

# THIS IS NOT A DRILL

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## Abstract

For the 2021 Cast in Steel competition hosted by the Steel Founder's Society of America (SFSA), our team was tasked with rendering and manufacturing our take on Thor's Hammer. Inspired from Norse mythology, Mjolnir is the hammer wielded by Thor, god of thunder, storms, and strength. Inspired by ancient art and drawings, we opted for a bowed hammer that incorporated more geometric details for a cleaner and more modern look. Given the material that the foundry we were working with had on hand, our material selection was limited, so we chose a 17-4 PH steel that would perform sufficiently. To cast our hammer, we chose to use investment casting as it would allow us to capture decorative runes to further cement its origin. With the help of additive manufacturing systems, 12 hammers were 3D printed using PLA and were then sent to Aurora Casting to be dipped in investment, burned out, and cast. As the casting process for the body of the hammer was being performed, our group worked on a similar investment casting endeavor to make a set of brass coins ourselves to decorate the side of the hammer that were similarly 3D printed. Once both castings were complete, all parts were brought together with a leather wrapped handle and assembled.

## Introduction

In this project, a hammer was designed and manufactured with the specifications given by the Steel Founder's Society of America (SFSA) for their Cast in Steel competition. This competition encourages college students to work together to apply their knowledge of computer aided design, material selection, prototype development, and casting methods to complete a project.

Given the immense creative freedom from such a task, we were given two important guidelines by which to design our hammer. First, the total weight of the hammer, handle and accessories included, must be less than 6 pounds. Second, a handle of 20 inches or less would ensure that this hammer would be preferably wielded one-handed, as Thor's Hammer is meant to be.

Before moving to the body of the report, it's important to mention that three of our seven students involved this year participated in the 2020 Cast in Steel project to create a bowie knife. We incorporated a lot of our lessons from our experience last year into this year's competition. Most notably, our bowie knife in 2020 was particularly unwieldy and difficult to use; this year, we focused on creating a hammer that feels comfortable to handle and paid close attention to prototyping to ensure it.

## Historical Background & Influence on Design ideas

Looking into Norse mythology and history, one of the first things that one might discover is that unlike the Mjolnir we are used to seeing in Marvel's Universe, the original mythic item was in fact a tool. Wielded by the gods, it could level mountains and shape the earth to their desires, much like the blacksmith's hammer is used to shape metal.

The legendary tales of Thor's hammer came about during the eighth century through the Scandinavian tribes that occupied most of western Europe. Vikings or Norsemen were a group of marauders who dominated the coastlines which expanded as far south as the Middle East to as far north into Russia. Archeological discoveries within countries like Norway and Sweden have revealed not only physical paintings and artifacts referring to the hammer but also documentation detailing the theology behind the hammer's origins.

Important archeological findings referencing Thor's hammer include the Altuna Runestone. The runestone, located in Sweden, is estimated to date all the way back to circa 1000AD (Viking Lore). The stone depicts a rudimentary painting of a person, most likely Thor, holding up a hammer artistically similar to that of the Mjölnir. In addition to paintings within rocks, jewelry had been also discovered taking on the similar shape of Thor's hammer. Jewelry, like that of the Rømersdal hammer, shows how the Viking people made replicas of Thor's hammer out of metal, bone, and even soapstone (Viking Lore). Many academics believe that the jewelry was crafted to provide a sense of protection for the wearer. A way of channeling the strength of Thor to protect them either at sea or to bless them throughout life. Along with the physical artifacts, there is also a complex series of mythological tales providing a detailed account of the origins of Thor's hammer (Ravilius).

The Mjölnir, or "bright-one," first appears in the stories of *Gylfaginning*, where the character Snorri Sturluson describes the hammer as the first of three weapons that the Gods of the Æsir hold in the highest regard. The second weapon was Járngreipr, which translates to "Iron-gripers," which was the iron glove that Thor needed to wield the hammer. The Third tool was the Megingjörð, which translates to "power-belt," enabling Thor to exert unlimited strength (McCoy) (Encyclopedia Mythica).

The origins of the hammer are first told in the book of *Skáldskaparmál* when Loki shaves the head of Sif, Thor's wife. Loki was given an ultimatum, either face the wrath of Thor or find a new headdress more beautiful to replace the cut hair of Sif. Loki went to *Svartálfaheimr*, the home of the Dwarfs, who were known for their métiers in forging the most extraordinary crafts from jewelry to powerful weapons. While in the caves of *Svartálfaheimr*, Loki set up competition amongst the dwarfs to craft the finest gifts to bring back home. The forging contest devolved into the teams sabotaging each other to win the glory of the gods. Loki added to the tension by disabling one of the dwarfs, Bokker, who was working on the mighty hammer. While Booker was tending to his wounds, he left the hammer in the furnace for too long, causing the hammer to have a stunted handle (McCoy).

Now with the head dress in hand, Loki returned to *Asgard* with new gifts to give to the Gods. When Thor took up the stunted hammer, he marveled at the craftsmanship, declaring that it was one of the most incredible weapons created in all *Asgard*. In attempts to sabotage Brokkr's work, Loki inadvertently created the most powerful weapon for his brother (McCoy).

The tales of *Asgard* guided the Norse people through hundreds of years of culture, art, and history. The symbol of the hammer bears the ideas of both strength and protection; a device that can be used as either a valuable tool or a powerful weapon. Like in the tales of *Skáldskaparmál*, the families of dwarfs competed to cast the best tools to win the glory of the Gods. Now we find the poetic parallelism of competing in a modern competition by sending in our own version of Thor's mighty hammer.

## CAD Modeling of the Hammer

We began the modeling process by brainstorming various profiles and sizes to get a feel for the details and size achievable within our constraints. You can see a few of the initial designs below in Figure 1, which cover a wide variety of shapes and sizes.

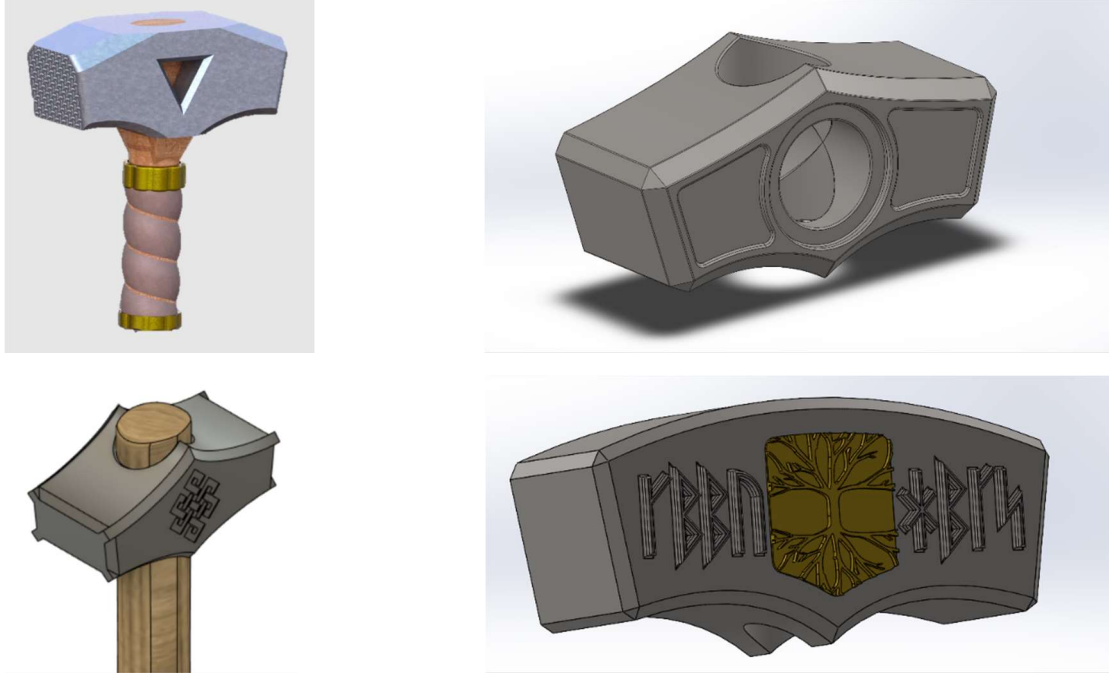


Figure 1: Initial Hammer Designs

Comparing our initial hammer designs to profiles of Thor’s hammer from our research, we noticed that many depictions featured a symmetrical, arced, anchor like shape. This seemed to give these designs a strong, powerful shape. We decided to create a new design that incorporated some of these elements, shown in Figure 2.



Figure 2: Hammer Profile Compared to Historical Depictions

To add some flair to what would otherwise be a mostly monochrome hammer, we decided to add a circular, brass insert to the center of the hammer. Embossed onto this insert is a depiction of Yggdrasil, the world tree. Yggdrasil holds and connects each of the nine worlds of Norse mythology together, making it central to the legend of Thor and the creation of his hammer. The coin design depicting Yggdrasil is below in Figure 3. The insert also features a triangular locating pin on the back used to clock the brass insert to the correct rotation. The insert is epoxied to the hammer to ensure it would not come off.



Figure 3: Coin Insert of Yggdrasil

Since we were casting multiple hammers, we encouraged team members to create their own custom designs for inserts to attach to their own personal hammers. Through this endeavor, we created a variety of new coins, some very detailed, others more abstract, and some minimalist. Shown in the top left of Figure 4 below, one of these designs was inspired by the Cal Poly SLO seal and was chosen as the insert for the opposite side of the hammer. Featured below are more of our team member's designs.



Figure 4: Personal Designs of Coin Inserts

Two brass pieces for the top and bottom of the hammer were also designed to match the shape of the hammer, Figure 5. These were mainly aesthetic pieces, however when we attached them to the hammer, we found that while these pieces looked cool, they caused significant discomfort to the wielder of the hammer. We ultimately scrapped these in favor of making the hammer more ergonomic.

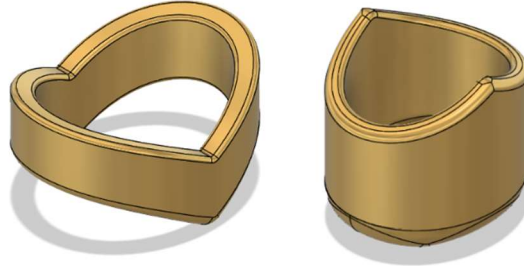


Figure 5: Brass Endcap and Top

We also wanted to give our hammer a unifying personal touch. For this we decided to inscribe Norse Runes into each side of the hammer. These runes are a translation of each of the 8 people who contributed to the hammer's creation's initials into Long Branch Younger Futhark Runes, shown in Figure 6. These runes were used mainly in Denmark but spread to all Scandinavia during the 10<sup>th</sup> century.

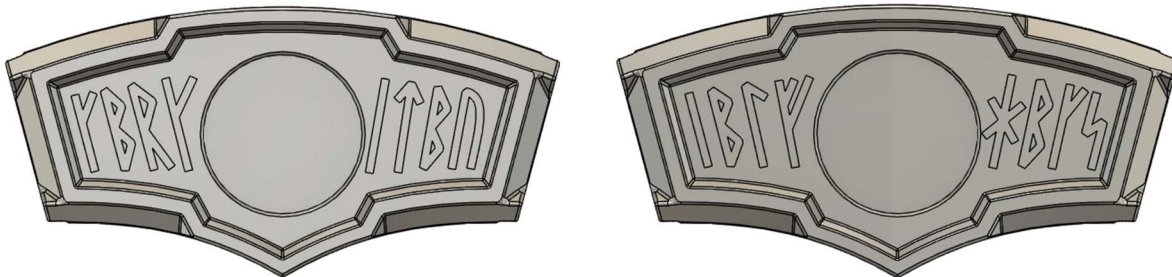


Figure 6: Hammer Design with Long Branch Younger Futhark Rune Initials

Thor's hammer is also depicted as being very large in size. However, to produce a large hammer that weighed less than 6 pounds, we began experimenting with pockets on the underside of the hammer. Using Fusion 360's shape optimization simulation, we were able to view where material was needed the most to maintain rigidity during a blow to the face of the hammer. From the results of these tests, shown in Figure 7, we determined material was needed most in the center of the design and needed least towards the outer walls.

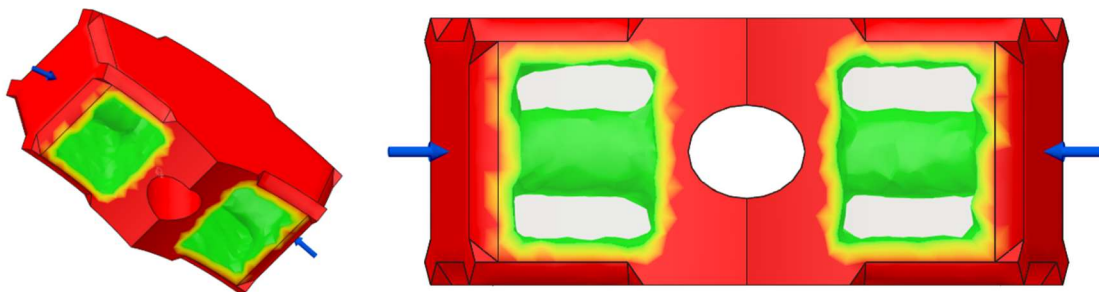


Figure 7: Fusion 360 Shape Optimization Results

Based on the results of the shape optimization, we created 2 possible pocketing designs, in Figure 8. The first had 3 pockets per side with smaller thickness ribs dividing them. This created a triangle over the area most critical to the hammer's rigidity. The second design had 2 pockets per side, with a much larger rib in the center, where mass was most critical.

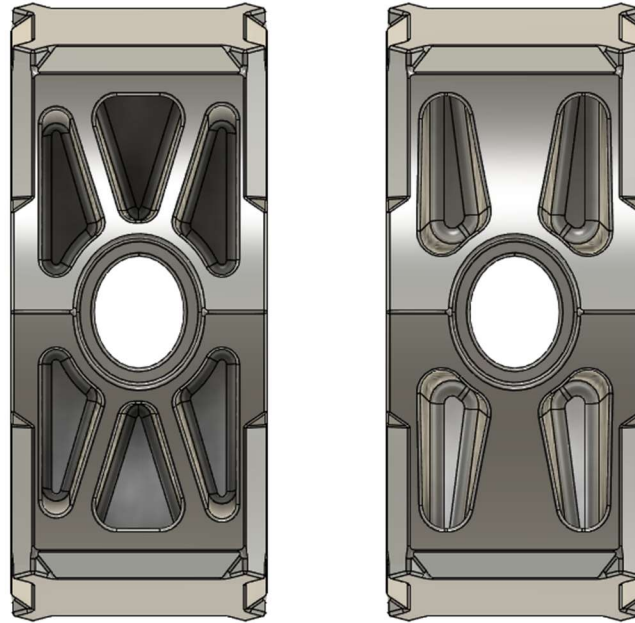


Figure 8: Pocket Designs

Each design was iterated upon extensively until they reached the point below in Figure 9. Due to the 3-pocket design having smaller holes, the castable depth was much smaller. Because of this, the pockets do not extend as far as the 2-pocket design. Both designs featured drafted walls to aid in the cooling of the metal. That way metal filling the thin sections would cool before the thicker areas, drawing the heat upwards from the ribs and walls to the top of the hammer where the gating connects.

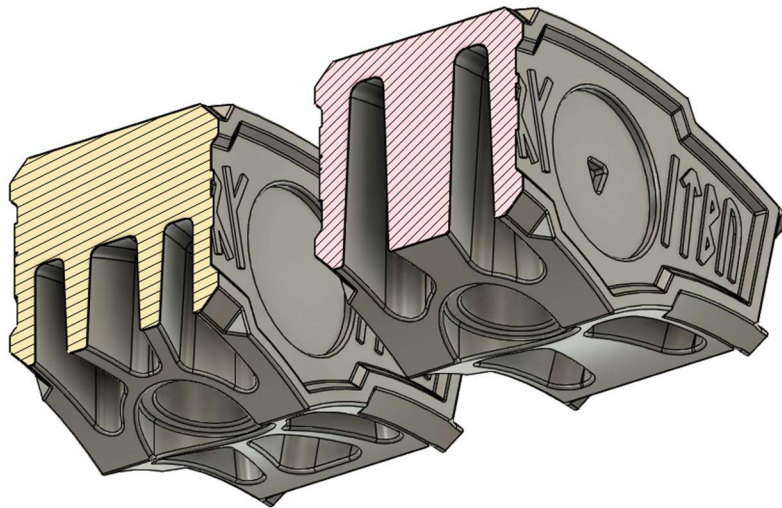


Figure 9: Hammer Designs



We applied Finite Element Analysis to both designs to test their capabilities when the hammer strikes an object. The results can be seen below in Figures 10 and 11. Both designs performed well in the simulations, and both had large factors of safety. Neither design was significantly stronger than the other. The 2-pocket design had slightly more stress concentrated in the hole for the handle, while the 3-pocket design had more stress concentrated in the base of the pocket.

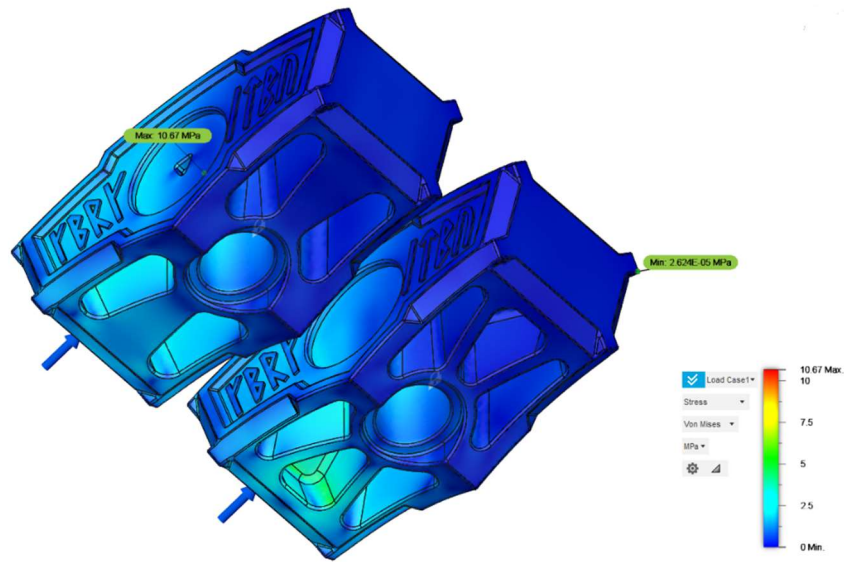


Figure 10: Finite Element Analysis of Front Impact, Isometric View

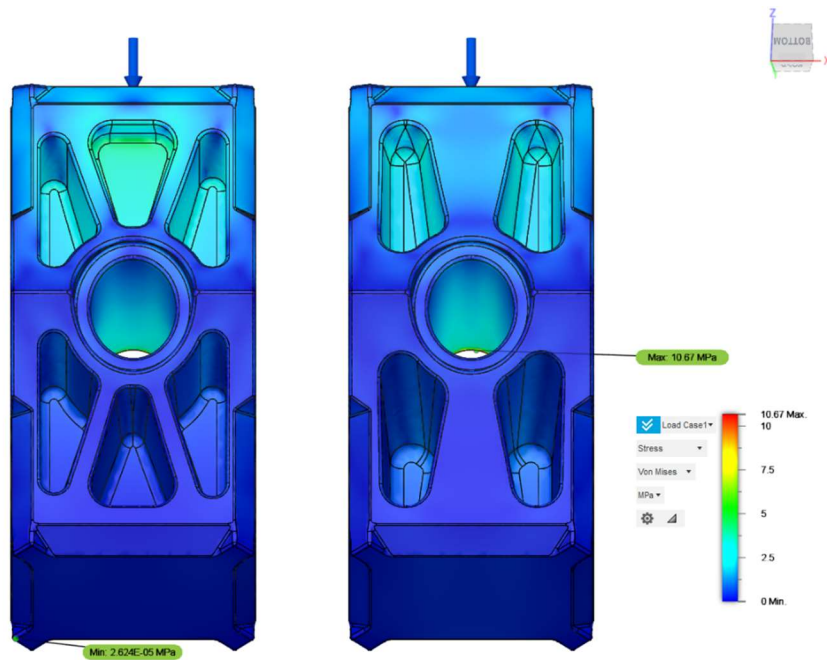


Figure 11: Finite Element Analysis of Front Impact, Bottom View

After consulting with our contact at Aurora casting, we decided on the 2-pocket design for the final version. This was due to the large rib having larger likelihood of casting without defects. Neither design was significantly stronger nor noticeably reduced more weight, so it made sense to choose the design that would have the highest chance of success in the casting process.

Below is our final CAD model in Figure 12, incorporating all of the components discussed above.



Figure 12: Hammer CAD Model with all Designed Ornamentation

## Gating Design

Our goal for the design of the gating for the hammers was to treat it like a production part that could be made in larger quantities and sold. Therefore, having six hammers on each tree would be the target. Our sponsor recommended that we use a standard figure-8 shaped riser system that would serve as the base of our gating. It would then be our job to figure out how to properly gate the hammers from this riser system.

The first step of our gating was to try a couple of simplistic cross sectional designs using rectangles to see where the problem areas of porosity might be. Through this initial testing we found that the problem areas would be around the handle cutout and in the top rib of the hammer. The major iterations of our gating designs and their results are in Appendix A.

The design that was ultimately selected is shown in Figure 13. This design directly feeds each of the thickest portions of the hammer. These feeding gates would fill metal shrink while the hammer is solidifying. Additionally, the two smaller gates that reach out to either side of the handle hole meet to the same area on the tree.

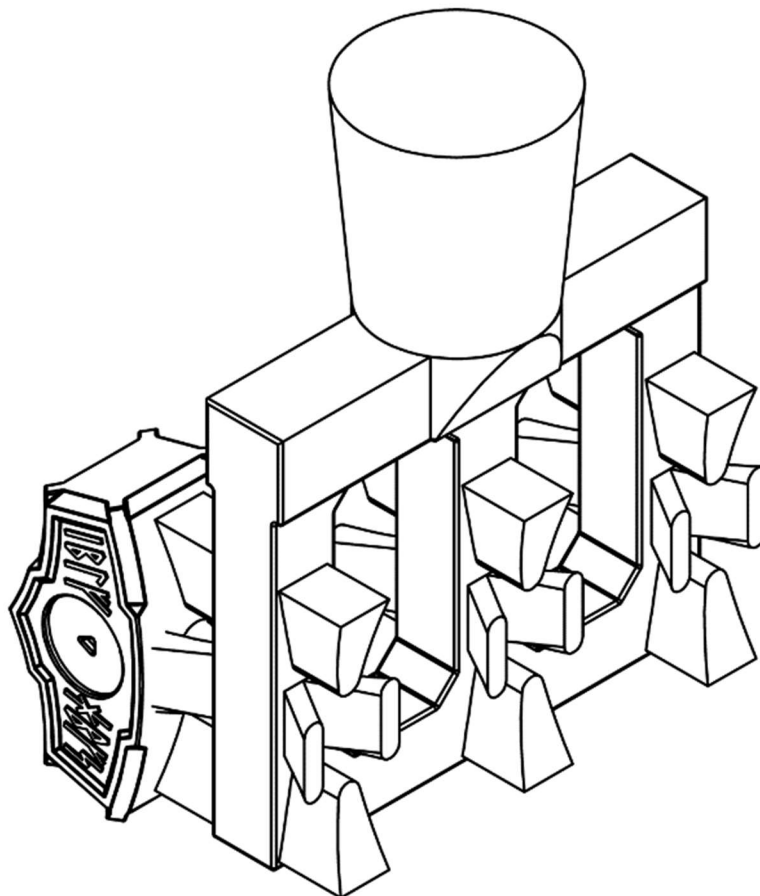


Figure 13: Final Gating Design

Simulations were run using SolidCast 8, which allowed us to test metal flow and post-casting material properties like density. When simulating, settings were consistent between simulations and consistent orientations/alignment of the gating and the parts. The assembled components for the simulation are below in Figure 14. The gray parts are the hammers, the red is the gating system, and the green cylinder at the top is the fill area.

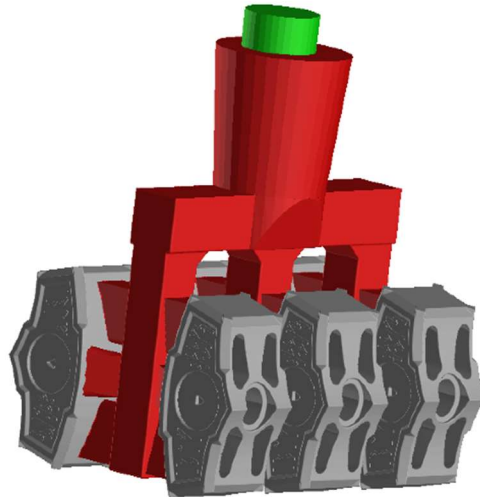


Figure 14: Final Gating Design on Tree

This design ensures that there is no waterfall effect by having a gate at the very bottom of the part and consistent gating through its height. This has the goal of reducing turbulence within the metal as it is cast. A capture of the flow mid simulation is below in Figure 15.

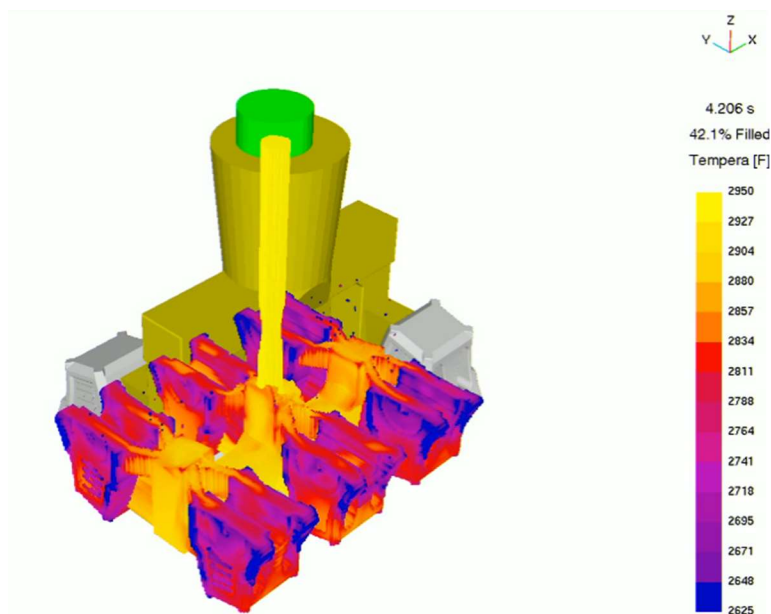


Figure 15: Final Gating Simulation

The orientation of the part on the tree allows for a consistent cooling gradient where the metal solidifies from the thinnest sections on the outside to the thickest sections on the inside, as shown in Figure 16 below. This should reduce the possibility of porosity due to solidification shrinkage.

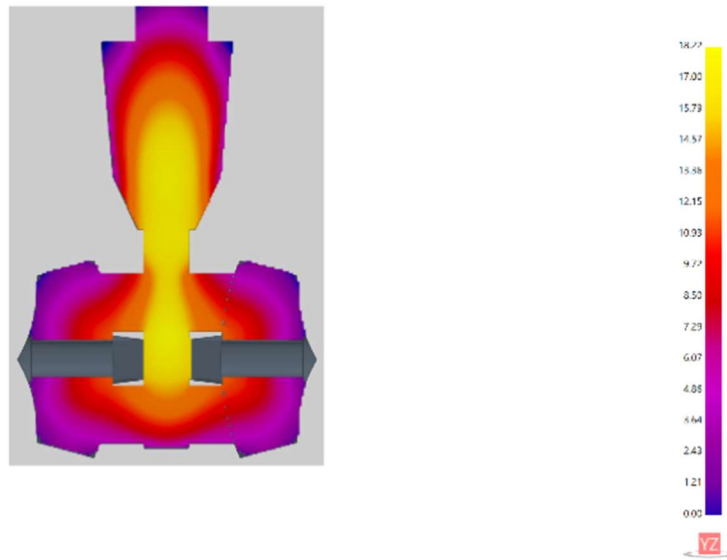


Figure 16: Final Gating Solidification Time Graph

Lastly, this design addressed the issues of porosity that were predicted in other simulated versions. The simulation showed no porosity within the part, as shown in the cross-section below in Figure 17.



Figure 17: Final Gating Simulation Porosity

The gating in mid-assembly at the foundry is shown below in Figure 18. The layer lines on curved surfaces were smoothed out with wax to reduce the postprocessing required. The wax gates were then adhered to the surface with molten wax. Each of these units would then be attached onto a figure-8 shaped common riser system.

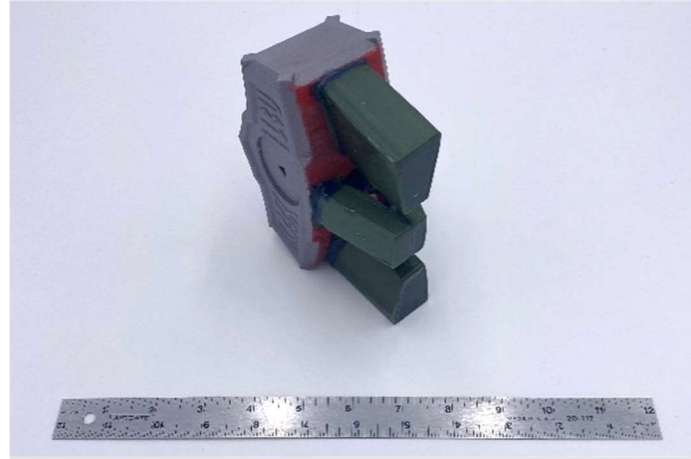


Figure 18: Gating Assembled on Pattern

## Material Selection

Working with Aurora Casting, we were limited to the material options of 17-4 and 15-5 as those were the alloys they had on hand and were familiar with. While these alloys are typically used for aerospace, nuclear, and chemical applications, these two precipitation-hardened steels were determined to be more than capable of the strength and hardness required of our hammer.

From our research into the two alloys, we found that the two alloys had strikingly similar properties (AK Steel). However, referencing Aurora's material properties we found that the 17-4 alloy had slightly better ultimate tensile strength as compared to the 15-5 alloy. Considering the trends of ultimate tensile strength with relation to properties like yield, impact resistance, and toughness, we realized that the 17-4 alloy would be better suited to withstand the stressed that our hammer would be placed under during use (AK Steel). Therefore, we chose a 17-4 PH alloy to produce our Thor's hammer. The composition of the 17-4 PH Stainless Steel alloy is shown below in Figure 19.

COMPOSITION		(wt %)
Carbon	(C)	0.07 max.
Manganese	(Mn)	1.00 max.
Phosphorus	(P)	0.040 max.
Sulfur	(S)	0.030 max.
Silicon	(Si)	1.00 max.
Chromium	(Cr)	15.00 – 17.50
Nickel	(Ni)	3.00 – 5.00
Copper	(Cu)	3.00 – 5.00
Niobium*	(Nb)	0.15 – 0.45

Figure 19: 17-4 PH Stainless Steel Composition

## Heat treatment

When considering heat treating the hammer, we first had to establish the base level of the as-cast hammer. This was accomplished with a series of hardness tests in Rockwell-C, which found an average hardness of 28.96. The hammer post-casting could air cool while still shelled before breakout, meaning that the recommended heat treatments for 17-4PH Steel like an H900 heat treatment would not likely be as effective (AK Steel). This is because such heat treatments rely on a pretreatment of 1900F for two hours and a quick cool to alter the grain structure of the steel.

Due to our time constraints at the end of the academic quarter at Cal Poly, there was not enough time in the labs to do a test run of the pretreatment, then H900 heat treatment, then repeat the process on the competition hammer and repolish if the results turned out well. Instead, we decided to run the H900 heat treatment on the as-cast test hammer without the pretreatment to see if the air cooling of the castings in their shell was enough for the H900 heat treatment to be effective.

As outlined in the AK Steel 17-4 PH Product Data Bulletin, the H900 heat treatment involves heating the hammer to 900F for an hour and then air cooling. A student putting the hammer into a 900F furnace is shown below in Figure 20.



Figure 20: Test Hammer H900 Heat Treatment

After the H900 heat treatment was completed, another round of hardness testing was completed, shown in Figure 21. The average hardness of the heat-treated hammer was 33 Rockwell-C. The competition hammer was also measured where the coins would cover the test marks and the average hardness was 34.5 Rockwell-C. Therefore, with the higher hardness of the competition hammer and our required timeline, we decided that the time remaining would be better spent on the hammer testing, assembly, and other deliverables for the project rather than heat treating the competition hammer.



Figure 21: Test Hammer Hardness Testing Post Heat Treatment

## Hammer Casting

Because of the limited access to the Cal Poly campus and foundry resources, investment casting the hammer would allow us to do the most work on the hammer itself as well as most of the supporting work possible.

Investment casting can produce extremely complex parts with minimal surface defects. This benefit of investment casting reduced the total amount of finishing work that needed to be done on the hammer after break-out and cut-off. Even with this time savings it took a significant amount of time polishing to complete the exterior surface of the hammer.

As mentioned earlier, one of the benefits of investment casting was that it meant that we could be more involved with creating the final product. One of the primary ways we were able to do that is by relying heavily on 3D printing.

3D printing allowed us to implement lessons we learned from last year's competition. In the earlier parts of the competition, we were able to print prototype hammer heads to test if the real product would be as desirable as the virtual CAD model. This was an issue that came up in last year's competition, where some of our members' Bowie Knife seemed proportionately larger than they were expecting it to look from just using the CAD software. We did end up making slight changes to the design after we went through our 3D printed prototype process.

3D printing allowed us to have direct control over the pattern of our hammer, which would theoretically be the best possible case for the "as cast" hammer. Ways we were able to control the final result were by changing printing parameters, hand detailing the printed patterns, and by conducting test prints throughout the design process. When finally printing our patterns, we were able to easily scale up our final design to create the pattern without even creating a separate part file. Finished prints as well as a failed 3D print are shown in Figure 22.



Figure 22: 3D Printed Hammers



Our industry contact at Aurora pointed out that one of the biggest issues of 3d printing patterns is layer separation. Microscopic layer separation on the surface of our pattern would allow the ceramic to penetrate the mold during the shelling procedure. These shell “splinters” could then stay behind in the mold after melt-out and end up as large porosity zones in the final casting. To overcome this, a soft and malleable wax was rubbed into any separated layers or surface defects on the 3D printed pattern, shown in Figure 23.

Our team was able to pool our resources and cumulatively printed 12 hammer patterns which we then shipped to Aurora Casting.



Figure 23: Pattern with Wax Gating

In the investment process, multiple layers of investment are added on top of the pattern to build up the shell. This process starts with fine layers of the investment for accuracy. As the layers build on the shell, coarser materials are added to increase the bulk of the shell and are cheaper to use. After approximately ten layers of investment and other materials, the shell has been built up and will be strong enough to withstand the heat and pressure of the investment casting process, Figure 24.



Figure 24: Shelling Process Completed

Once the shell is formed around the wax and 3D printed pattern, the pattern is melted out first using an autoclave to get most of the wax out. The shell is then burned out at 1800 degrees Fahrenheit to get any remnants of the pattern that would be left in after the dewaxing process. Lastly, the shells are insulated to make sure that they retain their heat during the preheat process.

The insulated investment shells were preheated to 1800 degrees Fahrenheit for 15 minutes to prevent the mold from cracking upon contact with the molten metal or for the casting to cool too quickly or unevenly.

The 17-4 alloy Steel was melted in an induction furnace and heated to 2850 degrees Fahrenheit with a tolerance of +/- 20 degrees. Once cast and cooled, the castings went into knockout and the investment shell was broken off the finished casting. This was done carefully to avoid damage to the hammers. The gating was ground off at Aurora Casting and Engineering.

## Ornament Casting

As mentioned earlier, we decided to add design pieces onto the sides of the hammer for students on the project to mold and cast for themselves. These coins would be made using investment casting with a solid flask and 3D printed patterns. The coins would be cast in brass.

First the coins would be 3D printed on an FDM 3D printer in PLA, shown in Figure 25. These plastic coins would serve as the pattern for the investment castings.



Figure 25: 3D Printed Coin Pattern

Three plastic coins were glued onto a tree and placed in a steel flask about 3" in diameter. The solid flasks were then filled with plaster, as shown in Figure 26, and vibrated to loosen any remaining air bubbles. Once solidified and set, the PLA plastic patterns along with the gating were burnt out at 1350F for four hours.



Figure 26: Coin Investment Solid-Flasks

To prepare for casting, the flasks were preheated to 200F. The flask that was ready to be poured was placed on top of a vacuum chamber that would assist the metal flow into the crevices of the mold. Students were then able to cast the coins in Brass, as shown in Figure 27.



Figure 27: Student Vacuum Assist Casting Coins in Brass

After solidifying, the coin trees were cooled and broken out of their solid flask, as shown in Figure 28. Lastly, the coins were then cut off the tree and sanded to final dimensions.



Figure 28: Coin Breakout

## Hammer Finishing and Assembly

The hammer and coins were ground and polished incredibly well at Aurora Casting. The final steps needed to finish the hammer were to attach the handle to the hammer head, leather wrap the handle, and adhere the coins. The hammer was attached to the handle using the traditional technique of hitting the base of the handle on a hard surface to use the weight of the hammer head to drive itself onto the handle, demonstrated in Figure 29. Then the metal wedge was inserted into the top of the hammer to make sure the hammer would not come loose. Once the hammer was securely on the handle, another student wrapped the handle in a leather cord to make a sturdy grip for the user. Lastly, the two coins that would be on the hammer were adhered into place, taking care to put the coin on the side of the hammer that had its designer's initials.

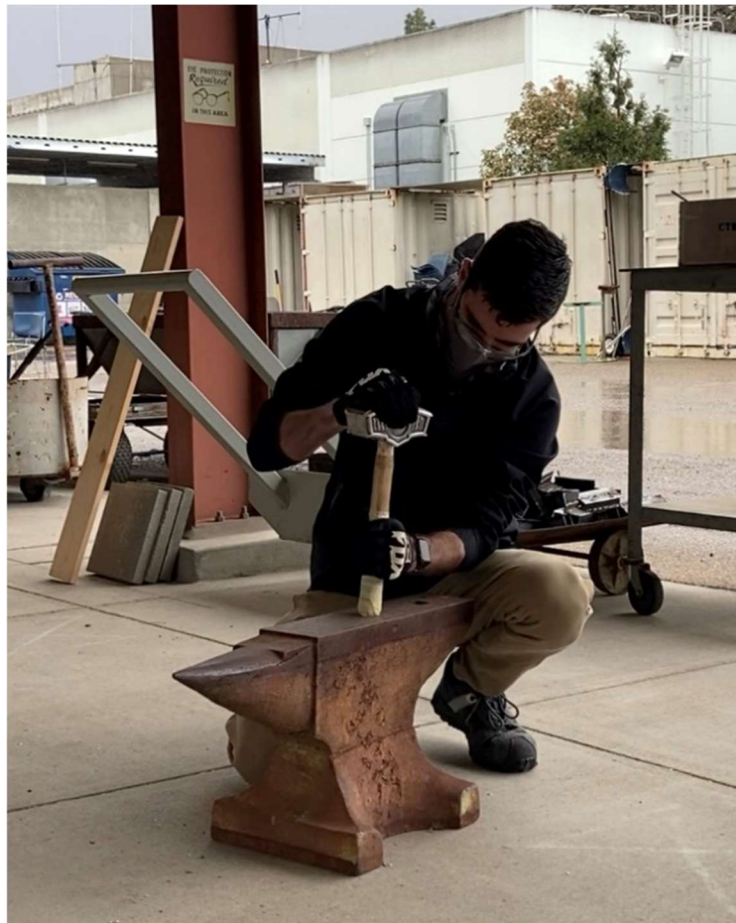


Figure 29: Student Attaching Hammer Head to Handle

## Conclusion

Over the past three and a half months, the Cast in Steel competition tested our group's skills, knowledge, and ability to plan and work together on a multifaceted problem. Each member of the team had a unique opportunity to take on a particular task, whether familiar to them or foreign, such as the leather wrapping of the handle, or the coin ornament design.

Overall, we feel that we navigated the challenges and tribulations with grace, but if we were given a change to begin anew, we would have done more to prepare for the 3D printing stage of the project. Being on such a tight time frame, the quality of our 3D printed hammers varied as we worked to find the optimal settings for the highest quality with reasonable print time. Due to this constrained time frame, we split the printing workload between 3 members of our group, contributing to more variation between parts. Additional difficulties in the project were related to the COVID-19 pandemic, which limited our access to machines on campus and impeded our capability to work together in person, which would have been most effective for such an undertaking. Overall, our team is incredibly proud of the work we have done and the methods via which we have overcome difficulties and successfully delivered our adaptation of Thor's Hammer, Figure 30, to the Cast in Steel competition hosted by SFSA.



Figure 30: Completed Thor's Hammer

## Acknowledgements



On behalf of our team from the Industrial and Manufacturing Engineering department of Cal Poly SLO, we are incredibly grateful for all your support and the opportunity to learn more about casting and manufacturing in the 2021 Cast in Steel Competition put on by the Steel Founder's Society of America. Despite the limitations in place due to COVID-19 making it challenging to work together, we succeeded in creating an amazing hammer that we have all fallen in love with over the course of its inception. We impatiently await to discover what our fellow students have created and look forward to participating again next year to test our mettle once more.



We would like to thank Andrew Penrose at Aurora Casting & Engineering, Inc. in Santa Paula, California for all his support, time, and resources put into this project. Andrew gave us advice on material choice, gating/riser design, post processing, and many more fields. Without his help and the impeccable work of his team, our hammer would not be possible.



Lastly, we would like to thank Rob Carter in the Industrial and Manufacturing Engineering Department at California Polytechnic State University in San Luis Obispo, California. Not only has Rob assisted us in finding and working with our project sponsor, given us gating advice, and otherwise assisted us throughout our project, but Rob is the professor that kindled our passion for metal casting and challenged us to take part in the Cast in Steel competition. We would not be where we are today without him.

Appendix A

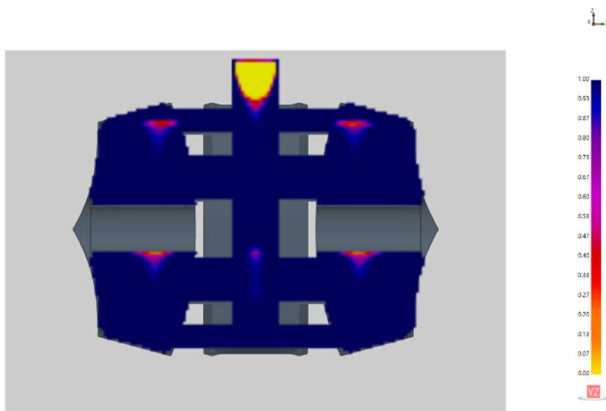


Figure 31: V3 Gating Design Density

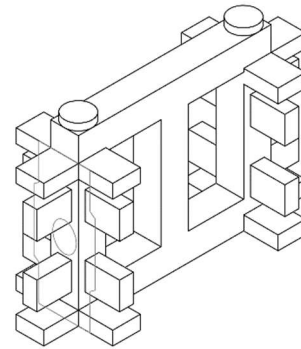


Figure 32: V3 Gating Design Wireframe

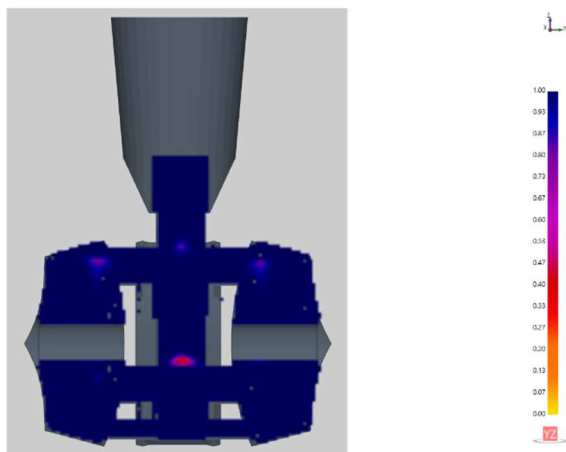


Figure 33: V4 Gating Design Density

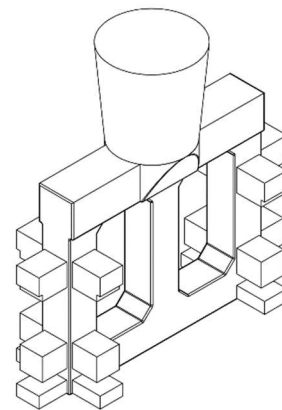


Figure 34: V4 Gating Design Wireframe



Figure 35: Final Gating Design Density

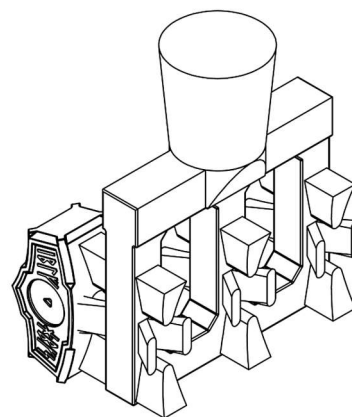


Figure 36: Final Gating Design Wireframe



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