Submission for the 2021 Cast in Steel Competition by the University of Northern Iowa

Team members: Brian Borkowski, Matt Baskerville

Faculty Advisor: Dr. Scott Giese

Commercial Foundry: Waukesha Foundry

Abstract

The Norse God Thor is well known for wielding a powerful hammer to channel his powers through; this SFSA challenge allows students the opportunity to design and cast their own hammer based on the ancient god. The design was based off of Marvel's modern revival of Thor and utilized several additive manufacturing processes in partnership with the UNI Additive Manufacturing Center to create the tooling and cores for the hammer. Waukesha Foundry provided guidance and support during the process, in addition to crafting the mold and pouring the hammer. A machined handle and counterweight finished the hammer.

Introduction

The mythological Thor is surrounded by intense imagery of a thunderous, hammer-wielding god who channels his power using his hammer *Mjölnir*. The traditional depiction of Thor paints a picture of a red-haired man who utilizes his power to protect humanity.

Modern pop-culture adaptations of Thor, like those seen in the popular *Marvel* movies paints a similar, albeit different rendition of the god. The changes turn Thor into a boisterous blonde man who wields *Mjölnir* for the sake of protecting his realm, using his hammer for solely violent purposes. While this is a firm departure from the traditional mythos surrounding the god, it has resulted in a consistently styled and instantly recognizable image of a burly god wielding an iconic hammer to fight evil forces. This imagery served as the basis of the University of Northern Iowa SFSA team's choice to style the hammer with traditional Celtic motifs merged with the modern styling that *Marvel* has created.

Figure 1 –Marvel Studios rendition of Thor as played by Chris Hemsworth. Marvel Studios, Thor (2011)

Figure 2 – Traditional styling of Thor. Adler, M. (2011). Norse Thor [Digital Media]. ifanboy.com

The hammer was created using a wide spread of manufacturing processes that combined together, craft a hammer that would be worthy of a Norse god. Using Fused Filament Fabrication to create the hard tooling and Binder-jetting printing to produce the cores and inserts, the UNI Additive Manufacturing Center served a pivotal role in the project by utilizing burgeoning and industry-leading additive manufacturing technology to make a hammer with intricate details and incredible design flexibility. The engineers at Waukesha Foundry provided guidance throughout the project and facilitated the mold creation, assembly, pouring, and cleaning processes to deliver a fantastic product to the group for final processing. The hammer was cleaned and processed to have a soft sheen to match the polish of Thor's hammer. The handle, cap, and counterweight were machined to continue the concise modern aesthetic, with the final detail of a leather-wrapped handle sealing the fusion between traditional Norse Mythology and Modern design. Overall, this hammer represents the continued growth of the legend of Thor, bridging the gap between tradition and innovation.

Hammer Design

Figure 3 – Example of a Trinity knot. "Trinity Knot Meanings." Celtic Wedding Bands & Engagement Rings, Celtic Rings LLC,

While designing the Thor hammer for the SFSA Cast in Steel Competition a couple ideas were considered; the final design decided upon was styled after the MCU (Marvel Cinematic Universe) Thor hammer rather than a more traditional design due to the delta added and time contrast our members have during the semester. This design allows for a maximized size when hollowed while still coming in under the 6 lb. limit. It also is a practical design, during the time of the middle ages it was common to forge a hammer head into a rectangle shape and blacksmith a hole through the middle to allow mounting of the handle.

The details added to the hammer to increase the Norse aesthetic include the Norse trinity knot (also known as the Triquetra) to signify Asgard, Midgard, and Utgard - three major locations within Norse mythology. On the outside of the hammer there are Celtic knots wrapping around the faces of the hammer alongside the logos of the University of Northern Iowa and Waukesha Foundry. This design allowed the practical rectangular head design while also maintaining a hollow interior.

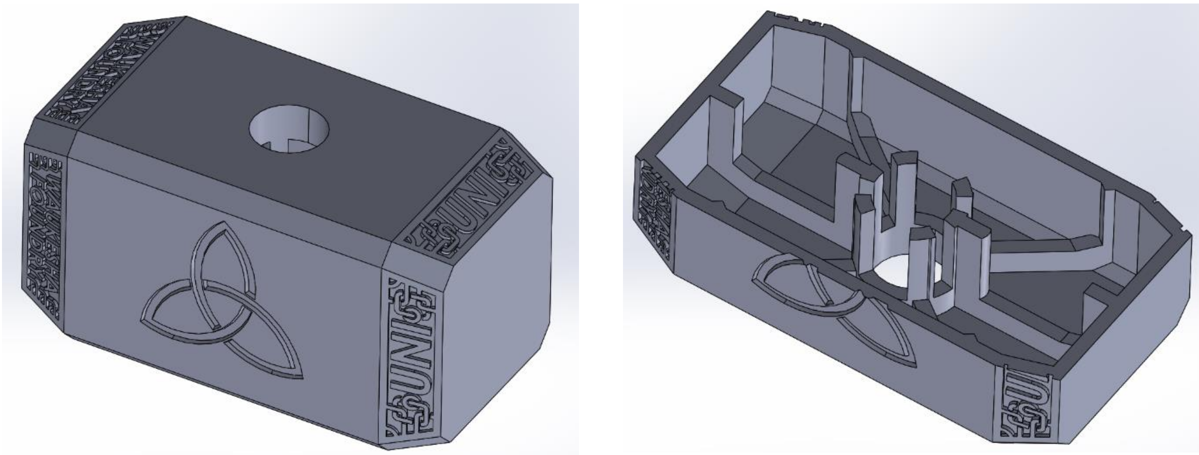

Figure 4 - CAD model of the Hammer's Final Design (Left), 3D section view of the same CAD model (Right)

This movie-based hammer also allowed for thinner walls on the casting, increasing the overall size while not increasing the weight. The internal core also allowed for support ribs to be created within the casting increasing the stresses that can be allied to the face of the hammer with the thinner designed casting walls.

Once the hammer design was completed rigging designs began using a 1:2:2 AFS Gating system and MAGMAsoft for design verification. Overall, this is a simple design to rig due to the near net rectangle shape, with the largest over all consideration being the placement of the gates for optimized filling. The chosen placement of the gates allows for faster filling into the support system and movement of metal onto the opposite side of the casting to combat cold shuts.

It was decided that hard tooling and an AFS gating system was the best option for the hammer because it allows a cost-effective pattern construction for under $20. This also provided the opportunity for multiple castings to be poured readily due to the ease of producing no-bake molds in a mass production setting.

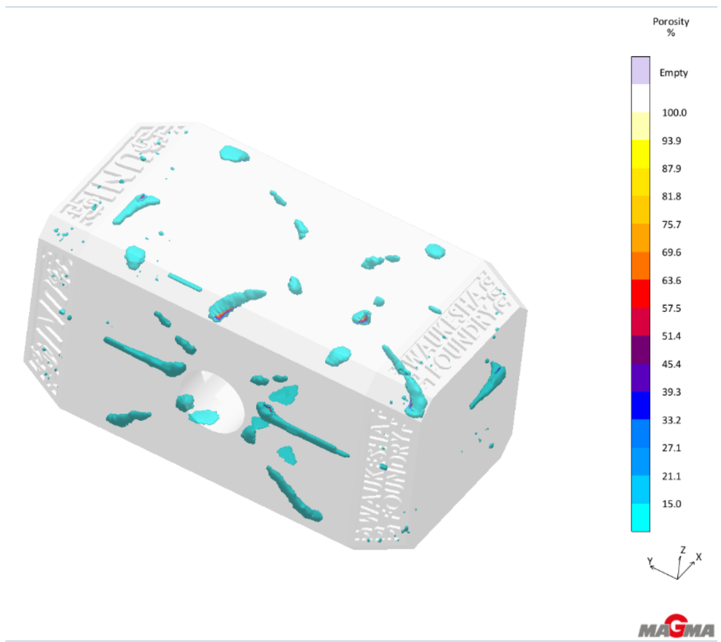

Figure 5 - MAGMAsoft simulation porosity results

The original core design had one monolithic core that combined the external cores - this singular core would have been responsible for creating the engravings and the internal ribbing. This design, however, was unsuitable for 3D sand printing as it was difficult to clean the excess sand out of the core - this ultimately led to the 3-piece core design to allow cleaning of hard to reach and delicate features (with the downside of a difficult set up operation to place all three cores at the same time).

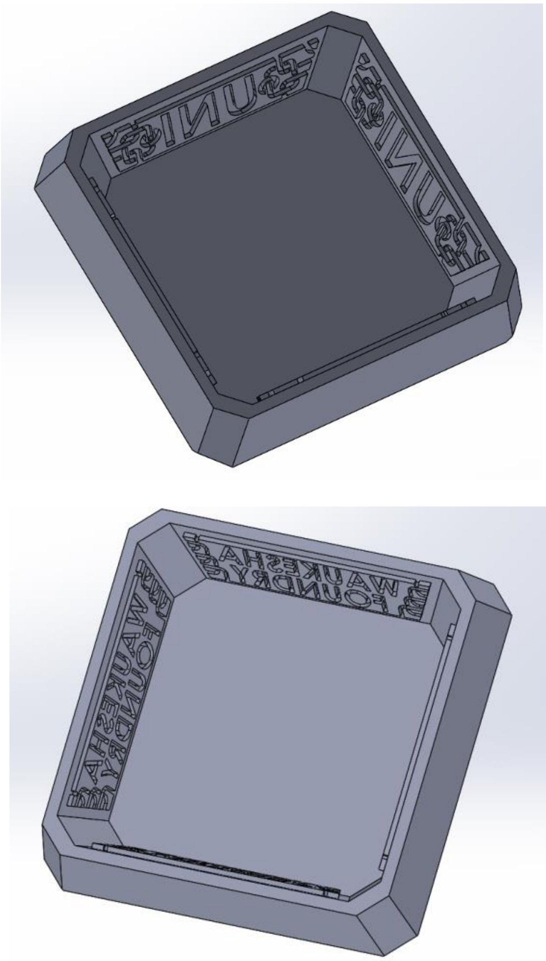

Figure 6 - UNI Insert (Top), Waukesha Foundry Insert (Bottom)

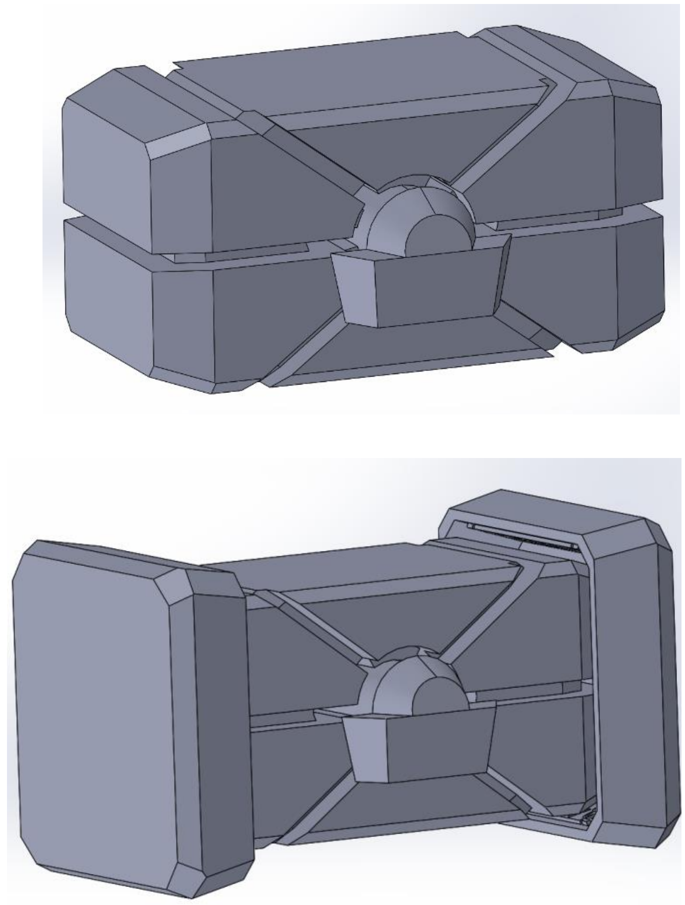

Figure 7 – Core (Top), Core assembled with Inserts (Bottom)

Molding

The mold was created by using a combination of hard tooling and sand-printed cores. The hard tooling was created using PLA (Polylactic Acid) filament using Fused Filament Fabrication (FFF); the hard tooling created the external features and the gating for the design, in addition to the core print for the core and inserts to set into. The FFF process is the stereotypical additive manufacturing process where a polymer filament (in this case PLA) is heated to the point where it can flow out of a nozzle and be deposited as a thin layer. The printer then translates the nozzle along the print bed until one layer is complete, before moving vertically to gradually create the part layer-by-layer. The PLA tooling was ideal for this situation as it was able to be printed rapidly,

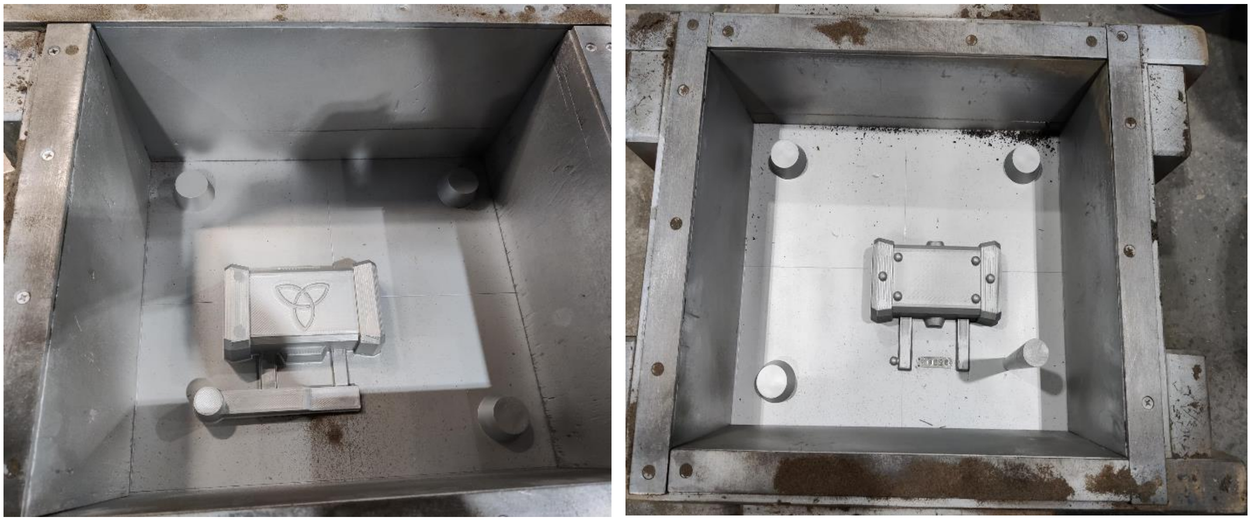

Figure 8 - Cope Pattern in flask (Left), Drag Pattern in flask (Right)

while maintaining a relatively fine level of detail. This was advantageous as one side of the tooling has a traditional “Triquetra” Knot (also known as a Trinity Knot); 3D-printing using PLA provided a means to accurately create the pattern with relative ease while also being conveniently cost-effective. Before creating the no-bake molds, the hard tooling was sprayed with a light coat of a mold release agent, which helps prevent the sand from sticking to the tooling. The release agent also has the advantage of slightly filling in and smoothing out the lines created by the different layers of PLA that are fused together, resulting in a finer overall surface finish.

Figure 9 - Finished no-bake Cope (Left), Finished Drag (Right)

The hard tooling design did have some issues during the assembly process that Waukesha Foundry discovered: firstly, the tooling did not include proper venting, which the foundry added before pouring. Venting is a vital part of the casting process as it allows gasses that are released during the pouring process (in addition to the air being displaced in the mold) to escape; without venting, the mold has the potential to not fill properly, and could also cause cold shuts within the casting.

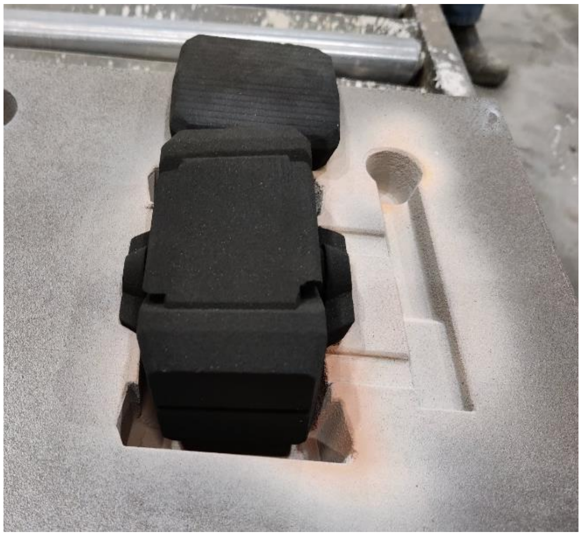

Figure 10 - Carboceramic core with fitment issue.

Secondly, the insert design was not entirely finalized when the PLA tooling was printed. Due to design oversight, the insert design did not match the tooling perfectly - this required some hand-filing on the inserts to allow it to fit into the drag during assembly. Finally, Waukesha Foundry raised concerns over the thickness of the wall between the casting and the runner and decided to extend the ingates by about 1-1.5 inches to provide additional thickness.

The core and inserts, meanwhile, were 3D printed using a binder-jetting process to fuse Carbo ACCUCAST ID80 ceramic media. The ceramic material acts as a chill in comparison to the no-bake sand used for the mold material allowing the text and Celtic knotting to solidify first, preventing surface porosity and preserving the detail. Several inserts and cores were also printed using a more typical silica (Badger Mining IC80); these samples did not preserve the detail as well as the carboceramic samples, despite having the same GFN and printed resolution.

Figure 11 - Balance of the cores and inserts. Green parts are Silica, brown parts are carboceramic.

Material Selection & Pouring

There were several variables that went into the steel selection. The first issue was choosing a steel that had good fluidity. Due to the thin walls on the hammer, steels such as nickel based alloys and tool steels were considered as a possibility; a Materials Engineer at Waukesha Foundry recommended against these alloys however to minimize the potential for cold shuts to occur during the pour. The next consideration was the Waukesha Foundry pour schedule. Due to Covid-19, Waukesha Foundry has a reduced pouring schedule to combat the potential for the spread of Covid-19 in the workplace. The combination of material selection and pouring schedule availability created the most limitations, which created a significant timeline constraint to produce a hammer successfully with an alloy that was an ideal fit for the hammer.

k6152	Alloy:	556015	8620		Col:	2/16/2021	8:00:00AM	Pour:	2/12/2021
C	0.200	MN	0.640	SI	0.620	P	0.010	S	0.010
CR	0.760	NI	0.560	MO	0.240	SE	0.000	CU	0.020
CB	0.000	FE	96.910	CO	0.000	SN	0.000	MG	0.000
AL	0.020	TI	0.020	V	0.000	ZR	0.000	W	0.000
PB	0.000								

Figure 12 - Material Composition from Pouring.

Based upon these factors, it was decided that a 8620 steel alloy was ideal due to the high Brinell hardness, good core strength and toughness with small and medium casting sections before heat treatment, and great tensile strength as well as reasonable toughness. If time permitted, carburizing the hammer head would also increase the hardness as high as 62 Rockwell hardness C.

During pouring, Waukesha Foundry measured a tap temperature of 3000 degrees Fahrenheit with an estimated 100-degree heat loss from furnace to ladle/mold pour. During pouring there was a 3.5 second pour time which was less than calculated during simulation testing. This was beneficial in combating cold shuts from appearing, in addition to the vents added to the cope of the mold for gasses to escape. Another difference from the simulations was the pouring temperature. While simulated at 2850 F, the increased pour temperature of 2900 F had no adverse effects to solidification.

Figure 13 - Waukesha Foundrymen pouring the 6 hammers created.

Initial Cleaning

Initial cleaning was conducted by Waukesha Foundry after solidification had occurred and casting temperatures had cooled to safe handling regions.

Following breakout from the mold, degating occurred to remove the rigging and vents. Afterwards, the hammer head was taken to a grinder and deburred of any flashing as well as grinding down all the flat surfaces to a more manageable near-finish state. After degating the details surrounding the heads of the hammer can be seen including the finer details provided by the 3d printed sand molds.

Figure 14 - Hammer casting after shakeout.

Figure 15 - Hammer after initial cleaning.

Final Grind and Heat Treat

Prior to the final post-processing steps, the hammer head was heat treated; this was intended to harden the metal, however due to errors during the normalization process the head was heated for too long, softening the hammer rather than hardening it. This was an unfortunate consequence that resulted in a lower Rockwell hardness than the initial pour, with a final hardness of 27 HRC compared to the 34 HRC for the as-cast hardness and 36 HRC for the heat treatment target.

Despite the setback from the heat treatment, the hammer was ready for the final finishing steps including grinding, sanding, and wire-brushing. The heat treatment created a layer of scale across the surface of the hammer that needed to be removed before moving on to sanding the metal surface below. This was achieved with an angle grinder, and a 60-grit flap disk to remove the majority of the scaling on the 6 primary flat surfaces. While quick, this process was ill-suited for creating a flat surface; once the scaling was removed, a belt grinder with a 120-grit belt was used to flatten the surface. Further sanding was performed by hand using 500 grit sandpaper to finalize the surface finish. The chamfered edges and the faces with detail were cleaned using a wire brush to remove the remainder of the scaling, which preserved the finer details that an angle grinder would have removed.

Figure 16 - Hammer following final grinding and cleaning.

Handle

The handle went through 4 revisions from the time the hammer head was shipped back from Waukesha Foundry to the final version that will be presented to the SFSA judges. The first idea was to use 7075 aluminum bar stock to create a high strength and light weight handle with a machined counterweight out of 1020 steel threaded to the end with a 1 in-8 thread.

Due to a shortage at the local metal distributor, the next plan was a 1-inch Black steel pipe commonly used for oil or gas applications. This allows for a lightweight handle that can be easily hidden and machined. On the end of the pipe a 1 in-14 die was used to create a 1-inch-wide thread. On the bottom hole created by the internal core an identical specified thread was tapped.

Figure 17 - Hammer with end cap installed.

The counterweight had to be modified in revision 3 to allow for a lip to go over the edge of the pipe rather than a 1in diameter threaded hole. This was due to a lack of tools available to tap and die materials above half an inch. The counterweight was now attached by a 5/16-18 threaded bar spanning the length of the hammer and mounting to the cap by drilling a hole and welding in place. This cap was designed and machined with the same tread to mount to the top of the hammer as the handle, but due to the shrink of the steel casting's hole compared to the specifications of the thread revision 4 was devised.

With revision 4 the threads were machined down .03 hundredths of an inch and JB weld was coated around the thread. This JB welded cap was then pressed in the top

Figure 18 - Hammer with counterweight and handle installed (Left), Finished hammer with leather-wrapped handle (Right)

hole to cover and seal the inside from the elements as well as give the threaded counterweight a solid base to create pressure with and hold the hammer together.

Around the handle a 3/4th inch wide 1/8th inch thick cow leather wrap was added that allows for a better molded feeling within your hand compared to the bare 1-inch diameter steel pipe which is too small within your hand. The addition of the leather wrap accents the wire brush aesthetic. It also archives the correct width within your hand most experienced hammer experts recommend of just slightly more than touching your palm with your middle finger.

Finally, 2 inches were cut from the handle to create a more historically accurate look to the hammer as compared to how it is described in Norse mythology. The counterweight before shipment was also mounted with red Loctite to create a solid hammer that will not come apart under extreme stress. The leather also helps with gripping the handle with the shorter length without it moving vertically unnecessarily caused by the shorter length.

Conclusion

Overall, this project has been an intriguing challenge that has pushed the boundaries of this team's creativity and experience within multiple medians regarding metal casting. The most intriguing concept explored was the application of thin wall design within steel sand castings and the challenges it represents. Another unique feature of the SFSA Cast in Steel competition is the opportunity of creating a unique weapon that you would not see in an industry setting. By using creativity, design, and out of the box thinking vastly challenging castings can be produced with great success.

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