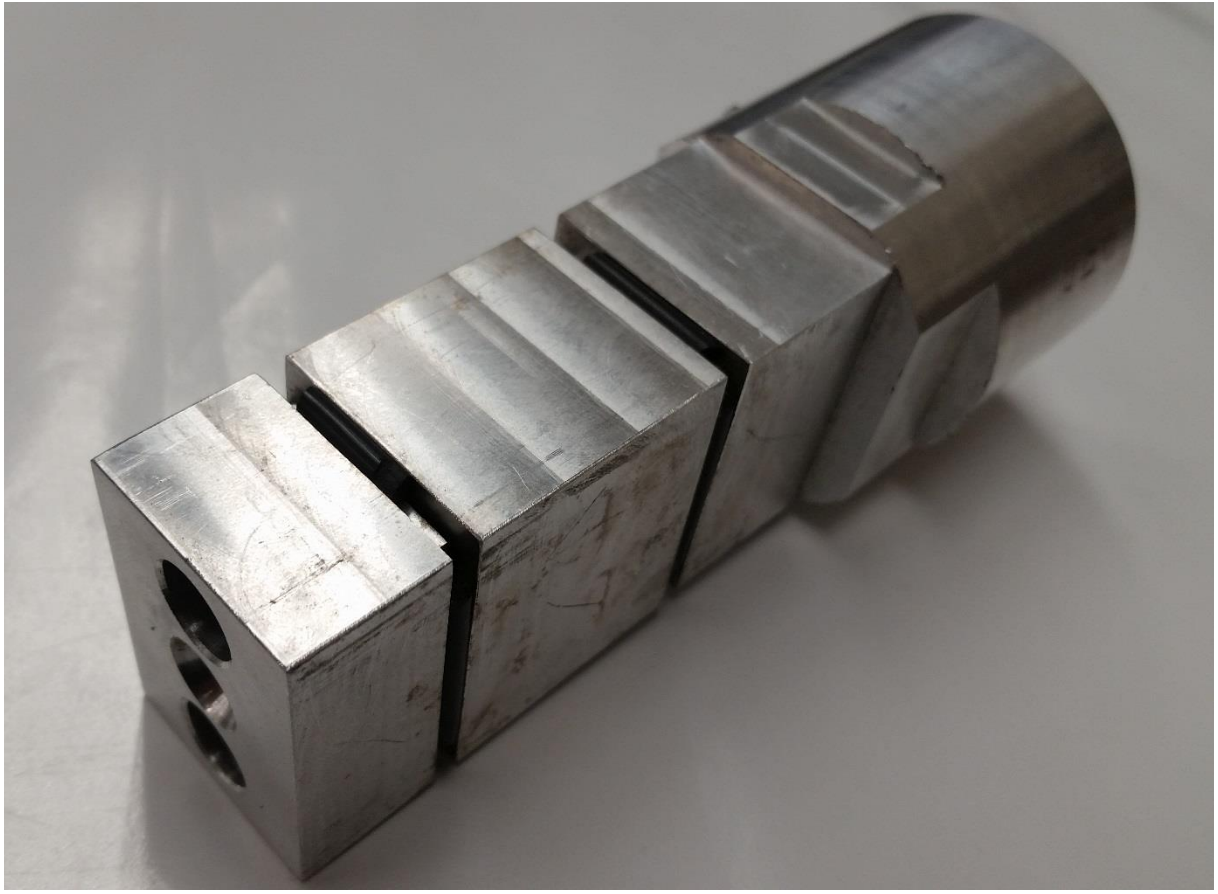

Figure 2.29: An image of the finished fixture that supported the infill mallet during machining.

hole of the last section. With the fixture bolted and aligned the rectangular shapes were milled using the 4th axis to index the assembly. Machining the fixturing with the 4th axis on the mill ensured alignment of the square features to the machine. The fixture was then taken apart and the ledges were machined into two individual sections. When reassembled gasket material was wedged into the ledges, and the infill mallet would be slipped over. The tightening of the bolts would secure the assembly. An image of the final fixture assembly is shown in Figure 2.29. An image of the infill mallet mounted to the fixture is shown in Figure 2.30.

Figure 2.30: An image of the completed virtual 5-axis infill mallet attached to the machining fixture.

2.5.3.2 Operation 1

Like the 2.5-axis version of the hammer the first operation after facing was to create the through holes. The same process was followed as described in the 2.5-axis version. The holes were milled with drilled corners to remove as much material as possible. The large hole was then broached to achieve the square corners for the beech infill. At the end of this operation the mallet took a form to the end of operation 1 in the 2.5-axis version, but with the addition of the handle hole as shown in operation 2. The product of these operations is shown in Figure 2.31.

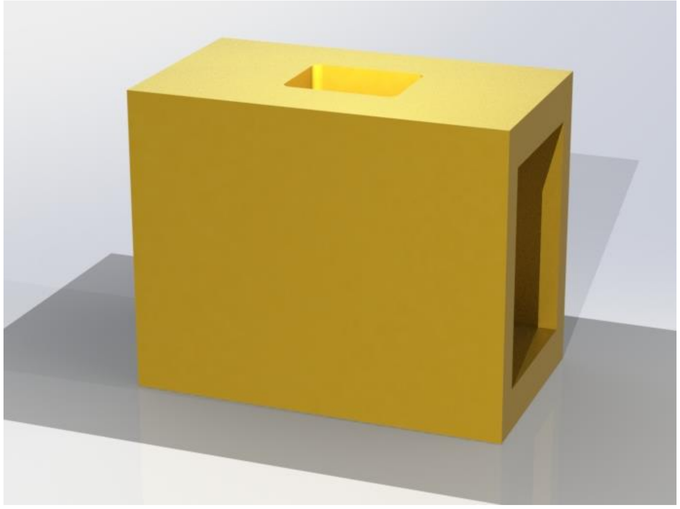

Figure 2.31: A rendered image of the infill mallet with all holes milled into it.

2.5.3.3 Operation 2

The second operation in creating the infill mallet was adding the curved chamfered sides at the ends of the beech insert. This feature was added before attaching the block to the custom fixture. Because the outside of the block was still square we could clamp to these surfaces with a sine block beneath it. A sine block consists of two ground cylinders at a known distance that are connected by a flat piece of metal. Using a combination of gauge blocks one of the cylinders can be raised to provide a desired angle from a flat surface. The sine block was set so that the infill mallet was angled to the same degree of the chamfer and a standard endmill was used to add a rounded side on the angle given. This step was repeated on both sides of the mallet.

2.5.3.4 Operation 3

This operation was the first that the infill mallet was mounted to the custom fixture. Because of the chamfered sides the origin of the part was set to the center of the hammer in the x and y directions. The z origin was located at the center of rotation of the 4th axis. These locations were found off of the center hole and by offsetting each tool by the calculated radius from the measured diameter of the fixture. With the infill mallet mounted to the fixture, surface machining could commence. Using a linear machining pattern step over passes a 1/2-inch ball endmill was used to take .01 step overs across the surface to create the final shape of the surface. A 1/2-inch endmill was chosen because a larger the ball endmill will leave less scalping than a smaller diameter. When it came to the bosses the ball end mill was also used to give the curvature to the top and bottoms of these surfaces as well. This was repeated on all four sides using the 4th axis to index the part then hold stationary during the surface machining. An image of surface machining process is shown in Figure 2.32.

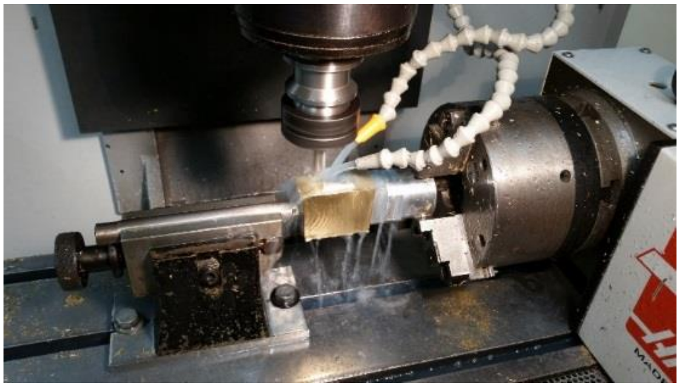

Figure 2.32: An image of the machining process using the 4th-axis to index the part while machining the shape of the hammer head on each surface.

2.5.3.6 Operation 4

At this point in the process the hammer had all of the complex curves creating the overall shape of the hammer and just the cove details and boss definition needed to be added. Using a 1/8-inch ball endmill the cove details were added by following contours while the hammer was at a fixed indexed position. To create the square edges on the bosses is where the process became more involved. As described in the introduction of the 4-axis hammer head in order to get the square corners on the bosses the 4th axis has to be utilized. This is because the only way in order to not scalp the surface while cutting the sharp corner is for a standard endmill to remain tangent to the surface during machining. Because the curvature of the surface was not concentric with that of the axis of rotation of the 4th axis a virtual axis was created. A virtual axis creates an axis that is offset from the center of rotation of the 4th axis by changing the height of the tool while rotating the 4th axis underneath it. This combination of motion allows the machine cut radius that are not concentric with the axis. Because our machine does not have true 5-axis capabilities we could not follow the same procedure when cutting along the x-axis, however because of the curvature of the surface we were able to mitigate the consequences of this motion as the surface rounded off the tool as it moved forward. This left sharp corners surround the top boss. This was repeated on both sides of the hammer head leaving the finished version as displayed below in Figure 2.33.

2.5.4 Discussion and Conclusion

The 4-axis hammer head has the best geometry out of the three manufacturing process. This version of the hammer head includes all of the complex geometry of the sand casted version with the surface finish, dimensional accuracy, and square internal corners of the 2.5-axis version. It is almost by definition the best of both other processes. With the increased quality in surface finish and geometry comes increased cost. Although the modeling process took just as much time to come up with the model the cost of designing the fixturing and the machining process would be costly as it is very time consuming. In order to get the cam software to follow a virtual 4th axis we were forced to using the 5th axis software of SolidCAM which does not come with their standard license. We also ran into the problem of getting a proper post processor to utilize our 4th axis on our machine. All of this time to set up these features hurt the production time for the one off or initial run. These problems would be common with any other facility that did not commonly use these functionalities. This hammer also cost a lot of machine time. Surface machining when trying to get quality requires very small step over in order to reduce scalping. Using HSS tooling and a 1/2-inch ball endmill the process of surface machining and cove detail took a total of 5 hours. This is a much longer time that the machining on the surface of the 2.5-axis hammer head. With all of these factors I estimate that the machining cost of $1000.17 per item with a machine cost of $50 per hour and a machinist cost of $50 per hour.

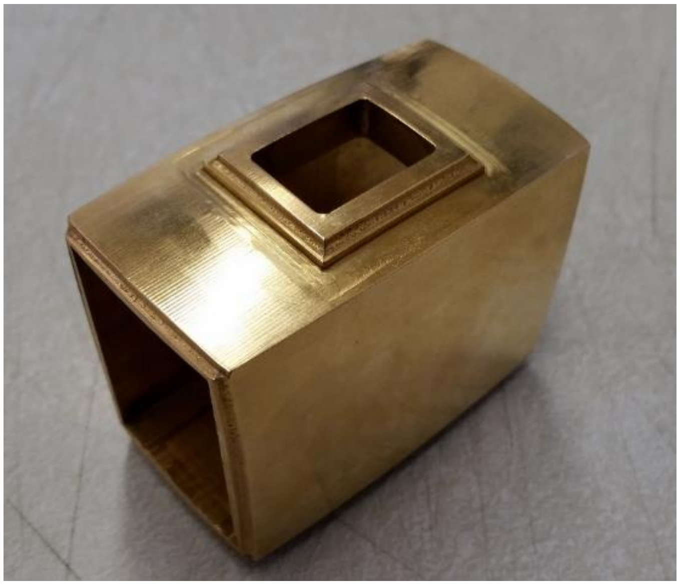

Figure 2.33: An image of the finished 4-axis hammer head.

Table 2.2: A table of the machining calculations for the virtual 5-axis infill mallet.

4Axis	Machine Time (min)	Change Time (min)	Fixture Changes	Total Time	Machinist cost per hour	Machine time cost per hour	Operation Cost
Facing block to size	60	10	0	60	50	50	$ 100.00
Operation 1	26	10	2	46	50	50	$ 76.67
Broaching	57.6	5	4	77.6	50	50	$ 129.33
Operation 1B	5.5	10	2	25.5	50	50	$ 42.50
Operation 2	6	10	2	26	50	50	$ 43.33
Operation 3	342	20	1	362	50	50	$ 603.33
Operation 4	3	0	0	3	50	50	$ 5.00
			Total Time (hrs)	**10.00**		**Total Cost**	**$ 1,000.17**

2.6 Overall Results and Conclusion

When comparing the infill mallets there is little room for debate on the attributes that each achieve. When examining the cost, the sand cast infill mallet was considerably less expensive than the other two manufacturing methods. Sand casting is an excellent way to achieve complex surface geometries when dimensional accuracy does not have tight tolerances. Sand casting allows a design to be made out of easily formable materials such as clay, plastics and wood and result in a metal component. This form of manufacturing is fast and repeatable. The scale of production is easily increased for little additional cost, and for the design intent of the mallet a smooth surface finish isn't necessary.

The manufacturing of the sand cast infill mallet gave invaluable insight to the same types of problems that Mr. Studley would have faced when creating the original. The draft angle considerations, how to cast a hollow shape, and how to create a functional piece of art, were all questions that Mr. Studley had to answer. Presented above is our best approximation on how he would have conducted this process. There are some discrepancies between his mallet and our own. Looking at the finished model the front face curvature of the infill mallet designed at the University of Idaho was more drastic than the original. Also, the draft angles on the internal surfaces of Mr. Studley's mallet are essentially non-existent. It is possible and likely that we pursued the same goal with different methods. The results of this method in the hands of a true master like Mr. Studley created is a timeless product.

The 2.5-axis infill mallet was more expensive than the sand casting at $460. The mallet also did not achieve the geometry of the virtual 5-axis version. However, this manufacturing method was a required stepping stone in exploring this topic. The manufacturing of this infill mallet built the necessary confidence and provided the required experience to pursue the virtual 5-axis mallet. The simplified version of the mallet is relatively easy to machine and does not require extensive milling experience with the only control being in 2.5 dimensions. The simplification of the infill mallet shined light onto what the important surfaces were for the manufacturing method and which were more aesthetically pleasing. It was important for this model to retain the largest curves on the top surface and the front of the hammer to exemplify the curvature. This is not the only correct way to build a simplified version of the infill mallet as seen with Mr. Jim Moon's mallet which had different geometry considerations. This mallet was the most simple to manufacture, but still crucial in the exploration of this topic.

The highest quality of the infill mallets was the virtual 5-axis mallet. Using the virtual 5th axis and surfacing machining methods geometries were achieved that otherwise would not be possible by subtractive methods. The surface finish, and dimensional accuracy of this version of the hammer head is high and is superior to the other two versions. This hammer was by far the most expensive to produce costing $1000 to produce each hammer without including engineering cost, or the cost of creating fixturing. With this infill mallet the manufacturing of complex surfaces was significantly explored. The previous two mallets provided the knowledge of the shape and manufacturing process, and this mallet was the cultivation of it all.

Despite the manufacturing method the infill mallet would serve its obligation to theory. The intent of the overall design was to create a concentration of mass as the end of tool and assist in the assembly of the mallet. In that way regardless how the shape is obtained they all serve their purpose.

Each of the manufacturing methods also have their own claim to creativity. Mr. Studley originally designed the mallet to be sand cast which resulted in the complex curves of the metal that are still awe inspiring. Everything about the mallet from its shape to its material serves its purpose and is beautiful enough to justify obsession. The 2.5-axis version's creativity is with its simplification. The contours that were chosen to keep and the manufacturing methods derived to achieve them is what makes this a clever design. The creating of the internal fixturing and design of the process gives merit to the creativity of the virtual 5-axis manufacturing method.

Perhaps the largest impact of the study is the indication that using modern manufacturing methods the shapes of the past may become more difficult to create. Sand casting is a practice that has been in use since the Bronze Age, and using that method these complex shapes are easy to produce and reproduce. This process could have easily been replicated by an experienced craftsmen at home using hand tools. The final product of a backyard production would yield many of the same benefits as were achieved by the sand casting in this thesis. At the first instance of modern manufacturing being implemented the process becomes much more challenging and much more expensive. With 2.5 axis control a

CNC mill was used. Much of the geometry that was achieved could have been attained on a manual mill with extensive experience and the proper set ups. This need for skill and the machine greatly effects the manufacturability of the mallet. This concept is exacerbated in the production of the virtual 5-axis version. To create the final version of our infill mallets advanced computer software and hardware are required making the endeavor essentially infeasible by most metrics. In this case the mallet that Mr. Studley had developed was perfectly designed for the manufacturing method that was available to him. Sand casting being the easiest way to create the shape, he designed a piece of art that utilized the manufacturing constraints to create a useful, and beautiful final product.

The knowledge gained and the experience achieved indicates that this infill mallet, which utilized complex surfaces for its aesthetics and manufacturability, is a timeless design that exists on the intersection of theory, creativity, and manufacturability.

Chapter 3: Modeling and Manufacturing of the Noxon Rapids Scroll Cage

3.1 Introduction

As a part of a hydroelectric dam turbine blade update on the Noxon Rapids Dam in Montana, Avista Utilities, and Wagstaff supplied the University of Idaho with a set of Legacy engineering drawings of the Noxon Rapids Dam from the Allis-Chalmers Manufacturing Company. These drawings were used in our Senior Design Program to create a solid model of the assembly, conduct a GD&T analysis, and build a scale model. Our students created a CAD model of the dam internals in SolidWorks and began machining the model, but due to time constraints were unable to finish. The project was handed over to the graduate students in the Idaho Engineering Works (IEW) office and the machine shop manager at the University of Idaho. This thesis focuses on the work that was conducted in designing and creating the scroll cage of the hydro-electric dam using a vacuum forming manufacturing method.

The manufacturing method was chosen based on the needs of the design. The intention of the original design is to create a uniform pressure and water flow through the veins and wicket gates of a hydroelectric turbine. The clients of the project who provided the drawings added the stipulation that the cage was to be transparent. The working fluid for the model was unrestricted and could be forced air.

In the Mechanical Engineering Department at the University of Idaho there are four main forms of manufacturing. These methods are machining, welding, 3D printing, and laser cutting. Other resources are available, but these options can be done easily with our facilities. Welding was not the ideal method for this project because of the need to be transparent. Clear plastics such as acrylic could be machined, but the geometry of the scroll cage would make it difficult and expensive with a high risk of fracture in the material. Transparent 3D printing filaments are available, but due to the layering of the plastic they tend to me more translucent than transparent. Laser cutting would leave the final shape discretized because of the multiple layers that would fastened together and would obstruct the view. With significant issues in the typical forms of manufacturing another method needed to be employed that was not typical to our processes.

Dr. Odom suggested the concept of vacuum forming. Vacuum forming is the process of using a vacuum in order to create a shape from a formable material over a rigid mold. This process of manufacturing would allow for complex shapes to be created out of a clear material. Vacuum forming of thermo-plastics requires the material to be heated to a point that it becomes malleable, placed over a mold, shaped using a pressure differential, and allowed to harden. Once cooled the thermo-plastic holds the shape of the mold. It was decided that this manufacturing method would be the most practical to achieve our design goals.

To manufacture the scroll cage in this way we would need to make a mold in the shape of the scroll cage, a heat source that was capable of heating the plastic uniformly to the correct temperature, and a way to create a pressure differential between the top and bottom of the plastic. The senior design team and fellow graduate student started this process. Their attempts are described in the next section.

3.2 Previous Attempts

After the completion of the SolidWorks CAD model the senior design team proceeded with creating a scale model of the dam as a show piece for the client. Sizing the scale model off of what our facilities could process the team decided on a 1/40th scale. This project however went beyond the scope of the initial project and was taken over by the graduate student and fellow IEW member Alex Olson. The team designed and built a wooded vacuum form table that was used to form of positive molds. The molds were printed on our in house 3D printers, because of the scale they had to printed and formed in sections and fastened together once completed. Multiple tests were ran using this apparatus and following are the lessons learned that were taken into the next integration.

Figure 3.1: An image of acrylic melting PLA during vacuum forming.

The first material that was to be vacuumed formed was acrylic sheeting. Acrylic is a readily available thermoplastic that can be purchased at most hardware stores. During the initial vacuum forming attempts due to the high temperature of $350°F$ to make the plastic formable the 3D printed molds melted before forming like in the image in Figure 3.1. Because of this problem other plastics were evaluated.

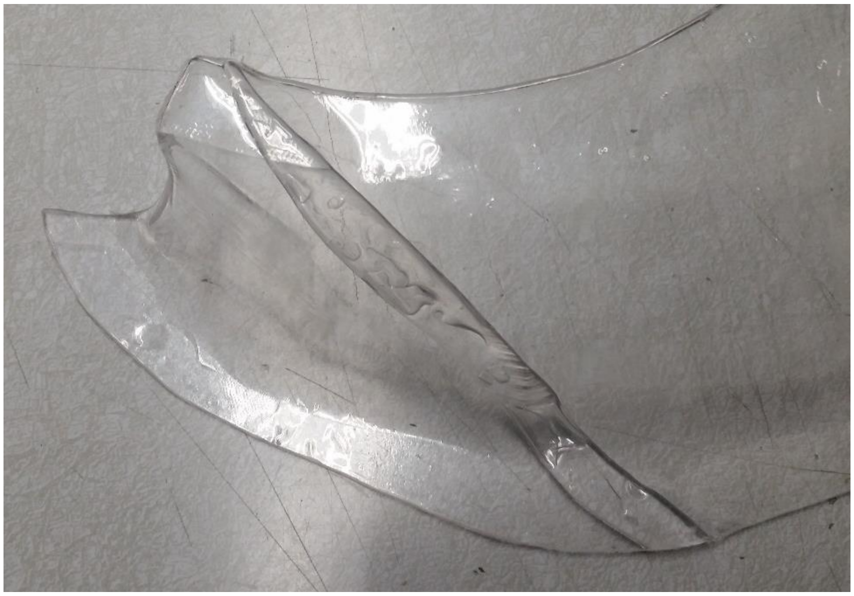

Figure 3.2: an image of the overlapping plastic that occurred during vacuum forming.

PETG plastic was the second material that was formed using this method. This material is formable at a much lower temperature than acrylic and was chosen to resolve the melting issue of acrylic. The new material did not melt the 3D printed mold, but had problems of its own. Because the vacuum table could not be heated with the plastic when it was time to form the PETG was drooped over the mold onto the table. This process created issues with overlapping of the plastic as shown in Figure 3.2. The accuracy of the plastic was also poor due to the plastic not sealing against the base to create a large pressure differential. Mating the multiple pieces of the plastic together would also decrease its quality and transparency. Because of the difficulties with this method of vacuum forming we moved onto a new design.

Evaluating the problems with the previous attempts a solution that was one continuous piece and would avoid melting and overlapping was desired. As a result a metal negative mold of a smaller scale was to be used. We reached out to Wagstaff for some assistance. The company supplied us with two blocks of aluminum that were large enough to make a vacuum form for the 1/80th scale scroll cage.

3.3 CAD Modeling

Using the hand written drawings from the 1950's as shown in Figure 3.3, a solid model of the external scroll cage inlet was to be created. This full scale model would be the basis of the scaled version. The scroll cage according to the original drawings, was to be made up of pipe sections that would be welded at the seams. The first 13 sections of the cage were made out of two sections that were welded together at offsetting seems. The combined structure gave a discretized spiral appearance. To produce a model of the geometry a 2D sketch of the profile was drawn to provide a general shape. The 2D sketch included the outside profile and the lines that represented different sections of the pipe. The sketch created is shown in Figure 3.3. The drawing shown in the figure was the guide which the rest of the model would be created.

The next stage for a three dimensional model of the scroll cage was to create the profiles of the pipe. A close examination of the drawings shows that the dimensions of the outside profile were given where the pipe sections met. In Figure 3.4 these are the radial lines from where the hydro-turbine would be located to the outside edge. For this reason the profiles were created at these intersections in order to get the general shape of the scroll cage in three dimensions. To make the full sized version of the model, the profiles were extruded with the wall thicknesses given in Figure 3.3 in the direction of the straight outside lines from the ends of the pipes met. This gave a relatively accurate representation of what the shape of the scroll cage. Because of the "Field Weld" callout on the drawings this model left a gap in between the sections from the use of the straight pipes that would be welded together at the seams. In these drawings the attachment of the scroll cage to the stay rings that support the wicket gates is described. The pipes were to be formed such that they curve into the opening of the stay rings. This feature varies throughout the shape and was not important for the purposes of this model. As a result the model was cut at the diameter of the stay ring to create finished product of these operations as shown in Figure 3.6.

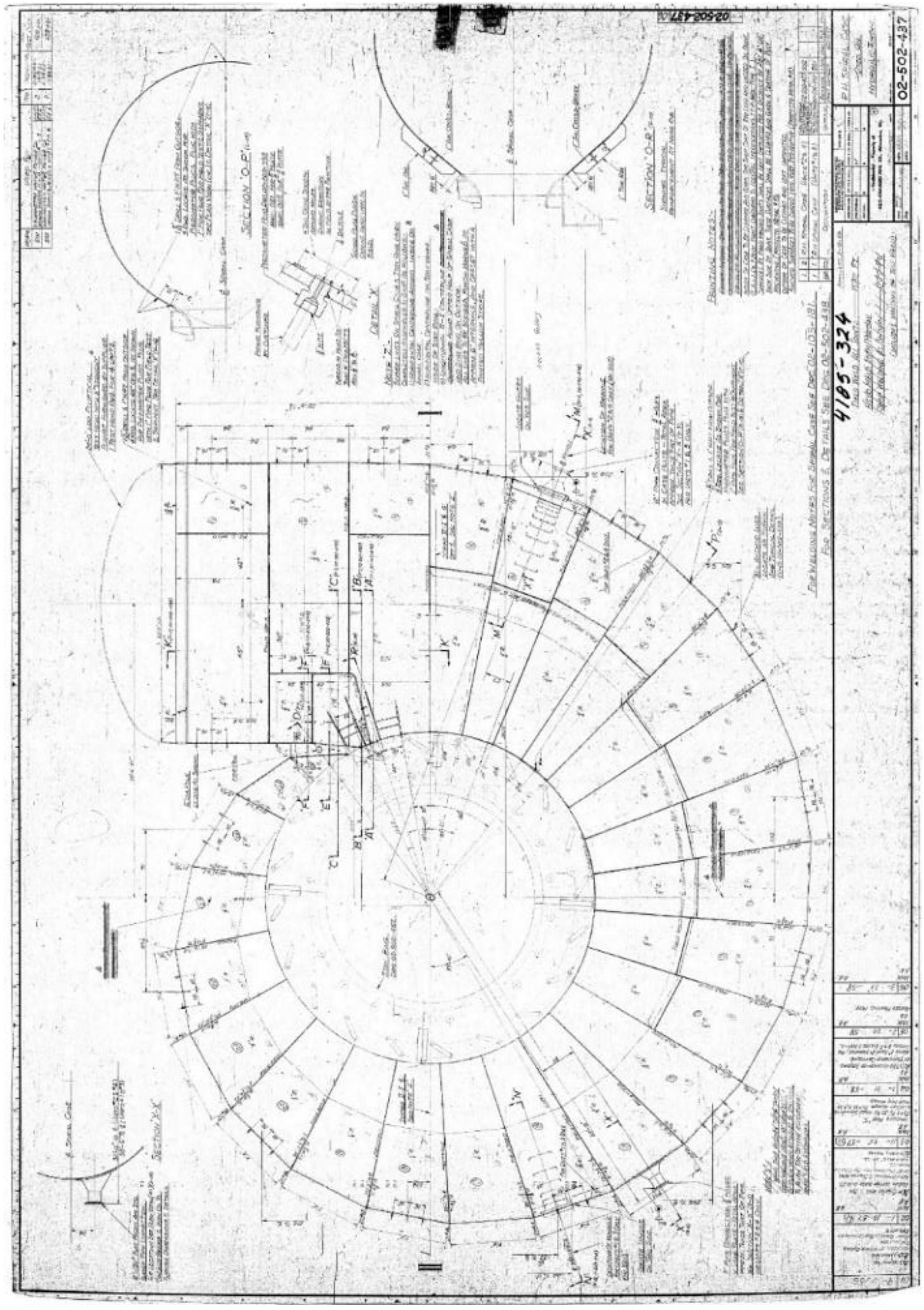

Figure 3.3: A provided drawing of the scroll cage from the Noxon Rapids Hydroelectric dam.

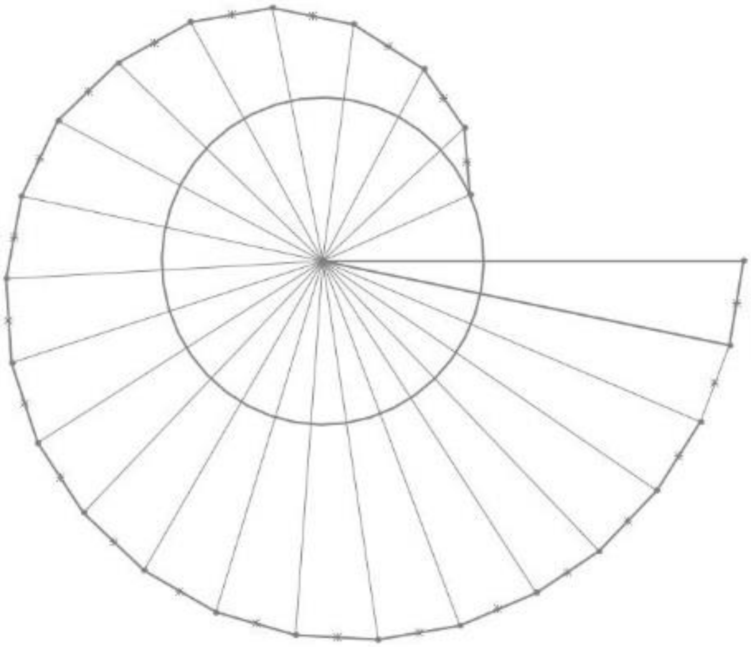

Figure 3.4: An image of the initial sketch that was used to base the geometry of the model off of.

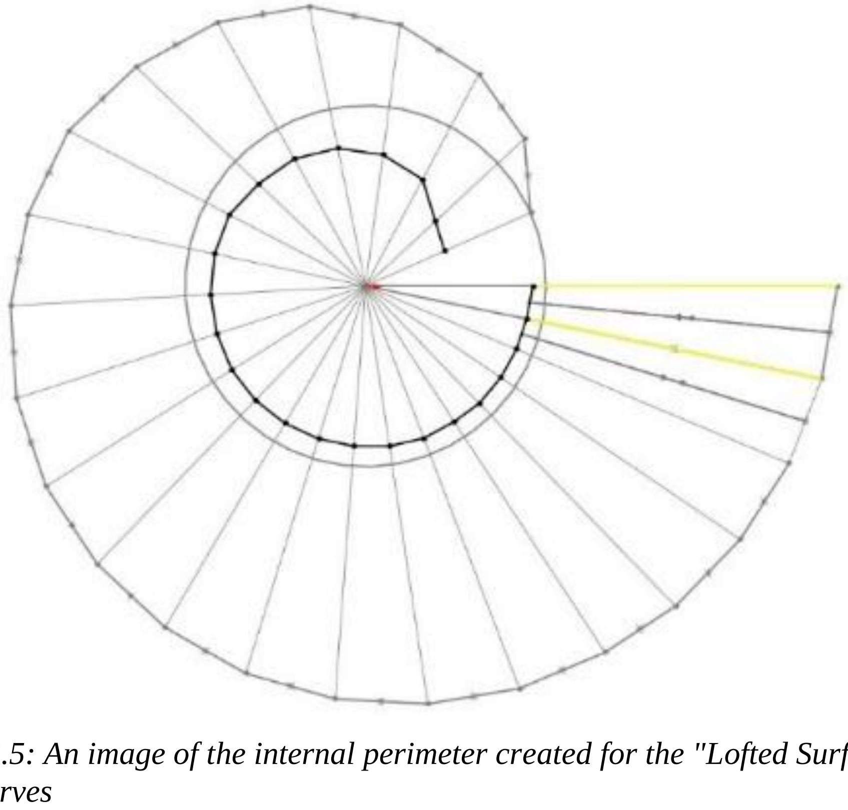

Figure 3.5: An image of the internal perimeter created for the "Lofted Surface" guide curves

Figure 3.6: A rendered image of the full scale model as it was called out in the drawings cut at the diameter of the stay ring.

3.4 Scale Modeling

Creating the scale model of the scroll cage took more than just a uniform scaling of the part. Knowing that we were going to manufacture negative molds to create the final shape, the scale model had to be made such that the mold could be to be manufactured in the University of Idaho Mechanical Engineering Department machine shop. As explained by "Fine Scale Modeling Magazine," the scale of a model is largely determined by the final size of the model and the ability to recreate the detail of the larger product at that scale. 1/80th scale of the scroll cage was large enough to show detail, but was small enough to fit on the HAAS CNC mill, and in a standard home oven. The original construction of the dam is symmetric over exactly one plane which made it the only choice to split the model and create two halves. For this line of symmetry only one model was needed. This is because the finished half could be mirrored in order to create the opposite side of the scroll cage shape. The curve of the pipes and the construction method made it possible to retain most features of the scroll cage and still be able to machine the shape using surface machining methods.

Like the infill mallet we wanted to preserve as much of the original geometry of the hydroelectric dam as was reasonably possible. This project was not just to recreate the intent of the design, but to also design and create an aesthetically pleasing piece that represented the original form. The ledges between the pipe sections at the seams as well as in the center of the sections could not be easily machined without modification, but the overall shape could be preserved.

To model the new geometry for the scaled version, the profiles from the previous model were used as guides to create simplified arcs. These shapes would serve as the profiles for the scaled surface geometry. Each of the stepped pipe sections were reduced to a simple circle to represent the overall shape of each section. The inside edge of each pipe profile sketch was used to create a 2D sketch on the plane of symmetry. This was done by connecting the inside edges of each profile with straight lines where they intersected the plane. The resulting sketch is shown in Figure 3.5. This sketch was used in conjunction with the outside profile sketch to connect the circular pipe sections using the SolidWorks “Lofted Surface” tool. This created a three dimensional surface that would continuously connect all the profiles. The inside sketch in Figure 3.5, and the straight perimeter lines in Figure 3.4 were used as guide lines to shape the sections while the profiles accounted for the decreasing diameter size. To make the discretized shape the “Lofted Surface” tool was only used to connect two profile sketches at a time. An image of the process inside of SolidWorks is shown in Figure 3.7. The final shape of this process is shown in Figure 3.8. The result of this process was a single

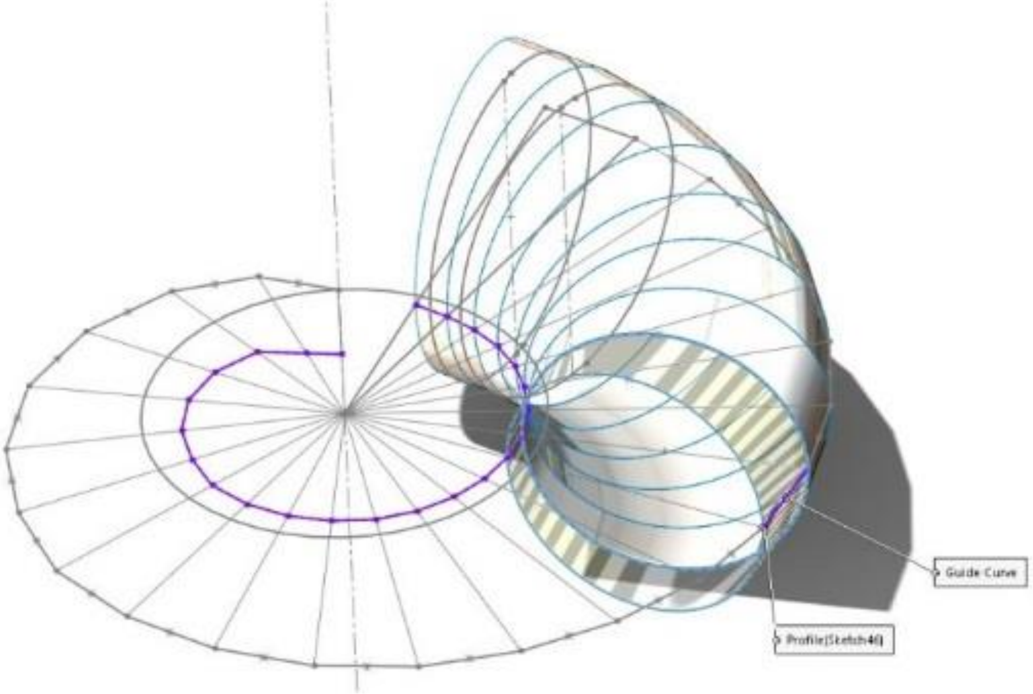

Figure 3.7: An image of a pipe section being created using the "Lofted Surface" tool.

Figure 3.8: A rendered image of the external shape by using the "Lofted Surface" tool in SolidWorks.

surfaced that represented the pipe sections without gaps and a smooth transition from the largest to the smallest section.

Due to the thickness of the vacuum form material and scale of the model the scroll cage would not be attached to the inside of the stay ring as was done on the original hydroelectric dam. Instead the scroll cage would be bolted to the top and bottom of the stay rings. This design required a few liberties to be taken in the smaller portions of the scroll cage. Because of the need for the cage to be attached to the top of the stay ring, the smaller sections had to increase in size in the direction normal to the plane of symmetry. This increase in size was necessary to make a proper flange. The sections were modified following outside edge of the original scroll cage and increasing the diameter of the sections until they were at a height that the flange could be made. This process is shown in Figure 3.10. To create a smooth transition for the vacuum form material the surfaces of the initial inlet and the smallest section were extended into one another creating one self-connecting surface and cavity. The results of this surface modification is shown in Figure 3.9.

To model a vacuum mold the surface had to be transformed into a solid object. This was accomplished by using the surface model of the scroll cage to cut into a solid model of the purposed aluminum stock. To create the vacuum mold at 1/80th scale two 12 x 10 x 2.5 inch aluminum blocks would be machined out to create the two halves of the mold. The surface was cut into the mold by the thickness of the vacuum material to create the cavity. A draft angle on the inlet of 3° was added so that the finished plastic could be removed. A 3/4-inch fillet was made at the connection for the ball endmill to follow along the edge. The solid shape can be seen in Figure 3.11.

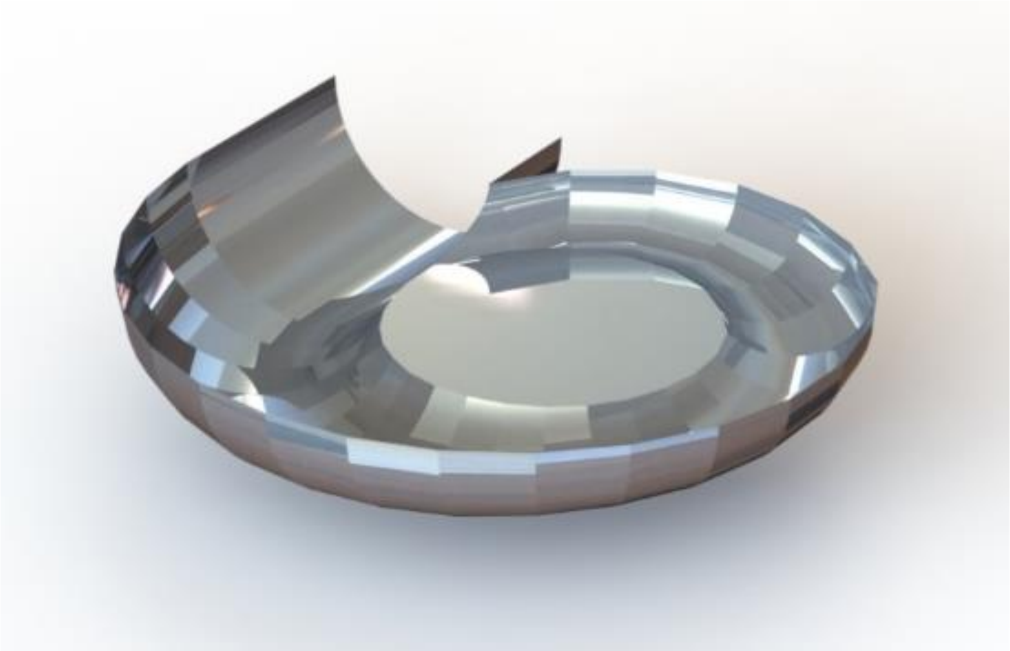

Figure 3.9: Rendered image of the inside of the scroll cage surface after the smallest and largest surfaces were connected.

As this was a vacuum mold, pathways for the air to travel had to be created. Because of the relatively low pressure required to vacuum mold many thermoplastics, the backside of the aluminum block was recessed leaving a 1/4-inch edge without support material. Holes were created according to the geometry of the scroll cage impression. As the mating surfaces of the mold would be the plane of symmetry and the top of the stay ring the vacuum holes were created larger in these areas. The diameter of the holes in these locations was 1/4-inch. This was done to evacuate air more quickly and increase clamping force in these areas. This was an important feature to create sharp corners and accurate well-formed mating surfaces. To place these holes two sketches were offset from the outside edge of the scroll cage, and lines drawn to connect all the end points. This sketch is shown in Figure 3.12. Every point on the sketch was a location for a quarter inch hole. The central disk that created the flange to attach to the stay ring used radial patterns to create the vacuum holes on this platform.

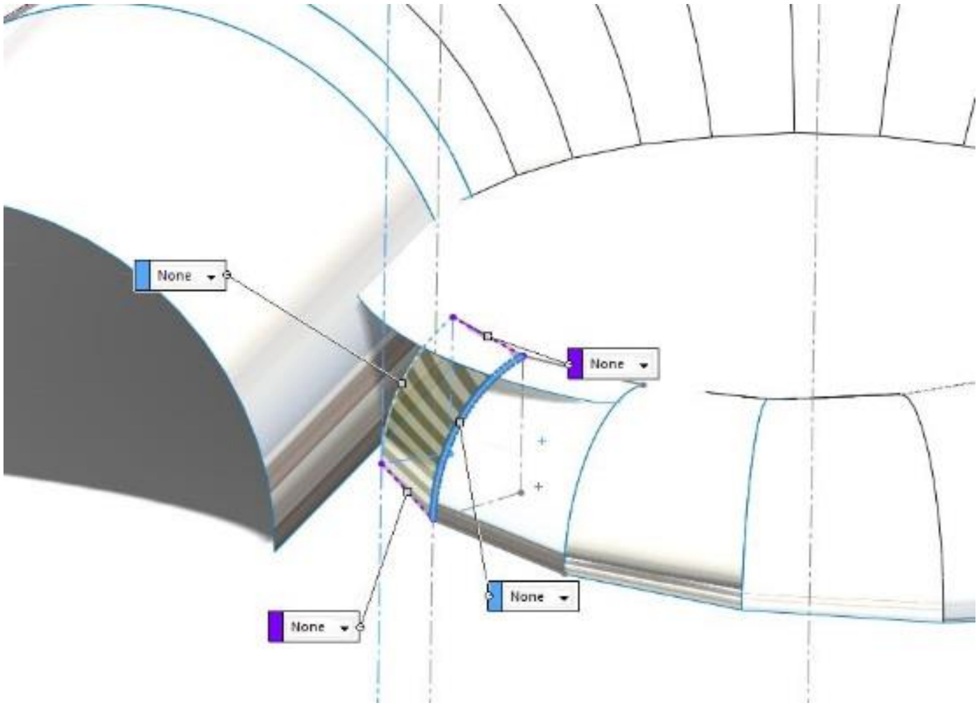

Figure 3.10: An image of the boundary surface created to extend the smaller sections to the flange height.

The spacing was chosen to match with the spacing of the wicket gates on the scale model. The rest of the full depth holes on the outside surface were created using a linear pattern. Three 1/8-inch holes were created in each section to slowly evacuate the air from the remaining cavity and stretch the plastic into its final shape. To evacuate the air from the mold a half inch hole was added to the bulk of the material and the fitted for a 3/8-inch NPT pipe fitting from the side. The final model of one side of the mold is shown below in Figure 3.13, and Figure 3.14. To create the other half of the model the solid body was mirrored across the top surface and the original was suppressed.

The model of the final product was created by thickening the same surface that was used to cut the impression in the extruded block that ultimately became the vacuum mold. The surface was thickened to the dimension of the thermo-plastic. A flange in the shape of the pipe sections was offset from the edge surface, and a hole was cut out through the center in order to produce the final shape. The predicted final shape of the mold is shown in Figure 3.15.

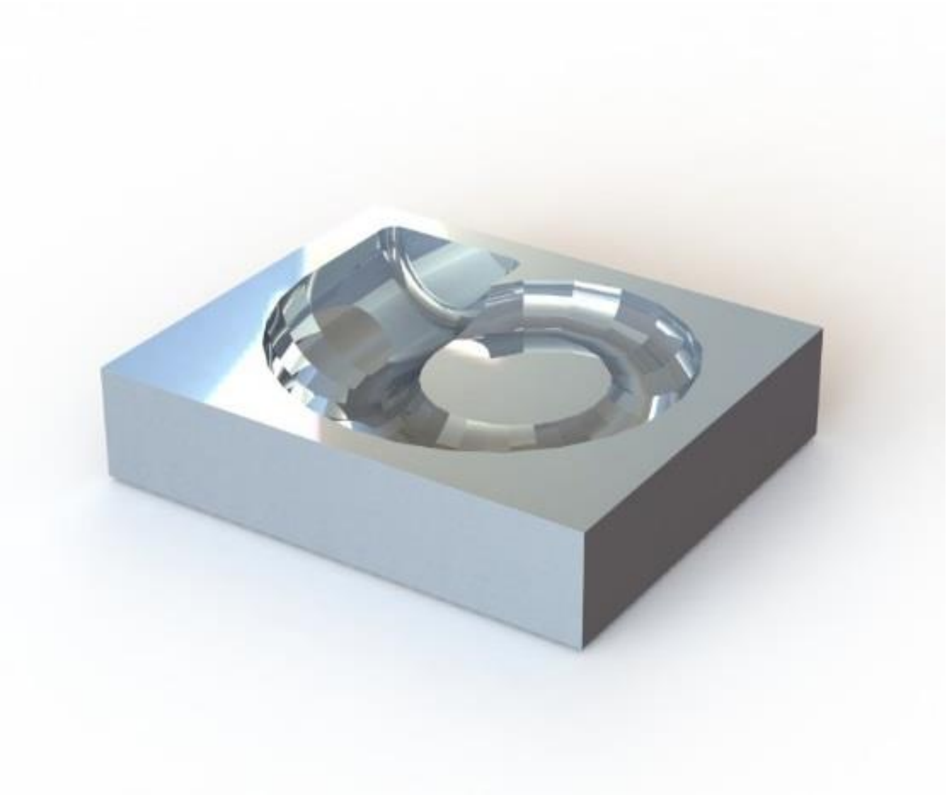

Figure 3.11: Rendered Image of the block surrounding the scroll cage

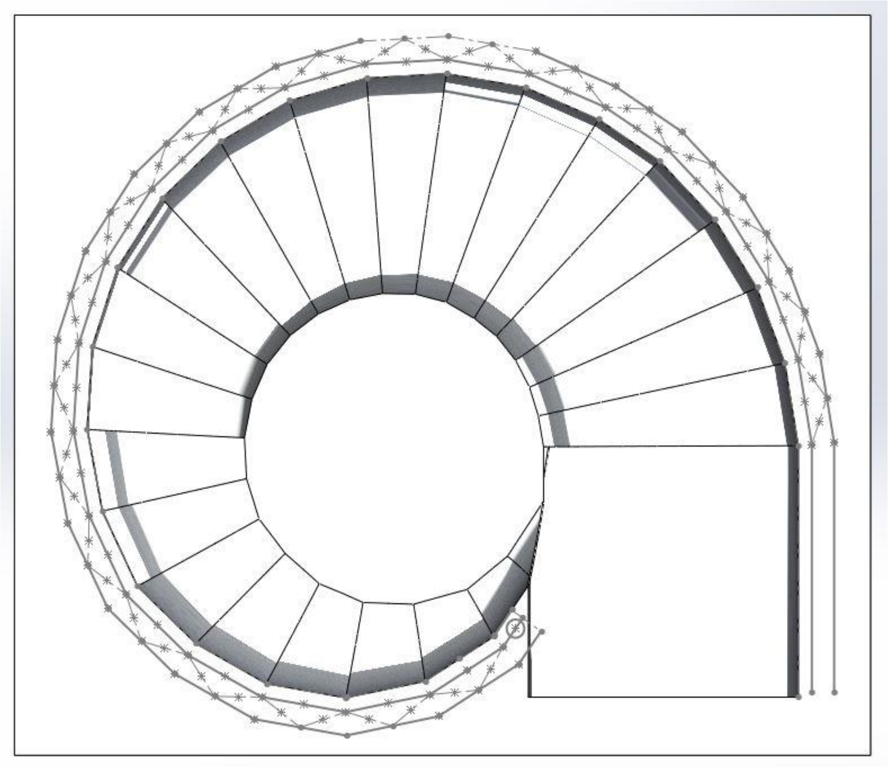

Figure 3.12: An image showing the sketch used to pattern holes around the outside edge of the recessed geometry.

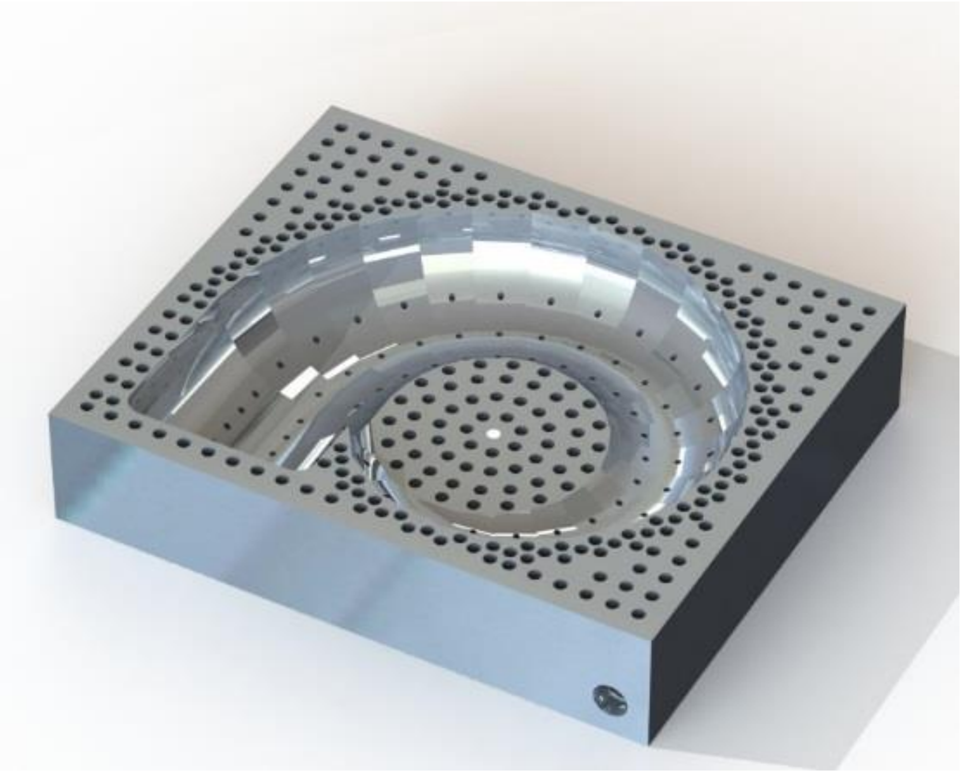

Figure 3.13: Rendered Image of the finished vacuum mold model.

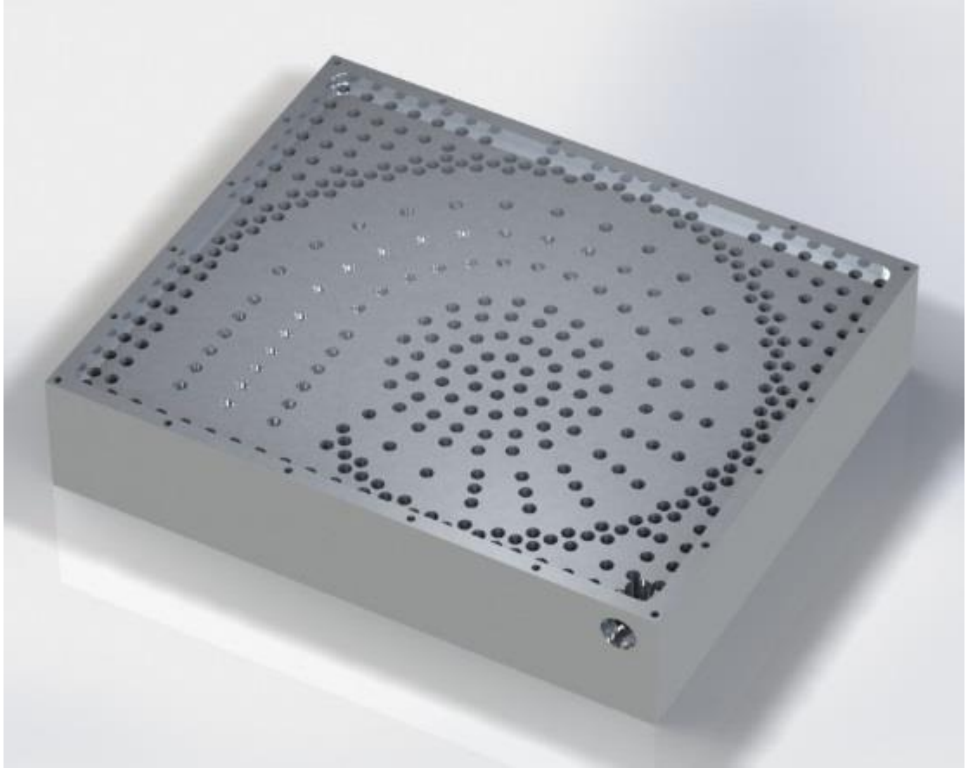

Figure 3.14: Rendered image of the finished mold from the vacuum side.

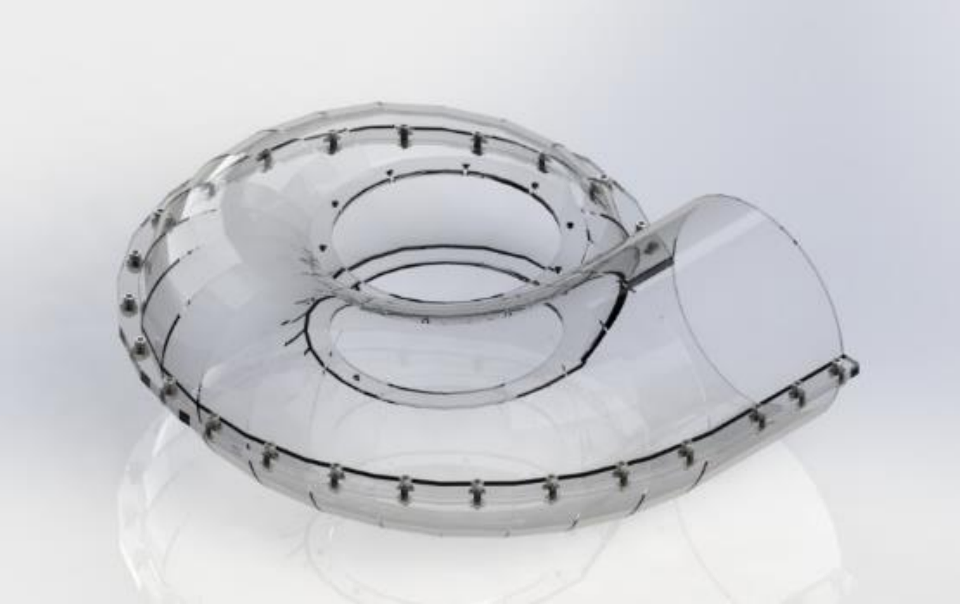

Figure 3.15: A rendered image of the final shape of the vacuum formed material.

3.5 Machining Negative molds

When Wagstaff delivered the metal for the molds the aluminum blocks were cut slightly larger than what was requested, thus the first step was to bring the molds down to size. Bill Magnie the machine shop manager took on this task. He also added the 1/4-inch recess, and the tapped holes around perimeter of both molds as seen in Figure 3.14. With the block machined down to size and the recess machined, the process of creating the vacuum mold could commence.

The first task of creating the vacuum molds was to drill the holes though the aluminum stock. By drilling the holes first the later machining process would leave a smoother finish. This is because the later operations would push any burr created back into the drill hole. The holes were drilled to their breakthrough depth where the cavity would be machined. The exception of this was the 1/8-inch drill holes that extend to the cavity itself. As shown in Figure 3.16, 1/4-inch holes were drilled 1/4-inch off of the surface and a 1/8-inch drill bit finished the final depth. This precaution was taken to avoid breaking small bits during the machining process. Parabolic drill bits were used to complete this operation as they perform better than traditional bits in removing material and in creating deep holes. The amount of machine time required to complete the operation was 4 hours and 48 min.

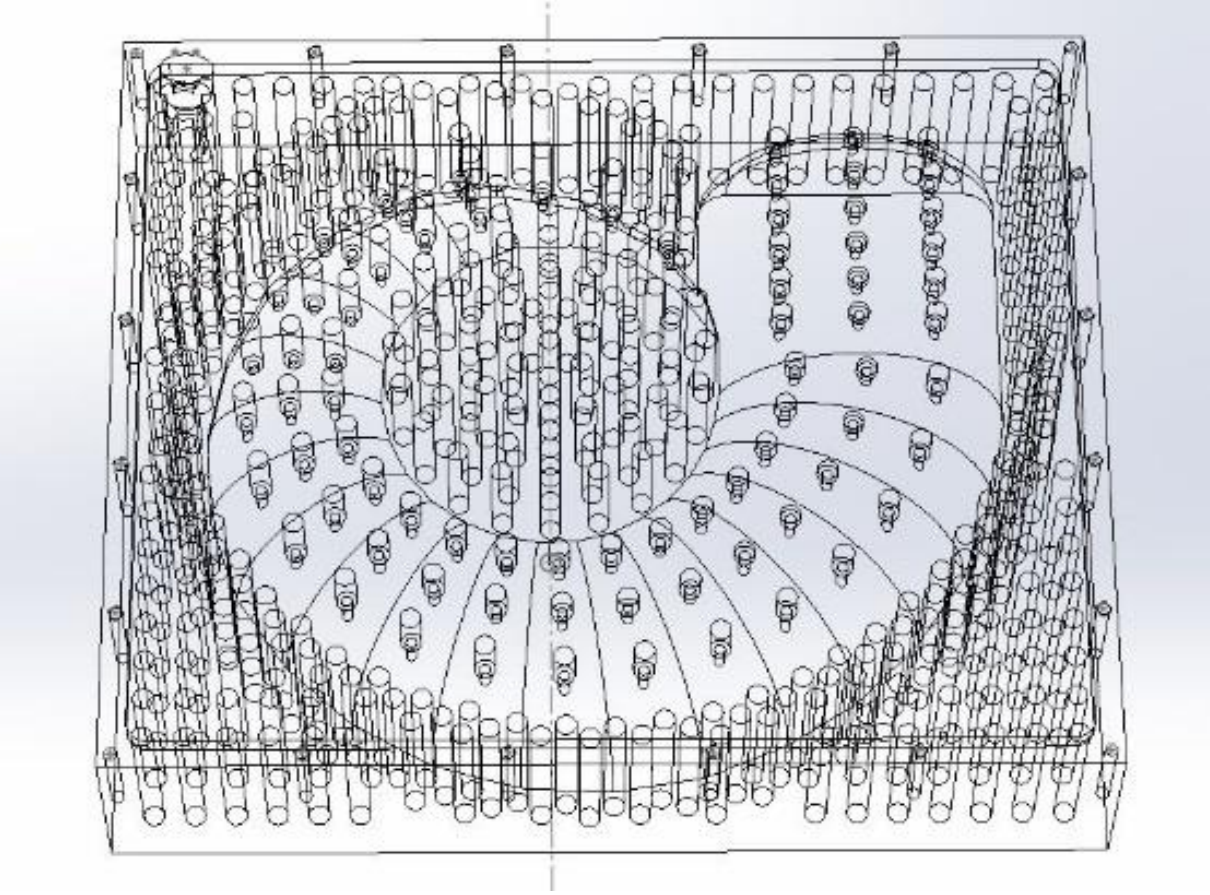

Figure 3.16: Wireframe view of the vacuum mold design showing the offset drill holes.

The next step in the process was to rough out the shape of the internal cavity. Using a 3/4-inch endmill the shape was milled out in layers until a stadium seating finish is all that remained. After the initial roughing the flat center of the mold was finished. This was also done at this point so that the surfacing passes would deburr the edges of the island. An image of the mold at this stage in the machining process can be seen in Figure 3.17. To rough the general shape and finish the island floor the machine time totaled 3 hours and 51 min.

The final stages of creating the vacuum mold were completed using a 3/4-inch ball endmill. Using a ball endmill as discussed with the infill mallet in the previous chapter, allows for contour machining when advanced control is available. The ball endmill can remain tangent to the surface as it removes material allowing complex surfaces to be created. Parallel linear passes were used to create the cavity as it offered the best surface finish. Machining the surface at each Z level or in a spiral pattern would create small islands at the bottom of the mold because the angle of the decreasing slope of the scroll is small. This means that even

Figure 3.17: An image of one side of the vacuum mold being machined. At this stage the roughing pass of the cavity and finishing pass of the island are complete.

with a small stepdown there would be small bits of material in between passes that would be larger than a typical scalp caused by the tool. By using linear passes back and forth in the x-direction the step over could be more effectively used to decrease amount of deviation from the desired surface. Using linear passes would leave more intense machine lines toward either edge of the mold, but these lines impacted the aesthetics of the mold surface less than small islands at the apex of the curve. A combination of the two could be used, but this would leave to a mismatch of the machining lines which had the potential to show in the final plastic product. This inconsistency of machining lines was to be avoided to improve the aesthetics of the final part.

To prepare the surface for final machining the 3/4-inch ball endmill following the linear path option in the direction of the x-axis was set to have a step over of 1/4-inch. This reduces the amount of material that the final finishing passes would have to take to improve the final surface. The results of this roughing operation is shown in Figure 3.18 with a small example of the final surface machined finish. This process required 64 min of machine time to complete.

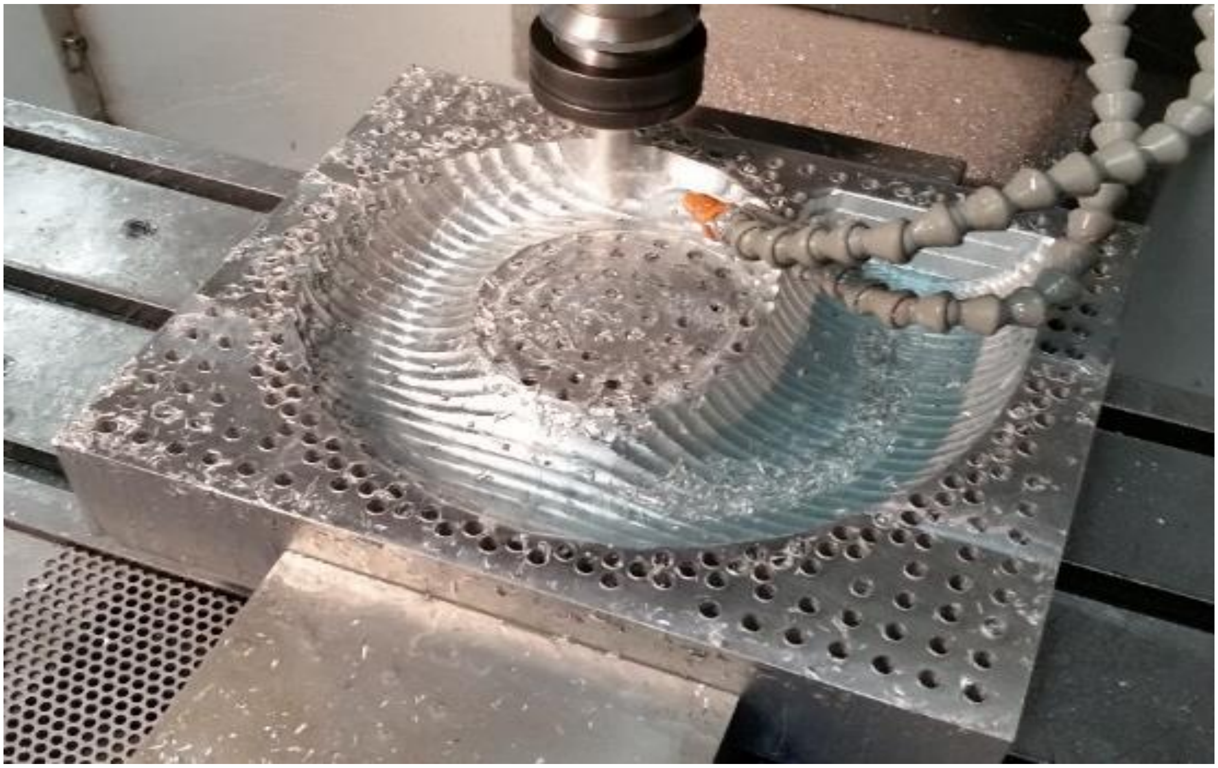

Figure 3.18: An image of the final finishing passes of the mold with the result of the roughing passes with a 1/4-inch step over.

The finishing passes of the mold were accomplished in the same manner as the ball endmill roughing passes. The finishing passes were linear passes along the x-direction of the machine. The step over of these passes was reduced to 1/100th of an inch to result in a scalping that was almost completely eradicated. The use of a larger ball endmill translates into a smaller scalp height as the contact of the ball along the surface is closer to being flat than that of a smaller endmill. The result of these small steps is a smooth almost continuous surface representing half of the mold shape. This final results are shown in Figure 3.19. The finishing passes on the mold had a total machine time of 14 hours and 32 min. The generated G-code for this process was so long that it maxed the memory of our HAAS Tool Room Mill and had to be split into 4 different sections. Because of the amount of data to be transferred to the controller each section of the code took approximately 10 minutes to upload before resuming the machining process.

To assemble the mold and prepare it for vacuum forming, a 1/8-inch thick aluminum plate was bolted onto the back of the form using the tapped holes described previously. A seal was needed along the contact edge of the aluminum plate and the aluminum block. To ensure

Figure 3.19: An image of one of the two vacuum molds once completed.

that the plate would be removable after the seal was applied high temperature lithium grease was used along the edge. This grease was rated for the temperatures being applied to the mold and should inhibit any channels forming on the sealing edge. An image of the applied grease is shown in Figure 3.20. A 3/8-inch brass hose fitting was threaded into the pipe threads that connected to the cavity below. Teflon tape was fitted to the outside of the threads to ensure the seal.

Figure 3.20: An image of the applied grease to form a seal around the outside edge.

3.6 Vacuum Forming Negative Molds

The size of the scale model hydroelectric dam was partially determined by the size of a typical home oven as that was the easiest way to evenly heat the plastic. A home oven has built in temperature control, is spacious, insulated, and many thermal plastic become malleable below $400°F$. The first vacuum forming tests conducted by Alex Olson attempted to use a heating element and a brick oven. This method because it only heated the plastic from one side caused the material to boil before becoming malleable enough to form. Boiling of the plastic leads to small bubbles in the surface of the material which ruins the transparency and surface finish. This learned information and the other reasons listed above lead to the use of an at home oven to conduct this vacuum forming.

The setup for vacuum molding in a home oven was simple. A mold would be placed on a cooking sheet on the middle rack of the oven. The temperature of the oven would be set based on the material that was being used. A vacuum hose would be attached to the brass fitting on the side of the mold and insulated using aluminum foil. The hose would be running out of the oven door where the gap would be insulated using aluminum foil and towels. A piece of thermo-plastic would be placed on the top of the mold and allowed to heat up. Once the plastic was heated to a malleable state the vacuum pump would be engaged and ran until the plastic sealed against the holes and formed into shape. An image of the vacuum molding setup is shown in Figure 3.21.

Figure 3.21: Vacuum molding setup in a home oven.

The first material that was used was used to vacuum form on these molds to prove proof of concept was PETG plastic. PETG forms exceptionally well at low temperatures which made it ideal to run the initial tests. The initial tests with PETG were successful and the quality was high with little modification to the process. An image of the initial test result is shown in Figure 3.23. The next step in the process was finishing. The shape had to be cut from the rest of the material. The ideal way to conduct this process is by utilizing a laser cutter. Laser cutting plastic leaves a clear edge and does not stress the plastic. It was discovered shortly after the initial tests that PETG releases benzene gas when melted. As a result it could not be cut on the University of Idaho Mechanical Engineering Department's laser cutter. The lead to exploring other material options.

One of the more common clear thermoplastics available is acrylic. Acrylic is readily available, inexpensive, and able to be cut on a laser cutter. For these reasons it was the next material that was to be vacuum formed. To vacuum form acrylic a higher temperature than PETG is required. It is accepted that the surface temperature of acrylic not exceed $350°$ F (Altuglas International Arkema Group, 2006). Exceeding this temperature can run the risk of surface boiling as shown in Figure 3.22. To prevent this from occurring during the vacuum forming the oven temperature was set to $350°F$ and aluminum foil was used to line the bottom of the oven. By adding this layer of aluminum foil the temperature of the oven was more uniform decreasing the hot spots on the material. With these adjustments successful molds were made.

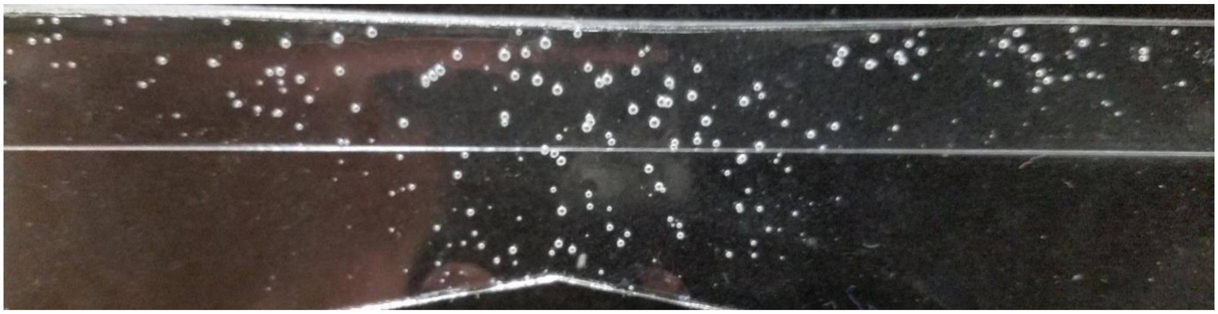

Figure 3.22: Boiled acrylic that occurred during vacuum forming.

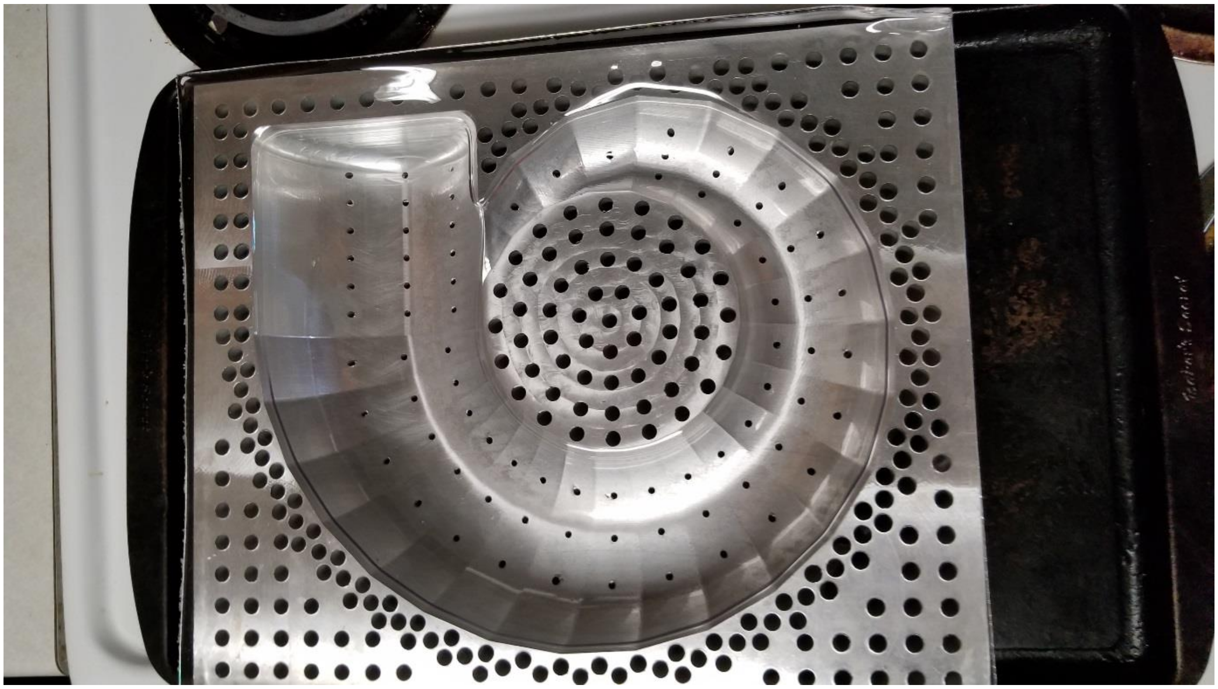

Figure 3.23: Initial PETG vacuum form test result still on the mold.

3.7 Results

The end result of all this work was a successful acrylic product using the machined aluminum mold. An image of the final assembly is shown in Figure 3.24. The two halves that were created were free of bubbles and were clear enough to observe the inner workings of the scale model. By using the laser cutter to cut the molds from the rest of the plastic the edges were clear. This is due to the melting of the plastic as it is cut. Because of the accuracy of our laser cutter the joining holes of the two halves to the stay ring resulted in a flush edge around the shape.

Throughout the plastic shape small dimples can be observed. These dimples are the locations of the vacuum holes. When the air was evacuated the plastic sealed over the mold. The vacuum pump did not have a pressure regulating valve and continued to pull the plastic through the drill holes. As the plastic hardened these dimples remained. A similar effect occurred on the surrounding flange. The dimples in these locations were significantly larger due to the increased diameter of the holes. Due to the design of the shape these dimples coordinated with the screw hole locations of the flange and where the scroll cage meth the stay ring.

3.8 Discussion and Conclusion

The results of the final product very closely resemble that of the CAD model that is displayed in Figure 3.25. In this final product the internal dam parts were designed by Melisa Bogart and Bill Magnie. The machining of all parts except for the scroll cage was also completed by Bill Magnie. With the addition of the scroll cage a final product could be delivered to the client. The process to make the scroll cage was not an inexpensive endeavor. As tabulated in Table 3 the final cost of machining the vacuum molds was $2,625.00 per half with a total cost of $5,250.00 for the pair. These cost exclude material cost and engineering cost.

Figure 3.24: An image of the final assembly of the scale model hydroelectric dam.

Following suite with that of the infill mallet the scroll cage presented in this chapter hits the marks of great design. This shape however is judged by different attributes than the complex curves of the previous chapter. The intent of this design is not to be a functioning hydroelectric dam but rather a representation of what is. By keeping the multiple pipe section and as much of the original geometry in the scale model the intent of the model was achieved. The creativity of design is supported by the form of manufacturing. Attaining clear complex shapes is not a trivial task. The development of the methods to create the final shape is a tribute to the creativity to us as engineers. Manufacturability can be judged in on the production of the final plastic shape and that of creating the mold. Vacuum forming the acrylic as a straight forward and easy process that is very much repeatable and suitable for production. Machining the molds however was a lengthy process that without large production numbers is hard to pursue. What was shown is that it is possible to do without advanced manufacturing method. Due to the metrics of great design purposed in chapter 1 the scroll cage developed here withstand time.

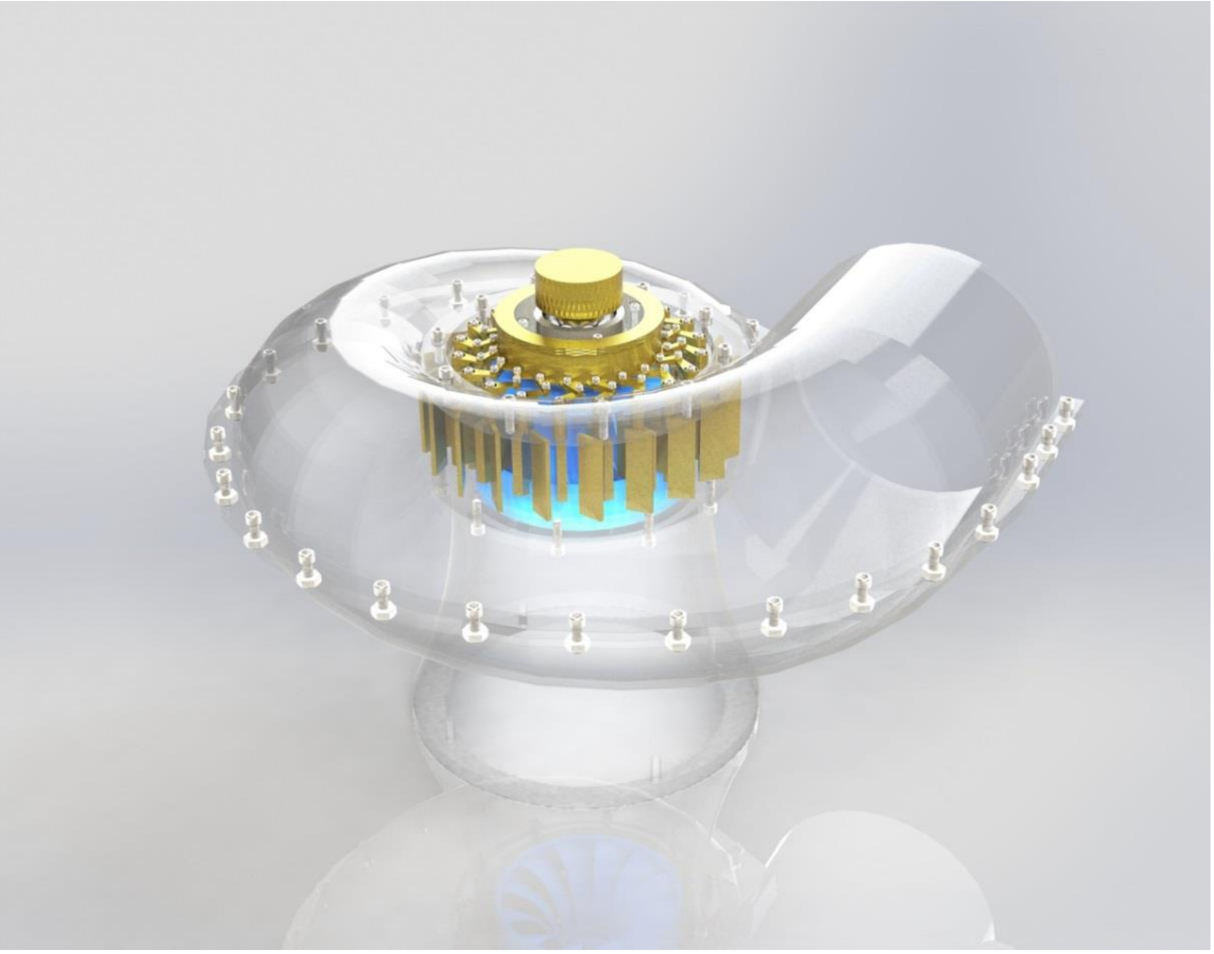

Figure 3.25: Rendered image of the completed hydroelectric dam scroll cage.

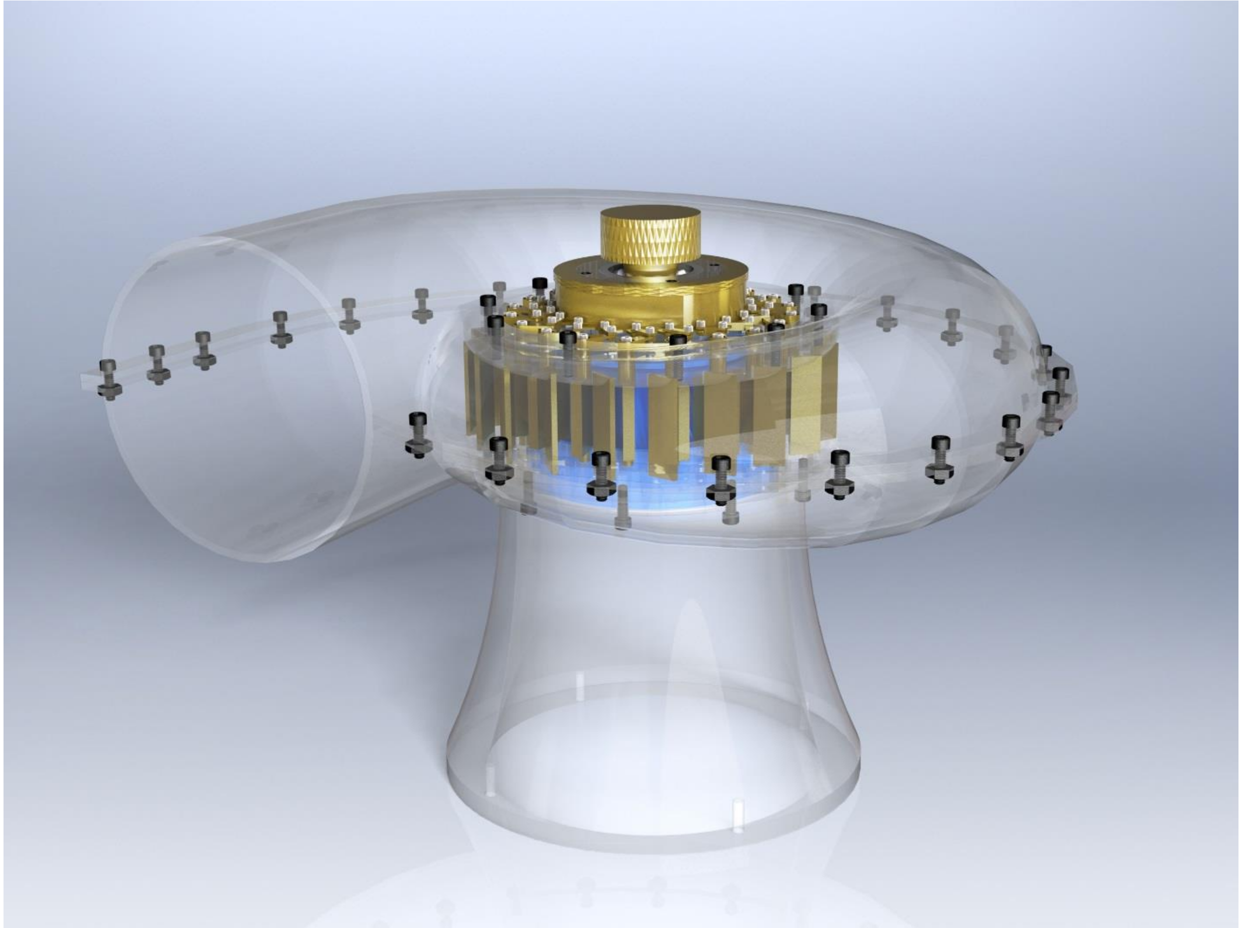

Figure 3.26: The inlet side of the scale model hydroelectric dam.

Table 3.1: The machining time calculations for the scroll cage molds.

Vacuum Molds	Machine Time (min)	Change Time	Fixture Changes (	Total Time	Machinist Cost Per hour	Machine Time Cost per Hour	Operation Cost
Facing Block to size	60	10	0	60	50	50	$ 100.00
Holes	288	10	1	298	50	50	$ 496.67
General Roughing	224	10	1	234	50	50	$ 390.00
Flat Island	7	0	0	7	50	50	$ 11.67
Ball Roughing	64	0	0	64	50	50	$ 106.67
Ball Finishing	872	10	4	912	50	50	$ 1,520.00
			Total Time (hrs)	**26.25**		**Total Cost**	**$ 2,625.00**
						Total Cost Both Molds	**$ 5,250.00**

Chapter 4: Discussion and Conclusion

4.1 Manufacturing of Surfaces

The manufacturing of complex surfaces as shown in this thesis is a challenging task. From concept to production, surface manufacturing is a complex subject that is time consuming and labor intensive. The addition of curves and non-linear geometry drastically increases the cost of production and the time it takes to produce. The two cases that were presented here were both driven by the same three principals: intent, manufacturability and aesthetic appeal. In the case of the infill mallet the complex curves were included to allow for the pattern to be released form the sand and maintain its beauty. Mr. Studley designed the mallet around the manufacturing method to achieve aesthetics and intent. The scroll cage was no different. The intent of the cage was to swirl water and maintain constant pressure to increase efficiency. However, the scroll cage originally was design around the manufacturing method of welded pipe sections. The original designers of the scroll cage designed around manufacturing and intent. It was in our model that the aesthetic appeal was added as well.

As was discovered during the work of this thesis manufacturing complex shapes in ways beyond their initial design is a difficult task. As shown with the infill mallet the addition of modern technology changed how the mallet would be manufactured. These modern methods increased the time and production cost of the final product.

It is hard to draw the same conclusion from the manufacturing of the scroll cage. Because the original cage was made from steel 80 times the size of our model, comparing the two is difficult. However, to reproduce the geometry using vacuum forming is definitively challenging. With the added design parameter of transparency the difficulty increased by a significant amount. In this case the design of the product drove the manufacturing method unlike that of the infill mallet.

4.2 Final Thoughts

The production of a great design is not a trivial endeavor. The creation of a timeless design takes time and thought to not only the function, but the aesthetics, and manufacturability. Described in the paper have been two designs that are being offered in an attempt to reach this criteria. The Studley tool cabinet infill mallet is truly a design that is timeless. To this day it is still a coveted tool 100 years after its creation. When these ideas of design were applied to the scroll cage another satisfying product was produced. For the restrictions imposed and the limiting physics and science it was relatively easy to make and just as beautiful as it is functional. The complex geometry and manufacturing methods resulted in worthy products to stand against time. It is of my opinion that these designs are supported by the criteria of great design listed in chapter 1: theory, creativity, and manufacturability.

References

Altuglas International Arkema Group. (2006). *Acrylic Sheet Forming Manual.* Retrieved from Curbell Plastics: https://www.curbellplastics.com/Research-Solutions/Technical-Resources/Technical-Resources/Plexiglas-Forming-Manual

Dassault Systemes. (2017). *Loft Property Manager.* Retrieved from SOLIDWORKS Help.

Fine Scale Modeler Magazine. (2014). First, What is a Scale Model. Kalmbach Publishing Co. Retrieved from Fine Scale Modeler: FineScale.com

Gomez, A., Krueger, C., Thompson, D., & Speers, K. (2016). *Mindworks WIKI*. Retrieved 2018, from GD&T for Reverse Engineering: http://mindworks.shoutwiki.com/wiki/GD%26T_for_Reverse_Engineering

Kolko, J. (2010). Abductive Thinking and Sensemaking: The Drivers of Design Synthesis. *In MIT's Design Issues: Volume 26, Number 1 Winter 2010*.

Moon, J. (2016, December). Re-creating the Studley Tool Chest. *American Period Funiture, 16*, 34-47.

R.H.S., & K.W.K. (1955, September 18). R.H. Spiral Case Used On Hydraulic Turbine. Milwaukee, Wisconsin: Allis-Chalmers MFG. CO.

Rankl, K. (2017, May 8). Basic 4 Axis Setup. Retrieved from https://www.youtube.com/watch?v=7NKCE51eV3I&t=386s

Reliance Foundry. (2017). *What is Sand Casting? How to form Complex Castings with Sand Molds*. Retrieved from Reliance Foundry: http://www.reliance-foundry.com/castings/sand-casting#gref

Williams, D. (2014, November 3). *Studley Tool Chest Final Exams - The Mallet*. Retrieved from the Barn on White Run: http://donsbarn.com/studley-tool-chest-final-exams-the-mallet/

Williams, D. C. (2015). *Virtuoso: The Tool Cabinet and Workbench of Henry O. Studley.* Fishers, Indiana: Lost Art Press.

Appendix: 3D Printing Sand Cast Molds with Complex Geometry

3D printing casting patterns requires a smooth surface. Any defect in the pattern will be present in every casting that it is used in. A rough surface on a pattern is also more difficult to remove from the sand than one with a smoother surface. For these reasons we tested the 3D printers at the University of Idaho to see if we could attain a quality pattern for use in casting the infill mallet. This appendix describes what was found.

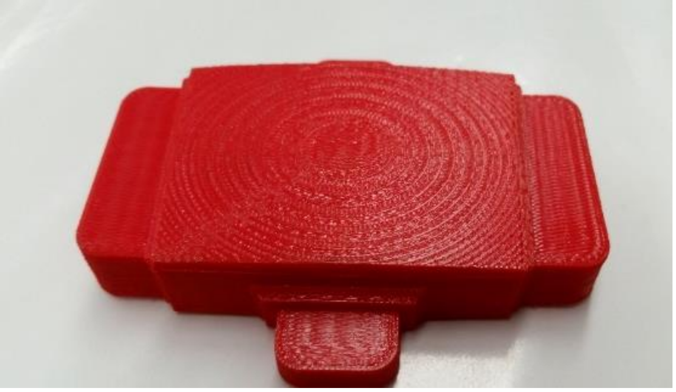

Figure A.1: PLA patter printed on the Makerbot Replicator 2.

The first prints were out of PLA using a Makerbot Replicator 2 desktop printer. The patterns were printed from the plane of symmetry lying on the printing bed. The shape of the prints were well achieved using this printer. The flatness of back face was acceptable and all the details of the hammer head were well defined. The most concerning issue that was discovered in these initial prints was the layer height that caused discretization the surfaces of the pattern. The 3D printers available in the University of Idaho Mechanical Engineering department build parts by layering plastic using an extrusion process. The layer height of the 3D prints on the top surface became apparent as shown in Figure A.1. With the PLA material the top surface would have to be modified using some form of subtractive manufacturing such as sanding. For this reason the ABS option was examined.

Printing with ABS is more difficult than printing with PLA and takes a more specialized printer. The printer that was available with the capability to print ABS plastic was a FlashForge Creator Pro. This printer featured a heated printing bed and an enclosure allowing for a slower and even cooling of the plastic which is required for ABS printing. The patterns for ABS were printed using the same techniques as the PLA versions. Both materials produced similar initial surface finishes. In an attempt to smooth the surface the ABS patterns were subjected to both acetone vapors as well as an acetone bath. It was important to ensure that only surfaces that were to be smoothed were affected by the acetone and not the alignment holes. Acetone washing the alignment holes warped the plastic enough that the two halves would not be straight. After acetone washing ABS patterns it was discovered the layer height of the prints was too large to completely eliminate the steps formed by the layering process. The amount of smoothing required to acquire a smooth surface started to have adverse effects on the rest of the geometry. After vapor smoothing the cove detail at the ends of the hammer started to lose their shape and melt into the rest of the surface. The dimensional accuracy of the prints was greatly decreased after smoothing. Unable to accurately control the smoothing also became an issue. The discrepancy of smoothing on two patters would could create a step or discontinuity on the parting line. For these reasons the vapor smoothing of the ABS plastic was abandoned. The final result of the process can be seen in Figure A.2.

Figure A.2: Acetone smoothed ABS pattern.

Due to the results of these experiments we turned to Schweitzer Engineering Laboratories for assistance. Using a high end 3D printer they were able to print PLA plastic with a smaller layer height. The surface finish on these prints was high quality and could be used as the final pattern.