California State Polytechnic University, Pomona

Steel Founders' Society of America

Industrial-Manufacturing Engineering Department

2018-2019 SFSA Viking Axe Competition Final Technical Report

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Abstract

This report describes the history, design process, post cast process and benefits of casting an edged tool using investment casting techniques in 440C Stainless Steel. Investment casting allows for the weaponsmith to cast a weapon with the most intricate details in a relatively short lead time. 440C stainless steel is a martensitic steel that is capable of achieving high Brinell and Rockwell Hardness values and impressive resistance to wearability of the edge due to complete dendritic formation, versus forging an edged tool which breaks up dendrites in the microstructure of the metal. The axe design is inspired by battle axes used by Vikings, with a very thin blade best suited for cutting through armor and flesh while maintaining maximum agility for a warrior in battle; This weapon was not designed for merely chopping wood, it was designed for battle.

1 Process Selection

1.1 Initial Selection

When determining what casting process to use for our axe head, the options apparent to us included green sand casting, chemically bonded sand casting, and investment casting. Pros and cons exist for each type of casting process, including dimensional accuracy, ease of production, lead time, production volume, and different process requirements. The final decision was made based on manufacturing lead time and final product quality.

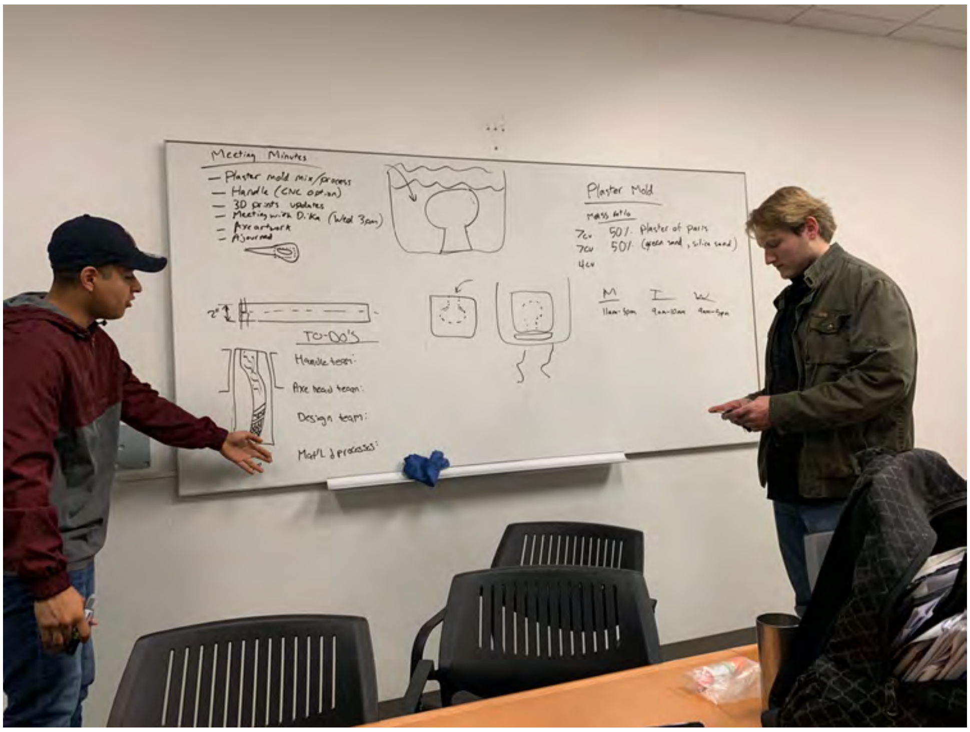


Figure 1: Brainstorming for process selection

1.2 Green Sand Casting

Green sand casting molds are built using water as the binder. The mold itself is shaped using a pattern, either with a cope[1] and drag[2] pattern, or a match plate which is designed as a single plate with the cope and drag features mounted on either side. Greensand is by far the cheapest and most available method of metal casting and can be used to achieve moderate part complexity and dimensional accuracy within relatively short lead time. The process, however, requires tooling, which includes a cope and drag pattern (or matchplate) and a core box to draw the mold and axe-eye core from, and will require a draft angle on the axe model to prevent the mold from breaking during the pulling operation. A side effect of green sand casting is the inherent formation of flash along the parting line, which will be clearly visible on the axe head post-cast.

The pattern features can be 3D printed out of PLA[3] using a readily available 3D printer. These features, along with the gating and runner system, can be epoxied to the surface of a plate and can serve as a low-volume production pattern.

In addition, the core box[4], from which the axehead-eye core would be shaped, can also be 3D printed in two pieces. The core itself would likely be made from a chemically bonded sand, most likely a two-part solution type binder such as SO_2 or isocure. The core would be inserted into the green sand mold to create the eye-hole feature for the axe.

1.3 Chemically Bonded Sand Casting

Chemically bonded sand casting is very similar to green sand casting and holds much of the same tolerances and part complexity. The overall process is the same,

[1] Upper part of green sand mold
[2] Lower part of a green sand mold
[3] Polylactic Acid
[4] A separate mold to form a core

with the key distinguishing feature being the binder type that is used in the mold. For chemically bonded sand, the whole mold is created using a two-part type binder such as SO_2 or isocure. The cores are made separately using the same process; the design requirements for the axe design, including draft angles and parting line locations, remain the same for chemically bonded molds as in green sand molds. The probability of a broken mold or sand inclusion is minimized by using a chemically bonded sand mold, and the surface finish of the casting is a noticeable improvement. This type of casting process was preferred over green sand.

1.4 Investment Casting

Investment casting is one of the oldest manufacturing techniques in human history, with examples of lost wax sculptures and tools dating back as far as 3000 BC in ancient Mesopotamia and ancient Egypt [Schleg, 2006]. The process involves investing, or building a mold around, an object made of wax or similar material with a low-temperature melting point. The shell of the mold would be made of a heat resistant material, typically clay or ceramic shell, which would allow the investment shell to retain its shape when the wax(or similar material) is melted out, and metal is poured in to fill the mold [Kalpakjian et al., 2014] Ancient craftsman did not have access to furnaces or crucibles that could reach the temperatures needed for iron or steel, but the process existed for copper, silver, and gold. The modern process involves constructing a tree from wax or in our case PLA, with the intended castings branching from the stem of the tree (Figure 2).

Figure 2: Brian Sararu

This tree assembly is then dipped into a slurry of refractory material such as very fine silica or zircon. After this initial coating has dried, the pattern is coated repeatedly to increase the thickness of the shell for added strength. After the shell is fully dried, the wax pattern is melted out of the shell, leaving behind an inverse mold that can be filled with molten metal [Kalpakjian et al., 2014]

The process is time consuming and is better suited for low volume productions, but an advantage to investment casting is that multiple castings can be made in a single pour by mounting additional duplicates to the tree assembly, which would ultimately yield more castings per pour than green sand or chemically bonded sand. A more notable advantage of using investment casting is the absence of a parting line, draft angles, or cores in the process, which significantly reduces processing complexity while producing the highest level of dimensional accuracy and part complexity. In addition, components for the tree assembly can be 3D printed out of readily available and affordable PLA (polylactic acid) to save tooling costs associated to die construction and further simplify the manufacturing process.

Figure 3: Alberto Smith

1.5 Final Process Selection

All the advantages listed above made investment casting the most obvious choice for this project. After There were several investment casting techniques which were available for this project, the key differentiating factor being the mold type. The three types of molds that were selected as options for this project were: Silica/Zircon shell mold (traditional investment casting technique), Plaster of paris mold, and Lost PLA shell (Evaporative casting technique). To test the effectiveness of each type of mold, and to determine which alternative can produce the level of detail intended for this project, the decision was made to cast a object resembling a tree with multiple axe heads attached using each of the alternatives proposed. Moving forward, the investment technique with the best results would be used to cast the final axe head tree. A trophy that closely resembled the final tree assembly and a sufficient level of complexity was designed specifically for this task.

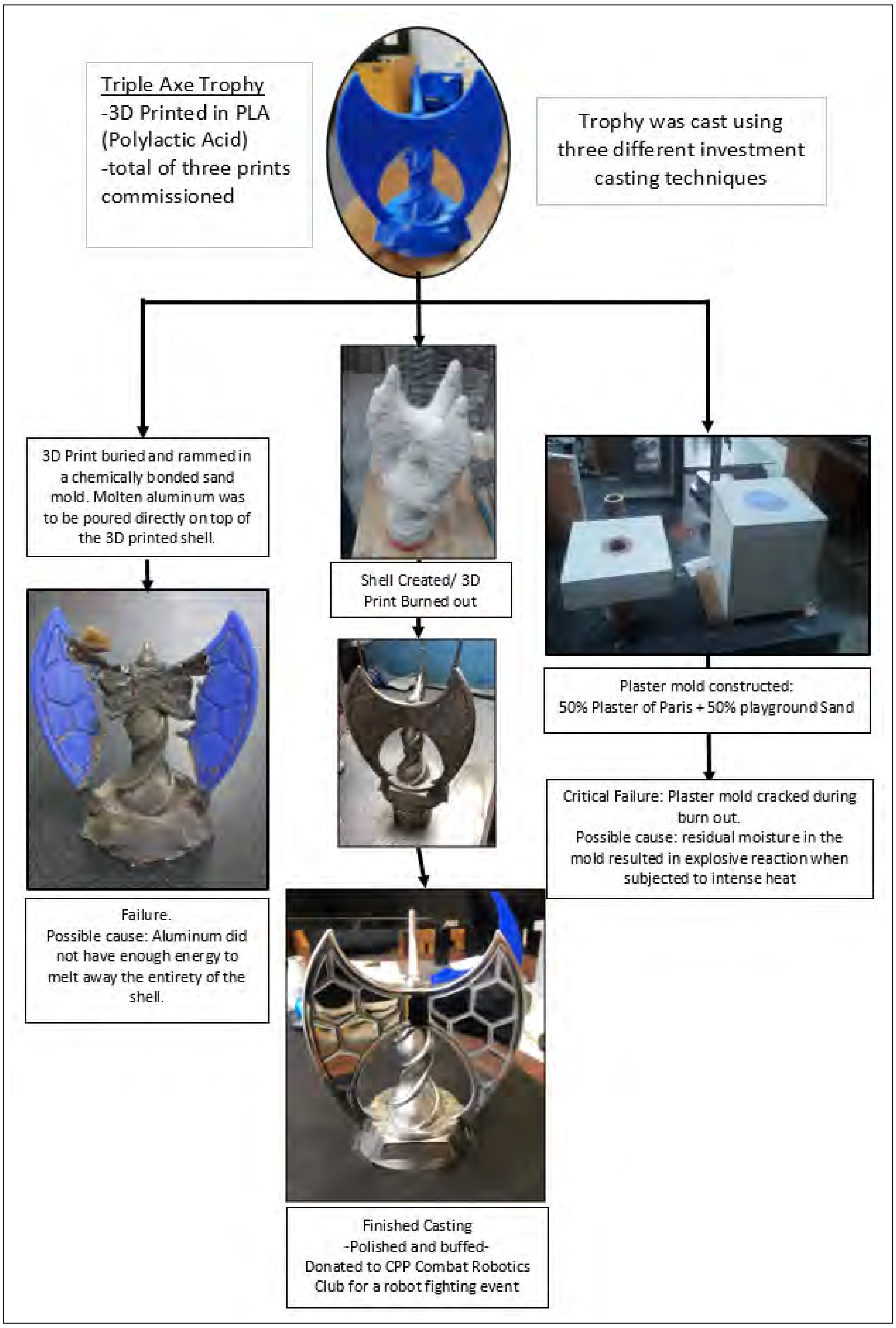


Figure 4: Trophy Process Tree: *Three different investment casting techniques (from left to right): lost PLA shell (Evaporative), Traditional investment casting, Plaster of Paris Mold*

1.6 Material Selection

Several options were initially considered for this project, including low and high carbon steels, general tool steels, and stainless alloys. Several design considerations were taken into account when choosing the materials for this project, including high impact resistance, edge retention, castability and fluidity, overall hardness, aesthetics after post-processing, and medium corrosion resistance. Since the vast majority of bladed weapons throughout history were forged, a special consideration was given for as-cast properties. The selection was ultimately narrowed to 440C Stainless steel alloy, and 4140 alloy.

4140 Alloy Mechanical Properties

Properties	Metric	Imperial
Tensile strength	655 MPa	95000 psi
Yield strength	415 MPa	60200 psi
Bulk modulus (typical for steel)	140 GPa	20300 ksi
Shear modulus (typical for steel)	80 GPa	11600 ksi
Elastic modulus	190-210 GPa	27557-30458 ksi
Poisson's ratio	0.27-0.30	0.27-0.30
Elongation at break (in 50 mm)	0.257	0.257
Hardness, Brinell	197	197
Hardness, Knoop (converted from Brinell hardness)	219	219
Hardness, Rockwell B (converted from Brinell hardness)	92	92
Hardness, Rockwell C (converted from Brinell hardness. Value below normal HRC range, for comparison purposes only)	13	13
Hardness, Vickers (converted from Brinell hardness)	207	207

Figure 5: Mechanical Properties Table for 4140. Taken from "Azom.com"

4140 was recommended for its castability and wear resistance. It is high strength steel well suited for investment casting, and it is used commonly for gun barrels and other military applications. 4140 alloy has a yield strength of about 60 KSI and an elongation at break of approx. 25.7 %. This alloy would produce a durable splitting axe, and would sooner deform than fracture, but is unsuitable for thin blades commonly seen on war axes.

440C Mechanical Properties		
Properties	**Metric**	**Imperial**
Tensile strength	760-1970 MPa	110000-286000 psi
Yield strength (@ strain 0.200%)	450-1900 MPa	65300-276000 psi
Bulk modulus	166 GPa	24100 ksi
Shear modulus	83.9 GPa	12200 ksi
Elastic modulus	200 GPa	29008 ksi
Poisson's ratio	0.27-0.30	0.27-0.30
Elongation at break	2-14 %	2-14 %
Hardness, Rockwell B (converted from Brinell hardness)	97	97
Hardness, Rockwell C	58	58

Figure 6: Mechanical Properties Table for 440C. Taken from "Azom.com"

440C has superior hardness, meaning it can maintain an edge much better than 4140 and better than most other alloys. According to most metallurgical sources, 440C is the hardest among the stainless steel alloys after heat treatment, which is ideal for edge sharpness. In addition, because 440C is a dendritic stainless steel, the grain formations branch out as the metal solidifies, making this alloy especially suitable for castings.

Convention demands that a bladed weapon be roll-forged or cast-forged to obtain the best physical properties, but in the case of 440C and similar dendritic steels, as-cast blades hold better edges than their cast-forged counterparts. The reason for this occurs at a micro-structural level: As a dendritic metal solidifies from a molten state, the grain structure branches out and forms "dendrites". These large crystalline formations in the metal structure are actually interconnected carbide crystals, which are extremely durable and capable of holding an edge even after subjecting the blade to significant wear. When forging a dendritic steel, these interconnected chains of carbide crystals are broken apart, and the dendritic structures are broken. Therefore the result of forging an alloy such as 440C is a weakened blade edge, which would otherwise be retained by keeping the blade edge as-cast[5] .Based on the results of our research, the ideal alloy within our selection for a cast viking axe was determined to be 440C Stainless Steel.

[5]History Of Boye Knives - Learn About How We Developed Our Blades — Boye Knives"https://www.boyeknives.com/pages/history"

2 Design Process

2.1 Overall Axe Shape

Initially, the axe design began by researching which axes were best used in battle by the Vikings, the most common design of choice was the bearded axe. Starting with a rough sketch of the SolidWorks drawing, not knowing exactly what dimensions were ergonomically appealing, through further research the consensus was that the axe head should be light enough to swing freely with the ability to maneuver with confidence in a battle. In order to achieve this, the design process went through a couple of phases until it was realized that it would be best to design the eye of the axe based on the handle of choice. Once the handle has been chosen the design process went substantially smoother, using surface modeling for the art on the axe head.

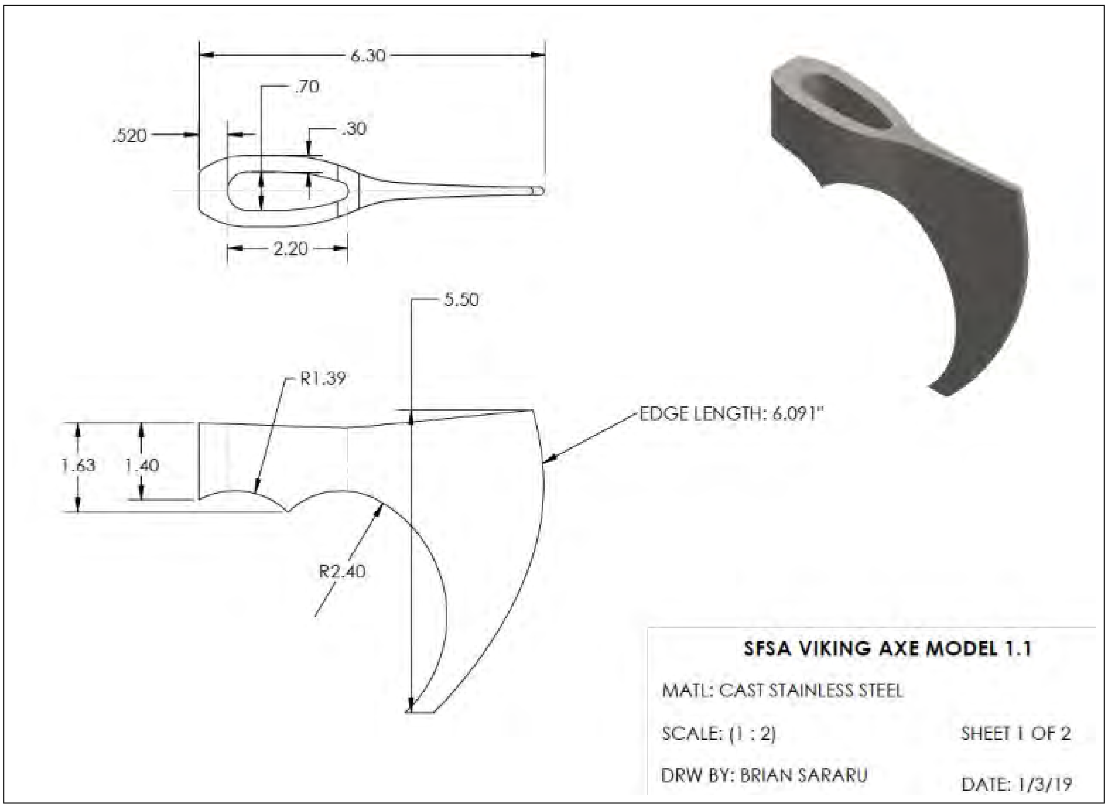


Figure 7: First Version of Axe Shape

With the overall shape and dimensions of the axe head narrowed down and decided upon, significant time was spent on creating artwork to make the axe head more aesthetically pleasing. To best showcase the level of detail and accuracy that can be obtained with investment casting, a very high level of detail in the artwork was favored over simple features, and special consideration was given to as-cast details on the axe. Since our axe heads were to be 3D printed and melted out of a shell using a lost-PLA type investment casting technique, and the detail capabilities of investment casting was unknown even by our industry partner, the hypothesis was made that dimensional accuracy of casting will be better than the accuracy of the 3D print. In short, the assumption was made that "if something can be 3D printed, it will certainly cast." This claim can be backed up by the results of our proof-of-concept trophy, which was able to cast even the individual layers of 3D printer filament; details that were measured to be below 0.2mm in resolution.

The final artwork design for the axe head contained features that were less than .002" in resolution, and runic letters which were embossed in 10 point font.

Figure 8: Axe Artwork

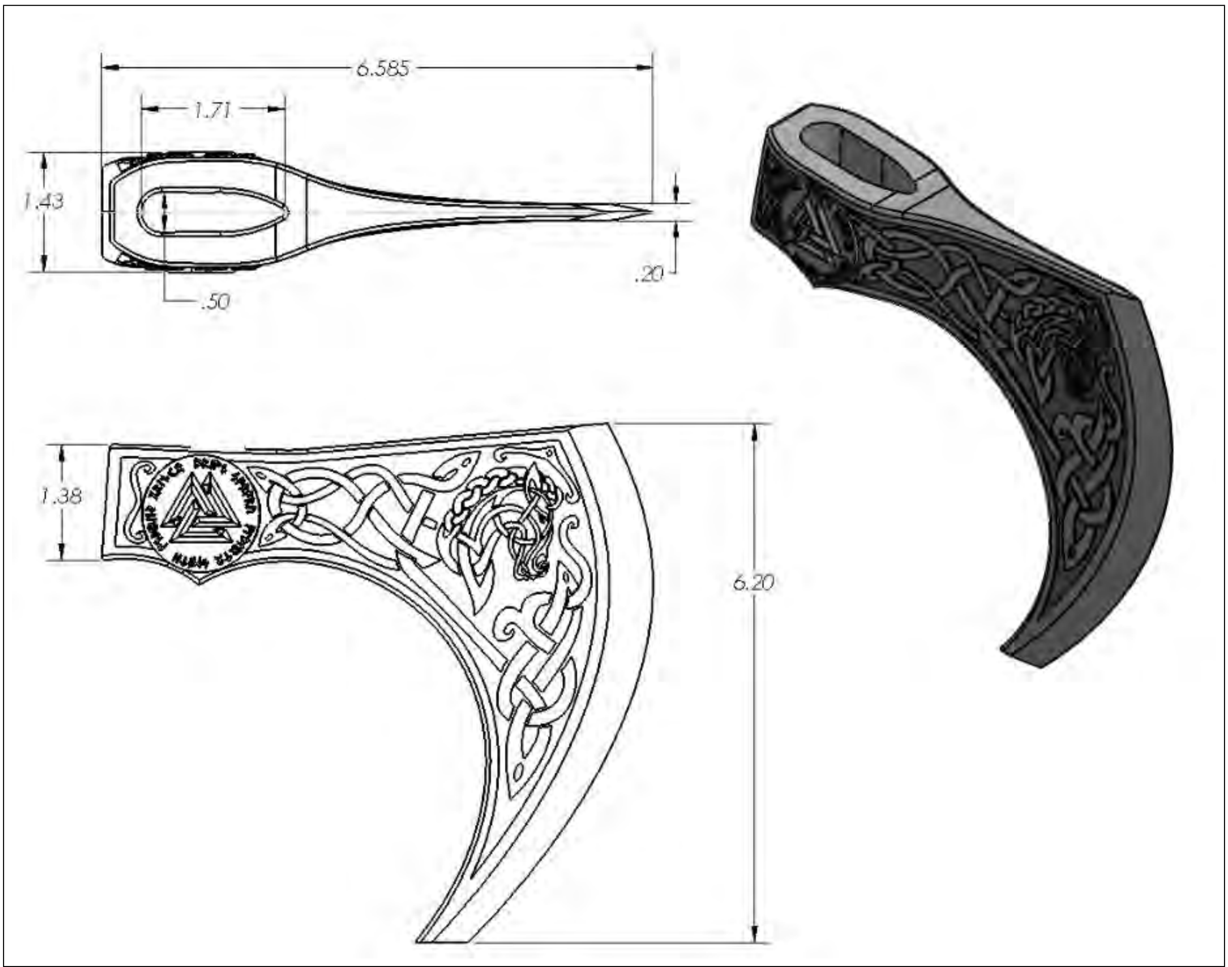


Figure 9: Projected view of axe model with artwork and simple dimensions

2.2 Historical Background

The design of our axe has been inspired by the skeggox[6] axe as it was the most prestige type of axe of the 11th century and the weapon of choice by the Huscarls[7]. For the Vikings, their axe was a representation of rank and power. An axe with low or non-existent artistic features[8] was considered no more than a wood-chopping tool [Harrison and Embleton, 2003]. In our mission to represent the weapon of a high ranked-noble warrior like the Huscarls, many details were incorporated in our axe. The most important features include the horse head, jelling art, axe shape, and valknut symbol.

Figure 10: Final Axe

[6] from Old Norse *skegg*, beard and *ox*, axe
[7] Warriors brought by King Sweyn Forkbeard of Denmark as Bodyguards
[8] Viking art

2.2.1 Horse Head

Figure 11: Horse Head

Is well documented that the Huscarls use to be cavalryman [Wise and Embleton, 1987] and had a great connection with their horses. In fact, horses were represented multiple times in the Viking culture as their favorite animal and many warriors used to be buried

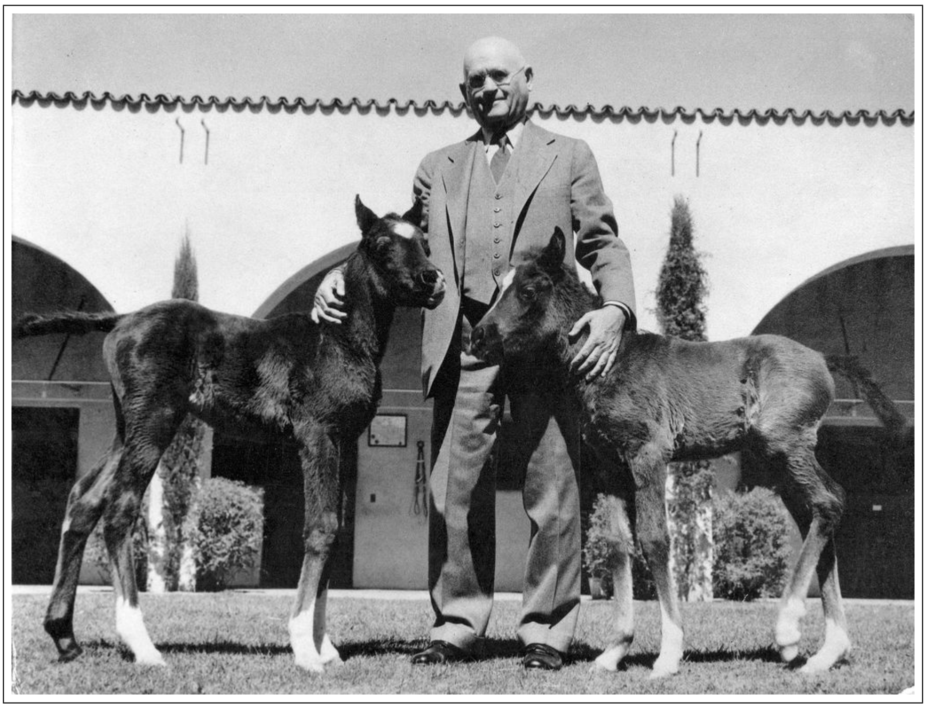


Figure 12: W.K. Kellogg and his Arabian Horses

with their weapon and their horses. Another reason why we chose a horse is because Cal Poly Pomona's mascot is also a horse. Cal Poly Pomona was founded on the residence of breakfast cereal pioneer and Kellogg Company founder Will Keith Kellogg . After his death, the Kellogg Foundation deeded the property and ranch to California's state college system to later become Cal Poly Pomona [CalPolyPomona,]. W.K. Kellogg's was a big advocate for higher education and shared a passion for horses. Our main goal with the horse head was to highlight the love Viking's had toward horses, to pay homage to the brave Huscarls warriors and to honor W.K. Kellogg's love of education and his passion for horses.

2.2.2 Jelling Patterns

Figure 13: Jelling Patterns

If there is something that separates Viking's weapons from any other weapon's found in Europe is the Jelling patterns. Many Swords, Axes, and shields with the same, unique artistic style have been found throughout Scandinavia. Jelling art style is based on the earlier Borre style. The name is derived from the location of the famous silver goblet silver cup, which was found on the north mound at the royal burial grounds of Jelling, Jutland (Figure 14).

Figure 14: Jelling Cup

Jelling patterns were mostly vegetal in appearance, even including animal forms to tell a story of current events or sagas. One of the most notable examples of decorative weapons in Viking culture is the famous Mammem Axe in Denmark (Figure 15). This axe has different shapes and forms inlaid with silver and while there is insufficient evidence to identify the owner, historians believe it likely belonged to a noble warrior. In our goal to re-create the weapon of a Huscarl, we created a foliate pattern around the horse's bust, which was faithful to the vegetal style of Jelling type art. The vine structure is continuous and inter-weaved as is common in similarly decorated weapons and monuments.

Figure 15: Grate Axe of Mammen

2.2.3 Valknut

Figure 16: *The runic letters that encircle the Valknut symbol spell out the names of all those who were involved in the final construction of the axe.*

The Valknut symbol consists of three interlocked triangles following an infinite loop. The meaning of this symbol still unknown but has repeatedly shown in many Viking artifacts and weapons. Many sagas have represented the Valknut symbol as the symbol of Odin as a god of slain warriors. The first appearance of the Valknut symbol was found on the Stora Hammars stone at Lärbro parish, Gotland, Sweden.Although this symbol's meaning still unknown we chose it as the representation of the braveness and honor of the Huscarls.

Figure 17: Stora Hammar Rune

2.2.4 Shape of the Axe

Figure 18: Shape of the Axe Head

One of the most important parts of our axe is the shape. In our goal to be as historically accurate as possible, we opted to create our design based on Petersen's Typology findings. Jan Petersen was an archaeologist who wrote the book "De Norske Vikingsverd" in 1920 [Petersen, 1920]. In this book, he explains the different shape of swords and axes found in the Viking era. Our axe has follows the shape of a combination of type B and type C (Figure 19). We create an asymmetrical profile with a deep and sharp curve and finish in a flat edge. This shaped give a great handeling to the axe as it has a long and extended cutting blade.

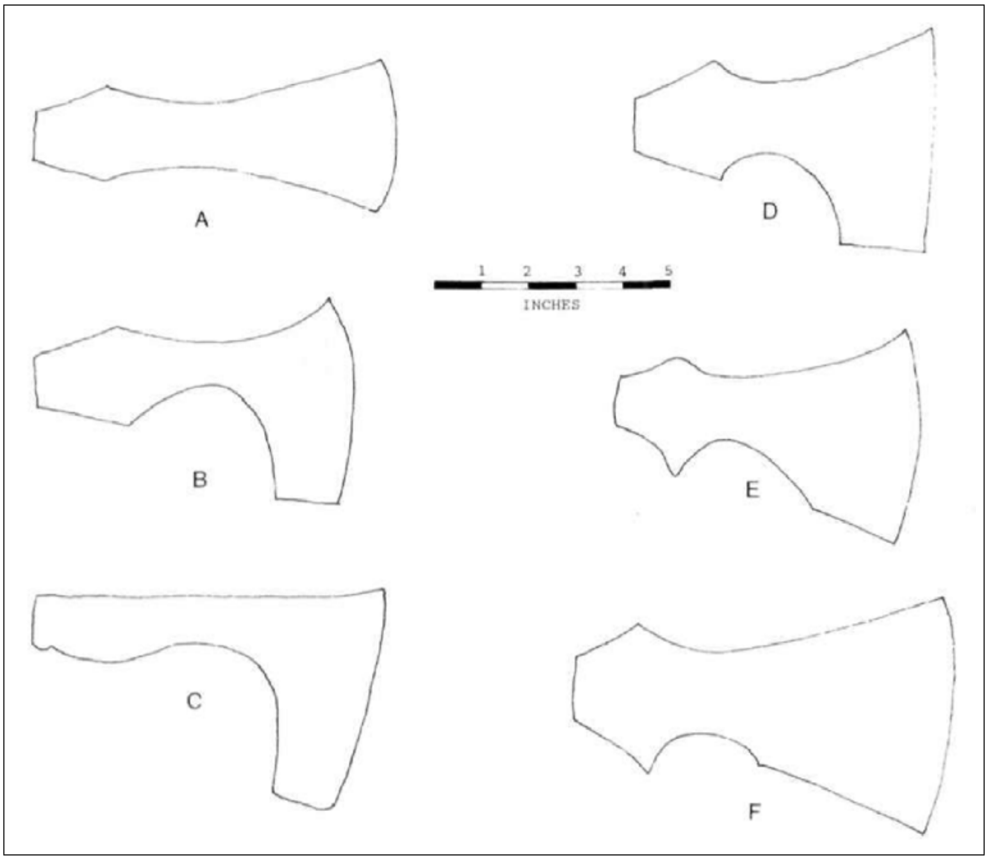


Figure 19: Petersen's axe heads

3 Engineering Simulations and Design Changes

Once the overall design of the axe head was settled on, it was time to design the runner and gating system and begin running simulations. Multiple simulations were run using SOLIDCast ® 8 software on various types of tree assemblies to determine which tree design was the most effective.

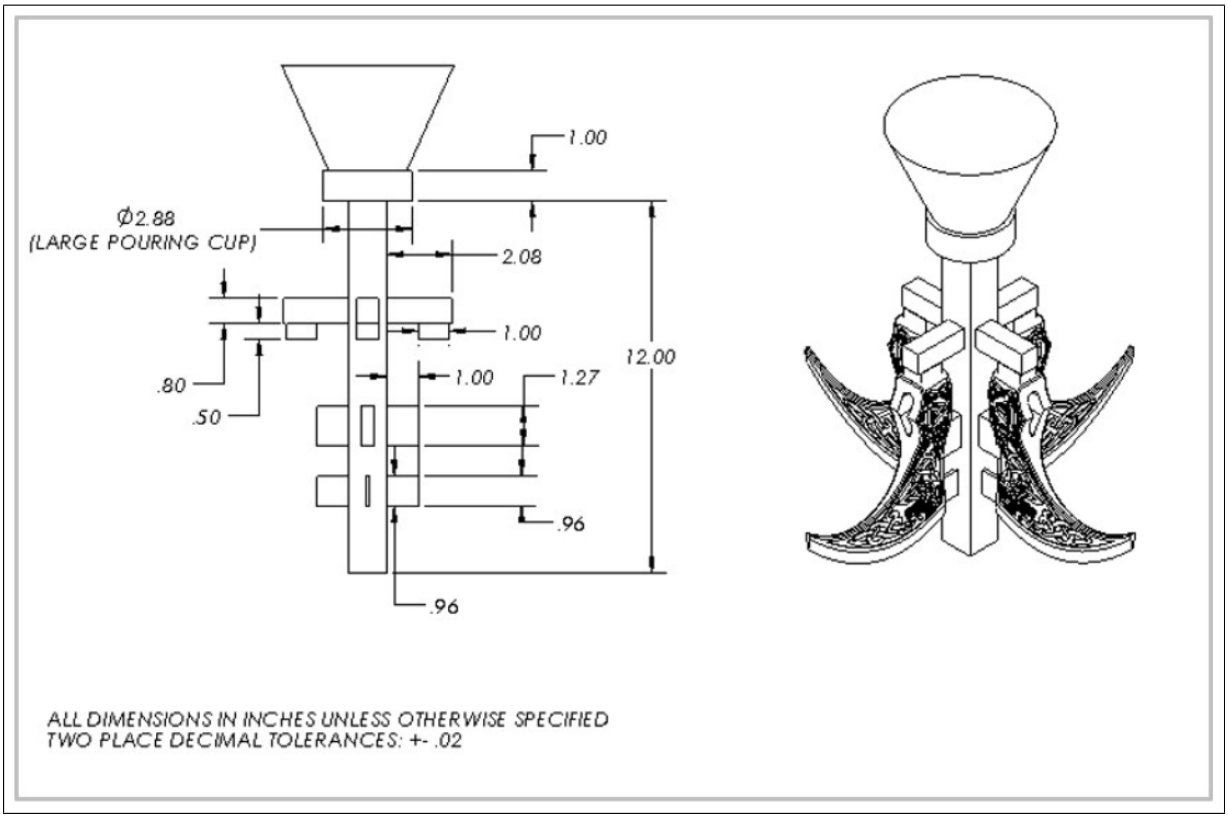


Figure 20: Basic drawing for the most feasible tree pattern design.

Several key factors were considered for obtaining a casting with minimum internal porosity:

- **Thermal Gradient / Cooling time**: The casting must cool evenly throughout. If one section of the casting solidifies slower than others, the slower freezing section will contain porosity.
- **Solidification time** : In general, faster solidification times result in less internal porosity, which is why permanent molds produce the best castings in lower-temperature metals. The permanent mold acts as a chill, allowing the castings to solidify faster.
- **Turbulence / Metal Flow** : Metal flow plays a small part in the formation of internal defects. If in-gates solidify faster than the area being fed, the supply of metal to that area of the casting is sealed off. Turbulent metal flow can cause mold erosion, which can break off sections of mold and introduce inclusions into the casting.
- **Proper Burn Out (Investment Castings Specific)** : in the investment casting process, the shell must be subjected to intense and sustained heat to completely evacuate the cavity of the shell of any wax. If any wax or PLA is left inside the shell after the burn-out process, inclusion type defects will appear in the casting.

Using the material density function in the output criteria of the software as a representation of porosity after solidification proved effective for detecting areas of potential issue. The process revealed several design flaws in the 3D model of the axe head which required corrective actions to avoid excessive porosity in the casting. The initial tree assembly designs revealed a problematic heavy section in the center of the axe head, which always generated significant porosity in simulations.

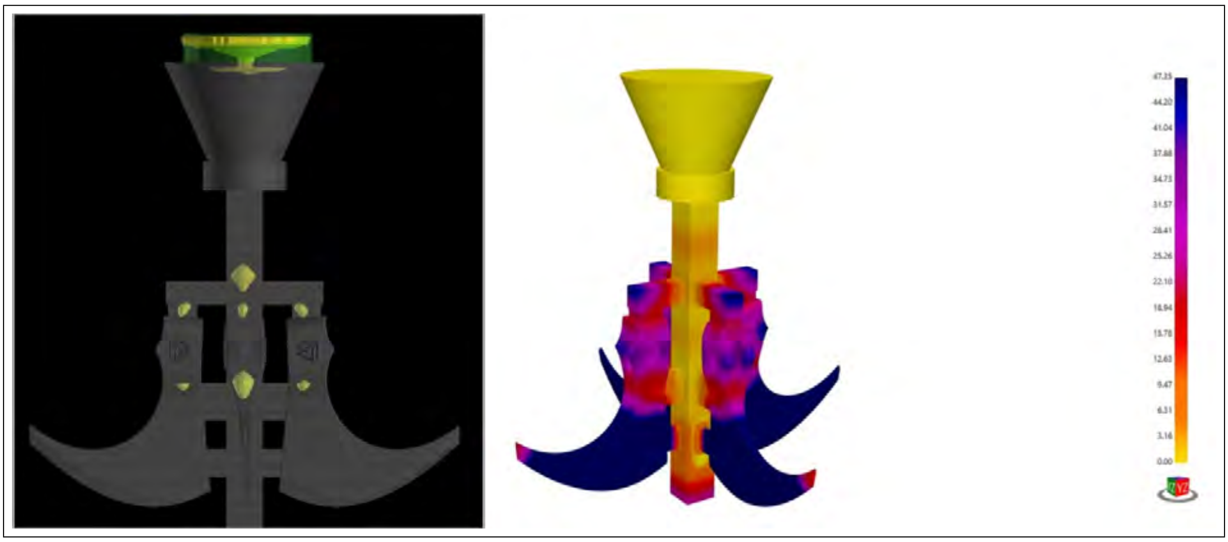


Figure 21: Material Density on the left, Cooling rate on the Right

This comparison in figure 24 shows the correlation between solidification rate and porosity formation. The heavy section in the area between the main body of the blade and the eye of the axe head was larger than necessary, creating a heavy area of mass which had a delayed solidification. As the surrounding area solidified first, the heavy section contracted to supply molten metal to the areas around affected by shrink, thus resulting in internal sponge shrinkage.

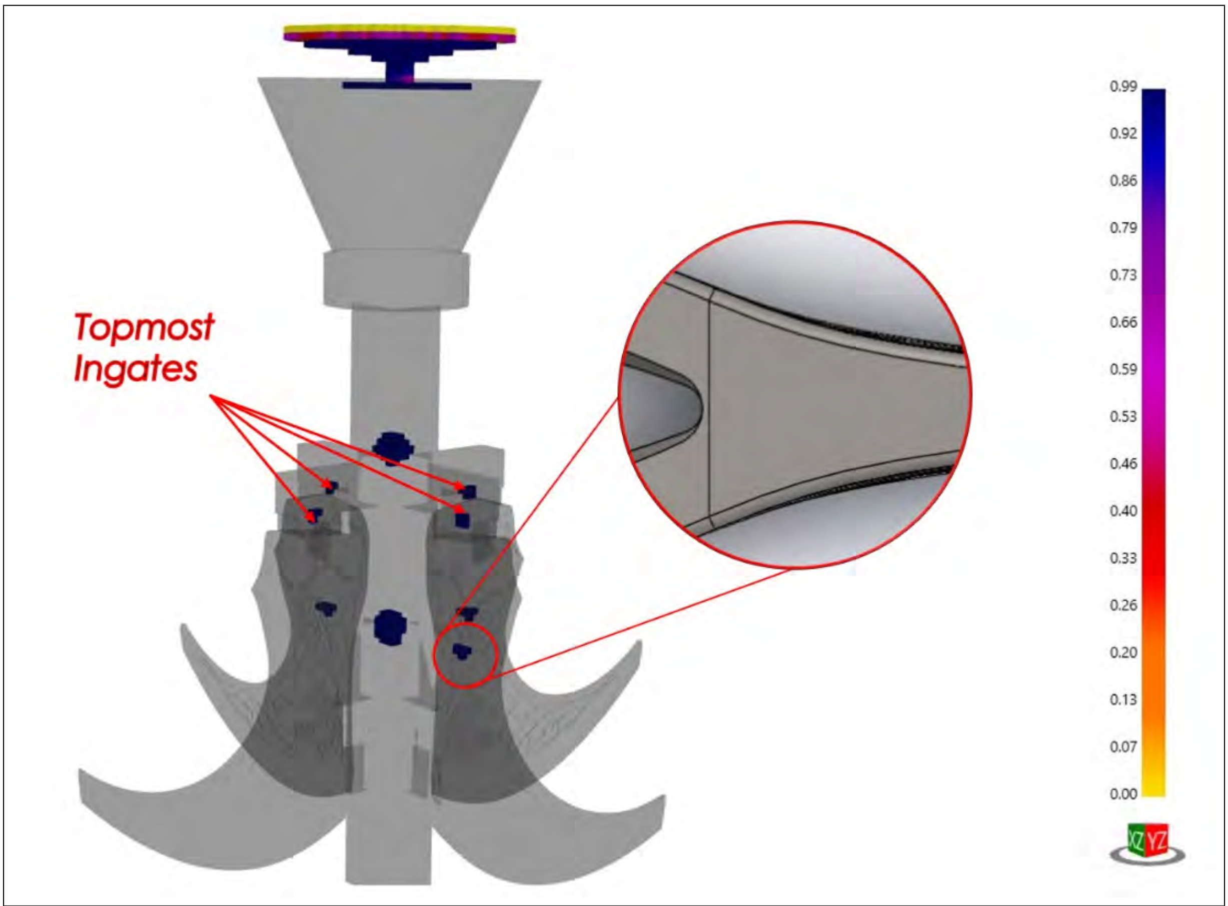


Figure 22: Isometric view of porosity formation

To mitigate the formation of unwanted defects, the axe head was modified to have a smaller cross sectional area in the shrink affected area. The eye dimensions were also adjusted to fit a full-sized handle, which also reduced the wall thickness of the axe head. These reductions decreased the total weight of the axe head to 1.34 lbs.

To avoid porosity in the gates located at the topmost feed points of the axe heads, the gates were also extended to better distribute the heat of the casting. Minor modifications to the axe head were also done as precautionary measures to prevent defects, including extending the blade edge, or adding a removable flange to account for miss-runs along the edge of the axe.

To increase the casting yield, alternative tree designs (Figure 26) were explored to

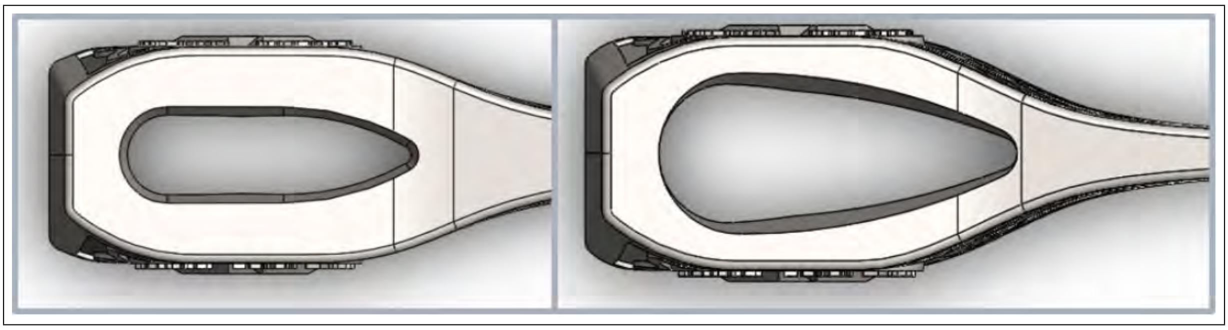


Figure 23: Top view of Axe Head: *Changes in cross sectional thickness and eye dimensions*

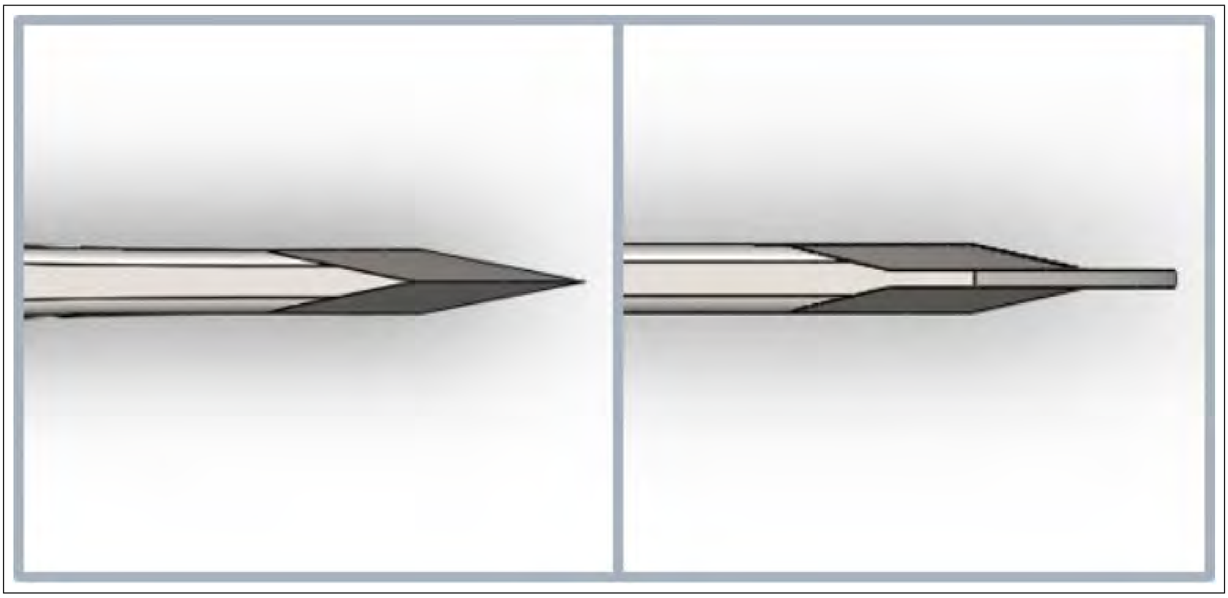


Figure 24: Top view of Axe Blade: *Added flange along the blade edge to be removed in post processing*

maximize the amount of castings that can be poured at one time. Using what was learned through the initial simulation results, the gating system was adjusted to reduce the mass of heavy sections and encourage uniform solidification. The gate that originally fed into the heaviest section of the axe head was removed, yielding simulation results were notable improvements.

Figure 25: *Some artwork features were found to be too intricate for the 3D printer and needed to be redesigned to prevent misprints.*

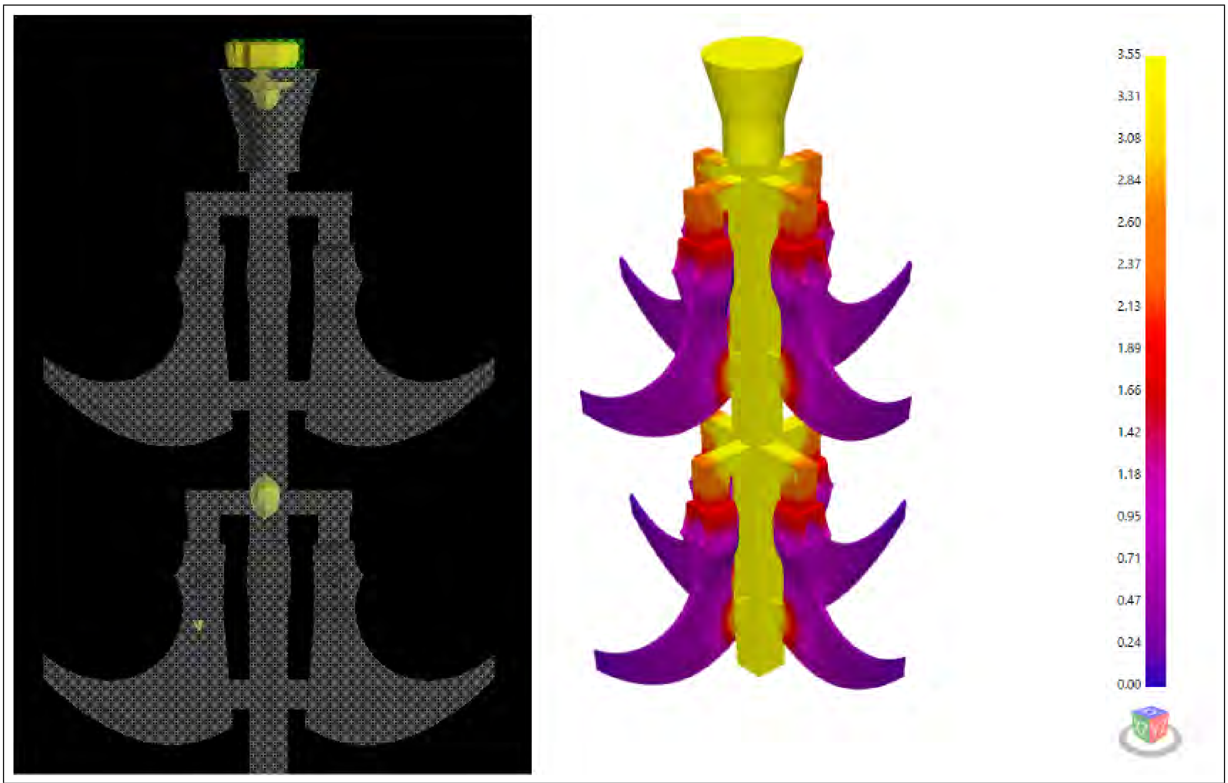


Figure 26: Double Decker tree Assembly: *Material density plot shown to the left, Solidification plot on the right.*

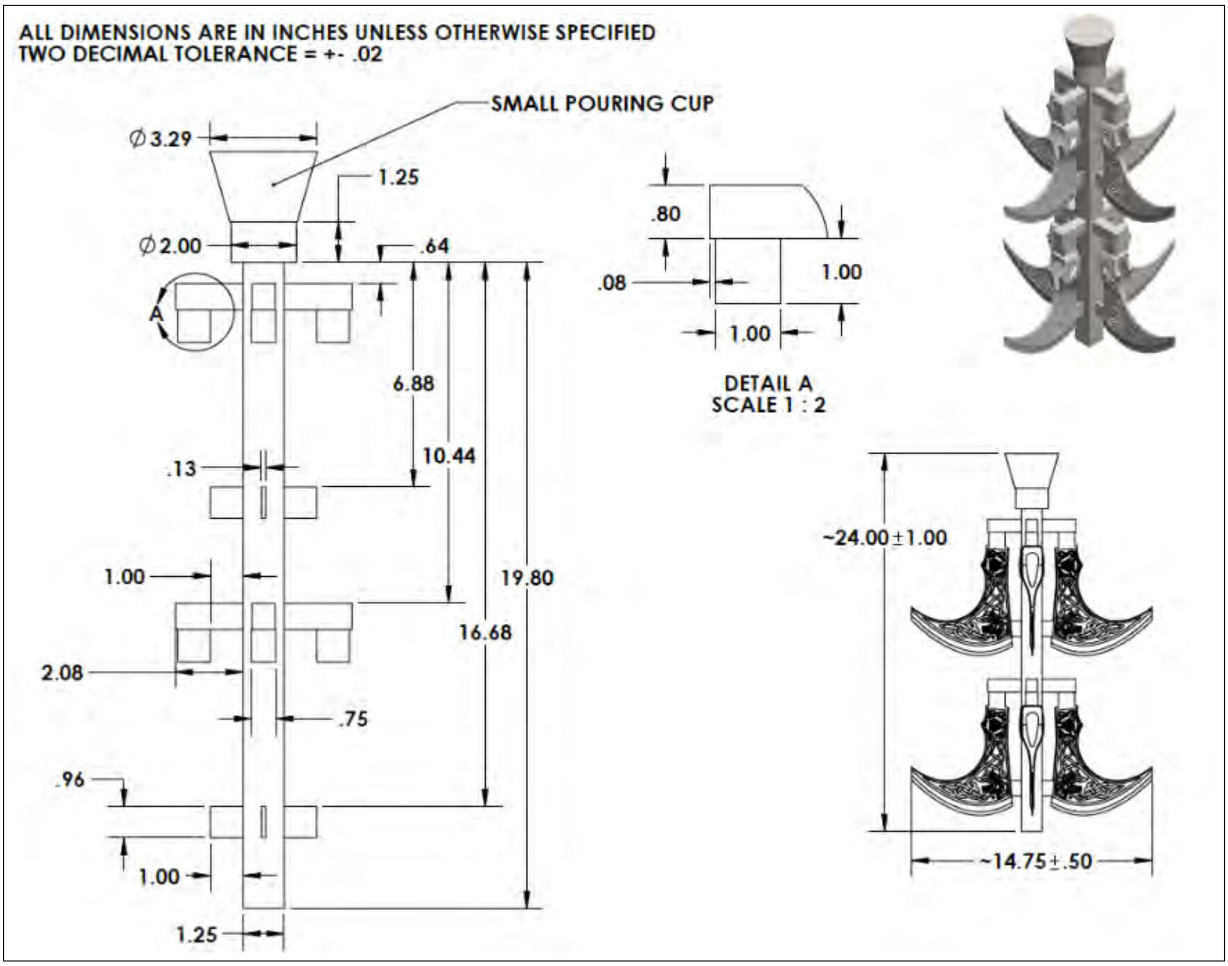


Figure 27: Double Decker Drawing

An additional design alternative was explored with the objective of producing a casting with absolute minimum porosity. The tree assembly included risers for each axe head which stemmed from the topmost ingates and fed directly into the heaviest sections of the axe. Any areas affected by shrink were supported by a riser to feed the system. Ultimately, the extra weight added to the tree with the addition of eight risers doubled the total casting weight. With very little improvement in porosity formation, the design was ultimately deemed un-feasible on the basis of cost effectiveness.

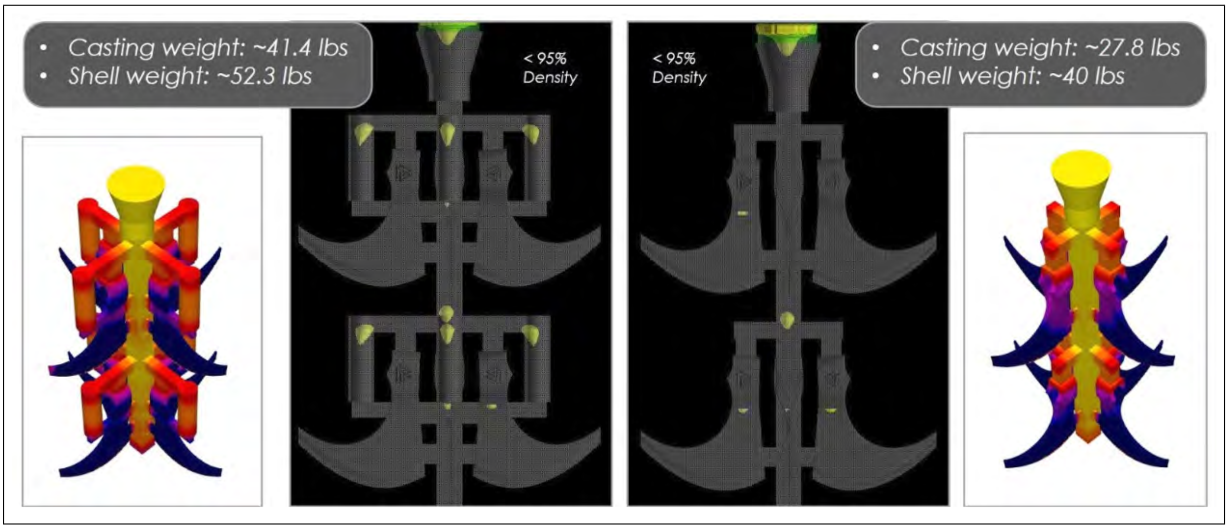


Figure 28: Double Decker Different Running system

4 Post-processing

4.1 Heat Treatment

finding the correct way to heat treat 440C was a bit of a challenge, there were many inconsistencies in information and incomplete material regarding the heat treatment process in our research. It was even difficult to find a reliable source for a TTT and Cooling curve for this specific alloy. This is where Techni-Cast was generous enough to provide the group an Aerospace Material Specification sheet with a method on how to heat treat 440C to achieve a certain hardness. Techni-Cast was provided with a 1.5 inch piece of the cold rolled ingot and tested the heat treating method to confirm the Rockwell Hardness desired. The company was able to achieve an HRC of 60, and was happy to share the information they have learned.

Aurora Engineering was performing the heat treat for the team, since they were pouring the metal, it was only convenient for both parties. The method was to place the tree in the furnace, and bring the temperature up to 1650 F and hold for 3 hours, then perform a furnace cool. In Aurora's case, using a vacuum furnace, the method was introduce enough nitrogen in order to cool the furnace 100-150F every hour until the temperature reaches 500-600F. This process was to anneal the casting and relieve it of its stresses. Hardening required to bring the temperature back up to 1875 F for 30 minutes then "air cooling". Aurora used nitrogen, to reduce flaking of the casting.

This process provided an HRC of 58, about the same hardness as a Japanese Katana sword. The hypothesis as to why Techni-Cast was able to achieve a harder HRC was because the ingot provided to them, had the hardness qualities from being cold rolled.

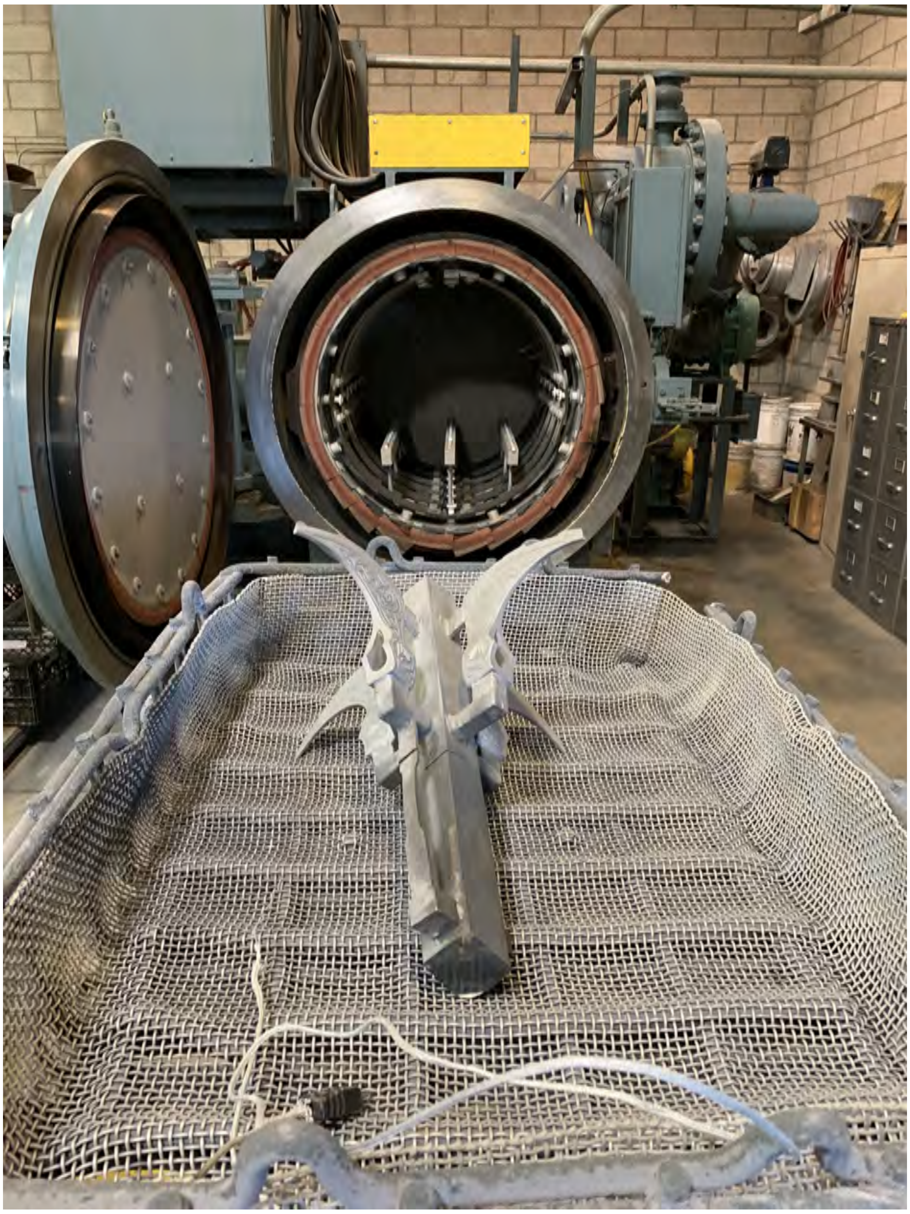


Figure 29: Heat Treatment

4.2 Polishing

Polishing was done in-house at Aurora using wire wheels, bench grinders, abrasive cutoff tools, and various other tools suited for stainless steel used in Aurora's finish department. The final product was polished using standard polish compound and buffed to a mirror finish. A natural black stainless shean was present after the polishing process.

Regrettably, the dark color was not retained after dye penetrant testing.

Figure 30: Polished Axe Head

4.3 Edge sharpening

The Edge was sharpened professionally by Mark Fleischman at “Man of Steel” blade sharpening. The edge was roughly ground to create a convex edge which is best suited for repeated impact edge retention. The rounded walls of the edge provides extra material to support the edge from impact. The hardness of the alloy meant that the edge would not likely fold or dent, but rather chip or fracture. At the very least the edge will retain its sharpness no matter what the axe blade is subject to.

Figure 31: Sharped Edge

5 Problems Encountered

The “double decker” tree assembly was deemed the most efficient design to cast our axe heads because of the high casting yield and ease of construction, and thus it was decided to use this design moving forward. However, as the deadline to produce a finished axe approached, and the pressure to complete a finished casting reached its peak, the 3D printer that supplied the PLA axe heads for the investment casting process had a critical malfunction and required replacement parts. At this time only four axe heads were fully printed. Because there was very little time to wait for parts, repair the printer, and print more parts before beginning the tree construction and dipping process, the decision was made to initiate an emergency re-design for our tree assembly in order to meet the deadline.

Three designs were rapidly produced, and the most feasible option was chosen as the alternative to proceed. The design shared many of the same dimensions as the “double decker” tree assembly, including the overall height, pouring cup, base diameter, ingate locations, and axehead mounting orientation. The extra space generated on the tree by not including the top row of 4 axe heads was filled with test bars which were previously 3D Printed. With a viable alternative chosen, and a plan set in place, the minor setback became advantageous to this project.

After the axe was casted, heat treated, polished, and sharpened, another critical problem was encountered when seating the axe head to the intended handle. The eye dimensions were designed on a previous handle which was only 18 inches long, when the decision was made to use a full sized 28 inch handle, consideration was not made for the eye dimensions of the full sized handle. The full sized handle ironically came with an eye shaft that was much more narrow than the original handle, the result of which was obviously an improperly seated axe head. To rectify the issue, it was required to add material to the eye shaft of the handle to make up for the lack of material to properly

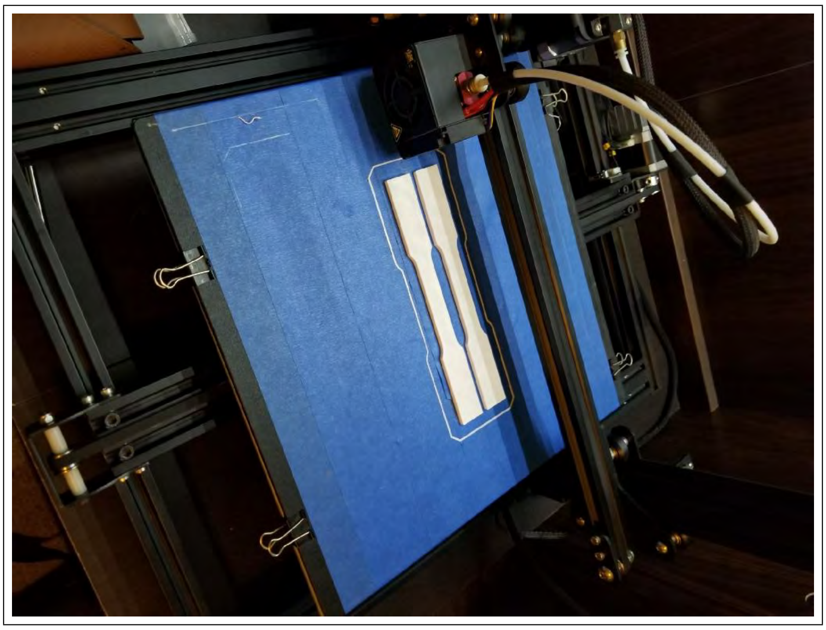


Figure 32: 3D printed Tensile Bars

wedge the axe head. During the process of bonding extra material, it was discovered that the eye hole on the axe head was too smooth and did not provide adequate friction to prevent the head from slipping off the handle when the axe is subjected to extreme forces. Our solution to this problem was grinding horizontal grooves onto the walls of the eye hole, which would allow the handle wood to expand and fill the grooves as the wedge is inserted, ultimately providing exceptional grip friction between the eye hole and shaft.

Figure 33: Inner Ribs

Figure 34: Eye shaft

Figure 35: Eye shaft

6 Destructive and Non-destructive Testing

6.1 Destructive Testing

For destructive testing the axe went through with chopping up a 55-gallon steel drum to test how well it can hold an edge and whether it will dent or chip, after more than 20 hits from three grown men to the steel drum the axe finally began to show some wear, specifically after a few blows to the very edge of the drum, the axes edge chipped in the lower area of the blade and developed a nick on the upper edge of the blade as well as developed a few scratches on the blade. The axe head was then thrown at a block of wood placed on the concrete floor, axe head missed it's mark hit the concrete floor at an abnormal angle and chipped off a substantial sized piece of the axe head.

Figure 36: 55-gallon steel drum

After testing on the steel drum, a separate axe from the same casting tree was tested on chopping on an unknown North American softwood in order to test its durability. A problem that was encountered when chopping wood was that, the wood would adhere

Figure 37: 55-gallon steel drum

to the artwork of the axe and would prove to be quite a struggle to pull the axe out of the wood. The axe was critically impacted on a tree stump and snapped the blade clean off. It is important to keep in mind that the axe was designed to be **a battle axe for chopping through flesh and bones and not wood**.

Figure 38: Piece of wood

Once testing with the softwood was complete, the same axe that was tested on the steel drum was tested on blocks of ice, with no new nicks, dings or chips. The axe was able to chop through all of the ice without any destruction to the edge.

Figure 39: Piece of Ice

6.2 Non-Destructive

Non Destructive testing included visual inspection, UV reactive dye penetrant, Hardness testing (on the Rockwell C scale), and X-ray scan.

The dye penetrant revealed porosity in the blade shown below, the porosity was not visible before the penetrant was applied. The porosity was revealed when Material was removed during axe sharpening. To rid the blade edge of the defect, additional material had to be removed from the blade edge.

Figure 40: Before Dye Penetrant

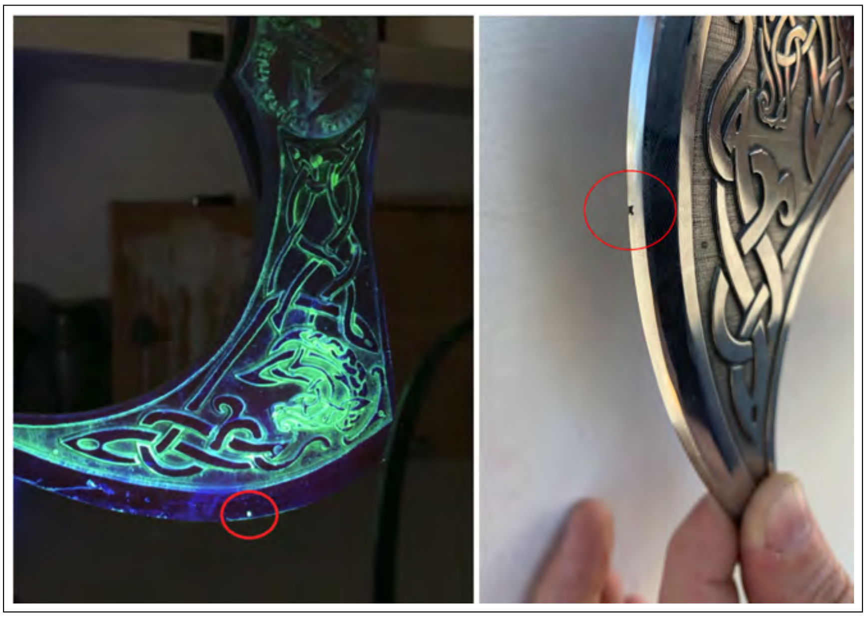


Figure 41: Dye Penetrant

7 Conclusion

This viking axe truly embodies the heart of a warrior. The symbols embossed in the face and handle of the axe faithfully re-create the spirit of viking culture, and pay homage to the Huscarls of old. The steel is of finest quality 440c stainless steel, which grants the blade edge a hardness and sharpness retention of no other alloy. This is a battle axe, meant for war, to hack through skulls, flesh, and armor, and has demonstrated the ability to split through shields of any unfortunate enemy brave or stupid enough to call himself a foe. This axe was meant for a king of all kings, it is hard, robust and holds its edge. This project has allowed the team to become familiar with the investment casting process with the team has faced many problems and was able to overcome them through hard work and determination.

Figure 42: Alberto Smith, Brian Sararu, Andrey Grinko

8 Apendix

8.1 Metal Certification

CERTIFICATE OF TESTS **ABNAHMEPRUEFZEUGNIS** **CERTIFICAT DE CONTROLE**

CERT SERIAL# 001134788

CARPENTER

Carpenter Technology Corporation
101 West Bern Street, Reading, Pa. 19601
Tel: (610) 208-2000 (800) 338-4592

11/20/18

CUSTOMER / BESTELLER / CLIENT

COPPER & BRASS SALES - WEST

13338 ORDEN DR
SANTAFE SPRINGS CA 90670

SELLER / VERKAEUFER / VENDEUR PAGE 1 OF 2

HVL

CUSTOMER ORDER NO. / BESTELL-NR. / N° DE COMMANDE	CARPENTER NO. / WERKS-NR. / N° DE REFERENCE	[illegible]	[illegible]
5400414865-R05-0020	W81720	11/20/18	1488.000

HEAT NUMBER / SCHMELZE-NR. / N° DE COULEE: 754244

PRODUCT DESCRIPTION: TYPE 440C ANNEALED GROUND
PART NUMBER: SSRD00490

SPECIFICATION: ASTM A276/A276M-17
AMS-QQ-S-763 REV D STABILIZED (03/ /15)
AMS 5630 REV L (04/01/13)
MOOG INC B01111A UNS S44004, COND A REV BN (11/24/14) EXCPT LTR (06/01/15) PENDING
DFARS 1998 EDITION

SIZE 1.000000 IN. (25.40 MM) RD BAR

HEAT CHEMISTRY (WT%): (TEST METHOD IS SHOWN IN PARENTHESIS)

C (COM)	MN (XRF)	SI (XRF)	P (XRF)	S (COM)	CR (XRF)
1.04	0.41	0.74	0.019	0.001	16.77
NI (XRF)	MO (XRF)	CU (XRF)	CO (XRF)	N (OES)	
0.16	0.43	0.09	0.02	0.016	

THIS HEAT MELTED BY THE ELECTRIC ARC/AOD PROCESSES

DISCS MACROETCHED AND APPROVED

HARDNESS AS SHIPPED, HBW - 233 (MIDRADIUS)

DECARB - NONE (VILELLAS)

CARBIDE SEGREGATION - ACCEPTABLE TO PHOTO 3 (VILELLAS)

MAX QUENCH HARDNESS, HRC - 61 - 1925 F(1052 C) 30 MN OIL TREAT
MAX QUENCH HARDNESS, HRC - 60 - 1875 F(1024 C) 30 MN AIR COOL

CONTINUED ON NEXT PAGE

From: ThyssenKrupp Materials NA
Cust. ONLINE METALS LAX
CstAr 15233
Wgt.: 96 LB

Del.: 2406423941
CstOr 108552
Date 12/11/2018

Tomas Sanchez

CERTIFICATE OF TESTS ABNAHMEPRUEFZEUGNIS CERTIFICAT DE CONTROLE

CERT SERIAL# 001134788

CARPENTER

Carpenter Technology Corporation
101 West Bern Street, Reading, Pa. 19601
Tel: (610) 208-2000 (800) 338-4592

11/20/18

CUSTOMER / BESTELLER / CLIENT

SELLER / VERKAUFER / VENDEUR PAGE 2 OF 2

COPPER & BRASS SALES - WEST

13338 ORDEN DR
SANTAFE SPRINGS CA 90670

HVL

CUSTOMER ORDER NO / BESTELL-NR / N° DE COMMANDE	CARPENTER NO. / WERKS-NR / N° DE REFERENCE		
5400414865-R05-0020	W81720	11/20/18	1488.000

HEAT NUMBER / SCHMELZE-NR. / N° DE COULEE: 754244

MATERIAL HAS BEEN MELTED AND MANUFACTURED IN THE USA WHICH IS A QUALIFYING COUNTRY TO DFARS REQUIREMENTS 252.225-7014 WITH ALTERNATE 1 FOR QUALIFYING COUNTRY 225.872.1, SUPERSEDED BY DFARS REQUIREMENTS DFARS 252.225-7008 AND 252.225-7009.

UNLESS OTHERWISE STATED, THE TEST WERE PERFORMED TO THE LATEST REVISION OF THE STANDARDS LISTED BELOW: 1) BEND TEST - ASTM E290, 2) CHARPY IMPACT - ASTM E23, 3)COEFFICIENT OF LINEAR THERMAL EXPANSION - ASTM E228, 4)FRACTURE TOUGHNESS - ASTM E399, 5) BRINELL HARDNESS - ASTM E10, 6)ROCKWELL HARDNESS-ASTM E18, 7)MICRO VICKERS HARDNESS-ASTM E92, 8)KNOOP HARDNESS-ASTM E92, 9)MACRO VICKERS HARDNESS-ASTM E92, 10)STRESS RUPTURE/CREEP RUPTURE-ASTM E139, 11)STRESS RUPTURE(COMBINATION)-ASTM E292, 12)ROOM TEMPERATURE TENSILE-ASTM E8, 13)ELEVATED ROOM TEMPERATURE TENSILE-ASTM E21, 14)DECARBURIZATION-ASTM E1077 15)DELTA FERRITE AMS 2315, 16)GRAIN SIZE-ASTM E112, 17)INCLUSION CONTENT/MICROCLEANLINESS-ASTM E45, 18) INTERGRANULAR ATTACH - ASTM A262, 19)INTERGRANULAR CORROSION-ASTM A262, 20)MACRO ETCH&TESTING - ASTM A604/E381, 21)PITTING CORROSION - ASTM A923, 22)CREVICE CORROSION-ASTM G48, 23) HARDNESS CONVERSIONS - ASTM E140, 24)XRF-ASTM E572/E1085/E2465, 25) OES - ASTM E415/E1086, 26)COM - ASTM E1019, 27)FUS - ASTM E1019, 28)MS - CARPENTER METHODS 206.8500/206.8530 THIS ORDER WAS MANUFACTURED IN ACCORDANCE WITH CARPENTER SPECIALTY ALLOYS OPERATIONS QUALITY PROGRAM MANUAL, REVISION 36 DATED 12/15/2017.

CARPENTER'S QUALITY MANAGEMENT SYSTEM WAS REGISTERED AS OF FEBRUARY 27, 2018 TO THE REQUIREMENTS OF ISO 9001:2015 APPROVAL CERTIFICATE 10806 BY PERFORMANCE REVIEW INSTITUTE. THIS CERTIFICATE OF TEST IS TYPE 3.1 PREPARED IN ACCORDANCE WITH EN 10204 (DIN 50049). WE HEREBY CERTIFY THAT THE ABOVE TEST DATA ARE IN ACCORDANCE WITH THE PURCHASE ORDER AND SPECIFICATION REQUIREMENTS. AS DOCUMENTED IN THIS CERTIFICATE OF TESTS.

TEST METHODS ARE PER THE ASTM STANDARDS ON FILE AND IN EFFECT AT TIME OF ORDER ACCEPTANCE, STANDARD PRACTICES, OR AS AGREED UPON BETWEEN CARPENTER & CUSTOMER.

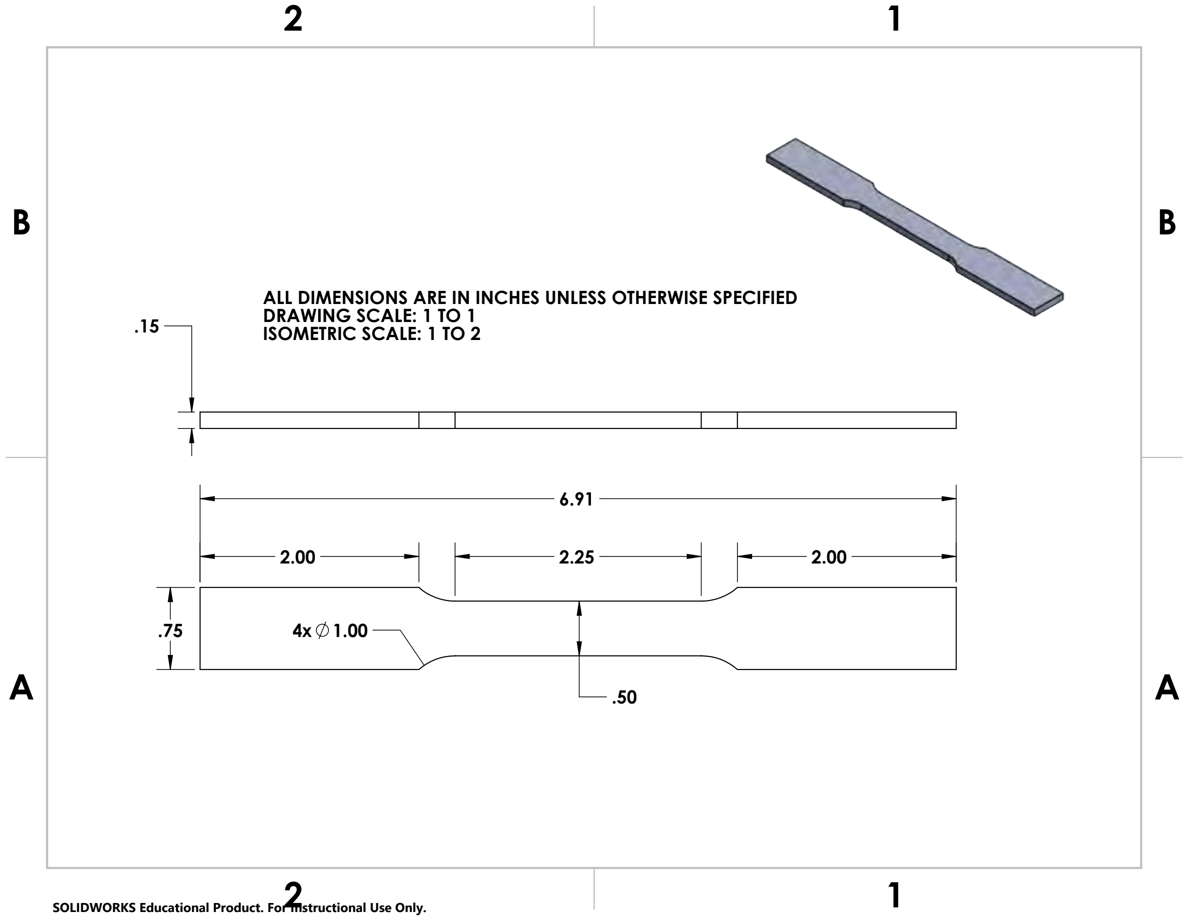
MICHELE L. HEFFNER
ADMINISTRATOR - QUALITY
CARPENTER TECHNOLOGY CORPORATION

Michele L. Heffner

From: ThyssenKrupp Materials NA
Cust. ONLINE METALS LAX Del.: 2406423941
CstAr 15233 CstOr 108552
Wgt.: 96 LB Date 12/11/2018

Tomas Sancke

8.2 Test Bar Drawing



8.3 Manufacturing Outline Technique

Manufacturing Outline Technique
Job # Axe Head MOT 3

AURORA Casting & Engineering, Inc.

Customer:	**Cal Poly Pomona**	Program:	
Part #:	**Model 3.5**	Model:	
Part Rev:	**NC**	MOT Revision:	**NC**
Authority Data Set:			
Classification:	**NA**		

5 Material Requisition — **Process per AQP 7.4**

Item	Vendor	Lead-Time
PLA axe head	**Aurora**	**1 week**

20 Set-up — **Set-up per AE-20 & AQD 039**

Wax Tree Wt. Lbs:		Parts/Tree:	**4**	T/B Type/Qty.:	**Integral/2**
Cup Size:	**C**	Cycle Time:	**30 min.**	WSAT Approval:	**3/25/19**

30 Molding — **Shell per AE-30**

Slurry	Sand	Dwell Time		Mold Weight
PrimeCoat	**Zircon**	**5 sec.**		
PrimeCoat	**Zircon**	**5 sec.**		
First Dip	**50-100**	**10 sec.**		
Back-Up	**30-50**	**20 sec.**	**Wire Mesh**	
Back-Up	**30-50**	**20 sec.**	**Wire Mesh**	
Seal	**NA**	**20 sec.**		

40 Cast — **Cast per AE 2000** — **Cast per AE 4000**

Alloy:	**440C**
Specification:	**AMS 5352D**
Metal Temp:	**2900**
Shell Temp:	**1800**
Kaowool:	**NA**
Pour Wt. Lbs.:	**0**

42 Knock-Out — Finish per AE-70

Cycle Time: **1 min.** Method: **Water blast**

45 Cut-Off — Finish per AE-70

Cycle Time: **1 min.** Method: **Chop saw**

50 Grind — Finish per AE-70

Gate Witness: **.010 max**

Specification	Tolerance	Zone/Note	Method of Measure
.400	**± .010**	**Model**	**Calipers**

52 Ceramic Clean — **Clean per AE-10**

Cycle Time: **5 min.**

55 Benching — **Bench per AE-75** — **Visual per AE-100** — Detail Finish & Benching

Surface Finish:	**√125**	Weld:	**Yes**
Radii:	**.025 max**	Spec.:	**NA**
Cycle Time:	**10 min.**		

Specification	Tolerance	Zone	Method of Measure
.400	**±**	**Model**	**Calipers**
	±		

XXX Heattreat — **Paste in**

Specification	Alloy	Cycle	Temp	Spec. Soak	Act. Soak	Comments
AMS 5352D Rev. L	**440C**	**Age**	**1875 F**	**NA**	**1.5 hrs.**	**30 min. forced Air Cool**

XXX Mechanical Test — **Hardness Test per AE-95**

Hardness Rqmt:	**60 HRC**	Qty. of Tensile Test Specimens:	**2**
Test Bar Type:	**Integral**	Tensile Requirements (Min.):	

XXX Surface Finish — **Process per AQP 7.4**

Polish: Vendor:

XXX Final Insp — **Final Inspect, Mark, and Package per AQD 002, AE-100**

XXX Ship — **Package and Ship per AE-100**

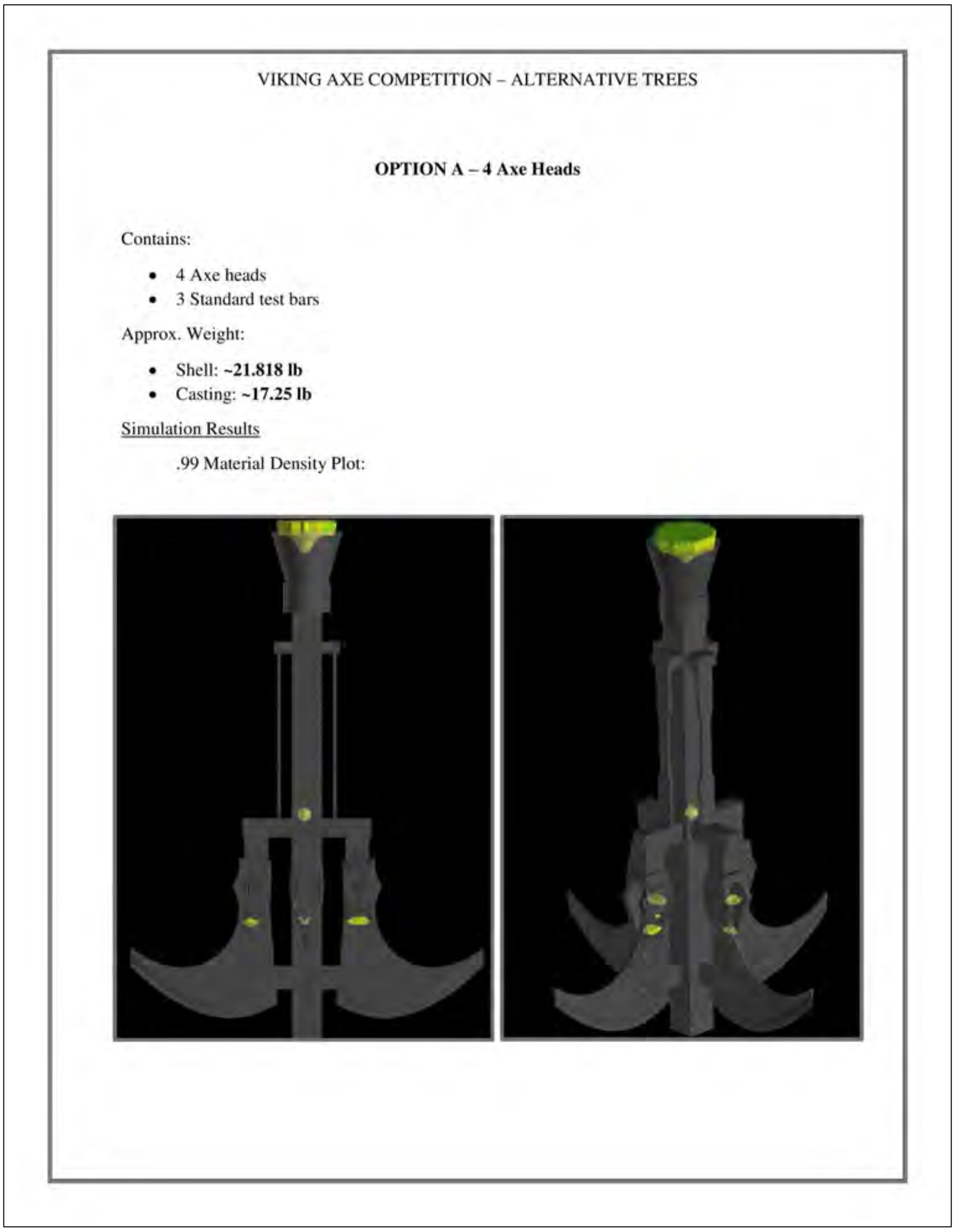
Place a sample of the part marking on the Traveler

Comments:

printed 4/8/2019

4/8/2019 Axe Head MOT 31 of 1

8.4 Alternative Tree Design



VIKING AXE COMPETITION – ALTERNATIVE TREES

OPTION A – 4 Axe Heads

Contains:

- 4 Axe heads
- 3 Standard test bars

Approx. Weight:

- Shell: **~21.818 lb**
- Casting: **~17.25 lb**

Simulation Results

.99 Material Density Plot:

Figure 43:

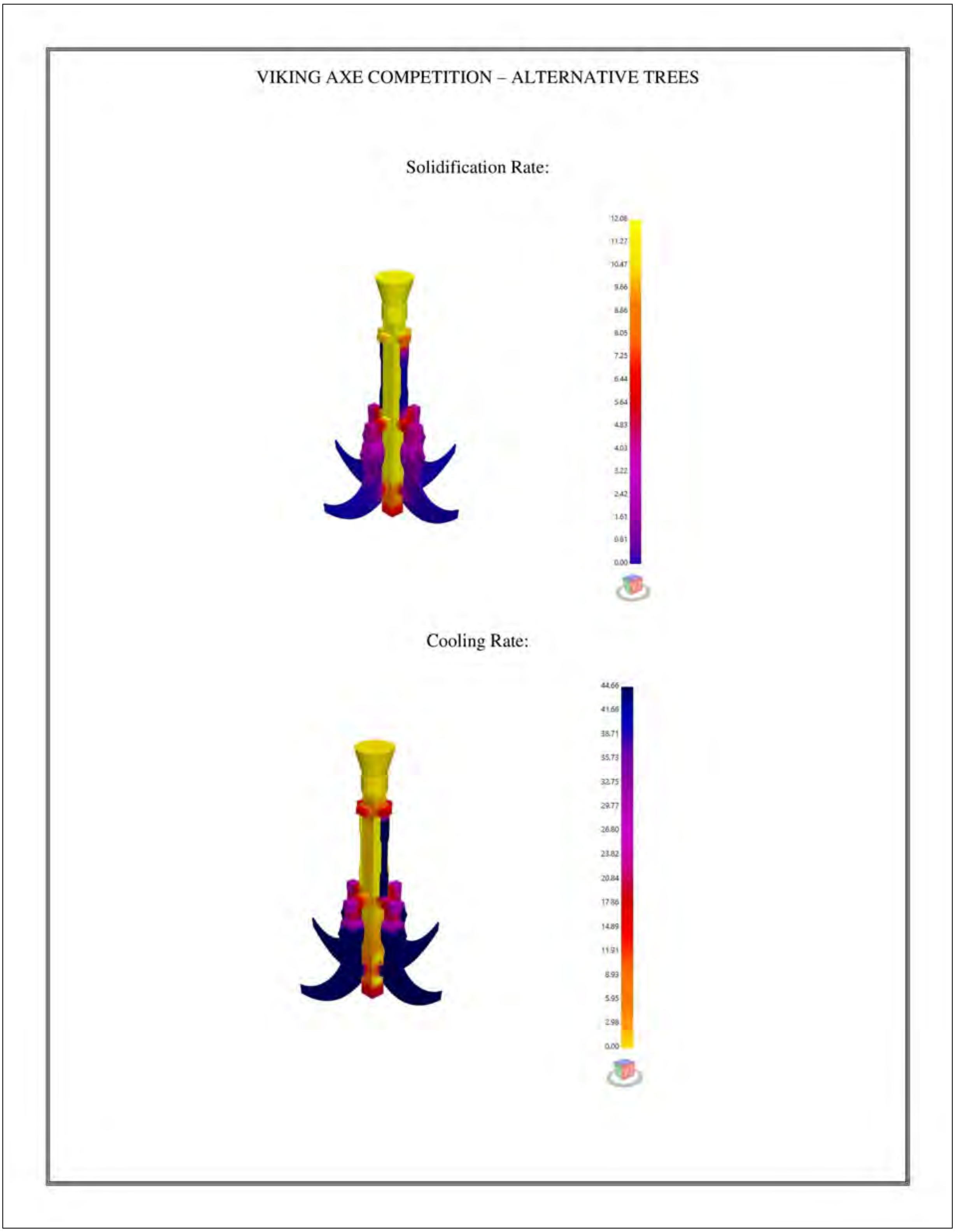

VIKING AXE COMPETITION – ALTERNATIVE TREES
Solidification Rate:
12.08
11.27
10.47
9.66
8.86
8.05
7.25
6.44
5.64
4.83
4.03
3.22
2.42
1.61
0.81
0.00
Cooling Rate:
44.66
41.68
38.71
35.73
32.75
29.77
26.80
23.82
20.84
17.86
14.89
11.91
8.93
5.95
2.98
0.00

Figure 44:

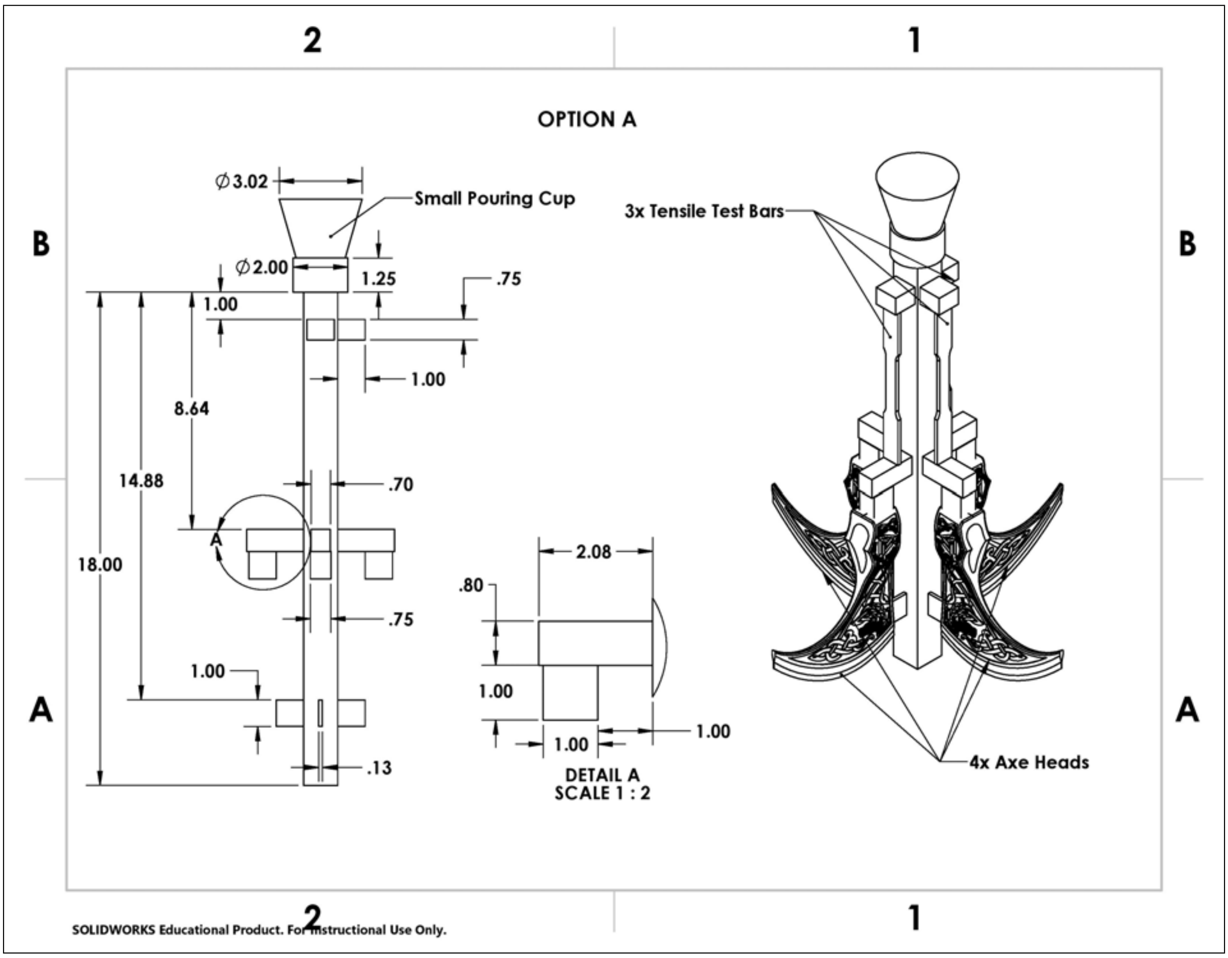

2
1
OPTION A
Ø3.02
Small Pouring Cup
Ø2.00
1.25
.75
1.00
1.00
8.64
14.88
18.00
.70
A
.75
1.00
.13
2.08
.80
1.00
1.00
1.00
DETAIL A
SCALE 1 : 2
3x Tensile Test Bars
4x Axe Heads
B
B
A
A
2
1
SOLIDWORKS Educational Product. For Instructional Use Only.

Figure 45:

VIKING AXE COMPETITION – ALTERNATIVE TREES

OPTION B – 3 Axe Heads

Contains:

- 3 Axe heads

Approx. Weight:

- Shell: **~11.721 lb**
- Casting: **~19.186 lb**

Simulation Results

.99 Material Density Plot:

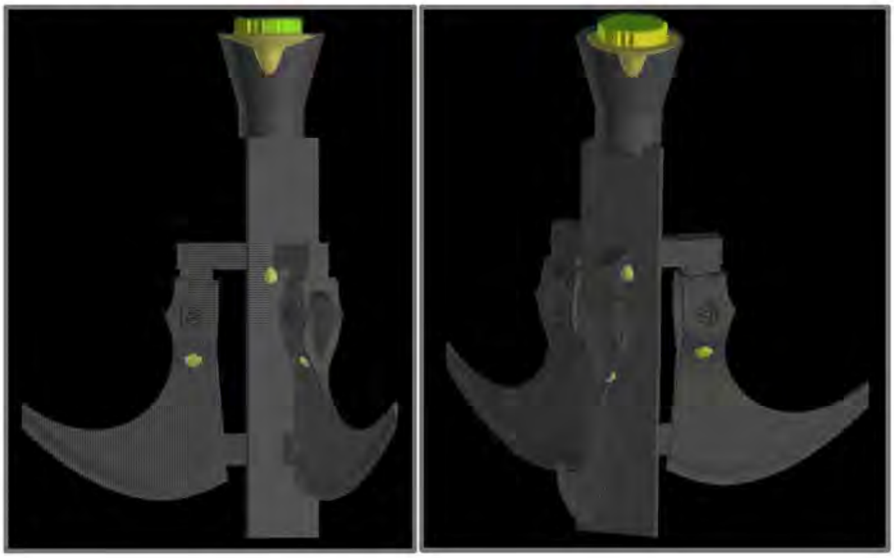


Figure 46:

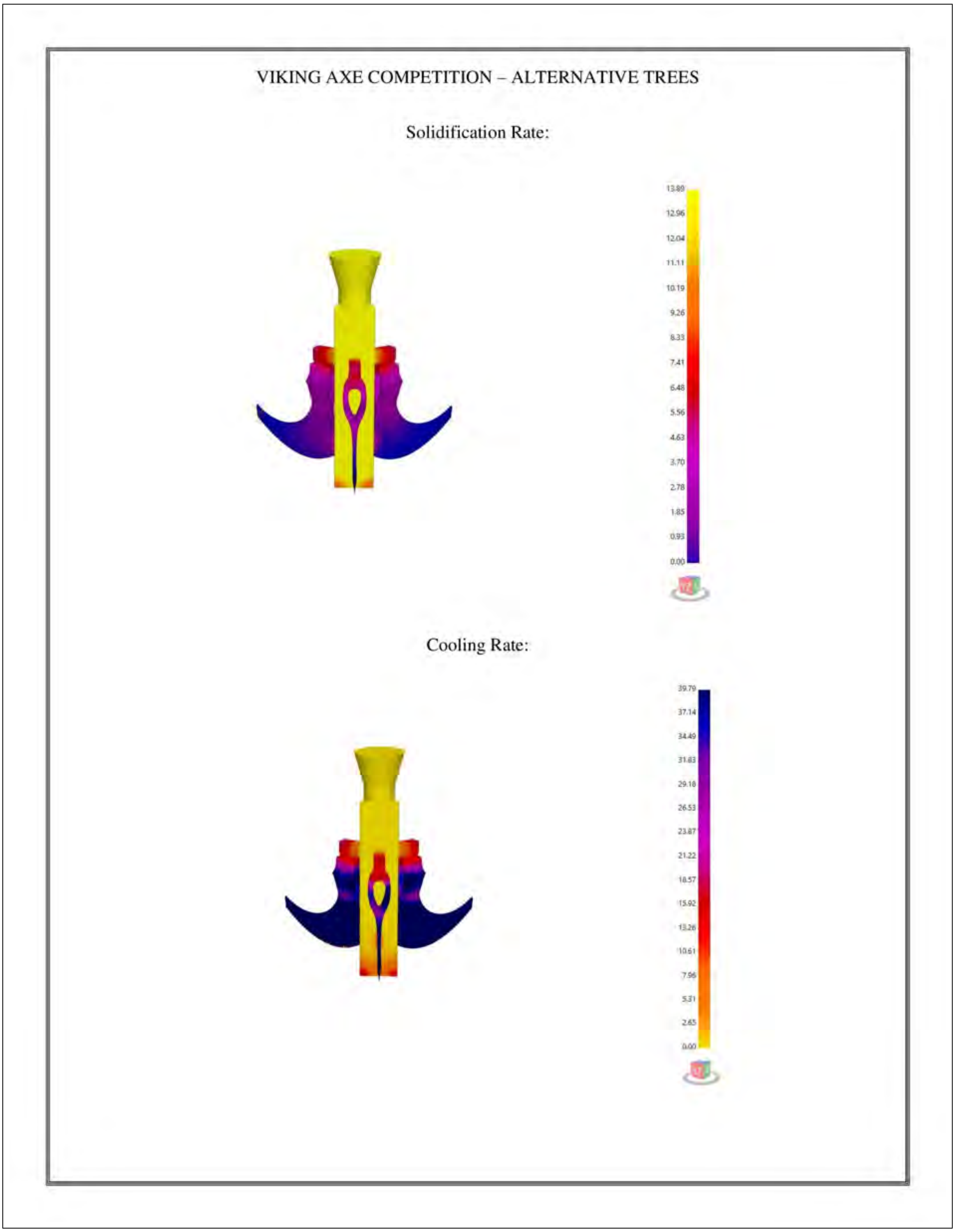

VIKING AXE COMPETITION – ALTERNATIVE TREES
Solidification Rate:
13.89
12.96
12.04
11.11
10.19
9.26
8.33
7.41
6.48
5.56
4.63
3.70
2.78
1.85
0.93
0.00
Cooling Rate:
39.79
37.14
34.49
31.83
29.18
26.53
23.87
21.22
18.57
15.92
13.26
10.61
7.96
5.31
2.65
0.00

Figure 47:

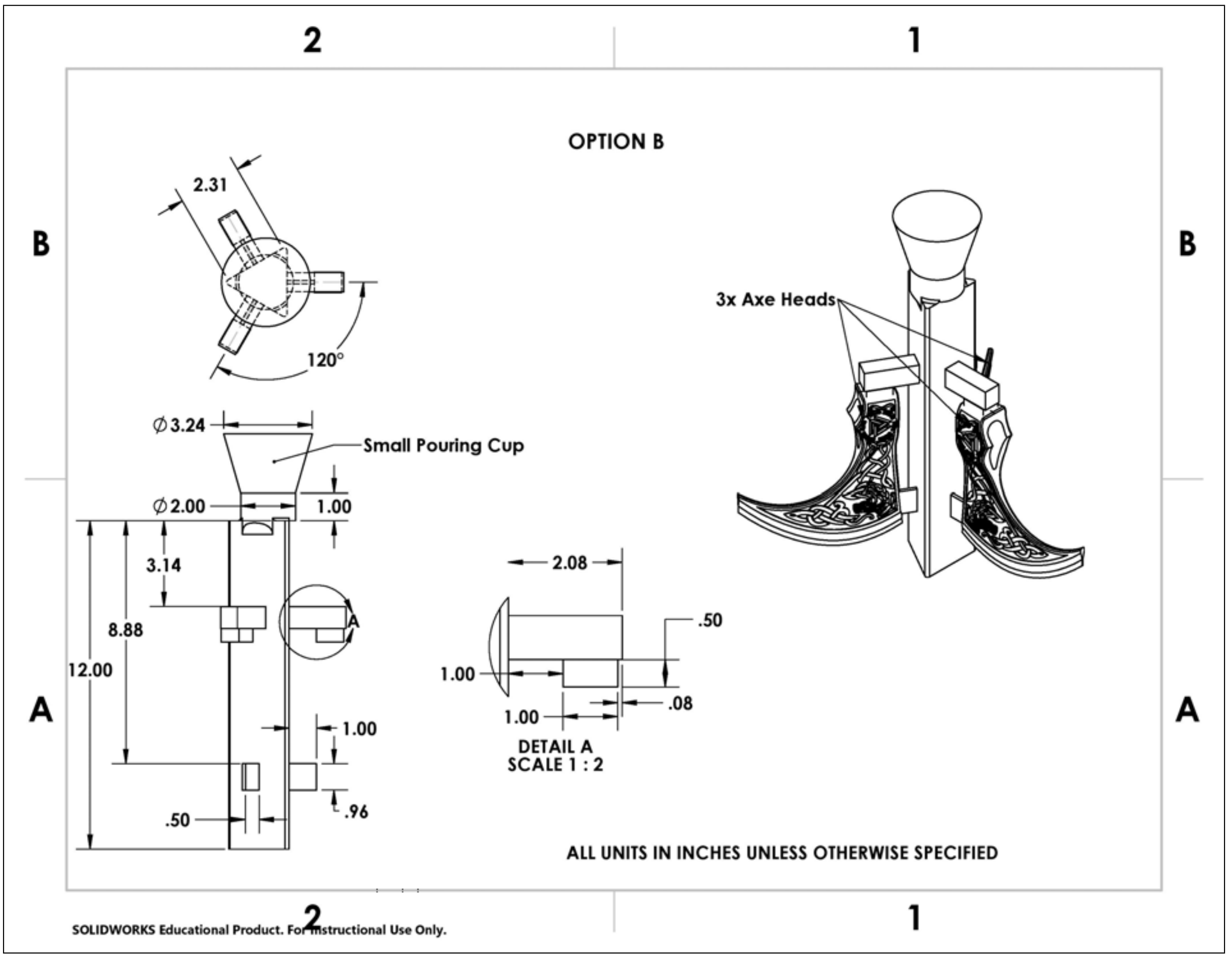

2
1
OPTION B
B
B
2.31
120°
3x Axe Heads
Ø 3.24
Small Pouring Cup
Ø 2.00
1.00
3.14
8.88
12.00
A
A
A
2.08
.50
1.00
.08
1.00
DETAIL A
SCALE 1 : 2
1.00
.96
.50
ALL UNITS IN INCHES UNLESS OTHERWISE SPECIFIED
2
1
SOLIDWORKS Educational Product. For Instructional Use Only.

Figure 48:

VIKING AXE COMPETITION – ALTERNATIVE TREES

OPTION C – 2 Axe Heads

Contains:

- 2 Axe heads
- 2 Standard Test Bars

Approx. Weight:

- Shell: **~17.483lb**
- Casting: **~13.661 lb**

Simulation Results

.99 Material Density Plot:

Figure 49:

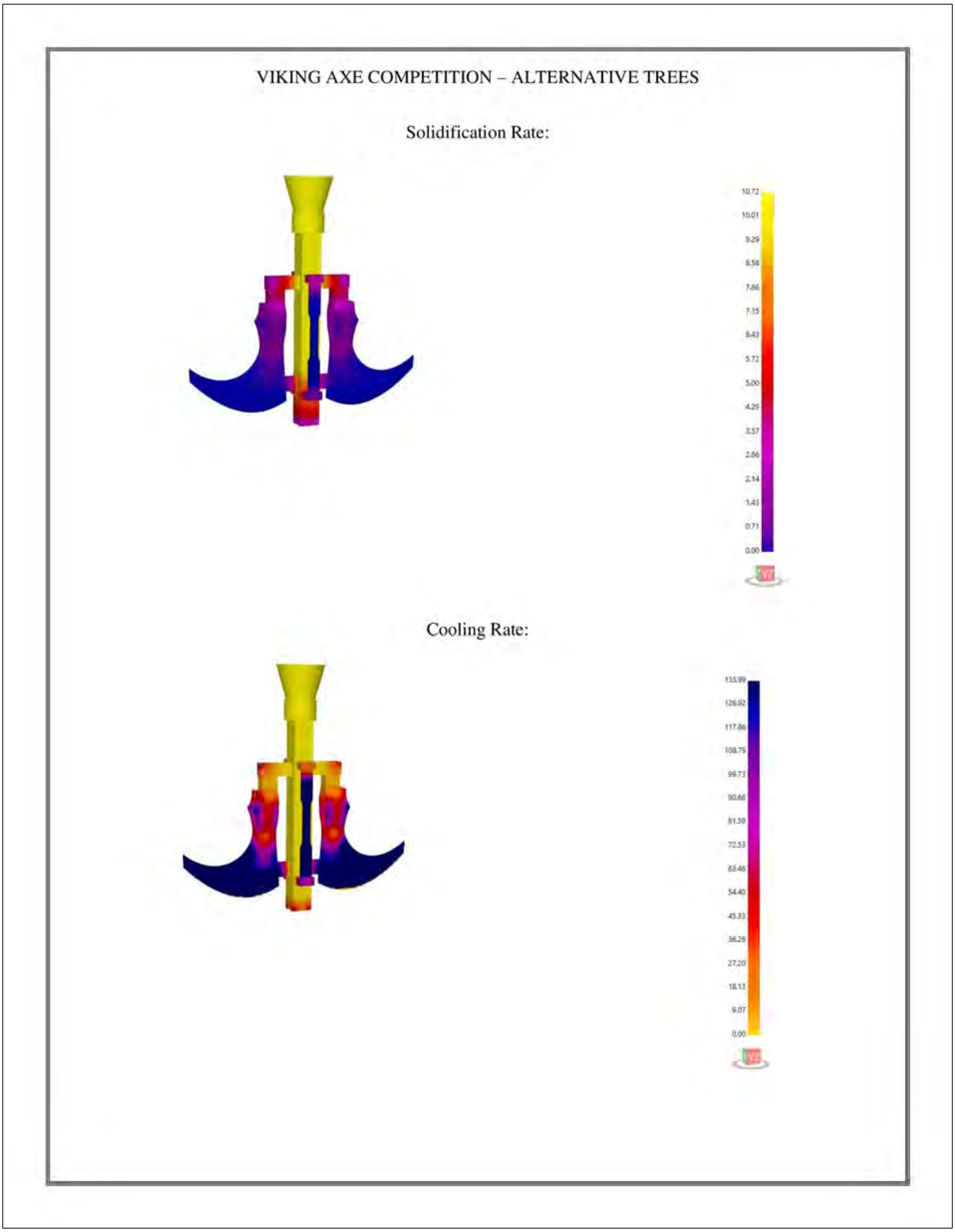

VIKING AXE COMPETITION – ALTERNATIVE TREES
Solidification Rate:
10.72
10.01
9.29
8.58
7.86
7.15
6.43
5.72
5.00
4.29
3.57
2.86
2.14
1.43
0.71
0.00
Cooling Rate:
135.99
126.92
117.86
108.79
99.73
90.66
81.59
72.53
63.46
54.40
45.33
36.26
27.20
18.13
9.07
0.00

Figure 50:

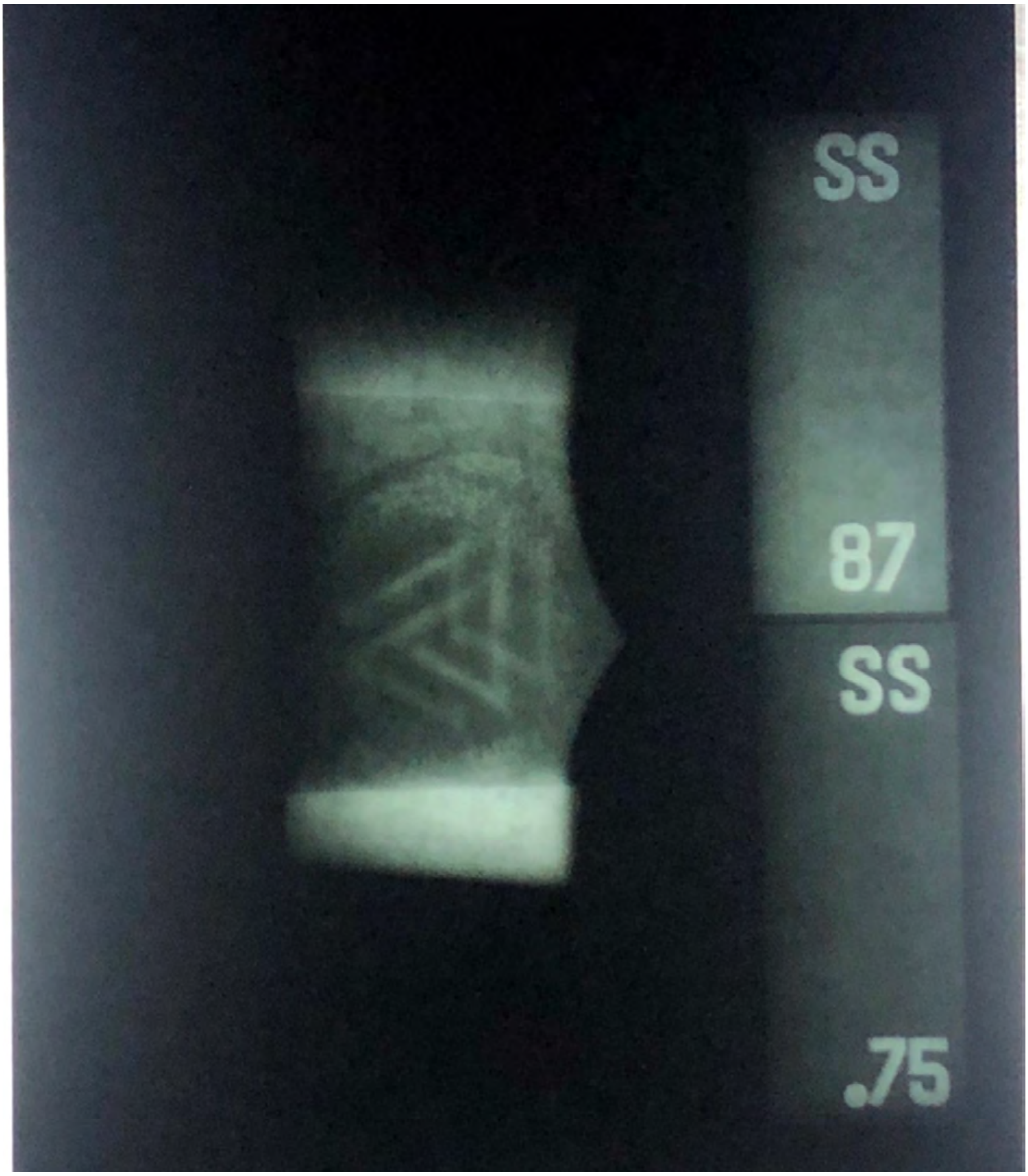


Figure 51: *There is no evidence of casting defects, however, it is hard to read due to the details of the casting*

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