

SFSA Axe Competition 2019

Technical Report

Viking Axe Investment Casting

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1. Introduction

The Viking Age, centered in the lands of Scandinavia and Northern Europe in 750 AD was a 300 year time period marked by the firm entrenchment of heathenism amongst the Viking people along with their widespread plundering attacks throughout most of Europe. While heathenism had long been accepted by the Scandinavian people for years prior to this point in history, it was not until approximately 750 AD that the Vikings achieved adequate technological advancements in both sailing and increased iron production that could support their plundering quests.

Central to their upsurge in iron production was the need for high quality weapons that could be used on the battle field. In general, there were four main weapons that were employed by the Vikings including the sword, spear, axe and shield. Swords and spears were widely indicative of higher societal status among the Viking people. Their narrow shapes lent them to readily to a process known as pattern forging which involved building a stack of flat iron rods of alternating alloys. These layered rods were then brought to a white heat in the forge and hammered on an anvil until one layer was formed which was then twisted at red heat. The most common decorative pattern, known as the fishbone pattern was generated when two of these rods, twisted differently, were placed next to each other. The thin geometric dimensions of the swords and spears brought several challenges to the forging process. To ensure blades would be durable, the iron used in the forge had to be of uniform quality, containing low amounts of sulphur which would lead to brittleness of the blade. Additionally, the iron needed to be repeatedly formed by a process that included folding, forging, and hammering, which led to the removal of slag impurities in the blade. Later on in the Viking Age, a technique known as drop forging was developed for the manufacturing of swords and spears, using a series of shaped dies and sending a glowing metal through them in order to form a desired cross section.

While swords and spears required a vigorous and detailed forging process, axes, with thicker and more massive dimensions, allowed for a lower quality of iron to be used in the middle of the weapon, while maintaining a higher quality iron toward the edge of the blade. The ability for a lower quality iron to be used for the bulk of an axe head, granted simpler forges the ability to produce these weapons. Generally, an axe head was produced using one of two methods. Heftier, wedge shaped axe heads were typically made from a single piece of iron, using a drift to punch

out a hole for the shaft. Thinner blades were often folded around what would become the hole for the shaft, and joined together with a steel bit for the edge.

Due to the ease at which they could be manufactured, axes were the most common weapon carried by Vikings. It was typically the first weapon that a free man obtained and was considered to be a weapon of the working class. While most of the early axes forged by the Vikings were seen as a working tool that could be used for cultivation, they began to evolve into specialized, lighter weight battle axes that could be used to cut and break shields in an attack. As time evolved, the different adaptations and improvements made to Viking axes led to a multitude of designs emerging that could be employed for different purposes. For the most part, three main, overarching categories based on size, shape, and function can be used to encompass the many axe designs that came out of the Viking Age. Below is a schematic, taken from Hjarðar and Víke's *Viking's at War*, displaying some of the distinct axe heads within the three different Viking categories, narrow, broad, and bearded as well as some of the various axe heads that were likely imported from lands in Eastern Europe:

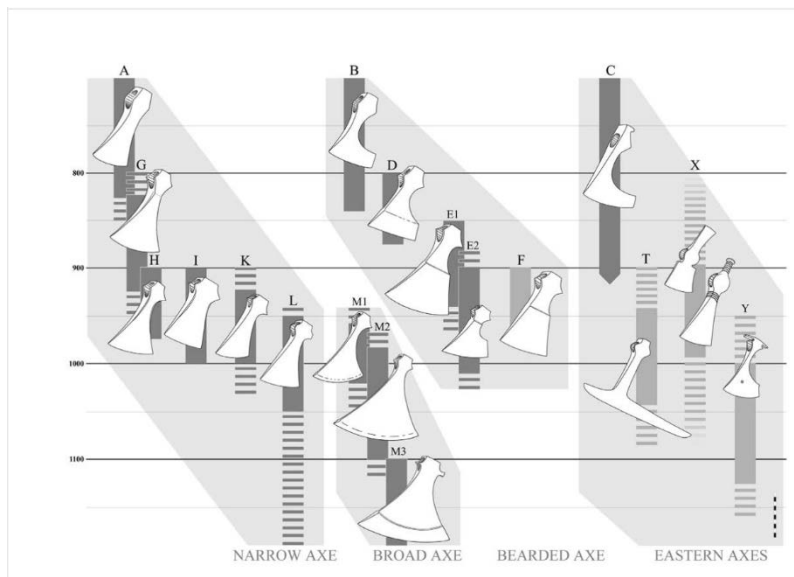


Figure 1: Evolution of Axe Head Designs

Narrow axes, typically the simplest of all three categories, were general working tools with a 5-10 cm long blade that were used in applications ranging from the felling of trees to simple cutting operations. Bearded axes with blades that were a slightly longer length, were initially used in more specific situations such as the smooth cutting of boards and planks. Later

on in the Viking age, certain bearded axes were developed into specialized battle axes that could be used in combat. Broad axes, emerging toward the latter half of the Viking Age, utilized a cutting edge that could be just as long as the axe head itself. Used primarily in combat, broad axes were thinly forged in all areas but the edge, to make the weapon lightweight and easy to swing.

Decorations were often used by the Vikings to increase the visual attraction of their weapons. Elegant shapes, noble metal ornamentations, and precious metals could be used for decoration to further the prestige and societal status of a Viking. A well-made, decorative weapon could even serve as a valuable gift in building political and familial relationships.

2. Materials and Methods

2.1. Axe Design

Our axe design, intended for use in combat, is modeled predominantly from the geometry and function of the broad axes. Featuring a large blade that optimizes damage upon contact, the axe head is intended to be well balanced so that it can be easily swung. Additionally, the handle requires two hands to be used, to maximize leverage in the swinging process and increase the force applied by one swing.

The elaborate decorations that were incorporated into the face of the axe head were based largely off those which would be indicative of a high rank in society. A modern flare was added to this design to pay homage to the university from which it is coming from (see Figure 2).



Figure 2: Axe design on the side

2.2. Investment Casting

The team chose investment casting as the method of production due to the complex shape capabilities of investment casting. As it was desirable to make an axe with very intricate designs, investment casting was a natural choice. By using investment, the team was able to design multiple variations in Solidworks and select a design based on the best combination of geometric complexity and part functionality. Working in Solidworks was also beneficial because the group was able to send the file back and forth, making modifications and commenting on each other's work. After the axe design met specific standards, a preliminary gating methodology was designed, and both were sent the file to Eagle Precision for their feedback. Working collaboratively a final design was developed, which would be sent by Eagle Precision to Spectra 3D to have the wax pattern made. The wax patterns, produced at Spectra 3D using 3D printing technology, matched our desired geometry closely and were sent to Eagle Precision (see Figure 3).

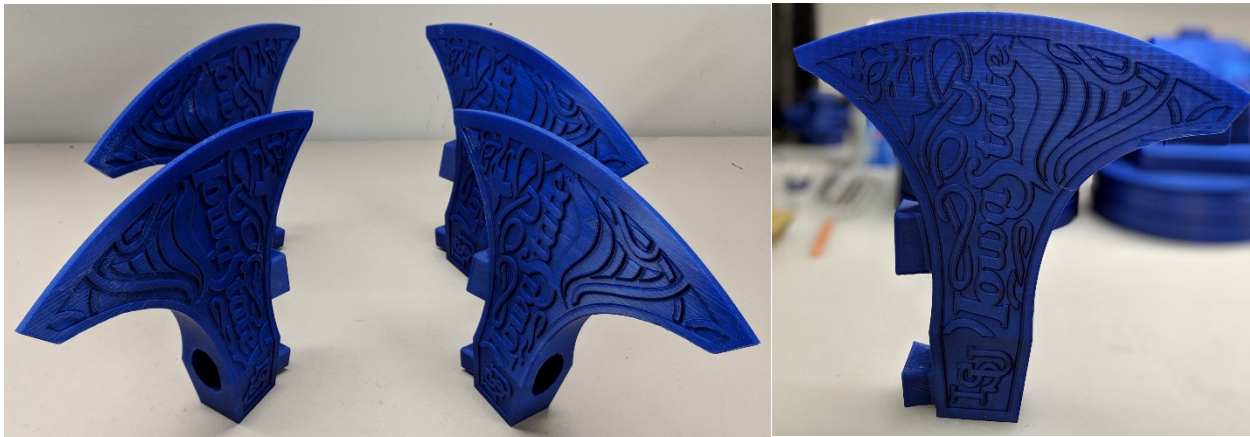


Figure 3: Printed wax pattern

At Eagle Precision the wax patterns were “invested” in a ceramic slurry multiple times, creating a shell around the wax pattern. Next, the ceramic mold was heated up, allowing for the wax to melt out. While the ceramic mold remained hot, the molten metal was poured into the cavity. The ceramic mold was then broken off revealing the battle axe! The alloy used was AISI 8620 as it is used by Eagle Precision to make axe heads for their customers. It also has very desirable qualities to make a great battle axe.

2.3. Gate Design

Due to the properties of our selected casting method, the gating design was fairly simple. The initial gating design consisted of attaching a single gate to the back of the axe, but this caused a big amount of porosity, especially around the hole for the handle. In our final design the gating connects in two spots on the side of the axe, once above and once below the hole for the handle, this way most of the porosity could be eliminated. Figure 4 below shows the MAGMASOFT simulations of the two gating designs.

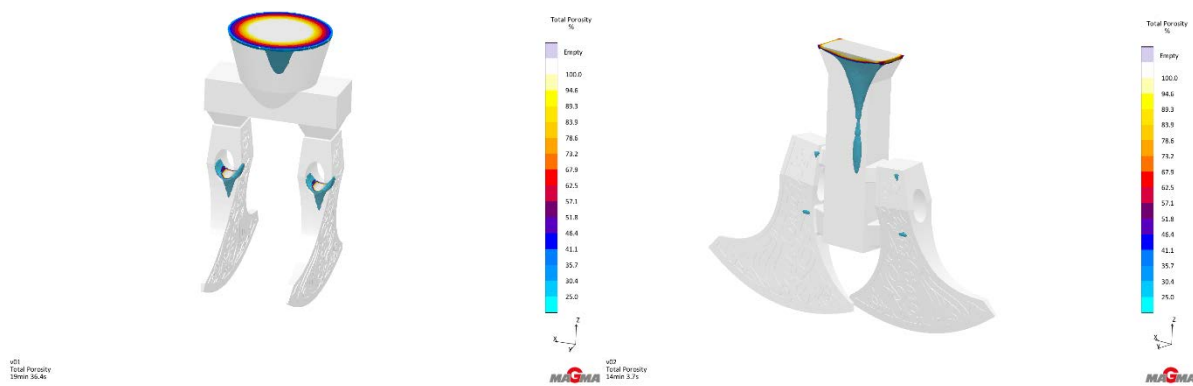


Figure 4: Porosity analysis for two different gating designs (left first and right final)

2.4. Post processing

After the casting process, some post processing was done. Due to issues occurring during the removal of the wax used by the 3D printing process, one side of the axe had some excess material; this was removed by grinding the surface while taking care to avoid removing the decorative detailing. The gating contacts were also removed via a grinding operation. The axe was then sandblasted to remove the discoloring from the hardening process (see Figure 5). Finally, the edge was ground to its rough shape and finished with a whetstone (see Figure 6). After completing post processing, the axe shaft was fit to the axe, and the two were secured together with a wedge and some glue, creating the final product (see Figure 7).



Figure 5: Before (left) and after (right) sandblasting and grinding



Figure 6: Grinding of the edge



Figure 7: Final product

2.5. Testing

2.5.1. Surface Roughness

The surface roughness of a casting has a big impact on the aesthetics of a casting, thus the surface roughness of the axe was measured in multiple positions with two different methods (SCRATA A1-A4 plates and a digital method developed at ISU). The surface roughness of the casting is very small. Using the SCRATA plates the surface finish was determined to be A1. The objective digital method supported this classification. The roughness value was determined to be 0.035 mm, in comparison the surface roughness of an A1 SCRATA plate is 0.058 mm. Another surface property are the lines visible in Figure 8, they are caused by the 3D printing process of the wax pattern. If one were to reduce the layer thickness during the printing process one could make these less visible. Overall these lines are no problem, but they are somewhat untypical for a regular casting.



Figure 8: Vertical lines are caused by the 3D printing of the wax pattern

2.5.2. Dimensional Variability

The dimensional variability was measured performing multiple scans of the axe with a laser scanner. These scans were then cleaned up and stitched together to create one scan containing all the axe's outer surfaces. After aligning the scan with the CAD file, the scan was

compared against the CAD file. A heat map shows the amount and location of variation between the CAD file and the scan. For this CAD file with desired dimensions, the 3D printed wax part was made 2% bigger in all dimensions to account for the shrinkage. Figure 9 shows that the casting is for the most part a little bigger than expected.

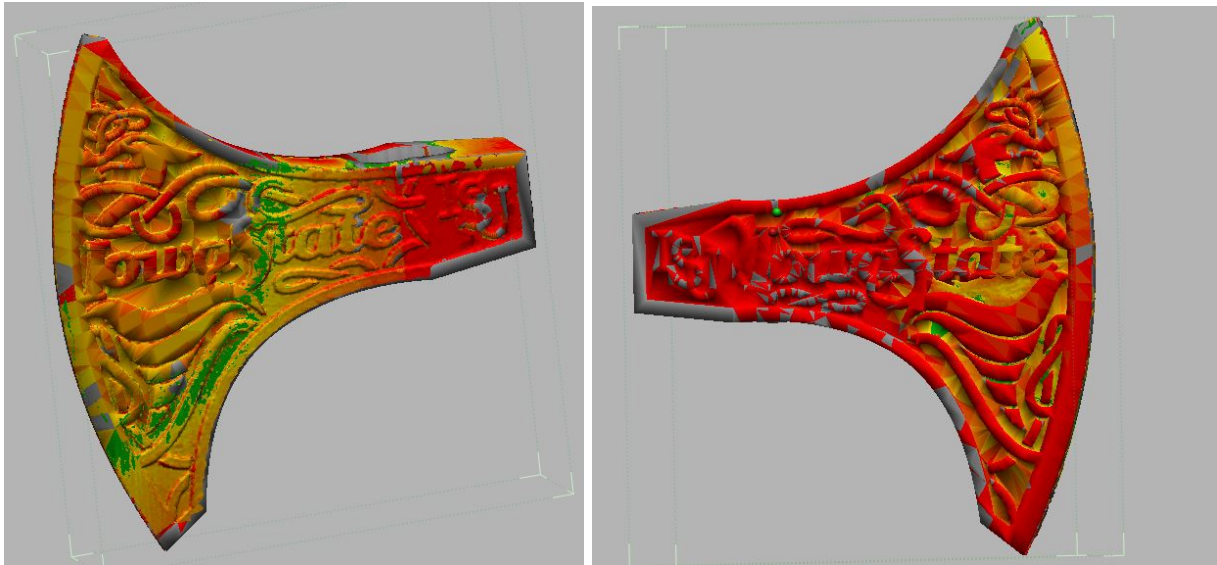


Figure 9: Dimensional Variability- Comparison of the ideal (theoretical) dimensions vs. The actual dimensions

2.5.3. Magnetic Particle Inspection

A magnetic particle inspection was performed on the axle to find possible surface or subsurface cracks. The magnetic particle inspection was run in two different orientations. Collections of particles can be seen, but they seem to be mostly caused by the geometry of the axle (lettering, etc.). There are some indications that are caused by scratches, but no cracks could be found.



Figure 10: MPI two different orientations

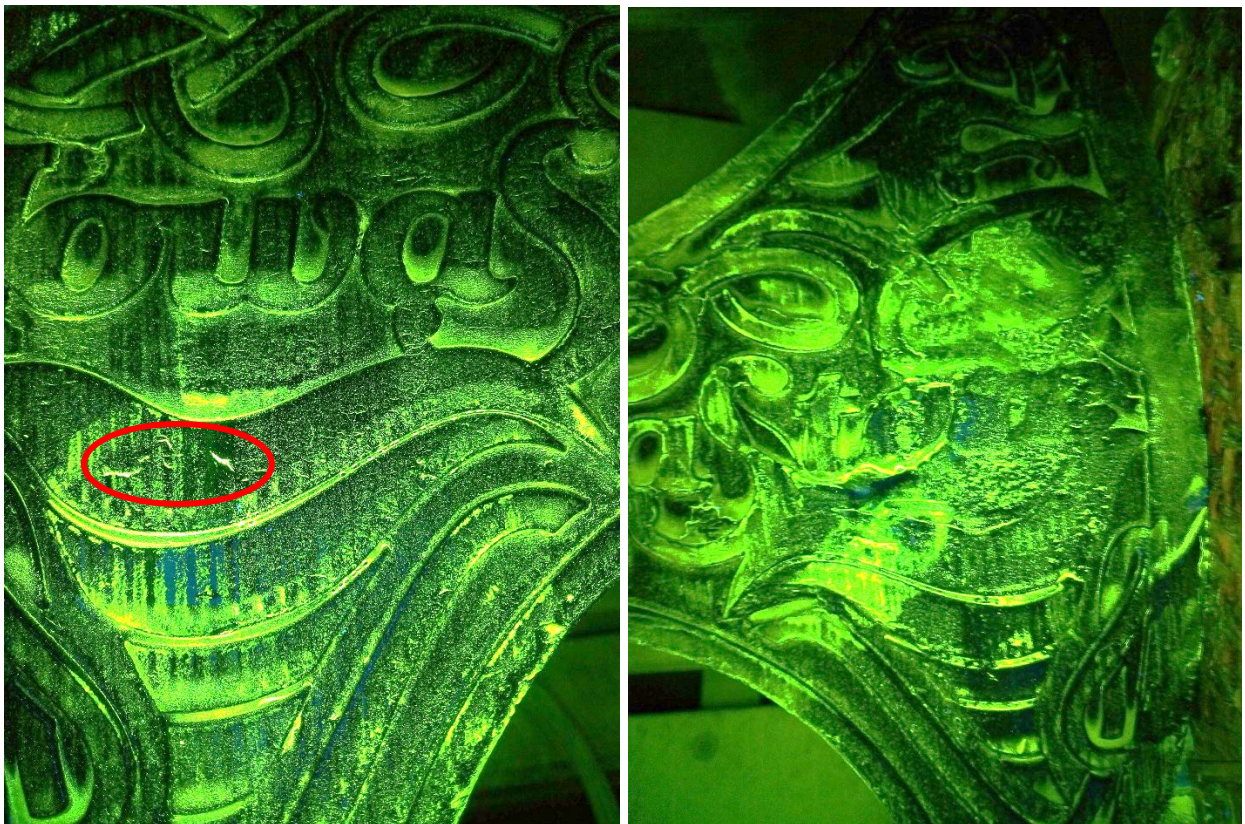


Figure 11: Particle collection caused by geometry and indication caused by scratch (red oval)

2.5.4. Other Comments

During the investment casting process, some problems occurred. On one side of the axe the surface does not match the printed one. The cause of this could not be determined with certainty by Eagle Precision, as they don't have much depth in experience in using these wax materials. One idea is that the wax stuck tightly to the ceramic coating and caused it to buckle during the dewaxing process in the autoclave with a steam pressure of about 100 psi. If this was the case, then the detail of our axe design might have caused this increased bonding force; however, as this buckling consistently happened only on one side while the other side behaved as expected and turned out fine, this is probably not the cause of the issue. A second cause for this might be that during the dipping process some of the layers did not dry completely before the next coating was applied. This could cause only one side to have some issues but is also improbable.



Figure 12: Issue with one side of the axe, before and after grinding

3. Conclusions

To have closer dimensional conformity, we would decrease the pattern allowance, as most of the dimensions of the axe were consistently larger than the intended geometry (see Figure 9).

This project showed us the steps (and frustrations) of a casting design process. It also showed us the incredible creative freedom casting, especially investment casting, enables, but also that some unexpected issues can occur when one is using an unfamiliar process. Overall, we are very happy with our results. The only thing that is not perfect part of one side of the axe.

4. References

- Hjardar, Kim, and Vegard Vike. *Vikings at War*. Vol. First English edition, Casemate, 2016.
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