SFSA Cast in Steel Competition
Mjölnir Project

Industrial and Manufacturing Eng.
Cal Poly Pomona

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Cal Poly Pomona: Team 1

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ABSTRACT

Hammers have been around as long as the human race has been in existence and have developed through history. In this project, the main objective was to produce “Thor’s Hammer” through casting, we named this the Mjölnir project. To achieve this objective, we worked through various stages where many changes were made before the final hammer was constructed. The stages were composed of: research, design, prototyping, pattern production, hammer production, finishing, final assembly, and testing. The alloy that the hammer was produced with was Cast Stainless Steel 420. With the help from our industry partner, Aerotec Alloys, and the use of casting technologies (solid modeling, rapid prototyping, and casting simulation), our team was able to manufacture a hammer that satisfied all of our goals and requirements.

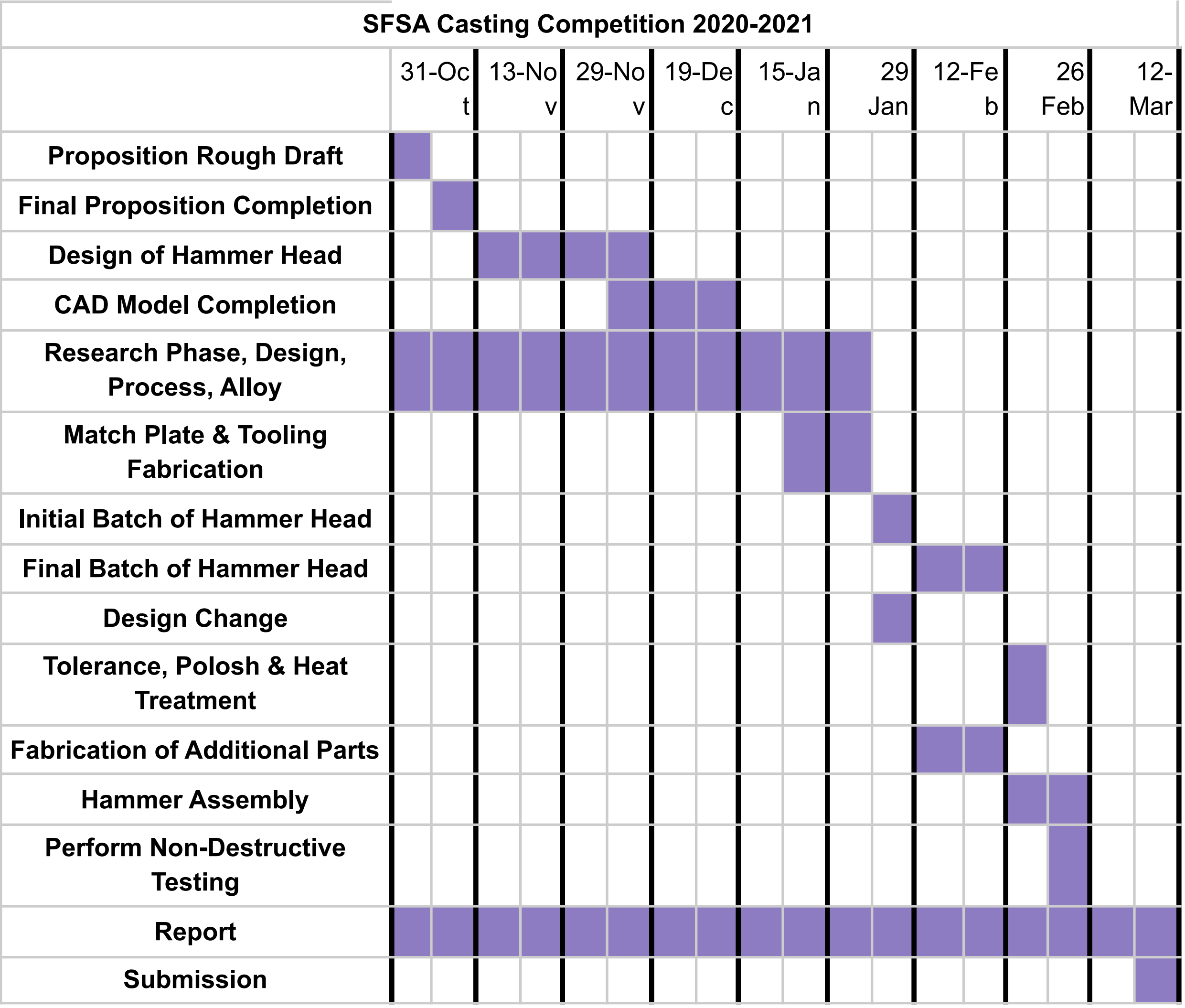
1. INTRODUCTION

1.1. Project Management

Figure 1 displays the original Gantt Chart generated for the Mjölnir project. Starting in October, the group began weekly meetings to discuss and brainstorm ideas for the hammer design, alloy selection, and casting technology. Once the design plans were determined, the group began to prototype by creating 3D models and deciding the features that they would like implemented on the hammer.

Once the group decided on the final design and approved of the 3D printed prototype, the group generated the required model to use in the casting simulation. Using Solidcast, we ran a simulation of our pour, gating, and riser system to ensure that there were no shrinkage, misruns, or excess porosity. After finding satisfaction with the simulation, the group first printed the prototype in PLA to check if the print details came out correctly. Once the prototype passed our test, it was then printed in moldlay to prepare for the investment casting process.

Without delay, the group worked with the industry partner to cast and pour the hammers in Cast Stainless Steel 420. After much sanding and detail work, the group had the hammers heat treated, polished, and assembled with it’s handles.

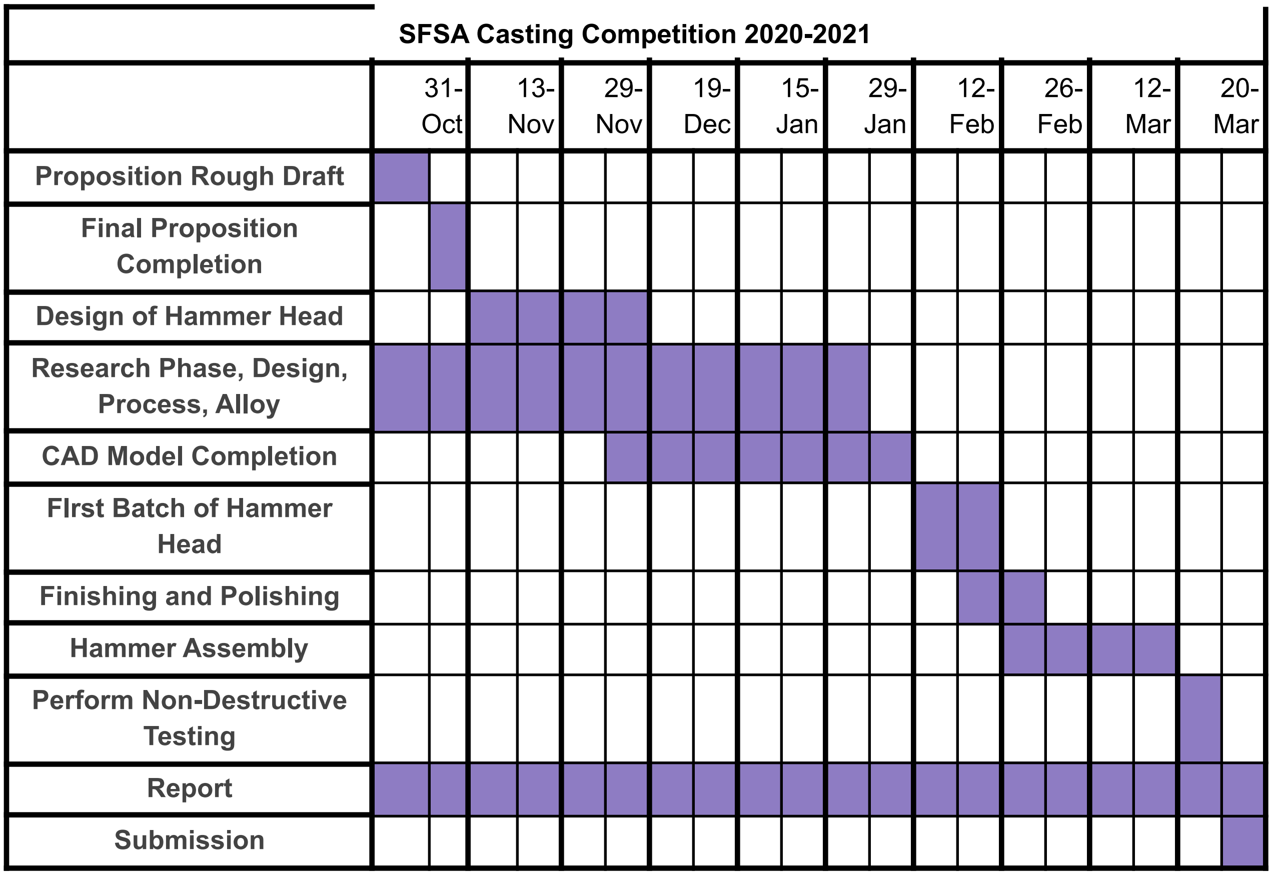


SFSA Casting Competition 2020-2021

	31-Oct		13-Nov		29-Nov		19-Dec		15-Jan		29 Jan		12-Feb		26 Feb		12-Mar	
Proposition Rough Draft	■																	
Final Proposition Completion		■																
Design of Hammer Head			■	■	■	■												
CAD Model Completion						■	■	■										
Research Phase, Design, Process, Alloy	■	■	■	■	■	■	■	■	■	■	■							
Match Plate & Tooling Fabrication										■	■							
Initial Batch of Hammer Head												■						
Final Batch of Hammer Head													■	■				
Design Change												■						
Tolerance, Polosh & Heat Treatment															■			
Fabrication of Additional Parts													■	■				
Hammer Assembly															■	■		
Perform Non-Destructive Testing																■		
Report	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
Submission																		■

Figure 1*: *Original Gantt Chart

Figure 2 is the adjusted and final gantt chart for our Mjölnir project. In the final gantt chart, there were changes that differed from the original gantt chart. Due to changes in our casting method, the dates of our activity deadlines changed. Since our team decided to do investment casting rather than sand casting, it saved a lot of time. In addition to that, our industry partner was extremely responsive and excited for this project, that the hammer was casted earlier than expected. With this, we were given more time to finish the assembly of the hammer. Furthermore, the deadline of the project was pushed back. Given this, the final gantt chart deadlines were changed.



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FIrst Batch of Hammer Head													■	■						
Finishing and Polishing														■	■					
Hammer Assembly															■	■	■	■		
Perform Non-Destructive Testing																			■	
Report	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
Submission																				■

Figure 2: Updated Gantt Chart

1.2. Literature Review

With our goal to create "Thor's Hammer," our team first thought of creating a hammer based on the Marvel Universe's version of Thor and its depiction of Mjölnir. However, our group thought that the design that is depicted in the movies would not be as interesting and would not meet the required design constraints. Given this, we researched more about the ancient Nordic mythology of Thor and his hammer.

Contrary to our initial knowledge about Mjölnir, it was not an actual physical hammer that we could base our design off of, but rather was used as a symbol with a deeper meaning. During the Christianization of northern Europe during the 8th and 12th centuries, Mjölnir was used as a pagan symbol and represented belief in the old gods. This symbol is still used today by Neopagans, representing Thor's vast power. In Norse mythology, it was believed that the Norse god of mischief, Loki, had played a trick on Thor. As an apology, Loki tricked some craftsmen dwarves into making gifts for the gods. One of these gifts was Mjölnir which had originated as a two handed war hammer. Although, due to Loki's mischief it had caused it to have a shorter handle making it into a single handed weapon. The hammer was said to have given Thor power, the hammer would never shatter, never miss, and it would always return to Thor.

Generally when we think of hammers, we usually have an image of a useful tool that is used for construction. In this case, the historical Thor's hammer, Mjölnir, was used more as a symbol of paganism during the 9th century. As seen in **Figure 3,** Mjölnir was a symbol that viking men and women wore as amulets. These amulets were not only worn as a symbol of paganism and honor to Thor in hopes for protection from ghosts and spirits. Frequently, the amulets were also accompanied by the cross from Christianity to double the protection from these souls. There were many ways to create these amulets, but the most common method was to cast them in silver, iron, bronze, and even tin and gold plating. In fact, some of the amulets had inscribed runic lettering on them, translating to "Hammer is" or " This is a hammer."

Figure 3: Mjölnir amulet

When we think about our ancient ancestors and the tools that they used, we generally think about civilizations in the bronze age and stone age. Well in terms of tools that we used the ancient nordic people were closer related to use than we think. As it is well known, steel is the most produced metal and metallic alloy in the world with 1,869.9 million tonnes (Mt) being produced in 2019, a 3.4% increase from the previous year. While the ancient nordic people did not have the knowledge or technologies that we have today to utilize steel and its alloys, it is believed that they were one of the first civilizations to use carbon based iron alloys and possibly the predecessor to steel.

Ancient nordic civilizations might have been one of the first civilizations to advance from the iron age to the steel age. In Denmark, archeological studies were done where it is found that in the early history of the people in this area steel swords and knives were made with impure iron. These tools and weapons were found to have many oval shaped slag inclusions that were detrimental to the mechanical properties of the metal as seen in **Figure 4**. Later in their history the ancient nordic people started to create more advanced systems and developed furnaces that would capture slag and begin to purify their metals. This allowed them to create some of the first crude steel alloys, seen in **Figure 5** which contained around 0.8% carbon and 0.9% phosphorus. This allowed them to create a harder steel that is also more corrosion resistant.

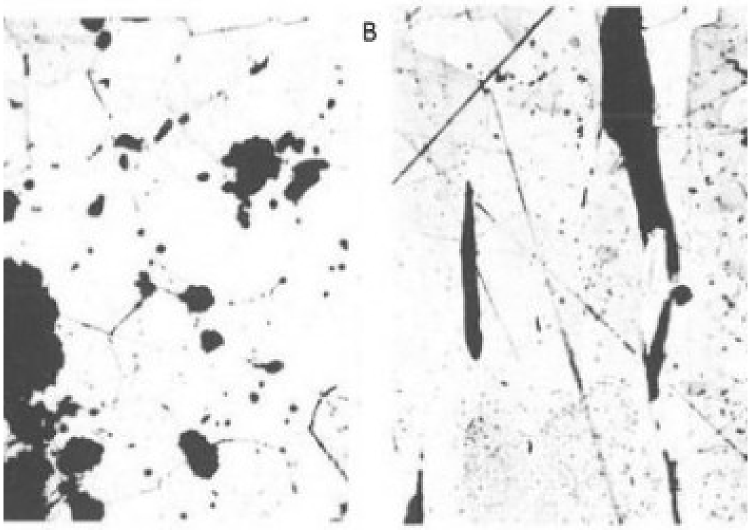

Figure 4: Slag Inclusions in Microstructure of Nordic Steel

Figure 5: Early Nordic Steel as Crescent Moon Knife

2. DESIGN

2.1. Design Selection

We wanted our Hammer to originally closely resemble a full sized replica of Marvel's Thor's hammer. However, due to the complications of casting within the weight limit, functionality constraints, and design complications, we had to scrap the idea. Following that we decided on trying to find a more traditional and functional design to base our design off of. After doing some research we found a more traditional variation of thor's hammer that closely resembled the traditional symbol for Mjölnir. This design has a pointed head design closely resembling an anchor. Our design came out to be a rectangular head with a pointed top and designs on the sides including a celtic symbol for mjolnir, lightning, and nordic runes saying mjolnir.

The head of the hammer is 2 inches tall, the width is 2.2 inches and 4.5 inches long on the side with our engravings. The handle hole is an oval with dimensions 1.125 by .812 inches. As for the size of thor's hammer including the handle it measures to be approximately 11 inches in length similar to the depiction of that in lore being a short hammer.

2.2. Alloy Selection

When debating on what alloy to use for this hammer, we were limited to the alloys that Aerotec Alloys had on stock. Aerotec had many steels available, as a team we decided to choose a martensitic stainless steel for its hardness. Aerotec had two martensitic stainless steels, 410 and 420. In the end, we decided to choose 420 SS because of higher hardness after heat treatment and because it was more convenient for Aerotec to pour for us.

2.3. Production Processing Selection

When deciding which metal casting process to go with, we were deciding between sand casting and investment casting. Either of these processes could aid us in our goal of casting thor's hammer. A sand casting foundry and an investment casting foundry was willing to aid us with this competition. After multiple discussions with the group, we decided to go with investment casting with Aerotec Alloys. This is because many of us already had experience with sand casting from previous projects, while none of us had experience with investment casting. We also had access to a new wax-like material called, "mold-lay," that our manufacturing department at Cal Poly Pomona purchased for their students for use in projects. Investment would be a fun new experience for all of our team members and a great addition to our resumes for future job opportunities in the future.

3. MANUFACTURABILITY

3.1. Design Analysis

In order to collaborate on the hammer design effectively, the group used Fusion 360 and 3D prints to bring to light design changes and achieve a better perspective on size and scale of details.

The initial revision of the hammer was focused on trying to achieve a large hammer like the MCU’s while staying under the weight limit by creating a hollow hammer. Unfortunately that idea was scrapped when we decided it could not be easily cast and we were unwilling to take the risk if it didn't turn out as expected. The second attempt shifted to a more traditional version of Mjölnir with an anchor-like shape and added celtic design on the sides that gives it a runic powerful feel. The third iteration added runes that spell out Mjölnir. One feature that was revised more than others was the eye profile to mate the handle and hammer head because our handle was to be determined. The handle used was an off-the-shelf replacement handle initially.

3.2. Final Design

The final Mjölnir design included all the previously mentioned features with added hand-designed lighting to the engravings. The striking faces of the hammers came out square, the bottom is rectangular, the sides are like squashed pentagons, and the top also rectangular. Fillets were added to all edges to allow for material to easily flow through the hammer while casting. The eye was designed to accept a commercially available axe handle that adds to the ease of manufacturing, reducing the time and resources needed to finish a unit. **Figure 6 and 7** is an engineering drawing of the final design with an isometric view.

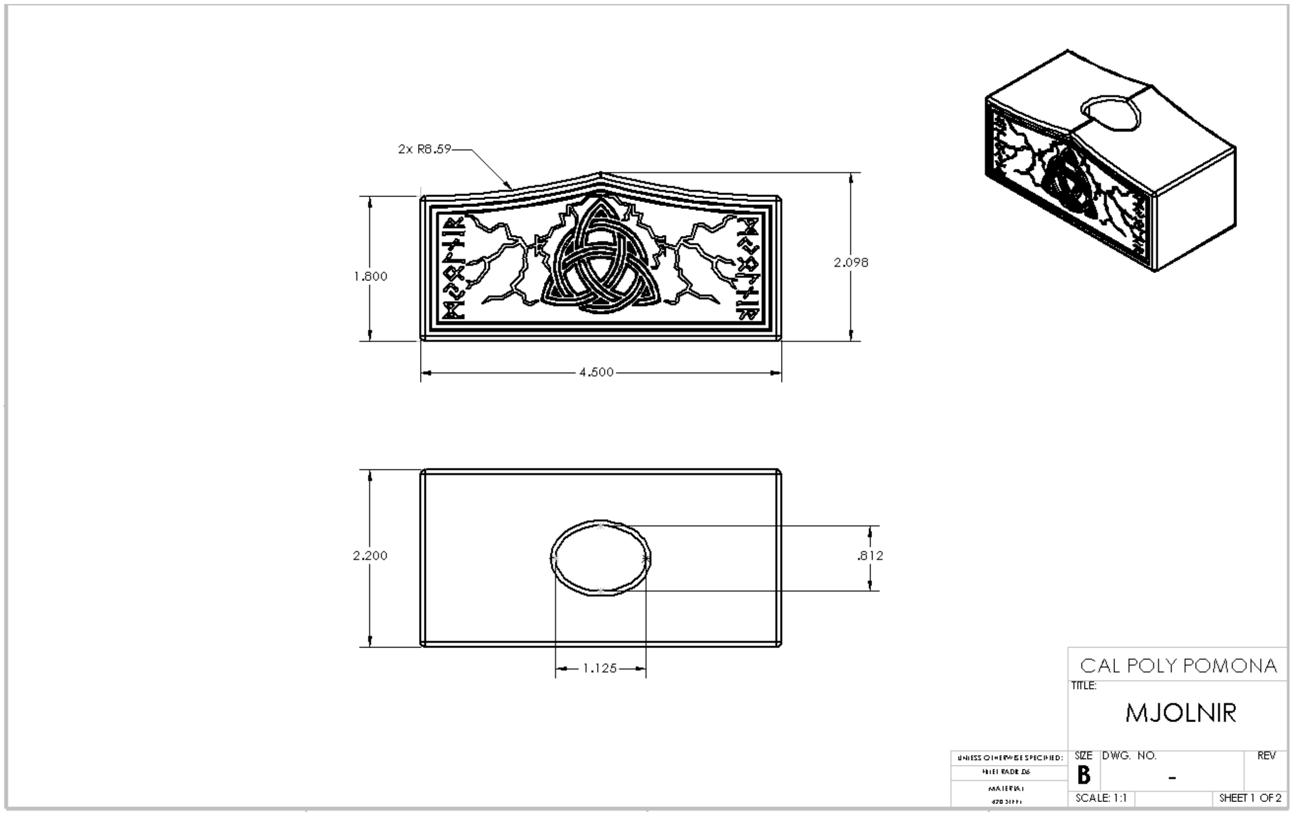

Figure 6: Hammer Head

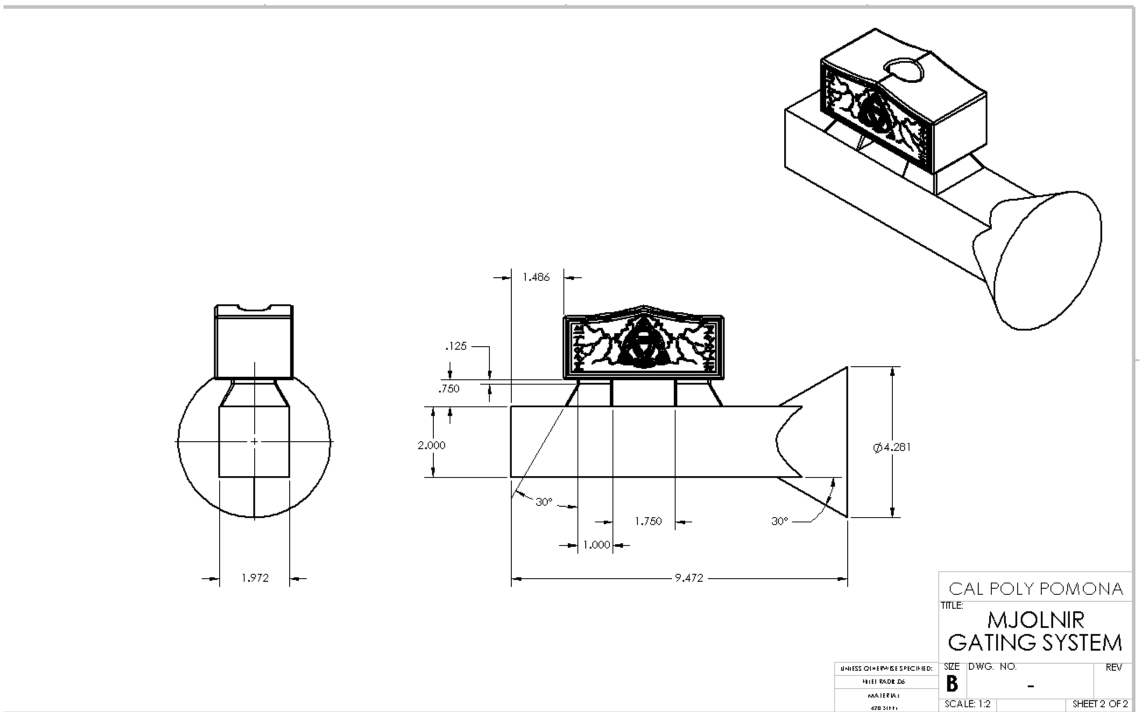

Figure 7: Gating System

3.3. Prototyping

Our first prototype was a 3d print out of PLA of our initial design **Figure 8**. This model was brought to aerotech so we could get advice on gating and giving them an idea of the size of our hammer. From this prototype we had to change the hole for better fitment of our handle, and aesthetically we decided to go with more realistic lightning bolts. Once we had our final design Aerotec did a test pour and found excessive pitting **Figure 9.** The cause of the excessive pitting was that not all of the moldlay melted out and there was excessive oxidation during the pour. In order to fix this we burned out the moldlay for longer and during the final pour flux was poured on top of the funnel to draw out impurities.

Figure 8: Prototype Print

Figure 9: First hammer poured

3.4. Production Processing

Having completed our final design and finishing prototyping, we began the process of part production. The first part of the production process was pattern creation. Before we started making patterns we revised our design so that we would be able to make a successful investment casting. All sharp corners were given radii of at least 0.06 inches in order to help mitigate turbulence inside of our mold cavity. Once we finished our revisions we began prototyping our pattern. The material that we used to create the patterns was a wax like 3D printing filament called moldlay. In our prototyping stage, we experienced difficulty with getting a successful 3D print. The main challenge that we faced with this pattern method was with our prints failing in critical areas as seen in **Figure 10.**

Figure 10

Once we finished the final design, we ran several solidification simulations using Solidcast. Our final gating system simulations can be seen in **figure 11**. As you can see in the simulation, we had no shrinkage in our casting. We ran filling simulations as well and saw no concerns.

Figure 11: Shrinkage in Casting

Once we were able to get minimal defects with our 3D. With the investment processes you start with the positive of your mold, which we had with our 3D printed prototype, and start the coating process. In this process you first coat the pattern with a ceramic slurry and then coat it with ceramic sand. This process is repeated several times until the desired mold thickness is achieved. As this process is repeated larger ceramic particulates are used to strengthen the mold for easier transportation and mold integrity. Examples can be found in **Figures 12** and **13.**

Figure 12:Shells in process

Figure 13: Final Shell

The next steps in the process are the dewaxing and mold preparation processes. First the mold is set in an autoclave and the wax is melted out of the mold. After this the mold is heated and held at a precise temperature before the metal is poured. This helps to achieve thin features as the metal will not freeze as easily with other casting processes. This also helps to mitigate the effects of thermal shock on the mold.

After the mold is prepared and the steel is melted it will be time to pour. The steel is heated to 3,000 degrees fahrenheit and is poured into the mold. After the metal and mold are cooled they are taken to the shake out machine where the mold is gently vibrated off. Once the mold is removed the excess metal from the gating is cut off with a plasma cutter.

Finally it is time for post processing. Before we start heat treatment some final touches are needed. We grinded away any surface defects before we heat treated our part so that it would not be too hard. After cleaning up the part it is time to change its properties through heat treatment.

Vira Tech was able to assist us with heat treating our hammers. They recommended their standard heat treatment for 420 SS to achieve adequate toughness for the hammer.

As for the details of the heat treatment, Vira Tech started by austenitizing the hammers at 1875 F and held for 2 hours. The temperature had to be held for 2 hours because of the large cross-section of the hammers. The hammers were then gas quenched with nitrogen gas to a temperature below 200 F. Vira tech said they use N2 because the gas is light and has a fast cooling rate. The fast cooling rate ensures that the material retains the austenitizing properties to achieve ultimate hardness. Once cooling is finished, the hammers are then tempered at 300 F for two hours. Tempering stabilizes the material so it does not crack.

4. QUALITY & PERFORMANCE

Table 1 shows the chemical composition of the hammer raw material. We were unable to use a spectrometer to find the full chemical composition of our hammer.

Table 1: Chemical Composition

	C	**Si**	**Mn**	**P**	**S**	**Cr**	**Mo**	**Ni**
	%	%	%	%	%	%	%	%
Min						12.0	0.4	3.5
< x > (1)	0.014	0.397	0.736	0.019	0.008	12.12	0.851	4.06
Max	0.015	1	1	0.04	0.04	14	1	4.5

Testing of the final hammers were used on items such as coconuts, watermelon, nails, and cinder blocks. The performance of the hammer was a success, the hammer successfully destroyed each item. This test can be seen in the test video we submitted.

5. CONCLUSION

Competing in this year’s SFSA Cast in Steel Competition has been an amazing and educational experience. This competition gave us an excellent opportunity to get experience working as a group to design and produce a casted product. Going through the design phase was a difficult but rewarding experience. We considered both green sand casting and investment casting; ultimately we decided on investment casting for its superior capabilities of getting small details. This decision was risky because no one in our group was familiar with the investment casting process but this allowed us to learn so much about not only investment but the industry as a whole. Being able to work with a local foundry, Aerotec Alloy, was very educational. We were able to learn about the investment casting process in a real life production setting, and we got to see some of the new technology being used in the industry.

After completing this project there are many things we would have liked to do differently now that we have more knowledge. The biggest change we would have made was to make our mold out of wax instead of 3D printed moldlay. The moldlay ultimately was more difficult to burn out and resulted in less than ideal detail including printing lines in the final product. We also would plan better post processing, when we were designing we were more concerned with getting a complete part out from casting. While this is a valid strategy, post processes could have led to a more intricate and elegant design.

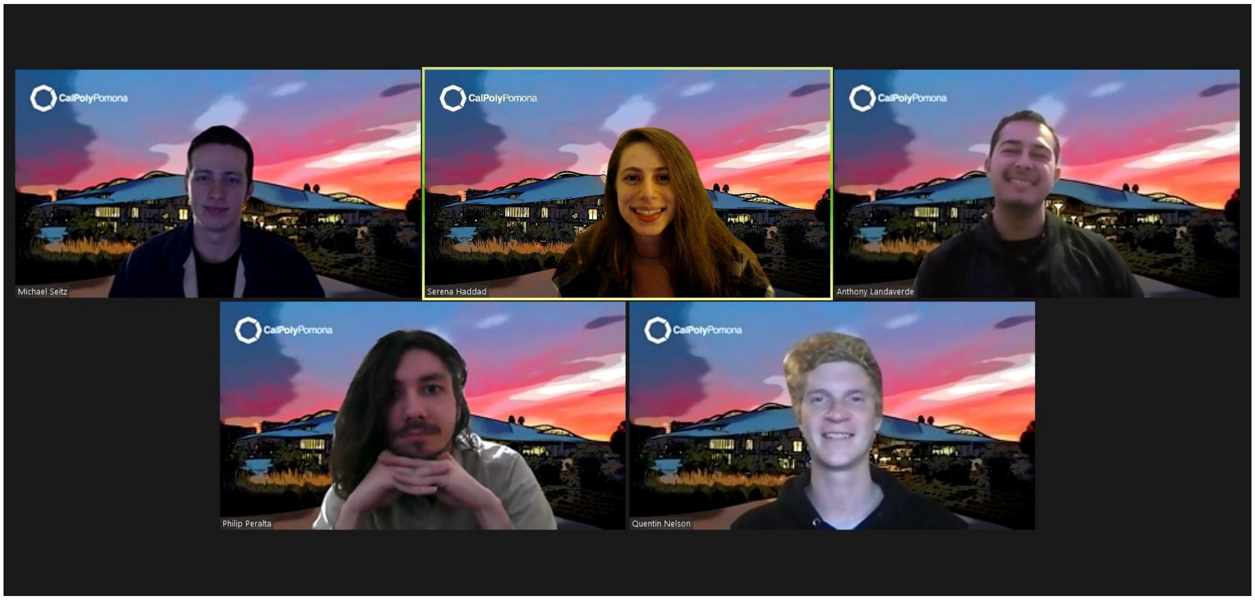

Figure 14: Cal Poly Pomona Team 1

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