**Department of Mechanical Engineering**
**Georgia Southern University**
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# Technical Report

## VIKING AXE STEEL CASTING FOR SFSA CASTING COMPETITION

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**ABSTRACT**

The design of the steel cast Viking axe was chosen from historical aspects surrounding the danish and norse bearded axe design. The 3D modeling of the axe was done in SolidWorks 2018 and designed to cast with horizontal parting line with the eye being formed by the use of a core. The split patterns and core boxes were 3D printed. Risering was designed using MAGMASOFT to minimize shrinkage porosities. To verify the pattern and riser designed, the axes were test cast in house with aluminum alloy 356 and green sand molds. The axes were then cast at Georgia Iron Works and Missouri University of Science and Technology with 4340 steels. 4340 steel was chosen for the good combination of hardness and toughness after proper heat treating. After the axes were cast, risers and gating systems were cut off. Castings were cleaned and a bevel was ground with an angle grinder. Heating treating was performed at Duramatic Products. Austempering was used to heat treat the castings. Castings were austenitized at 850C for 30 minutes, then were quenched and isothermally held at 350C for 1 hour. A consistent fine lower bainitic microstructure was achieved in the castings. Hardness of the axes were 40~42 HRC. The handle is made from hickory, detailed with Lichtenberg wood burning, and finished with boiled linseed oil. Finally, the axe was hung by driving a walnut wedge into the eye of the axe head. Final assembly of the completed steel casted viking axe can be seen in Figure 19.

**INTRODUCTION**

In this project, a fully functional Viking axe is to be cast which meets the design criteria set forth by the Steel Foundry Society of America's Cast in Steel competition. The purpose of this project is to explore the capabilities of metal casting by applying this process to a product which was traditionally produced through the forging process. As such, according to the Cast in Steel recommendations, this project should creatively use the metal casting process to produce a tool which expands the boundaries of what would have been impossible using traditional forging methods. [1] Advanced manufacturing processes are to be used in this project to cast an axe which meets the competition criteria and is capable of passing a rigorous practical test performed by the competition judges.

The competition guidelines indicate that the axe should consist of the following features. First, the axe head must feature a cutting edge which measures from 6-12 inches as a point-to-point distance. [1] Second, the axe head must be mounted to a handle measuring from 18-30 inches in length. Third, 80% of the final shape of the axe head must be attributed to the casting process. And lastly fourth, the final product must be historically qualified as a Viking axe. These are the guidelines which must be met by the final product.

An axe is a common implement which has been used throughout history as an implement of work and of war. A diagram is shown below in figure 1 which outlines the various parts of a modern axe which will be referred to throughout the paper. Although a traditional

Viking axe is to be produced, modern terminology will largely be used when referring to the various parts of the axe in order to avoid confusion.

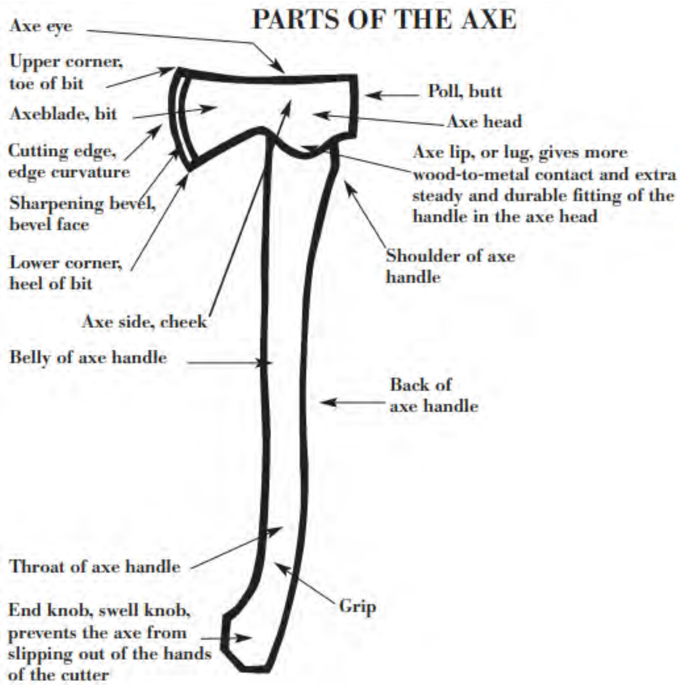



Figure 1: Diagram of Axe Components [2]

## -HISTORICAL BACKGROUND

Although the production of the Viking Axe to be produced would itself be carried out via modern processes, the form of the axe was highly influenced by historical sources. The overall form of the axe was designed as a combination of period axes which would have been in use in Scandinavian cultures through the middle ages. Additionally, the decorative features of the axe were inspired by norse mythology, using features which were discovered on archaeological finds dating back to the early middle ages.

In Scandinavian culture, three standard axe head styles were prevalent into which axes heads could be categorized. The first of these standards being known as a Bearded Axe, and the second being known as a Danish axe. A third axe head style is defined by an archaeological find which is known as the Mammen Axe. While there are many more categories of axe head shapes which existed through the middle ages, these three which are presented encompass the designs which are attributed to Scandinavian culture and thus make an axe distinctly "Viking" in function and appearance.

The Danish axe, an example of which is shown below in Figure 2, is a distinct shape typical of heavy bladed axes. This shape features an upward and a lower swept point, with the upward swept point being the larger of the two. The cutting blade of the axe sweeps in a crescent shape between the two points. Axe heads featuring this design were typically mounted on a longer pole shaft due to their large mass and used for powerful chopping strokes.

Figure 2: Modern Replica of a Period Danish Axe [3]

The historical basis for this weapon design is derived from archaeological findings demonstrating the existence of axe heads of such shape, and from tapestries depicting the haft length of the Danish Axe existing from the late Viking era. The Bayeux Tapestry dates back to the late $10^{th}$ century AD and depicts the battle of Hastings. [4] An archaeological finding of the Danish Axe is shown below in Figure 3, while depictions of the Danish Axe found in the Bayeux Tapestry are shown below in Figure 4.

Figure 3: Danish Axe Example from Archaeological Finding [5]


Figure 4: Danish Axe as Depicted in the Bayeux Tapestry [4]

The Danish Axe offers several notable advantages, while also possessing some distinct disadvantages. The prominent upward swept horn of the axe provides two distinct advantages. First, it shifts the center of mass to a point above the area in which the head is mounted to the shaft of the axe. This allows for greater power to be applied per stroke due to increased moment of inertia. Second, the upward horn serves as a means of delivering a stab wound through a thrust of the weapon. [6] This is a capability other axe designs do not possess. Moreover, as the point widens significantly, a stab wound delivered by a Danish axe would inflict a wound far more traumatic than that of a spear or sword, albeit with less penetration. The Danish axe, because of its great mass and moment of inertia, was primarily used as an implement of war rather than as a hand tool, and it was likely such a tool would primarily be own or supplied by wealthy nobility or upper class members of society. [6] Additionally, historically it is shown that the axe would have been mounted to a haft over 1 meter in length, which would be necessary to manage its otherwise unwieldy weight. [4]

Secondly, another style exists alongside of the Danish Axe in Viking history and can be viewed as the counterpart of the Broad bladed heavy Danish Axe. This style is characterized by an archaeological find which was discovered at the burial site in Mammen of a wealthy Viking [5]. A picture of the Mammen Axe is shown below in Figure 5, and shows an elaborately decorated axe of considerably smaller proportions when compared to a typical Danish Axe. This axe resembles the proportions of another axe type shown in the Bayeux Tapestry, which is being used by wood cutters for various tasks. This axe shape was commonly used for axes intended as a tool rather than a weapon, but historical sources indicate that such tools were often used in times of war by those who could not afford a sword or other implement of war. [6] This axe is lightweight and small and thus is ideal for hand-to-hand combat which requires agility rather than power. Additionally, in keeping with its role as a smaller hand tool, it was typically mounted to a short haft which would allow it to be easily concealed and used with one hand. [6] This weapon could be used in conjunction with a shield. [6]

Figure 5: Mammen Axe [5]

The third style of axe characteristic of the Viking era of Scandinavian history is known as the bearded axe, an example of which is shown below in Figure 6. This axe design is arguably the most widely recognized style as being distinctly "Viking." It is featured in countless books, films, and works of art depicting Viking culture a modern fantasy perspective. Historically however, less evidence exists which links this axe to Viking history. Some sources do show the historical existence of this style, but it appears more as an adaptation of the more prevalent Mammen Axe. An actual historical finding supporting the existence of the bearded axe is shown below in Figure 6.

Figure 6: Archaeological Finding of the Bearded Axe [7]

This axe style is of similar proportions to the Mammen Axe, the only difference being that this tool does not feature an upward swept point such as that of the Danish axe, but instead the lower portion of the axe sweeps down in a formation termed a "beard" from which the axe derives its name. This design offers distinct advantages of its own. First, it possesses all the advantages which the Mammen Axe boasts. It is small, lightweight, and easily concealed. However, adding the lower beard shifts the center of mass below the point where the head mounts to the haft. This shift, while it decreases the moment of inertia of the weapon, is advantageous because of the cut out behind the beard. This allows the operator's hand to be shifted up to be direction behind the center of mass, but the moment force in the direction of the shaft which is created by the weight of the axe head is eliminated. This would allow for greater control of the tool when used for delicate cuts. From a weapons perspective, this beard can also be used advantageously as a means of hooking objects, whether it be the opponents shield, limb, or another object. This ability is reportedly featured in old Norse sagas, which validate the existence of the bearded axe. [6]

## -DESIGN VALIDATION

The design of the viking axe was heavily influenced by historical data which details the traditional shape and function of viking axes. That being said, the design which was developed also drew heavily from modern advancements and research in axe technology. Details such as bit geometry and edge profiles were incorporated to ensure this axe would function as a versatile tool and weapon. Additionally, the unique production capabilities of metal casting were used to incorporate features which were unavailable to traditional bladesmithing methods. The final axe head design along with its haft are detailed in several views shown below in Figures 7 and 8.

Figure 7: Center of Mass

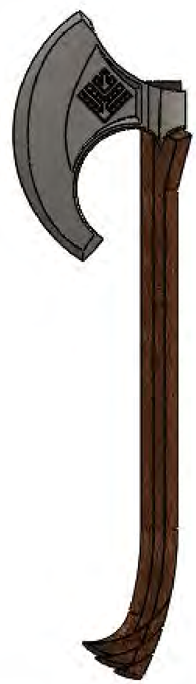
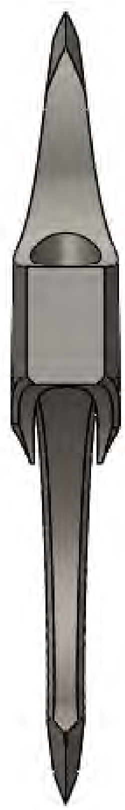
| Complete Axe Model | Axe Haft Model | Isometric Axe Head Model |
|---|---|---|
|  |  |  |
| **Axe Head Left View** | **Axe Head Front View** | **Axe Head Right View** |
|  |  |  |

Figure 8: SolidWorks Profiles of Axe Model

In choosing the form of the axe developed in this project, characteristics of both the Danish Axe and the Bearded Axe were combined. As shown in the front view of the axe head presented in Figure 8, The Danish Axe style was chosen as the primary shape of the axe, however the usually smaller downward sweep of a typical Danish Axe was enlarged and reshaped into a prominent beard. Thus, this hybrid Bearded-Danish Axe possesses the chopping power and thrusting abilities of the Danish Axe while also featuring the unique feature of the bearded axe. This gives the use the additional ability to use the axe as a hook and the ability to grip the axe behind the center of mass.

The beard and the point combined together do mitigate some of the advantages offered by the shift in the center of mass of the head, however, there are a few reasons why this mitigation is acceptable, even desirable. First, the head of this axe is to be mounted on a handle between 18 and 30 inches in length according to design restraints. [castinsteel] Thus, the added weight and increased moment of inertia may make the final product to be unwieldy if the axe is solely of the Danish style. The beard lowers the center of mass without proportionally increasing the weight of the tool and thus reduces the moment of inertia while negligibly increasing the mass. Second, the center of mass as calculated in the final design is slightly under the location in which the head would mount to the handle. This is reasonably low enough to ensure sufficient control over the axe to be used for finer detail carving. Given both of these considerations, this design is an acceptable way to hybridize the Danish and Bearded axe styles.

The blade profile of the axe was chosen based on functional considerations which focus strictly on the performance of the axe. Appropriate cutting ability is the primary focus of any axe design, and optimum effectiveness in this area primarily relies on proper edge geometry and bit design. Both of these considerations are crucial to optimizing the cutting abilities of an axe.

In designing the bit profile, a high centerline convex bit was selected. Two primary bit designs exist today, a flat bit and what is known as a high-centerline bit. An example of each design respectively is shown below in Table 1. In the flat bit design, the bit of the axe is forged perfectly straight, while the high-centerline bit has a convex rounded shape. [8] Flat bit axes are a predominantly european design, and offer the advantage of a thinner cross section which allows for the axe to make precise, clean cuts through a given medium. The high-centerline design however, while it does have a thicker cross section and thus will not necessarily cut quite as cleanly as the flat bit, clearly has the upper hand when chopping is to be a factor. The high centerline acts as an effective wedge for splitting through wood or other material while also maintaining minimum surface contact between the axe and that material. This allows for deeper penetration and easier removal. This axe style rose in popularity through the early american period, and is considered the industry standard today aside from a few notable exceptions, including high quality european manufacturers such as Gransfors Bruks and Rinaldi. [8] The high-centerline bit was chosen for this axe because it must service as a multi-purpose instrument. The high centerline bit is shown in the Top View of the axe head model shown in table 1. Due to the high-centerline bit, the axe will excel in chopping a variety of mediums from logs to steel. It will effectively split material while offering the advantage of easier removal for a follow-up stroke.

Table 1: Axe Bit Design Styles

| | | |
|---|---|---|
| Flat Bit Axe |  |  |
| High Centerline Bit Axe |  |  |

The edge profile was next selected using information provided in the Gransfors Bruks "Axe Book", which details various blade profiles and the material medium to which each is suited. A diagram taken from the Axe Book is shown below in Figure 9. For this project, the hardwood edge geometry was selected as this provides maximum blade strength while maintaining a moderate degree of sharpness. As the axe is to be designed to withstand blows against both wood and mild steel, blade strength is of equal importance to blade sharpness. As shown in Figure 9, noticeable bevel was ground into the blade to increase the strength of the cutting edge, reducing the possibility of edge rolling or deformation. This edge profile is seen implemented in the top view of the axe head model displayed in table 1. Additionally, a clip point was included along the top point of the axe to facilitate a better thrusting ability, while the bottom of the beard was also profiled to better grip and hook objects. Thus, the edge geometry selected for the axe are ideal for use in a multi-purpose tool.

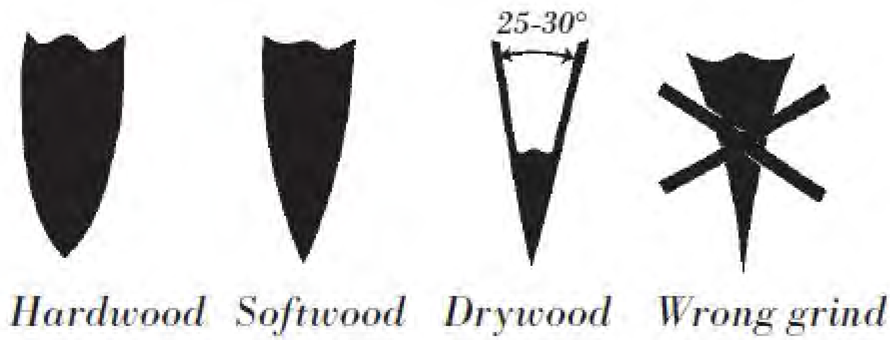



Figure 9: Optimal Blade Geometry Taken from Gransfors Bruks “Axe Book” [2]

The unique advantages of metal casting were used in the development of this axe by incorporating indentions into each cheek of the axe head. This is shown in Figure 8 in the isometric view of the axe head. In order to reduce the weight of the weapon, a segment normal to the front plane of the axe was taken out of the axe cheek on either side of the head. Reinforcement area remained along the top and bottom of the axe to ensure the strength of the axe head is not compromised by the weight reduction. An indention such as this could not be achieved via traditional forging methods without significant deformation of the axe head geometry during the forging process. However, this feature allows of **a 9.09% weight reduction without compromising the strength of the axe**. Additionally, an emboss was cast into each side of the axe for decorative purposes on the flat surface created by the cutouts. This is another advantage of casting, as fine features can be incorporated in the as-cast product without complex machining. The forging process would have required any designs to be acid etched or ground into the blade, a very labor intensive and time consuming process.

Two additional design features pertaining to the axe head include downward pointed axe lugs in either side of the axe head, and an elliptical tapered eye. The axe lugs provide better torsional strength without increasing the weight of the axe head. The eye of the axe features a 1.5° downward taper which ensures that once the axe is hung the head will not slip off the handle if properly maintained. The eye was chosen to be elliptical rather than round as would have been common for period viking axes so as to allow for greater lateral strength when chopping. Both of these features ensure that the head mounts securely to its haft.

The design of the haft, which is shown in Figure 8, introduces more modern concepts to the historical design. Traditionally, axes would have been mounted to a straight, cylindrical shaft which is tapered at the top to prevent the axe head from sliding forward off the shaft. [6] However, a more oval profile was selected as is standard among modern axes. Examples of modern axe handle designs are shown below in Figure 10. The straight handle was selected, combined with the oval handle profile and a scroll end. The handle was designed to be straight, keeping with historical tradition, however a curve was included at the end of the axe to bring the users grip forward closer to the center of mass of the axe head, as shown in Figure 7. Thus, the advantages posed by modern axe handle designs were incorporated to the traditional straight handle preferred by medieval culture.

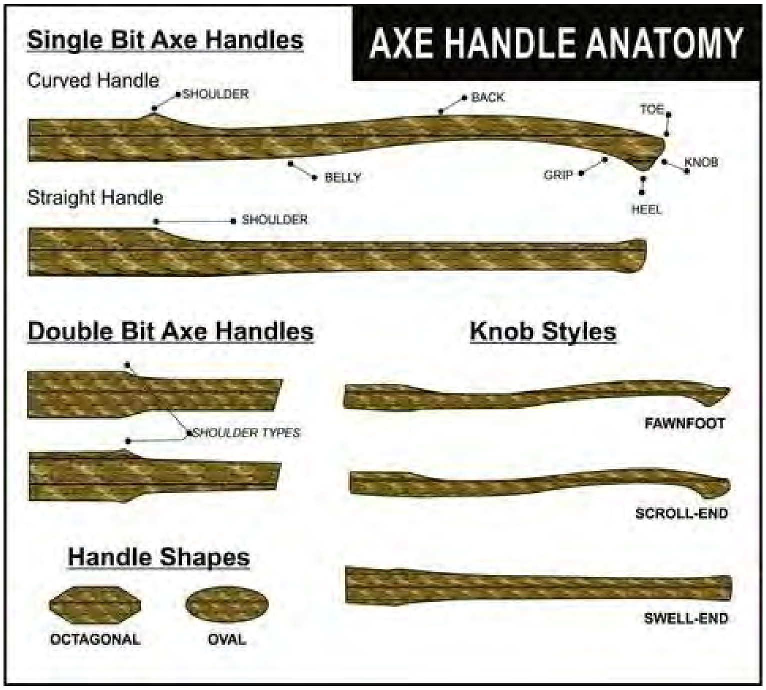



Figure 10: Axe Handle Design [9]

As a historical note, the emboss design which was chosen for this axe is a symbol depicting the Tree of Life, Yggdrasil, prominent in nordic mythology. This symbol was featured on the Överhogdal Tapestry, which was produced between 1040 and 1170 AD and depicts scenes of nordic mythology. [10] It has significant historical value because it is one of the few indisputable depictions of Yggdrasil which exist from pre-Christianized Scandinavia. [5] Additionally, a depiction of Yggdrasil was chosen in tribute to the archaeological discovery at Mammen which was previously been mentioned. The decorative Mammen axe discussed above also depicts a tree, although it is disputable whether the tree depicts Yggdrasil specifically or if it depicts the Tree of Life from the Christianity. Thus, the emboss was chosen for historical significance as well as for embellishment.

The haft of the axe was also designed to supplement the Yggdrasil emboss symbolically. On the haft of the axe, the end knob was carved to symbolize the three roots of Yggdrasil present in nordic mythology. Additionally, Lichtenberg wood burning was selected to decorate the handle with branching patterns representative of tree branches. Thus, all design features were intended to represent an aspect of nordic tradition and myth. Archaeological finds such as the axe which was discovered at Mammen indicate that the notion of decorating weapons by imbuing them with symbolic meaning was typical among nordic culture and that tradition was honored in the development of this project.

Thus, a complete Viking axe was designed following closely historical designs and features which would have been in use during the Viking era, while also incorporating advancements in axe technology which have occurred since the Viking period. The result was an implement which was well suited to both rigorous everyday working conditions and to the heat of battle.

## METHODS

### -CASTING PREPARATION

PATTERN DESIGN

A Split-Pattern design was chosen for the creation of the mold as this axe would be for a low-production type manufacturing situation. To begin the manufacturing process, Solidworks 2019 was first used to create a complete 3D model of the axe head. This 3D model was then converted for use as a pattern model by suppressing the edge features of the model, and slicing the model in half to make the split-pattern. To form the eye of the axe, a sand core must be used. Thus, the eye cavity was removed from the 3D model and a solid core was extruded in its place so that a core print would be generate in the mold. A 45° draft was used for the emboss to ensure the pattern could be removed cleanly from the mold. Lastly, pegs were extruded on the inside face of one half of the split pattern, and holes were cut in the other half of the model to ensure the two pattern halves locked together perfectly. The complete split-pattern model which was designed is shown below in Figure 11.

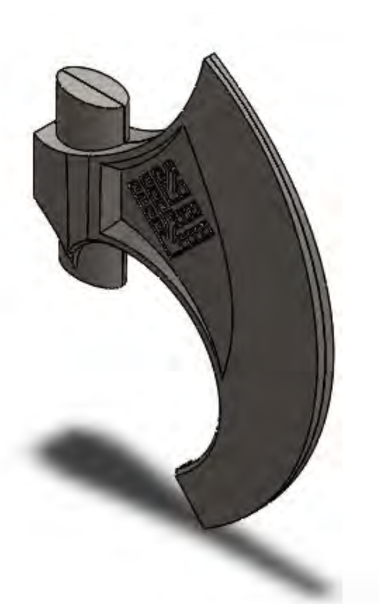


Figure 11: Split-Pattern Model

PATTERN MAKING

The split-pattern was then manufactured via additive manufacturing using the Stratasys J750 Polyjet Printer. This polyjet 3D printing technology was selected for clean surface finish, as the J750 3D printer prints at a resolution of 27 microns. [11] A core box was also printed out to produce a sand mold of the core to be used during casting. After printing, the split-pattern was cleaned of support material and was ready to be used for mold creation. The finished split-pattern is shown below in Figure 12.

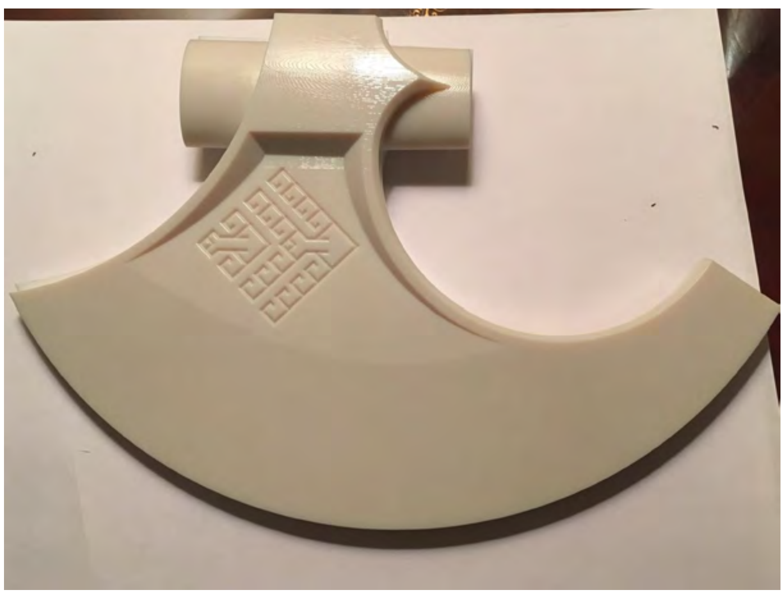
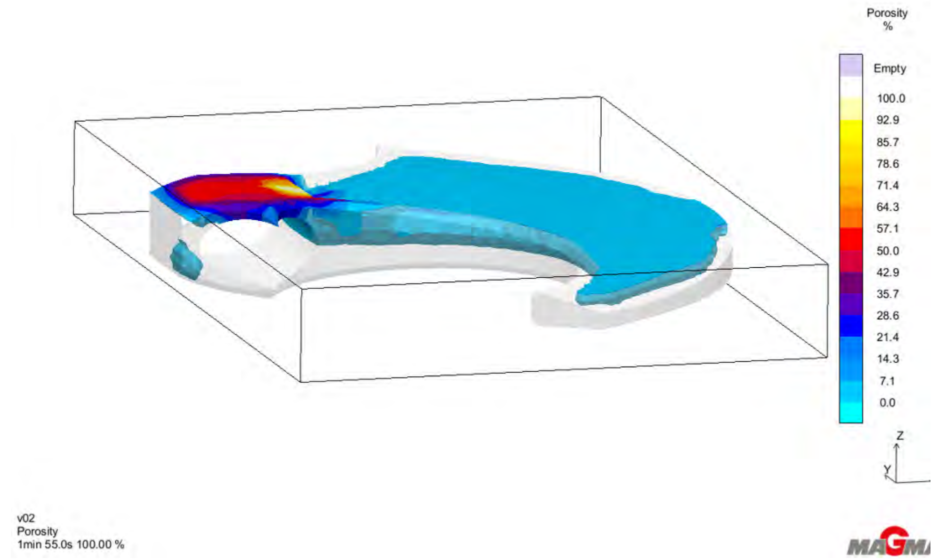


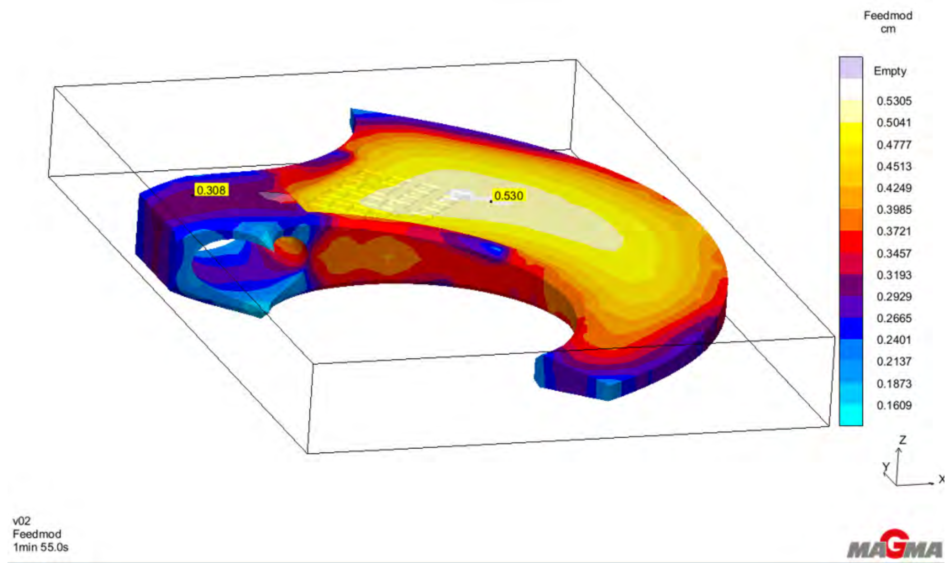
Figure 12: 3D Printed Split Pattern

SOLIDIFICATION SIMULATION

To minimize the solidification shrinkage porosity that may form in the axe head during casting, MAGMASOFT 5.2 software was used to design a proper risering system through simulating the solidification. Figure 13(a) shows the porosity distribution in the axe head without any risers added. Figure 13(b) shows the thermal moduli of the casting where porosities are expected between 0.308 cm and 0.530 cm. To make a sound casting, the riser needs to have 20% higher thermal modulus than these values, which is greater than 0.64cm. A side riser was added to the axe head using a FOSECO KALPUR sleeve that has a thermal modulus of 1.6 cm. This sleeve also acts as the downsprue in the mold assembly. The use of side risers was chosen as opposed to top risers so as to minimize the grinding required after the axes are cast. Initial simulation results in Figure 14 show that the riser was able to eliminate most of the porosity on one side.  A second side riser (1.5"D x 2"H) with a thermal modulus of 0.69 cm was added to the opposite side of the axe head to minimize the porosity within the entire casting.




(a)




(b)

Figure 13: Initial MAGMASOFT simulation shows (a) porosity distribution in the axe without risers and (b) thermal moduli at critical locations in the axe head.

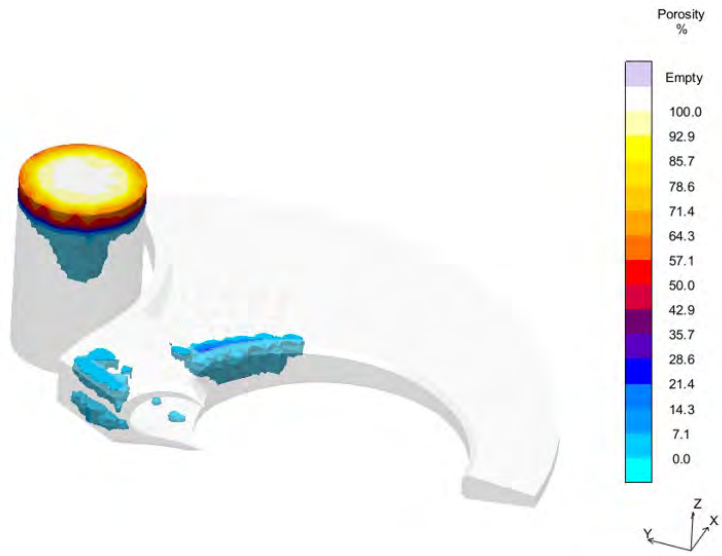



Figure 14: Initial MAGMASOFT simulation with a side riser to remove porosity on one side of the casting; a second riser (not shown) was added on the opposite side during the casting process

ALLOY SELECTION

As this axe is designed to be a multi-purpose implement, it should be capable of withstanding impact from a variety of mediums, from wood to steel, while also being able to maintain an effective cutting edge. Thus, a high work hardening steel with good strength and ductility was selected so that the metal can withstand blunt force tests upon logs and other mild steels without significant deformation or breakage. So, steel 4340 was selected as an ideal steel which would meet these standards, perform the strength and endurance tasks during testing and still have good toughness to maintain an edge for the edge sharpness testing. Also, any deformation that may occur during the tests against logs and steels will increase the hardness of the blade due to its high work hardening and thus minimize further deformation. The table below shows the listed chemistry for steel 4340 alloy. $T_L$ represents the liquidus temperature of the alloy which was calculated using the thermodynamic software FACTSAGE. Additionally, austempering was selected as a heat treatment method for increased toughness and impact strength as compared to traditional quench and temper methods. [12]

Table 2: Chemistry composition for the desired Steel 4340 alloy

| **C** | **Si** | **Mn** | **Cr** | **Mo** | **Ni** | **P** | **S** | **$T_L$ ($^oC$)** |
|---|---|---|---|---|---|---|---|---|
| 0.42 | 0.2 | 0.6 | 0.75 | 0.25 | 1.8 | 0.03max | 0.03max | 1490 |

## -MOLD CREATION AND CASTING

ALUMINUM CASTING

Two preliminary casts of the axe head were performed at Georgia Southern University. A 20 lbs gas furnace was used to melt aluminum alloy 356. The purpose of casting in aluminum alloy was to test our 3D model and pattern design, as well as to gain hands-on experience in the casting process before casting steel at an industrial foundry. The split pattern was used to make a greensand mold implementing the riser configuration determined in the Casting Preparation section. Both aluminum casts showed that the split-pattern/core design worked well in forming a greensand mold, while the rise configuration eliminated the the majority of the shrinkage porosity from forming in aluminum. After multiple tests of casting with 356 aluminum, the split-pattern as then cleaned and prepared to be used in creating a mold for steel casting.

STEEL CASTING

The first steel casting of the axe head was performed at Georgia Iron Works (GIW) R&D lab in Augusta, GA. Two castings were made to account for any mistakes that may be made during casting or any process that followed. The split-pattern was used with chemical-bonded sand to create the mold for the casting. Zircon wash was applied to the most surfaces after the chemical bonding had set in order to reduce penetration and allow for a better as-cast surface finish by reducing metal-mold interactions. An example of the molds before and after the zircon was is shown below in Figure 17. As recommended during simulation, two risers were used on either side of the axe head with a large downsprue serving as an additional riser. The steel charge was prepared by employees of GIW, and they performed the metal pouring. Pure Aluminum was added as a degasification method. This process is depicted below in figures 15 a) and b). After sandblasting the two steel castings made at GIW, both castings proved to have too much gas porosity, which compromised the structural integrity of the axe and is shown in figure 16. To resolve this issue, two more castings were made at the teaching/research foundry at Missouri University of Science and Technology (Missouri S&T). Both GIW and Missouri University used INDUCTOTHERM coreless induction furnaces, however the process differed in the following ways. A 50 lbs heat was produced at GIW and a 100 lbs heat was performed at Missouri University. At GIW, furan sand was used to make the molds and cores while at Missouri S&T, the molds and cores were made with a Tinker-Omega TOM-50 sand mixer using AFS #60 silica sand.


a)


b)

Figure 15: a) Ferrous alloys were poured into the furnace to achieve correct composition b) Pouring of molten steel into molds

Figure 16: GIW Casting with Large Amounts of Surface Porosities

For the first pair of castings at GIW, 4140 steel shaft returns were inserted into a 50 lbs furnace. Ni and Ferro-Mo was added to change the composition into a 4340 steel alloy. Charge was air melted with a small amount of argon protection. The metal was tapped on to 0.02wt% pure aluminum in a preheated ladle at 1680C. Next, the molten steel was poured into the mold to solidify in the cavity. However, once the expendable mold was broken apart, it was revealed that gas porosities covered both castings. This was due to an extraneous amount of dissolved oxygen picked up during the melting process. Also, when charging the last piece of steel, the metal solidified on top of the liquid pool. The furnace remained uncovered while the casting technician was trying to push down the "bridge" to get it dissolved. Another reason excess oxygen may have been picked up was because the melt size was only 50 lbs and the large surface-area volume ratio. Last but the least, the argon flow rate was not at an adequate level to provide protection.

For the second pair of castings, the AFS student chapter at Missouri University of Science and Technology recast the designs. During this melting process, virgin charge materials were used, listed in table 3 below. The melting of the steel 4340 was done by the following the high active oxygen practice expressed in Dr. Xu's earlier publication [13]. Briefly, induction iron was charged into the furnace, and after all induction iron was molten, the active oxygen was measured at 800 ppm. Now that there is a high amount of dissolved oxygen, the vacancies were occupied on the surface of the molten metal stopping nitrogen from entering the melt. To achieve the desired chemistry, graphite along with ferrous alloys were added into the melt. Calcium wire was then added to remove any sulfur and modify the inclusions. The molten 4340 steel was tapped and killed at 1680C with 0.02wt% aluminum. Finally, the molten metal was poured into the expendable mold.

a)

b)

Figure 17: a) Molds made at Missouri S&T b) Mold with zircon wash to minimize metal-mold interaction

Table 3: Charge table of alloys used at Missouri University

| Charge | Weight (lbs) |
|---|---|
| Induction iron | 83.60 |
| FeCr | 0.90 |
| Fe75Si | 0.22 |
| FeMn | 0.53 |
| FeMo | 0.15 |
| Ni | 0.71 |
| C | 0.37 |
| **TOTAL** | 87.14 |

## CASTING CLEANING

The 4340 steel axe head castings from Missouri S&T were removed from the downsprue and risers using a bandsaw. An angle grinder with an 80 grit flapper wheel was used initially to remove the remainder of the riser and to form a rough edge profile. A 120 grit flapper wheel was then used to achieve a final smooth surface finish across the entire axe head to prepare it for heat treatment. A few sand/slag related porosities were noticed on the axe head near the blade edge. As these were of concern in instances of high impact, TIG welding was used to fill in the larger porosities. After all TIG welding was done to repair the gas porosities, a 120 grit flapper wheel was used again to polish all welding down to ready the axe head for heat treatment.

## HEAT TREATING

As mentioned earlier, austempering was selected as the heat treatment method for this project to achieve a bainitic microstructure for a good combination of hardness of toughness. An earlier work by Niazil et al. [14] suggested that for alloy 4340, austenization at 850C followed by quench in a 350C salt bath and held for 1 hour gave the highest hardness at 392 BH. As another reference from the ASM handbook, the Time-Temperature-Transformation diagram of 4340 is shown in Figure 17. At 350C, austenite to bainite transformation finishes at around 1 hour, and the hardness expected is around HRC 42, which is consistent with Naizil's work.

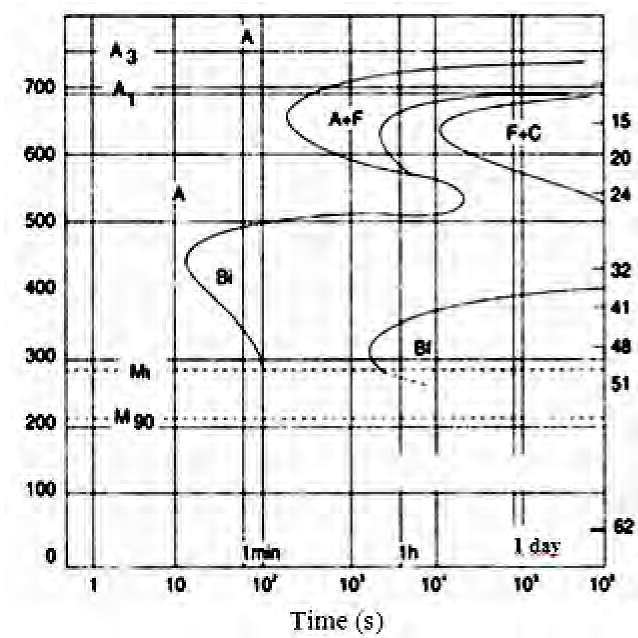


Figure 18: Continuous Cooling Transformation diagram of 4340 [15]

Prior to the heat treating, castings were cleaned and the bevels of the axes were ground with an angle grinder. This is to avoid any major grinding after the heat treatment, as the heat generated from grinding will alter the microstructure of the axes obtained through heat treating.

Heat treating was performed at Duramatic Products. Duramatic Products is a lawn mower blade manufacturer located at Glennville, GA. The axes were austenitized in a salt bath at 850C for half an hour. They were then quenched in another 350C salt bath and isothermally held for 1 hour. The axes were then quenched in agitated water at 35C, followed by immersion in a rust preventative tank. The risers for the axes were heat treated in the same batch, for the purpose of hardness measurement and microstructure evaluations.

### -FINISHING AND ASSEMBLY

AXE HEAD

The final blade profile was formed by hand using a progression of hand filing, whetstone work, and 2000 grit sandpaper. Once the overall edge contours were obtained, a surface treatment was applied to induce an oxide layer for rust and corrosion protection. After this treatment, the oxide layer was removed from the bevel of the axe blade only and the final sharpening was performed.

For a surface finish on the heat treated 4340 axe head, a forced patina was chosen as a historically accurate method for rust protection. Vinegar was used to force a patina on the surface of the blade. The patina consists of an oxide layer which prevents the steel from oxidizing. The axe head was attached to a wire to dip into a carefully temperature controlled pan of vinegar. A small amount of heat was used as a catalyst for the reaction but low temperatures must be maintained to prevent change in the heat treatment microstructure. The axe head was allowed to soak for 20 minutes, until the steel achieved a dark grey appearance, with the axe head resting in the pan. The head was occasionally flipped to achieve an even acid etch. The blade was washed with water and oil to get rid of any loose particles and/or vinegar remaining.

HANDLE

Hickory was selected as a handle material due to its unique combination of toughness and ductility. Hickory has been the standard for axe handles for more than a century. It is a strong wood material which resists fracture due to impacts due and also allows for shock absorption due to its slight ductility which spares the user's hands from undue jarring. [16] Additionally, the grain orientation is of great importance when designing an axe handle, and the optimum grain orientation was selected for this project as shown in the National Forestry Service guide, *An Axe to Grind*. [17] This orientation is shown below in figure 19. Additionally, white second-growth hickory sapwood was selected as recommended by the manual.

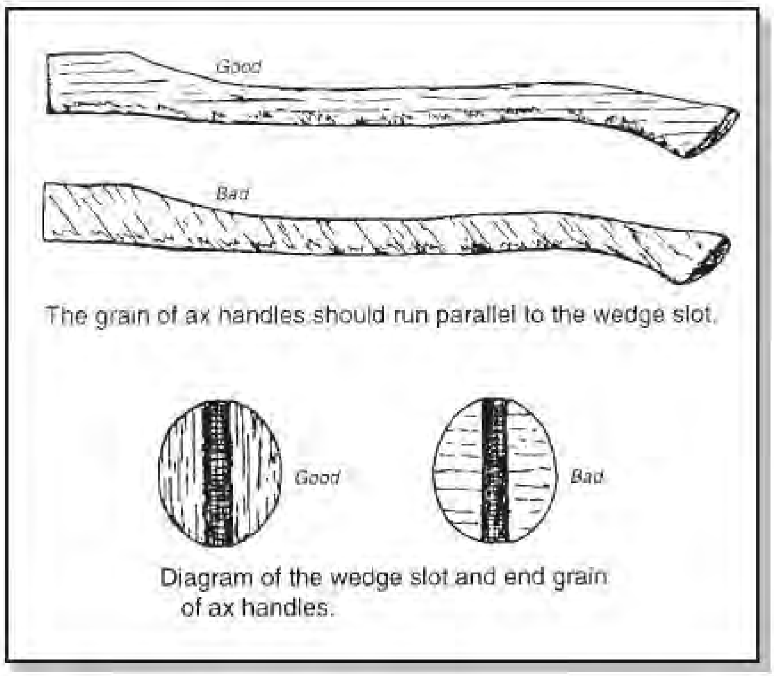


Figure 19: Optimal Hickory Grain Orientation [17]

The handle was shaped by cutting a rough form of the handle out using a bandsaw, and carefully removing the remainder of the material using a combination of electric and hand sanding techniques. Once the handle achieved a shape which was comfortable in the hand and closely resembled the handle designed and shown in Figure 8, the end knob was hand carved to show the three root design. The handle was then fitted to the eye of the axe carefully using sanding in stages while periodically testing the fit. Lastly, Georgia Southern was hand chiseled onto either side of the handle in Old Futhark Runes, which would have been used in nordic culture at the time to inscribe stone and wood.

Next, the handle was embellished using Fractal Lichtenberg wood burning. A transformer was used to convert the voltage of a standard power outlet to roughly 10,000-15,000 volts of electricity. The hickory was then coated in a 1:1 solution of baking soda and water which promotes the flow of electricity along the surface of the handle. A positive wire was place on one end of the handle and a negative on the other allowing the electricity to slowly burn its way through the wet handle via the path of least resistance. After the electricity detailed the handle, the handle was flame-hardened with a propane torch which darkened the wood and increased the surface hardness. Boiled linseed oil was then used across the entire handle to preserve and protect the wood. 4 coats of linseed oil were applied. The oil was allowed to soak into the wood, and then the excess was wiped off after 5 minutes. This was repeated until the wood no longer accepted more oil.

HANGING AND ASSEMBLY

The handle and axe head were assembled using a standard hanging method detailed in *An Axe to Grind.* [17] A kerf slot was cut with a hand saw parallel to the direction of the axe blade into the portion of the handle which would be mounted into the eye. A wedge was then made out of walnut hardwood which could be driven into the slot and spread apart the kerf. The top of the handle and the wedge were then soaked in linseed oil for 30 minutes to increase their ductility. The hande was then inserted into the eye of the axe and the wedge was driven into the kerf using a rubber mallet. This provided for a tight fit using traditional methods.

Additionally, a custom leather sheath was designed based on the final blade geometry of the axe. It was cut out of leather and hand stitched to fit the axe exactly.

## RESULTS

### -COMPOSITION

The final composition of the 4340 steel was analyzed with an OXFORD optical emission spectrometer and is listed below. Overall, the chemistry of the final heat carried out for the axes was very close to the targeted chemistry..

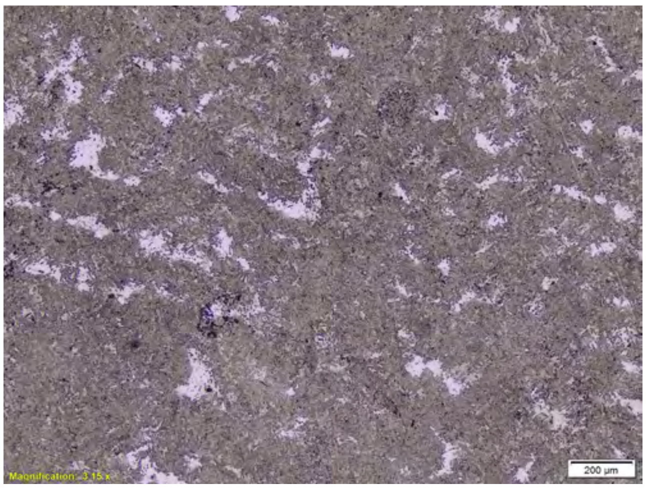
 

Table 4: Actual chemistry composition of the Steel 4340 alloy

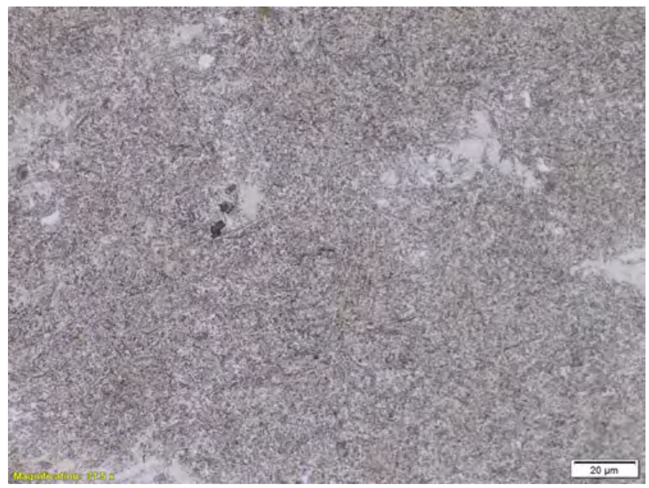
| | C | Si | Mn | Cr | Mo | Ni | P | S |
|---|---|---|---|---|---|---|---|---|
| Target, wt% | 0.42 | 0.2 | 0.6 | 0.75 | 0.25 | 1.8 | 0.03max | 0.03max |
| Actual, wt% | 0.45 | 0.21 | 0.66 | 0.80 | 0.27 | 1.91 | 0.011 | 0.015 |

### -METALLOGRAPHY

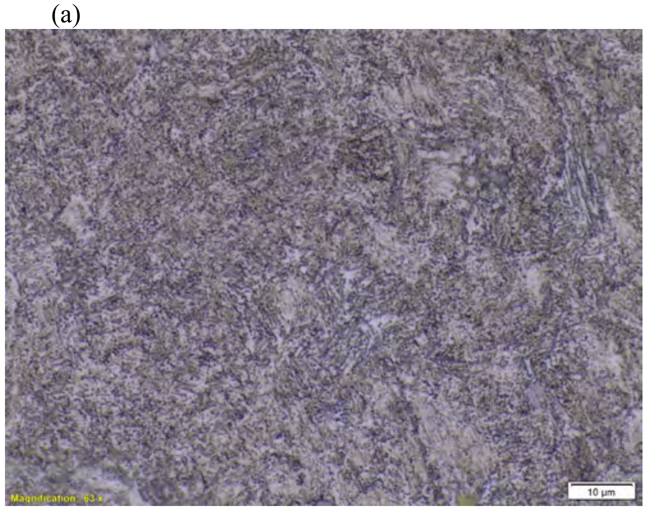
Metallographic images of the heat treated risers are shown in the figures below. A very fine lower bainitic microstructure was achieved throughout the specimen.




(a)




(b)




(c)

Figure 18: Optical metallographic images of the viking axe at different magnifications, a) 50x b) 500x, and c) 1000x, shows that the axe consists of very fine lower bainite

### -HARDNESS

The resulting hardness value was measured on the heat treated riser. Overall the casting achieved an overall hardness between 40HRC and 42 HRC. This is consistent with Naizil's work and the ASM handbook, indicating the heat treat was very successful.

## -FINAL PRODUCT

Figure 19: Final Product of the steel cast Viking axe

## DISCUSSION

Overall, the project was a success and the results achieved closely matched the desired results selected through the design process and predicted via previous studies regarding casting, metal treatment, and woodworking. However, some notable features occurred which were not expected.

The main complication experienced through the project was seen in the first set of castings done by Georgia Iron Works. The numerous gas porosity throughout the first pair of steel castings greatly reduced the strength of the axe head. The GIW foundry specializes in very large-scale slurry pumps cast out of white iron. 4340 steel is not an alloy which the technicians were accustomed to melting and pouring and thus the errors arose which resulted in the gas porosities. When the axes were recast at Missouri S&T, Dr. XU was in charge of the melt and the pour had more experience with advanced steel alloys and thus the chemistry was closer to the target and the gas porosities were reduced.

However, the final cast was not without issues of its own. Minor porosities resulting from sand inclusions were present nearly uniformly through the cast. Although these porosities were sporadic and minor, they become of concern as they approach the edge of the axe blade. The axe head cast in this project possessed several of these porosities close to or on the edge of the blade, and as these were uncovered after the heat treatment significant re-profiling of the blade was unfeasible. In future casting, a filter in the gating system is recommended to prevent inclusions from creating these porosities.

## CONCLUSION

A fully functional historically authentic Viking axe was produced which incorporated modern design and manufacturing innovations with features and techniques dating back to the Viking era. The overall design was creatively planned and carefully implemented and resulted in a final product which met and exceeded expectations. The casting process was used to create an axe which included features in the as-cast shape which would not have been possible to achieve from traditional blacksmithing methods without excessive post processing. The selected steel chemistry was achieved, and poured successfully to create a cast which was free of shrinkage porosities as predicted by simulation results. The selected bainite microstructure was achieved and the target hardness was obtained. All extraneous features of the project, including the shaping and detailwork of the axe handle, the surface protection, and the leather sheath were executed as planned and tie together result in a quality product which met the design criteria

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