Technical Report

Thor's Hammer

Cast in Steel

By SFSA

Group Members:	Sharon Lau
	Daniel Schimpf
	Grace Peterson
	Carley Haus
	Matthew Bindel
Faculty Advisor:	Dr. Frank Peters (ISU)
Industry Advisor:	Ryan Horak (Eagle Alloy)

Due Date:	3/20/2021

1. Introduction

In this year's Cast in Steel competition of Thor's Hammer, our team consists of a variety of skills and knowledge. Members include Ph.D. students aiding in steel casting research in the Industrial and Manufacturing Systems Engineering department and three undergraduate students studying Industrial Engineering at Iowa State University. Dr. Frank Peters, a faculty advisor, and Ryan Horak, a relatively recent Industrial Engineering graduate from Iowa State, helped in advising us throughout this project. The diversity in our team brought new perspectives, questions, and creative ideas.

To create Thor's Hammer using an innovative approach and focusing on quality, uniqueness, shape, and keeping in mind the restrictions of the competition (mass, length, etc.), our team eagerly accepted the challenge. Our approach for this competition was to create a functional hammer without compromising on the aesthetics. We constructed our patterns through CNC machining and utilized 3D printed sand for the internal cores and features. No-bake resin bonded sand was used to create the molds for the hammer. The material for the head of the hammer was chosen to be stainless steel SA-351 CF8M while the handle was integrally cast using a titanium rod. The quality of our hammer was analyzed by measuring the deviation of the casting compared to the CAD model, surface roughness characterization, finite element analysis (FEA), hardness testing, and durability testing. Surface roughness characterization was supported by the current research at Iowa State University, leading us to take advantage of those inspection techniques for the competition.

2. Materials and Methods

2.1 Rationale behind the design

The shape of the hammer was inspired by Thor's battle hammer from the *Avengers*. Originally, the first design was similar to Thor's hammer with a hollow center as shown in Figure 1, but this design was ultimately deemed too simple and lacked creativity.

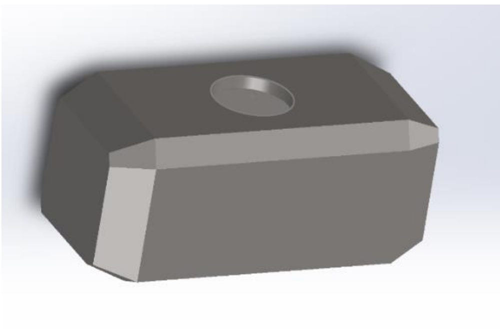


Figure 1. Simple Design of Hammer

Figure 2 represents the second design iteration which was packed with designs based on the Marvel theme. The initial thought with this design is to cast as many features as possible with the sand casting method and to machine the more intricate designs post casting.

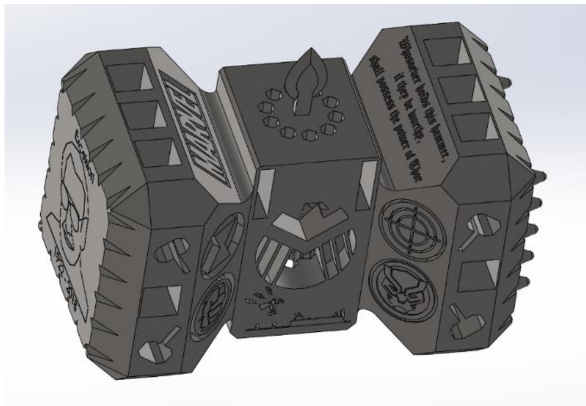
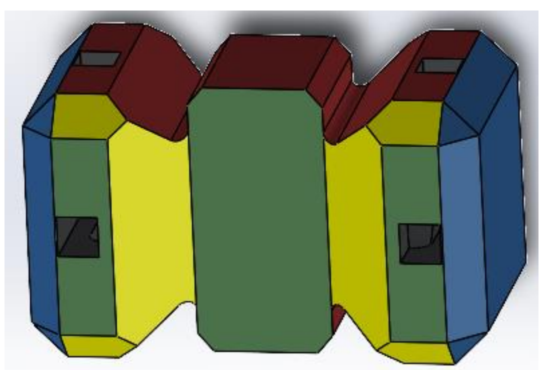


Figure 2. Intricate Design of Hammer

The design was sent to our industry partner and they provided great feedback. First, they provided a color-coded diagram of which features would have the best chances of pulling from the mold and retaining their details (see Figure 3). Another suggestion they had was to avoid machining as this could potentially open up indications in the hammer such as internal porosity. Additionally, machining removes the cast surfaces which defeats the purpose of the **Cast in Steel** competition as it does not leverage the shape making capability of the steel casting process



Green = Flat surfaces great for designs
Yellow = Angled surfaces designs can work on but would need to be heavily drafted
Red = Vertical surfaces that would not pull from the mold
Blue = Surfaces that could be picked up with a core and can follow different design rules

Figure 3. Color-coded areas of the hammer based on the ability of the design features pulling from the mold

This led to the final design which is shown in Figure 4. Our team's hammer is multifunctional with a flat side for smashing, a 6 x 6 grid of studs for tenderizing, and a spear for stabbing. We came up with a 6 x 6 grid by taking into account the 6 auspicious numbers according to the numerology readings based on Thor's name and birthday as shown in Figure 5. To combine these 6 lucky numbers into one number to be represented by our grid dimensions, we took a sum of all the numbers (24) and divided it by the number of characters in Thor's name (4), this resulted in an overall lucky number of **6** for Thor hence the 6 x 6 grid. Additionally, Thor's home planet, Asgard, has 6 letters to it further solidifying the significance of the number 6. Our team felt that these three features were essential parts of creating a functional battle hammer while maintaining the theme of Thor. The hammer has a hollow center to meet the weight requirement of the competition. The aesthetics of the hammer were taken into consideration while considering the casting process. Designs such as a lightning bolt (a tribute to Thor being the god of thunder) and a target symbol (representing Hawkeye's symbol) on the flat side of the hammer head were included to give the hammer a Thor theme look. The handle of the hammer was wrapped with leather tennis grip tape to simulate the original Thor hammer handle aesthetics. The manufacturability and uniqueness of design were at the forefront of our design process. This led to multiple iterations that resulted in a high-quality casting that retained its intricate design aspects.

Figure 4. Thor Hammer by ISU

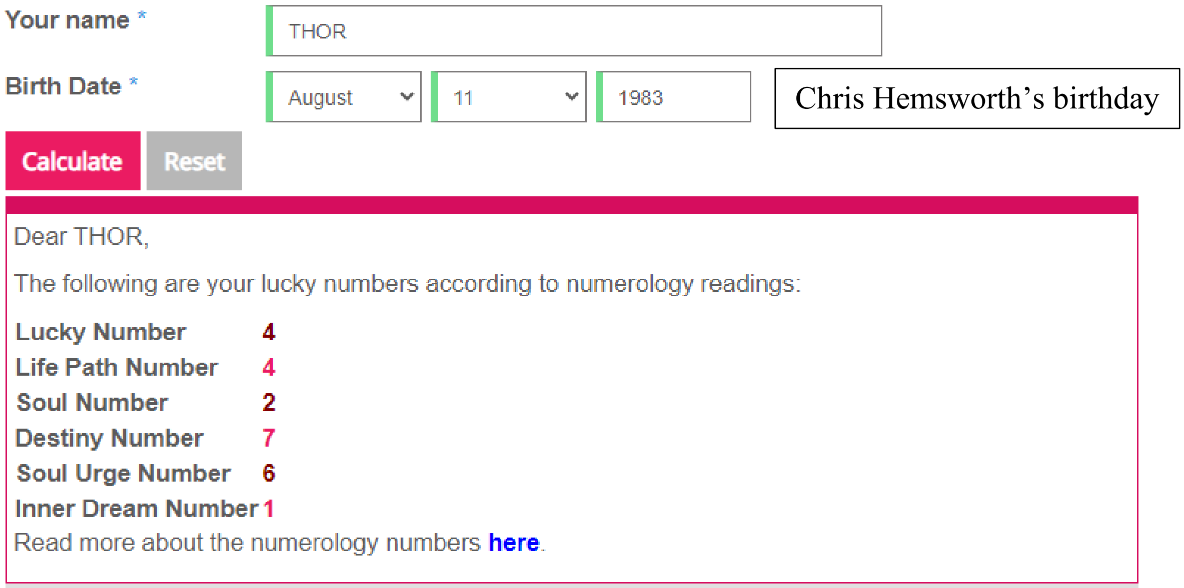


Figure 5. Lucky numbers according to numerology reading for Thor

2.2 Tooling Design and Fabrication

After the design of the hammer was finalized, Ryan Horak from Eagle Alloy designed the gating system as shown in Figure 6. Magmasoft 3D simulation software was used to optimize the gating and riser design. The bronze-colored parts in the design are 3D printed cores that capture the hollow internal cavity of the hammer and the designs at the end faces of the hammer. The 3D printed cores as shown in Figure 7 were provided by the University of Northern Iowa (UNI).

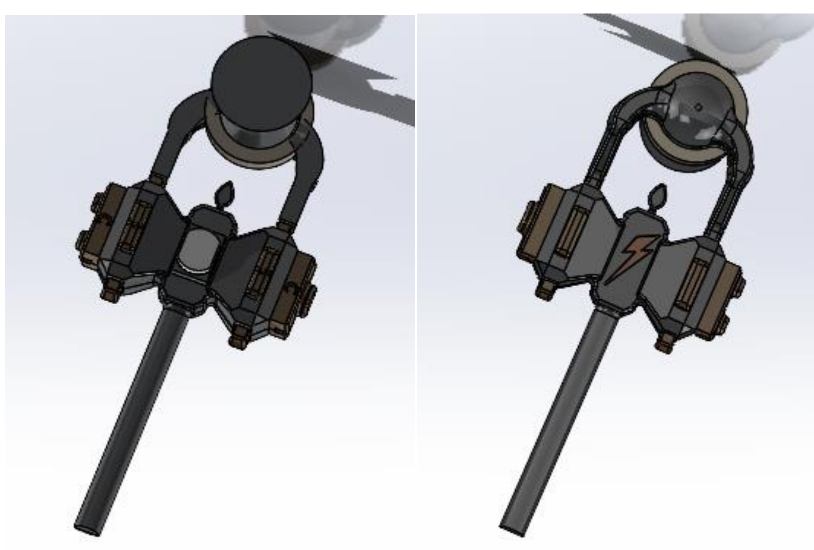


Figure 6. Design of the hammer with the gating system

Figure 7. 3D printed cores

The pattern was then machined at one of Eagle's local pattern shops as shown in Figure 8. The tooling for the cope and drag was made as shown in Figure 9. Mold release agent was then applied onto the tooling to aid the release of the sand from the tooling. This step is captured in Figure 10.

Figure 8. Thor hammer pattern machining

Figure 9. Tooling for Thor's hammer

Figure 10. Spraying mold release agent on the tooling

2.3 Mold Fabrication and Pouring

The ISU team participated in making the sand molds for Thor's hammer at Eagle Alloy. The steps were documented in Figure 11.

1) The pattern box is filled and vibrated.
2) After curing for 5 minutes, the mold is stripped from the pattern
3) The sand molds are assembled by adding a filter, alignment cores, and 3D-printed cores. Glue is then applied to the drag side mold.
4) The cope is placed on the drag; 3 mold alignment cores aid the location of the two halves.
5) Stainless steel at approximately 2900°F is poured into the mold
6) After cooling overnight, the casting is shaken out.
7) A band saw is used to remove the gating system.
8) Blast cleaning in the hanger blast to remove the majority of residual sand on the casting.
9) Once blasted, the riser was plasma cut off the hammer.
10) The casting is laser scanned for dimensions and surface characterization.
11) A color representation overlay indicating the closeness of the hammer to the nominal CAD file.
12) Solution anneal the hammers at 1,950°F for 1 hour
13) Water quench

Additional analysis and post-processing work on the hammer is discussed in further sections.

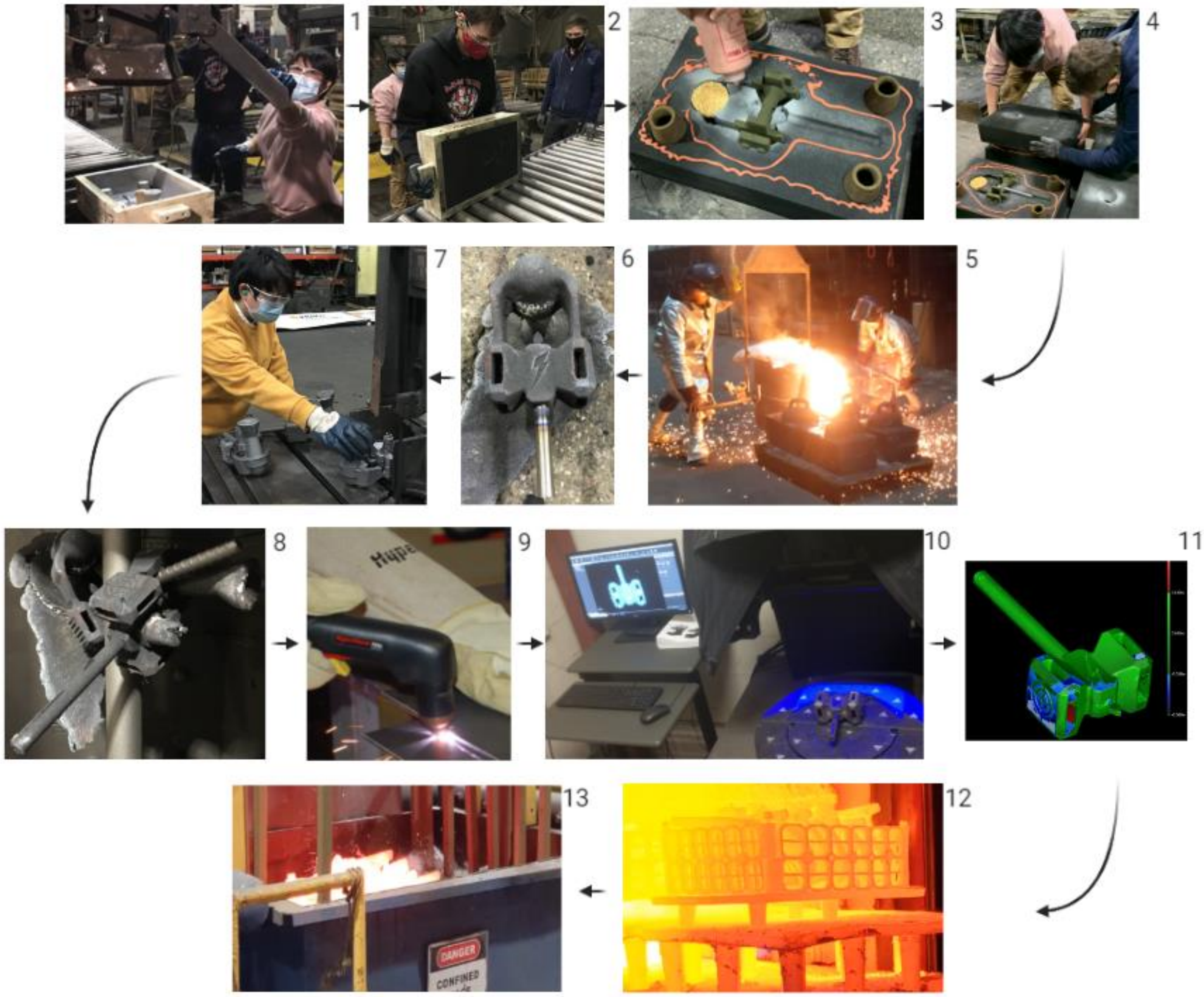


Figure 11. Procedure for creating sand molds and pouring

2.4 Materials and processing

The material for the head of the hammer was chosen to be stainless steel SA-351 CF8M. CF8M steel with solution anneal heat treatment was recommended by Jason Bergman from Eagle Alloy due to advantages such as increased strength, increased resistance to stress corrosion cracking, and corrosion resistance. A titanium rod was integrally cast with the hammer head (see Figure 12) as the handle of the hammer. Titanium was chosen as the handle because it has about half the density of steel (providing a lighter handle) with improved mechanical properties. Additionally, titanium has a lower thermal expansion rate than stainless steel which allows for the titanium rod to be compressed by the stainless steel during solidification. This provides a press-fit mating style between the head and the handle without the need to weld or bolt the two parts together.

However, during the first pour, it was discovered that the titanium handle acted as a chill which caused misruns as shown in Figure 12. The material used during the first pour was basic carbon steel used as a proof of concept (while Iowa State University visited Eagle) was not the final material used for the final hammer. Using CF8M, there were no signs of misrun which could be attributed to the difference in the fluidity between the two materials and the pouring speed.


Figure 12. Titanium rod placed in a mold (left) and misruns present on hammer due to chilling during first run (right)

3. Post Processing

After the casting was removed from the mold it went through initial blast cleaning. The gating system (one riser on top and two in-gates) was removed via plasma cutting and brought closer to the as-cast finish via grinding. Additionally, a brass piece was welded and polished into the lightning bolt cavity to provide color contrast giving the lightning bolt design an extra pop as shown in Figure 13. The original plan was to integrally cast a bronze lightning bolt in the mold, however, time and process restrictions did not allow for this. To produce a glossy finish, the casting was polished to a mirror finish to further improve the aesthetics (see Figure 14). Since the little spear on top of the casting cannot be cast with a sharp point, it was ground to the desired shape. Finally, the titanium handle was wrapped with a leather band to increase the comfort and handling when swinging the mighty hammer.

Figure 13. Brass piece integrated into the lightning bolt to provide color contrast

Figure 14. Mirror-finish on the competition hammer

4. Test Results for Quality and Properties

The hammer used in this section was not the final hammer submitted for the competition. We used our proof of concept hammer which was made of basic carbon steel with no polishing performed.

4.1 CAD file comparison to the final part

After the risers and gating were removed, the hammer was scanned using the Keyence VL-500 scanner at Eagle Alloy. This scanner uses structured light and has a moveable base to automatically scan the part from all sides. To get scan data from all outside surfaces, the hammer was scanned in two positions, and those two scans were then aligned and combined. This was done by selecting the same points or features in both scans to create a rough alignment. Following that, the software automatically does a precise alignment, finishing with an accurate scan of the casting. We then aligned the scaled CAD model, to account for the shrinkage, with the scan. Keyence software is then able to visualize the deviations by coloring the point cloud based on the deviation between the CAD model and the casting.

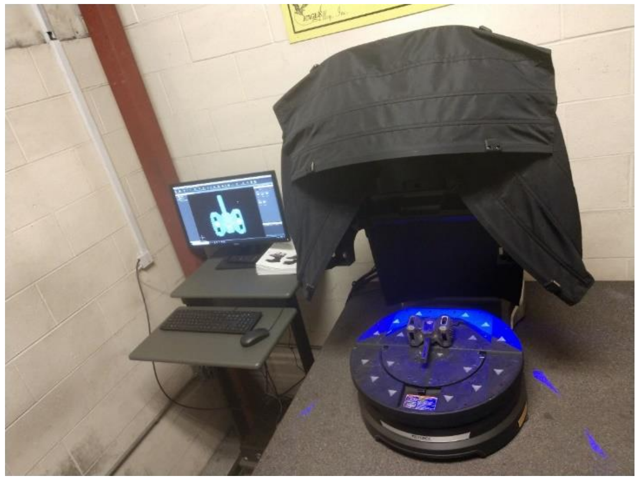


Figure 15. The 3D scanner at Eagle Alloy

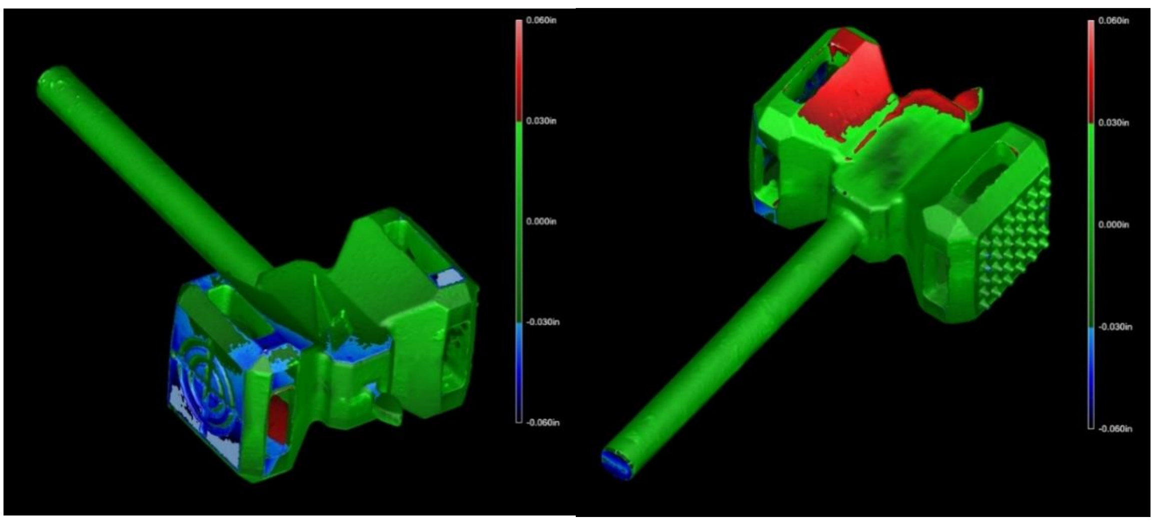


Figure 16. Colored 3D scans to visualize deviation between CAD model and a scan of the casting

4.2 Surface Roughness

We selected a representative area with simple geometry for our roughness analysis. We scanned the corresponding surface with a FARO arm with a laser scanner and used the in-house developed digital roughness method to determine the surface's roughness. We analyzed the roughness of the hammer both before and after the polishing. We picked a representative flat surface for the roughness analysis.

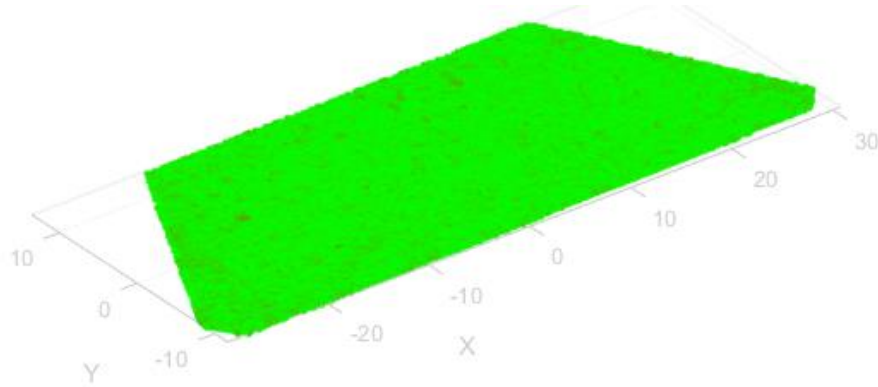


Figure 17 Representative flat surface on the hammer. The point cloud is colored based on its deviation from the underlying geometry. Green points being close to 0 while red points are further away.

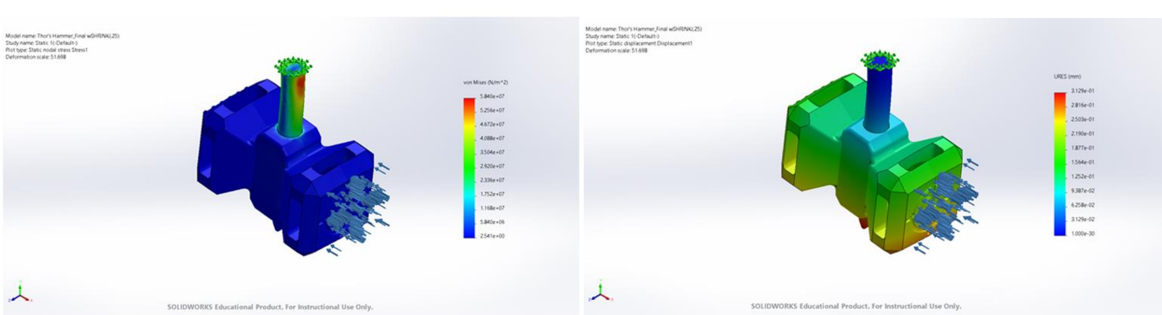
Before the polishing, the surface roughness is 0.03 mm, which corresponds to the A1 SCRATA plate and is a very good roughness for a sand-casting surface.

After the polishing, the completed hammer has a glossy mirror-finish on most surfaces.

4.3 Finite element analysis (FEA)

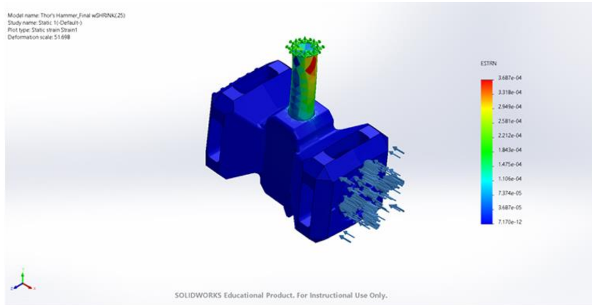
The hammer was shown in the finite element analysis to have large stress concentrations in the handle which is why we chose to use titanium for our handle. This allows the handle to under-go the large stress without breaking. The hammer body itself deforms much more than the handle does because of the mechanical properties of stainless steel compared to titanium. Based on the FEA results, the handle was found to be undergoing the most stress during impact which justifies the use of titanium since it has stronger mechanical properties.

Study Results



Name	Type	Min	Max
Stress1	VON: von Mises Stress	2.541e+00N/m^2 Node: 60261	5.840e+07N/m^2 Node: 28

Name	Type	Min	Max
Displacement1	URES: Resultant Displacement	0.000e+00mm Node: 1	3.129e-01mm Node: 14296



Name	Type	Min	Max
Strain1	ESTRN: Equivalent Strain	7.170e-12 Element: 28658	3.687e-04 Element: 302

Figure 18. FEA results

4.4 Hardness

We used a Rockwell hardness tester and the Rockwell B scale, which uses a 1/16-inch diameter ball indenter combined with a 100 kg load. Since the hammer used for this hardness test was our proof of concept hammer and not the final hammer submitted for the competition, we chose not to report the hardness results but wanted to list it as one of the tests that we considered.

Figure 19. Hardness test of hammer

4.5 Durability

Figure 20 was taken before running our test of hitting the metal sheet wrapped around a melon and 3D printed bones and Figure 21 was taken after all the tests were completed. As you can see there is little to no wear on the spiked end of the hammer. The complete video of our testing can be found at this link.

Figure 20. Hammer studs before testing

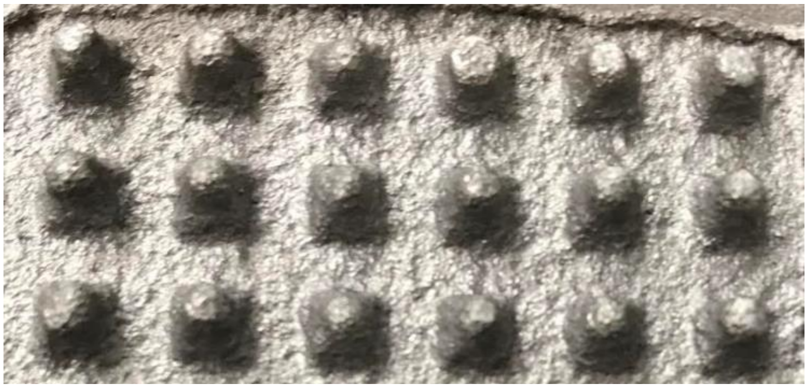


Figure 21. Hammer studs after testing

5. Key Takeaways

From this experience, we were able to gain a deeper understanding of the steel casting process from beginning to end. Through the design iterations, we learned to keep the manufacturing process in mind. In our second design which was heavy on the theme of Thor and Marvel, we wanted to create many small, intricate features on the surface area of our hammer. Looking back, we now know that these features were too small and not realistic in our sand casting method, and machining after the casting process might open up internal porosity. Armed with this new understanding, any future designs would require fewer design iterations.

Another piece of knowledge gained was understanding and hands-on experience of the casting process and indications that may arise based on our design. Our team learned how to use certain properties of materials to our advantage. Since titanium has a lower thermal expansion rate than stainless steel, we were able to have the titanium rod cast integrally causing compression around the titanium rod hence locking it in place without the need for welding or bolting. Overall, being able to go to the foundry and help in the process of casting the hammer was extremely helpful. Team members were able to see and help in the step-by-step process, taking part in all of it. A deeper understanding of how steel is cast in day-to-day operations was acquired.