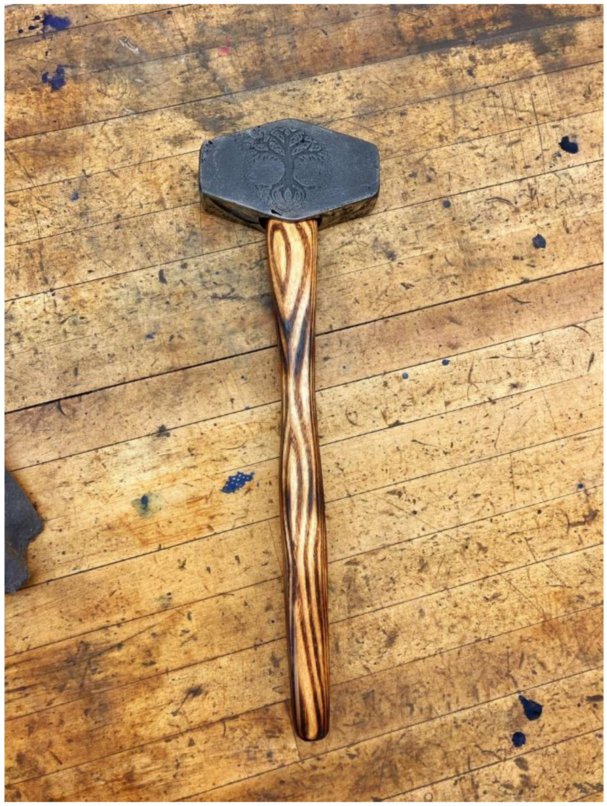

Cast in Steel: Thor’s Hammer

Presented by the Colorado School of Mines

Lauren Drew, Aidan Ravnik, Mason Weems, Naya Winkelstein

Partner Foundries: Western Foundries, Art Castings

Technical Support: Sarah Harling, Alexander Hansen, Donald Deptowicz

Design:

It was decided to model the hammer after hand hammers dating from the Migration Period of Northern Europe (circa 400 AD) when the Norse culture and religion were first established and became widespread in Norway. The hammer has traditional square facings and a trapezoidal cross section in order to maximize usability while maintaining aesthetic and historical considerations. Designs were chosen to reflect both the Colorado School of Mines and the Norse origin of Mjolnir. On one side is the rouleaux symbol of the Colorado School of Mines, with the school motto around it in Elder Futhark, the runic language used during the Migration Period. Surrounding the entirety of that is a stylized depiction of Jormungandr, the World Serpent, said to slay and be equally slain by Thor during Ragnarok. See figure 1 for the pattern depicting this side of the hammer.

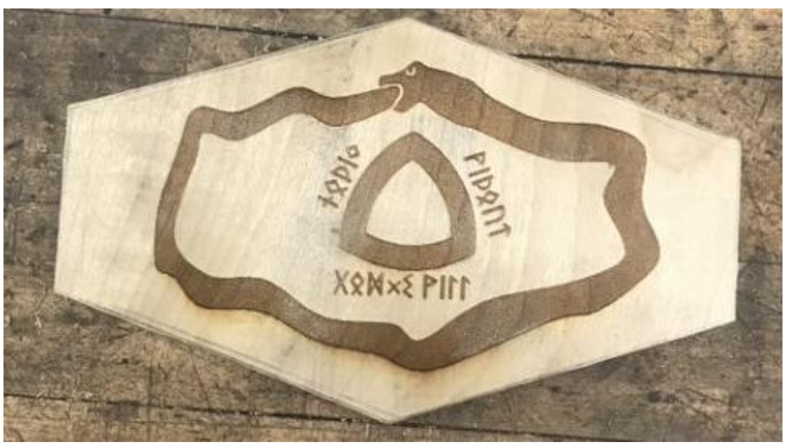

Figure 1. Wooden Pattern for Thor's Hammer depicting CSM and Jormungandr Designs

As Thor is the god of oak trees, and Yggdrasil, the world tree is the single most important symbol in Norse iconography; it was decided to emblazon the other side of the hammer with an image of Yggdrasil as an oak. See Figure 2 for an image of this side's pattern.

Figure 2. Engraved pattern depicting Yggdrasil

In order to minimize the complexity of the casting, and enhance the hammer's mechanical properties and usefulness, it was decided to cast the hammer as a solid piece, with an hourglass core where a handle may be inserted.

Pattern and Mold Making:

As a blend of cost and detail, poplar scrap from CSM's blade smithing supplies was laser engraved with a glowforge. Individual poplar planks were then wood glued together into hammer patterns with faces 1 ¾" square. Hourglass sections for the handle were machined from these poplar planks before assembly. Three patterns were made for repeatability purposes. In order to meet the high detail, large volume, and high temperature requirements of steel casting, high purity bonded silica sand with an American Foundry Society Grain Fineness Number of 80 was selected to make the mold. The molds were constructed according to green sand procedure, with cores for the handle holes. Figure 3 displays a half-completed mold with the cores inserted. The silica sand was bonded using an air-drying resin and catalyst intended to cause complete setting

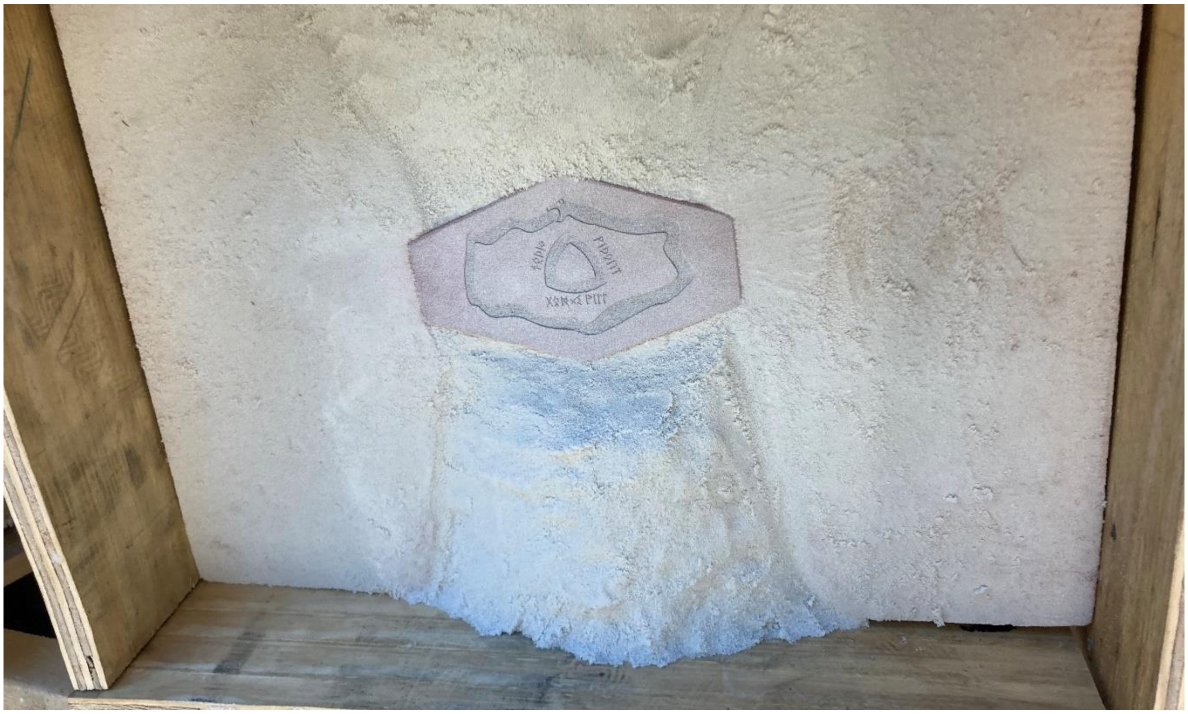

Figure 3. Half completed mold with cores inserted to set.

within an hour. Issues with the carving of the core sections lead to difficulties removing the patterns from the mold, causing light damage to the designs on two of the patterns.

Anticipated Alloy Composition:

The Colorado School of Mines has a large stock of toughened 1045 steel which it uses for the hammers in its forge. As 1045 is a cheap hardenable alloy, and proven to work in hammers, it was decided to use 1045 for Thor’s Hammer. Table 1 displays elemental assay data for CSM’s 1045 stock. Assay data was collected by vapor analysis.

Table 1. Elemental Assay Data for CSM Toughened 1045 Steel

Element	Wt%	+/-
Cr	0.1167	0.00701
Mn	0.83684	0.02048
Fe	98.71273	0.02665
Ni	0.09833	0.00997
Cu	0.17625	0.01201
Nb	0.02201	0.00144
Mo	0.03714	0.00192

Per the recommendations of Alexander Hansen, a PhD candidate providing metallurgical support on the project, the team decided to add 0.05 wt% titanium to one of the hammers as a toughening agent which could be tested against.

Pouring:

Pouring operations were to be conducted in-house using an induction furnace, which could reach the requisite melting point. During the initial melting of the 1045 however, failure of the refractory lining occurred, with the melt eating directly through the bottom of the furnace. In order to still produce a hammer before the deadline, the team reached out to local foundries, and was able to find a foundry which could pour steel for our molds.

Western Foundries was able to pour 304L stainless steel which caused a major change in the anticipated alloy type. The molds were brought to Longmont, CO, home to Western Foundries. The furnaces were tapped at 3180°F which is just below 1750 °C. Figure 4 displays a picture taken at Western Foundries as pouring commenced.

Figure 4. Casting Thor’s Hammer at Western Foundries

As-Cast Alloy Composition:

As Western Foundries is a professional foundry which exclusively casts stainless steel, the hammers were cast in stainless 304L, increasing its corrosion resistance, but likely severely impacting mechanical properties compared to the team’s planned casting alloy since 304L is not hardenable. Table 2 displays Western Foundries’ provided assays of their steel composition for the two heats that were poured into the team’s molds.

Table 2. Element Assays for Western Foundries’ Stainless Alloy

Meas.	C	Cr	Ni	Mo	Si	Mn	Cu
	%	%	%	%	%	%	%
	Type Corr. Conc.	Type Corr. Conc.	Type Corr. Conc.	Type Corr. Conc.	Type Corr. Conc.	Type Corr. Conc.	Type Corr. Conc.
1	0.0138	19.44	8.34	0.364	1.31	1.30	0.262
2	0.0120	19.45	8.37	0.358	1.28	1.29	0.262
W. Min		17.00	8.00				
<x>	*0.0129*	*19.44*	*8.36*	*0.361*	*1.29*	*1.30*	*0.262*
W. Max	0.0300	21.00	12.00	0.600	2.00	1.50	

Meas.	S	P	Al	V	N
	%	%	%	%	%
	Conc.	Type Corr. Conc.	Type Corr. Conc.	Type Corr. Conc.	Type Corr. Conc.
1	<0.00100	0.0345	0.0068	0.0735	0.0686
2	<0.00100	0.0300	0.0054	0.0726	0.0666
W. Min			0.0100		
<x>	*<0.00100*	*0.0323*	*0.0061 -*	*0.0730*	*0.0676*
W. Max	0.0400	0.0400	0.0500		

Heat Treatment/Finishing

Heat treatment of the 304L proceeded as follows. Hardness testing was conducted before and after heat treatment. Since 304L cannot be hardened the purpose of this was to anneal the hammer and relieve any residual stresses created during casting. Annealing was at 1065°C for 1.5 hours [1]. This was calculated using the thickness and a ratio of one hour per inch of thickness. The hammer was then left to air cool because the thickness of the hammer was not uniform in all parts of the core and water quenching was advised only if the thinnest section was not smaller then 0.1inches [1]. The hammer was then placed in a different furnace preheated to 350°C for stress relief. The stress relief was held for 1.5 hours. All values and sources were taken from ASM Heat Treating Society standards and Western Foundries' heat treatments.

Finishing the hammer post heat treatment consisted of creating and wedging a handle as well as some finishing of the faces. The faces of the hammer were ground and polished to a 1200 grit finish prior to testing. The wood used for this hammer was Ash, which is commonly used as a reliable hammer handle for high-intensity applications. The 18in handle was profiled and shaped so that it could be fit into the core of the hammer. The wood was then both burned and stained, as these processes target opposite parts of the grain and so both change the look of the wood. The hammer handle was then wedged (in both directions) and epoxied into place to make a secure fit. The hammer head weight was 4lb, 7.4 oz and including the handle the hammer was 4lb, 10oz.

Testing:

The quantitative analysis of the hammer consisted of Rockwell hardness analysis conducted according to ASTM E18 using HRA scale [2]. Table 3 below shows measured Rockwell hardness for the cast hammer pre and post heat treatment, and for a hammer used in the Colorado School of Mines forge.

Table 3. HRA Hardness Analysis

Trial	**Forge Hammer (HRC)**	**Pre Heat Treatment (HRA)**	**Post Heat Treatment (HRA)**
1(Calibration)	56.6	61.5	54.8
2 (Calibration)	70.0	45.7	54.2
3	64.4	52.5	52.4
4	68.2	54.0	55.5
5	74.7	59.8	50.9
6	74.5	60.2	52.4
7	73.6	60.1	52.6
Standard Deviation:	6.59	5.79	1.62
Average:	68.9	56.3	53.3

As can be seen in the table, the cast hammer has significantly lower hardness than the hammers used by the CSM forge, even post heat treatment. Much of this difference can likely be attributed to the unexpected alloy change from the 1045 steel used in the forge hammers to 304L stainless, which sacrifices mechanical strength for corrosion resistance. Additionally, as can be seen from the table, the heat treatment likely did not increase the hammer’s hardness. Even though a martensitic structure was not achievable with this alloy, the annealing allowed the steel to enter the recrystallization and recovery phase, which will likely help prevent sudden brittle failure and increase consistency of use. An additional qualitative test of Thor's Hammer was conducted by using it on the forge, where it worked well and was comparable to the forge's usual hammers.

Other potential causes of the hammer's lower hardness include casting defects. As the team did not have access to software such as SOLIDcast or similar foundry design packages, the sprue system was designed using the experience of Sarah Harling, one of the team's technical advisors, and as a result the gating is not exhaustively known to have provided enough superheat and head pressure to prevent shrinkage or interior voids. Additionally, there may have been unwanted turbulence during pouring, or heat imbalances which were not detected. These factors make it highly likely that the team was unable to achieve purely uniform directional solidification. This could have caused any number of issues such as segregation, although the heat treatment procedure likely eliminated any coring behavior. These factors, combined with mold damage during core removal likely caused the surface defects and pitting visible on the surface of the hammer, and contributed to the relatively weaker mechanical properties. However, per the qualitative analysis of use, the produced Thor's Hammer is more than fit for purpose.

Conclusions:

Based upon input from technical advisors and the experience of several team members, a design and alloy composition for Thor's Hammer was devised. Despite setbacks necessitating a change in casting venue and alloy, Thor's Hammer was cast and finished. Heat treating and finishing produced a hammer with an even surface finish and uniform mechanical properties, that was comparable in usability to those of the Colorado School of Mines forge, despite minor surface defects and slightly inferior hardness.

Special Thanks:

The team extends innumerable thanks to our technical advisors Sarah Harling, Alexander Hansen, and Donald Deptowicz. Without their advice and support, the team could have never gotten off the ground. Additional thanks are due to Drs. Gerald Bourne and Angus Rockett for their continued financial and departmental support of metallurgical engineering projects at the Colorado School of Mines. Finally, Art Castings and Western Foundries were integral parts in the production of a successful hammer. Words cannot describe how thankful the team is to Western Foundries for letting us use their facilities on such short notice.

Citations:

[1] H. Chandler, Ed., *Heat treater's guide: practices and procedures for irons and steels*, 2nd ed. Metals Park, OH: ASM International, 1995.

[2] "Standard Test Methods for Rockwell Hardness of Metallic Materials." ASTM International. *E18-20 Standard Test Methods for Rockwell Hardness of Metallic Materials.* West Conshohocken PA; ASTM International, 2020. doi: https://doi-org.mines.idm.oclc.org/10.1520/E0018-20