

**Modern Cast Methods and Materials for a Historic  
Viking Axe Design**

**UAB**

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## **Abstract**

The Viking axe is a staple of the Viking culture; modern technology as enabled the ability to recreate these historic weapons with modern processes out of high-performance steel. AF-96 was the alloy decided on due to its high impact toughness (measured by charpy v-notch), high ultimate tensile strength, and high Brinell hardness values. Multiple gating systems were designed, the main criteria evaluated being fill velocity, core erosion, minimal heat weight, and reduction in entrainment. A cnc router was used to machine the pattern faces as well as a core box, and a no-bake resin bound sand mold was created from these patterns. Two molds with identical gating systems were constructed and poured in tandem; consequentially, only one of the patterns filled while the other formed a cold shunt within the gating system. Machining was necessary to obtain the desired blade sharpness and remove any flash. Heat treating was required to obtain the impact toughness and hardness necessary to have the highest performing axe possible.

## **Introduction**

The period of the Viking Age followed that of the Germanic Iron Age. Between the 10<sup>th</sup> and 11<sup>th</sup> Century, Norsemen from the regions of Northern Europe that are now current day Denmark, Norway, and Sweden traversed rivers and the sea. Although the Vikings are primarily believed to be a mass of fearsome maritime explorers, they did not associate as one people but were rather comprised of many groups with a diversity of regional differences, traits, and cultural values between them. There are three prominent Viking groups: Danish, Norwegian, and Swedish. Much more is known historically about the Danish Vikings, as they had a myriad of interests outside of the seafaring conquests Vikings are commonly known for, but they are also said to have established the basis for what the contemporary cultural concept of 'Viking'. They were highly involved in political affairs, and are believed to have had great regional, cultural, and military power [1].

Though the Vikings had a wide assortment of utilitarian axes, there were many whose purpose and design was centered in warfare. One of these axes, known as "Danish axe", or simply "Dane axe", were characterized by their larger size. They were believed to have measured more than 1 meter (roughly 3.28 feet) in shaft length with relatively thin iron heads, so despite their dimensions pointing to a two-handed axe, they were less cumbersome to wield [2]. While most of these axes were more simply made, many ornamental versions exist that were found in the graves of Viking warriors past, researchers believing these artifacts to have either been reserved for ceremonial purposes, or as the property of a highly decorated warrior [2]. In many cases, these decorative axes were sturdy enough to function in practical applications. While the axes were made of iron, the ornamental details were either inlaid with silver or copper or were symbols bordered by negative space. The more detailed inlays commonly featured animals and pagan themes from Norse mythology, such as Yggdrasil, the "Tree of Life", but Christian themes like crosses also occasionally made appearances as the end of the Viking Age approached [2].

The axe design was modeled after a Dane Axe; however, slight modifications were made for the sake of castability and a reduction in post-processing machining time. Figure 1 shows an isometric view of the axe head design. The length of the blade is approximately 10.5 inches, providing ample surface for contact with target. The eye of the axe was modified to fit a standard axe haft, so the team could focus efforts on the casting, and not have to create a handle to fit the eye. Due to this compensation, the butt axe length was increased in accordance to this modification, adding approximately 1.4 inches to the

overall length. Prior to this, the eye Diameter was approximately 1.2 inches, whereas the length of the elliptic eye is approximately 2.6 inches. The entire cast was projected to weigh approximately 9.6 pounds. Figure 2 shows the dimensions of the axe on the 2D plane. The thickest portion of the axe- the area around the eye- is 2 inches thick which tapers down gradually to the thinnest portion of the axe at .24 inches.

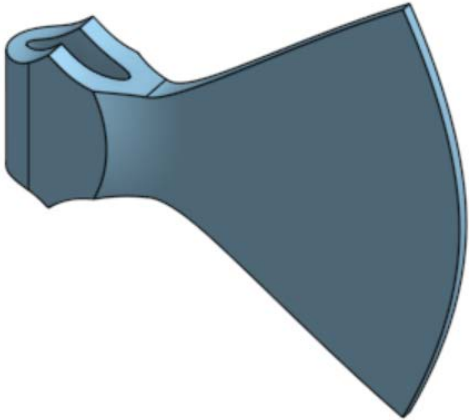


Figure 1 Isometric view of axe head

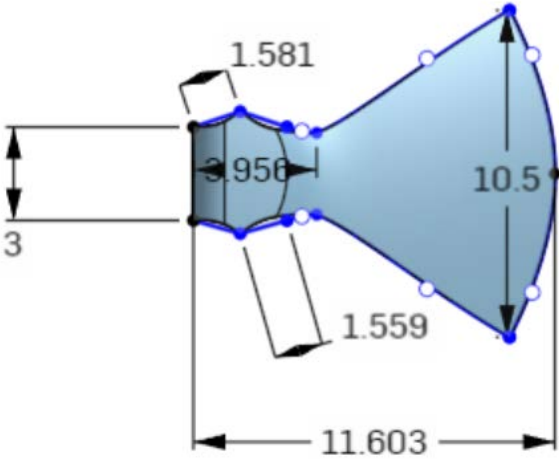


Figure 2 Dimensions of the Axe head (in inches)

To ensure peak possible performance during the durability trials, the team elected to use the highest quality steel at our disposal, AF-96. Figure 3 below shows the general chemistry for this alloy. This low alloy steel has a Charpy v-notch value of 25 ft-lbs at -40°C when properly heat treated. AF-96 has a Ultimate tensile strength of approximately 1555 MPa and an elongation to failure of 13% [3].

Compare AF-96 to a typical low carbon steels used in axe heads, 1080. Hot-rolled 1080 has Brinell hardness of approximately 293 and a UTS of around 965 MPa with an elongation to failure of 12%. 1080 has a Charpy v-notch value of 14.13 ft-lb [4].

With these physical properties outlined, it is clear that AF-96 out performs most normal steels. However, the cost of the processing this alloy makes it not economically feasible to use for standard axes. For this small-scale project, it is feasible to cast and demonstrate the effectiveness of this alloy to perform at a higher level than other steel alloys commonly used in axe making.

| Typical Composition<br>USAF-96 Steel |       |
|--------------------------------------|-------|
| C                                    | 0.28% |
| Mn                                   | 0.6%  |
| Si                                   | 1%    |
| Cr                                   | 2.6%  |
| Ni                                   | 1%    |
| Mo                                   | 0.90% |
| V                                    | 0.1%  |
| Fe                                   | Bal   |

Figure 3 General chemistry for AF-96[3]

### Model Development

Models of the axe were rendered with accompanying feeding and gating features in the Onshape product development platform and analyzed for thermal and flow phenomena in the casting process within MAGMASOFT simulation software. Three casting arrangements were considered, shown below as Gating Systems 1, 2, and 3.

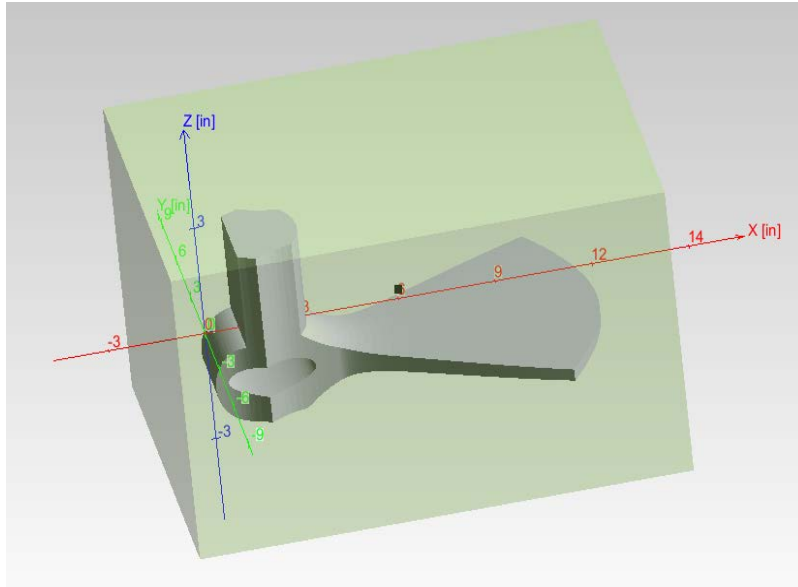
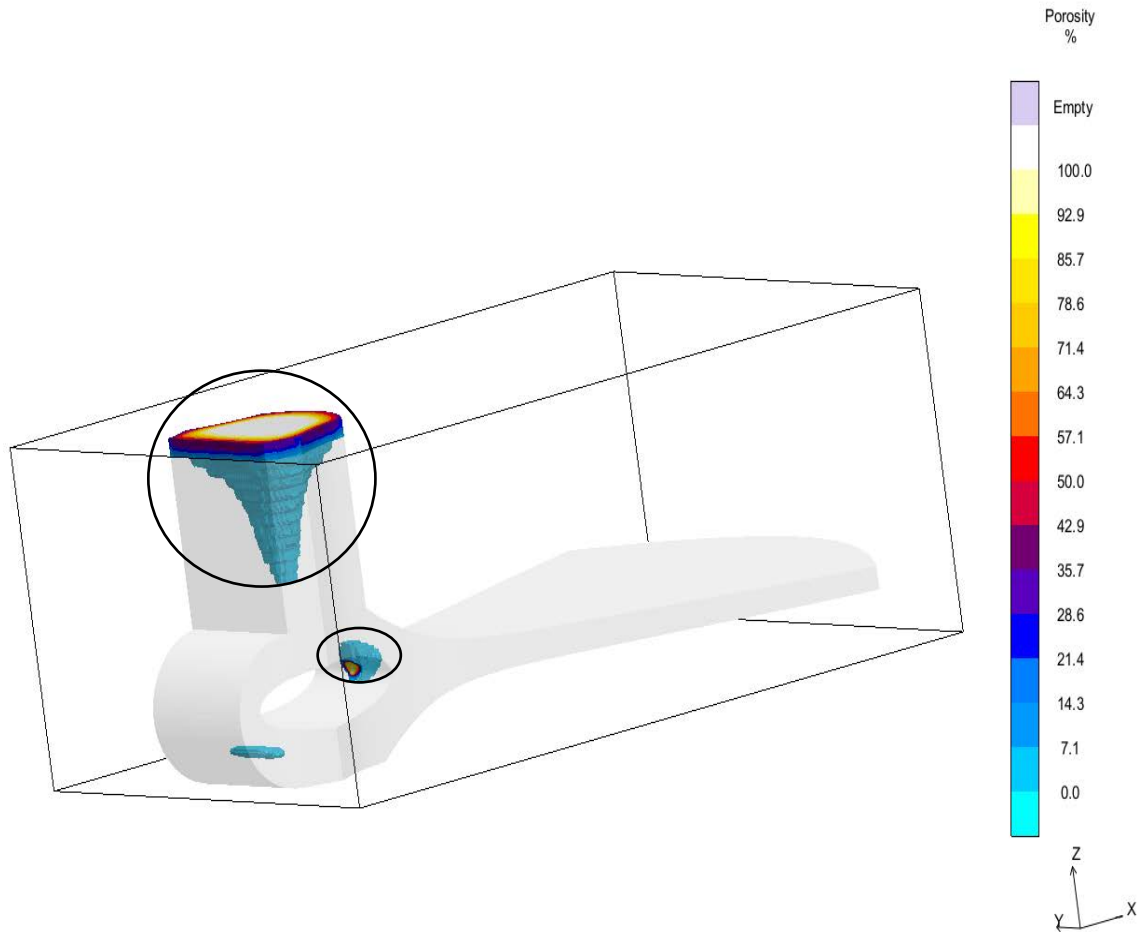


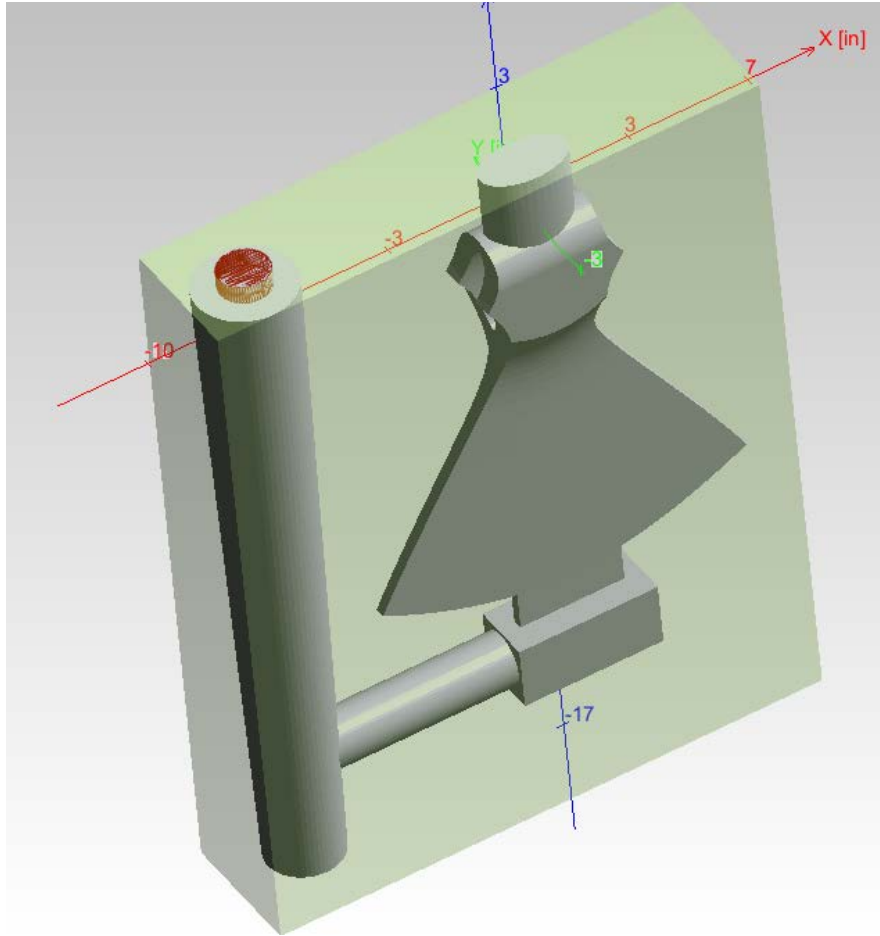
Figure 4 Geometry and Orientation of Gating System 1

Initial designs for the gating system, as seen in Figure 4, positioned the flat of the blade orthogonal to gravity with a combined gate and feeder above the eye of the axe head. This design required comparatively little post-processing, with minimized excess steel in an easy-to-machine gating system, but concerns were raised regarding potential erosion of the eye sand core. Project advisors cautioned (barring use of specialized filters) of turbulent flow resulting in sand burns along the blade surface, and MAGMASOFT simulation found issues in porosity as seen in Figure 5. Despite sufficient local feeding in the gate, a considerable void could form at the eye-blade junction, the cheek of the axe. Gating System 1 was abandoned without flow analysis.



*Figure 5 Predicted Porosity in MAGMA Simulation of Gating System 1. Though the gate/riser is maximally effective, with porosity within the riser not extending into the axe, a void remains at the eye/blade junction*

Gating and overall orientation were modified into Gating System 2, shown in Figure 6. The axe was reoriented with the flat of the blade parallel to gravity. The gating system now entered from the bottom of the axe and includes a well, runner and ingate into the edge of the blade, so chosen to minimize turbulence in sand core-steel interactions. Though this gating system will require more excess steel, this design was chosen in hopes of minimizing turbulence and improving final porosity and surface finish. A riser was placed at the butt of the axe to feed metal about the eye.



*Figure 6 Geometry and Orientation of Gating System 2*

Flow analysis of this casting found that the height of the sprue, in conjunction with a limited ingate area, could result in considerable, uncontrolled velocities in the metal entering the mold. Though somewhat mitigated by the runner design, the metal flow is expected to splash back upon entering the major cavity in a manner as shown in Figure 7. This turbulent flow could result in air entrainment and subsequent surface damage or interior porosity beyond that predicted in simulation. Porosity in the final part, as predicted in simulation and shown in Figure 8, appears less severe if wider spread about the eye.

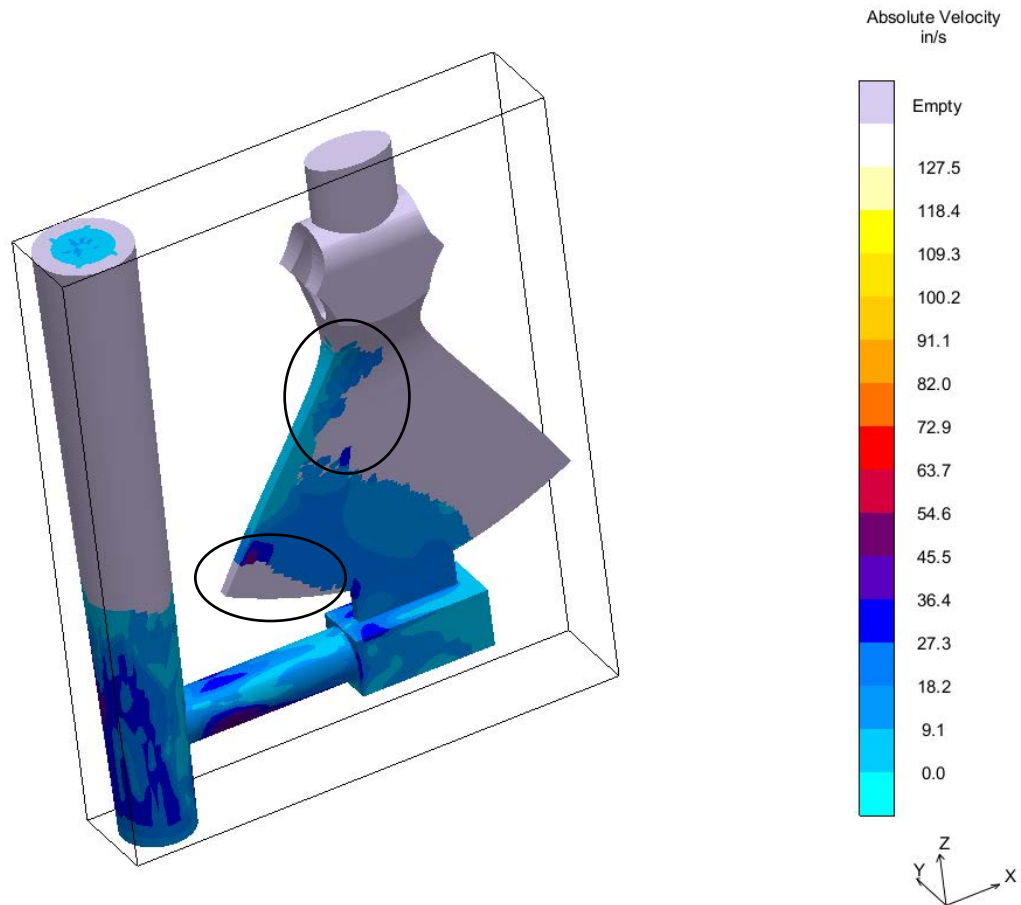


Figure 7 Flow Analysis in MAGMA simulation of Gating System 2, 6s into a 10s Fill/Pour Time. Note how flow is sufficiently turbulent to rise and fall again into the mold, posing a risk for air entrapment on its descent.



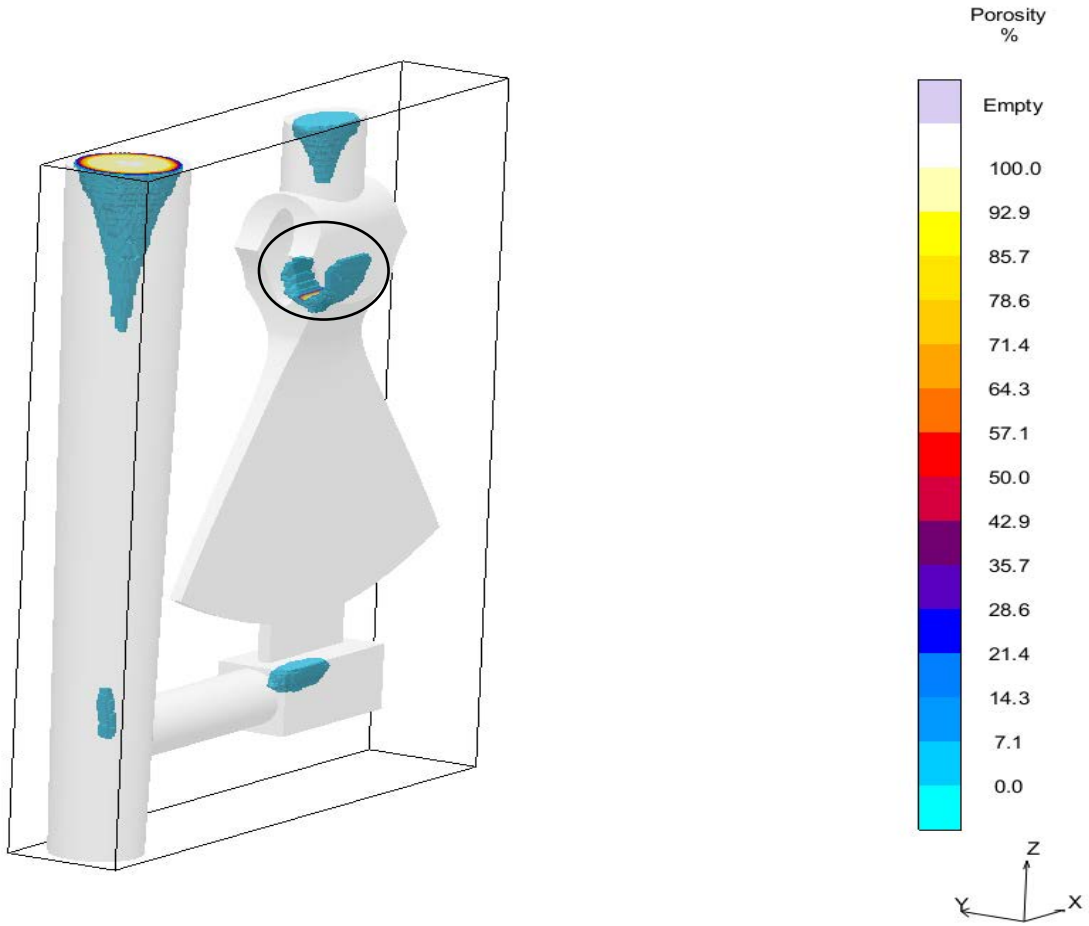
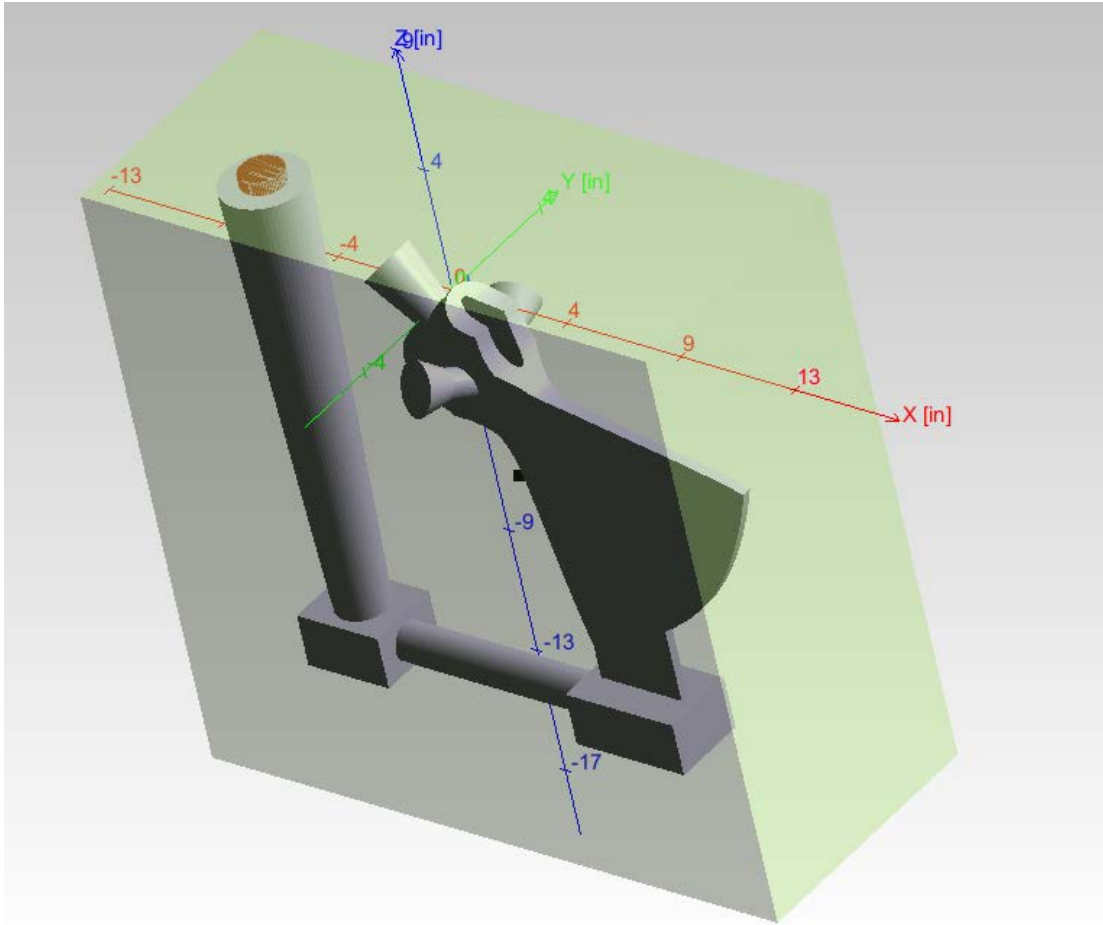


Figure 8: Predicted Porosity in MAGMA Simulation of Gating System 2. Compare the circled porosity with that seen by the axe eye in Gating System 1.

In Gating System 3, minor adjustments were made to the gating system to accommodate an angled orientation to the axe (Figure 9), positioned to mitigate splash and entrainment seen in the previous orientation. Additional risers were placed at either side of the eye in hopes of eliminating remaining issues of porosity.



*Figure 9 Geometry and Orientation of Gating System 3*

Flow analysis of this system (Figure 10) appeared to be sufficiently constrained by the mold wall to avoid the back splash seen in the previous orientation, though air entrainment could still occur in initial filling of the axe. Filling in both Systems 2 and 3 was sufficiently smooth by the time metal made contact with the core that erosion issues were thought to be mitigated. The side risers seemed to shift the position of porosity about the eye rather than reduce its occurrence (Figure 10), so these features were removed from the design. This mold design was agreed upon by the team and proceeded to production, with any further changes to feeding made in the manufacturing processes.

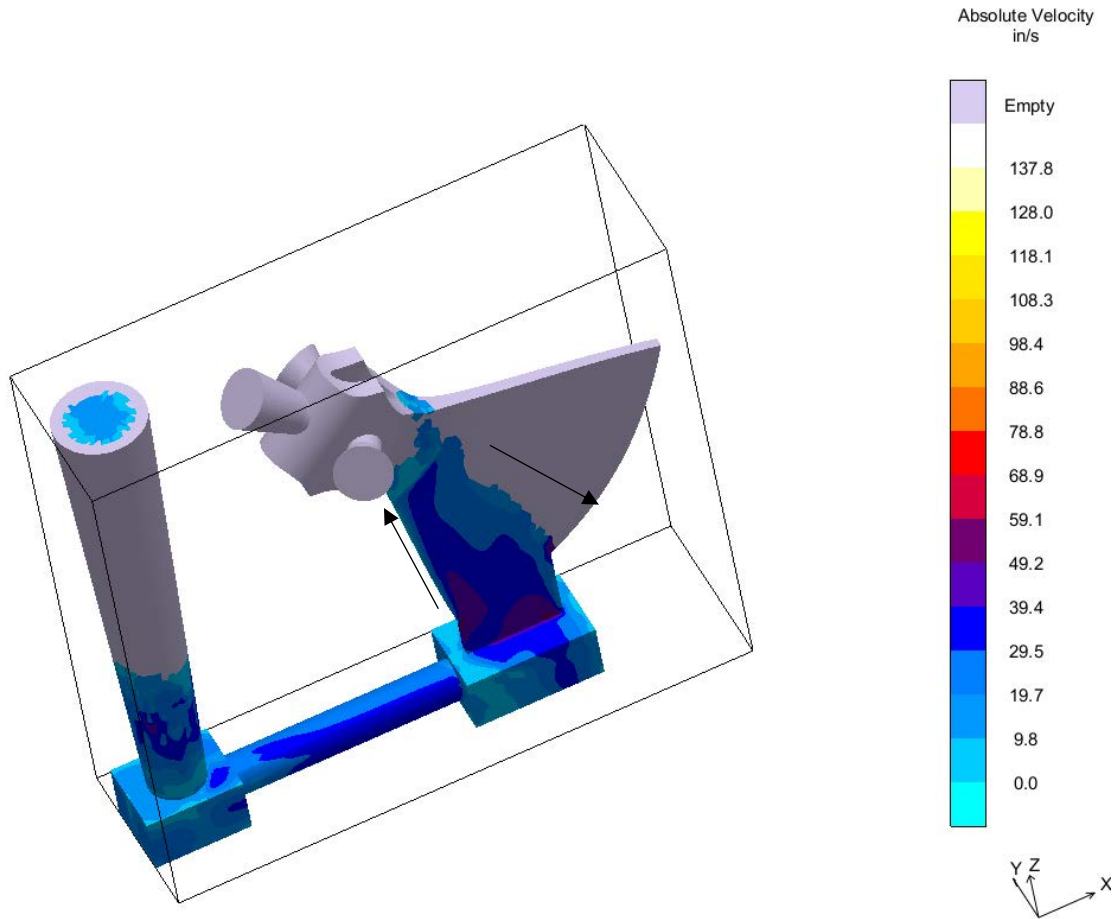


Figure 10 Flow Analysis in MAGMA Simulation of Gating System 3, 4.5s into a 10s Fill/Pour Time. Note how flow into the axe appears to trace the angled geometry, mitigating air entrainment in backslash.

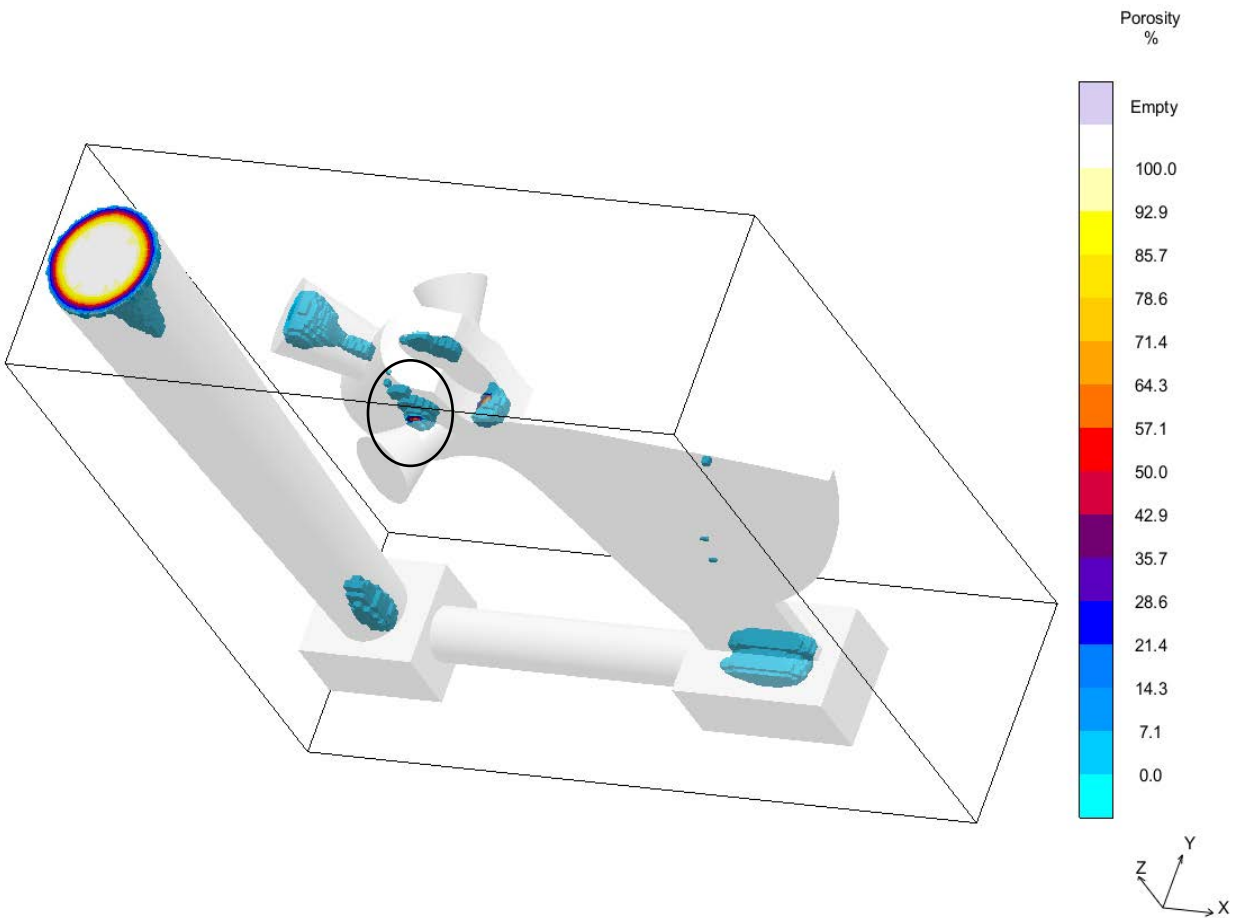


Figure 11 Predicted Porosity in MAGMA Simulation of Gating System 3. Porosity by the side risers has not been abated—compare to Gating System 2.

### Production and Manufacturing

A CNC router was implemented in the machining of our pattern. This ensured a precise and accurate model of our axe would be used during the mold making process. Due to the thickness of the axe head, the frame, core slot, and blade of the geometry were made in one cut. The material surrounding the eye of the axe had to be cut separately and glued into place. The gating system was not added into the pattern and was added manually later in the process to allow for changes in the event of unforeseen issues in filling. A pattern frame was used in place of a locator pin. This design choice was made due to the reliability of frames, and to eliminate the potential of pattern mismatch or unnecessary setbacks due to broken locator pins. One side of the frame can be seen in Figure 12 where a raised border is present around the perimeter of the mold. Figure 13 shows a mirror image of Figure 12, where the geometry is raised and has an indented border around the perimeter. This design is meant to key into the frame of the opposite geometry. A core box was also machined so that the eye of the axe would not have to be machined out in the post-processing stage.



Figure 12 CNC'ed pattern boxes used to make sand molds



Figure 13 CNC'ed pattern boxes used to make sand molds

Once a sand mold was produced from the pattern, the proposed gating system and risers shown in Figure 14 below were manually machined out using a pneumatic Dremel tool. The gating system and risers were measured precisely as to ensure a correct understanding of required heat weight and filling procedure. It should be noted that modifications were made to the agreed upon gating system, referred to above as Gating System 3. The side risers were removed in favor of one large riser at the top to mitigate surface porosity. The gating system itself was reduced in thickness, and the wells intended to moderate turbulence were removed to reduce the weight needed to fill the cast. After the required machining was completed, the entire geometry was given a mold coating and sanded to avoid a sandy texture on the final casting. These steps were also taken with the core, to allow a smooth surface that would reduce required machining.

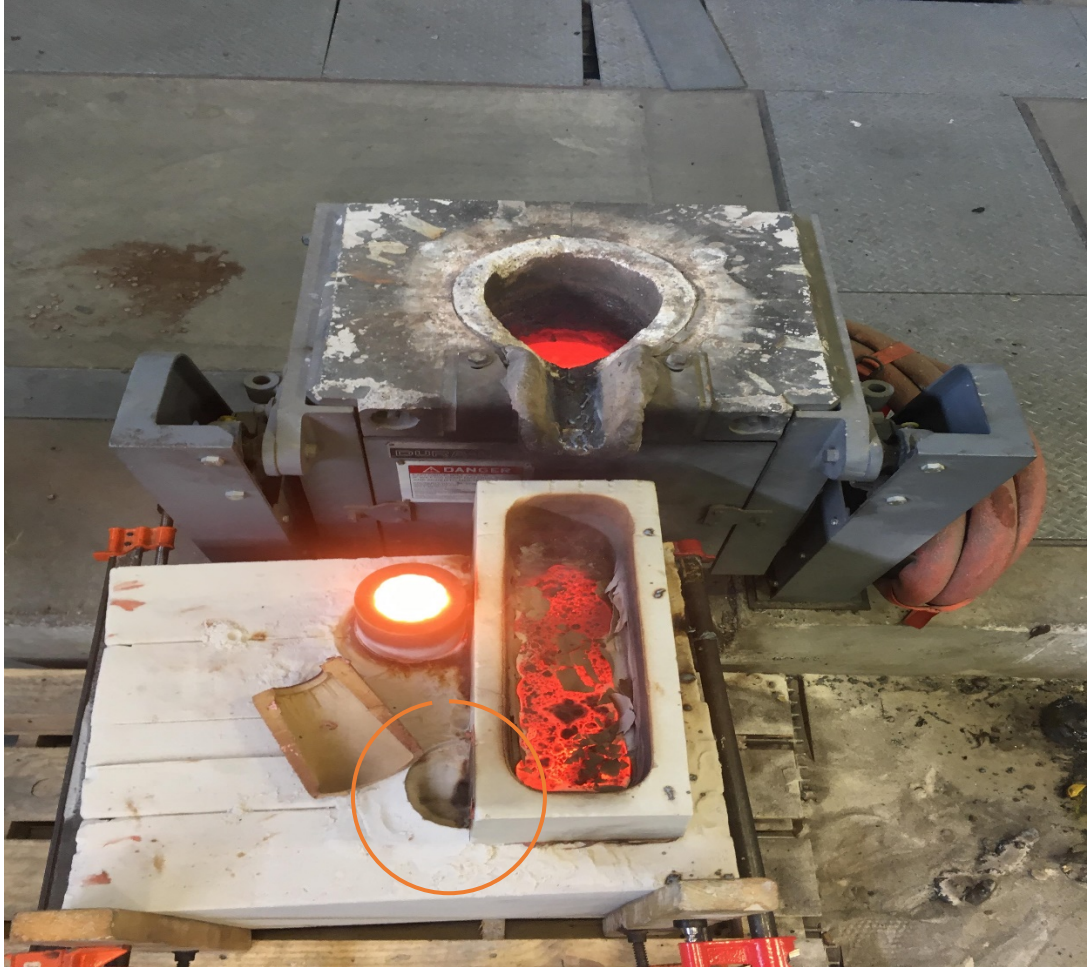
It was decided that two axes would be cast in tandem to prevent the need to charge two separate heats. This required the creation of a basin that could fill in both molds simultaneously and at a constant rate. Figure 14 shows the steps taken to ensure no spill outs would occur while the steel would flow from the basing, to the sprue. A heat resistant sleeve was cut to size to help guide the steel, and resin-bound sand was packed around the basin to act as resistance for the flow. Sprue sleeves were placed around the risers as well to reduce the likelihood of a spill out from the top of the casting. The

AF-96 was superheated to approximately 2950°F, deslagged, and poured into the molds as quickly as possible to fill up the basin and prevent any cold shunts in the filters.



*Figure 14 Set up of molds pre-cast*

Figure 15 shows the molds post- cast, but before the cast has been broken out of the molds. The mold on not directly under the induction furnace did not fill to the risers (circled). The mold directly under the induction furnace did fill past the machined riser and into the sprue sleeve extension; similarly, the pouring basin has an excess of steel still in it. The inadequate filling of the second mold could potentially be attributed to factors of low head pressure, a cold shunt in the gating system, or a restricted flow rate due to metal freezing at the filter.



*Figure 15 molds post-cast, but prior to removing from molds.*

Figure 16 shows the tandem casting after being removed from the molds. It seems the most likely reason for the second casting not filling is due to a cold shunt at the small 3mm entry gate at the blade of the axe, circled on the figure. This was not a problem in the first casting mostly likely due to the relatively high head pressure from being directly below the furnace and taking the brunt of the initial pour velocity. This small 3mm gate was decided upon to reduce the time it would take to prepare the molds, and was tested successfully in an aluminum casting. A potential reason it was successful in aluminum and not in steel could be the difference in fluidity between the two metals. Steel is much more viscous, so it is possible the small thickness of the gate coupled with relatively low head pressure caused a cold shunt to form, where in the aluminum, the liquid flowed through the gate easily.

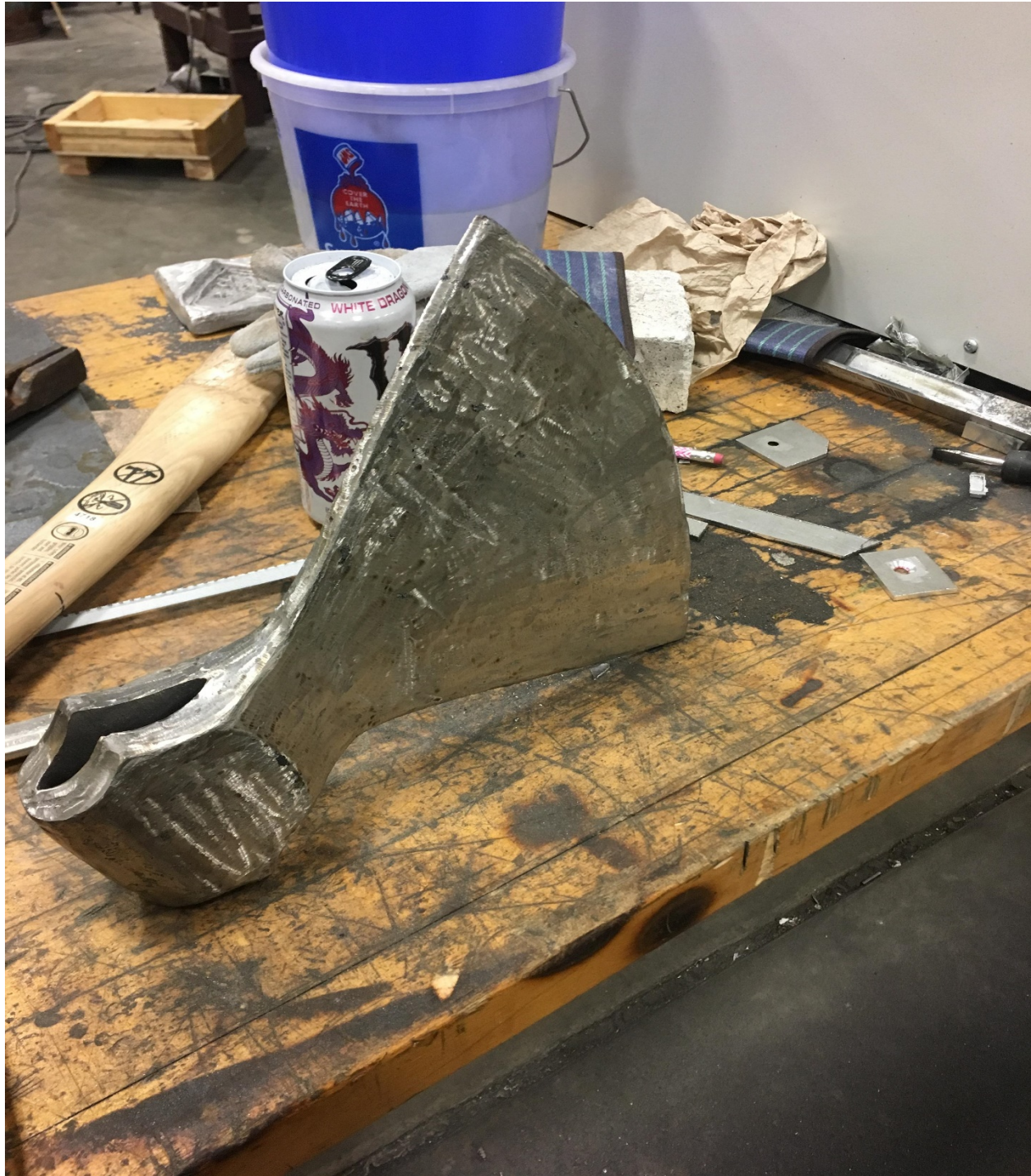
Figure 16 shows minimal flash around the casting, suggesting the patterns were well constructed and pattern mismatch was negligible. The core placed in the eye of the axe also prevented any metal from filling in the eye as well as any flash that would otherwise occur and there was virtually no porosity from the degassing of the binding agent in the sand or the mold glue used to hold the core in place.



*Figure 16 Castings after being removed from the molds*

Post processing of the axe was straightforward. A plasma torch was used to remove the bulk of the excess steel by cutting at the small gate on the blade as well as cutting along the riser at the top of the cast. Following these cuts, any remaining material from the gating system and the riser as well as the flash was removed using an angle grinder. The surface of the axe was also finished using the same angle grinder to remove any unwanted textures picked up by the mold. Figure 17 shows the shape of the axe after the machining phase was complete.





*Figure 17 image of axe head after machining*

The steel cast product underwent a heat treatment to ensure the physical properties desired for the axe. This process consisted of normalizing at 1850°F, then it was air cooled at room temperature. The axe head was then heat treated in its inter-critical temperature of 1250°F for four hours, then again air cooled at room temperature. The alloy was solutionized at 1850°F for one hour, then immediately

water quenched. After this quench, the axe head was sand blasted to a uniform patina in the final stages of heat treatment. The axe head was tempered at 400°F for four hours and was then air cooled. The patina that had formed on the blade of the axe was machined, and the axe blade was refined to be as sharp as possible.

After the heat treatment, the axe head was fixed to the haft. The haft was cut to size to fall within the maximum allowable length as outlined by the competition rules. Some sanding and staining of the handle was performed for aesthetic purposes. Figure 18 shows the assembled axe after a mineral oil coating was put on the head to prevent rusting.



*Figure 16 Final assembly of the axe*

## **Discussion**

Quality testing of the axe was done to allow both the team as well as the judging committee to have qualitative and quantitative data of the steel. A Brinell hardness of the axe head was taken and the average value found was a Brinell hardness of 450. This is expected of AF-96; however, it is possible that the surface of the steel is slightly softer due to decarburization, and the internal hardness is harder than what testing resulted in. Some surface inclusions are present within the steel. This is likely because such a high temperature material was poured into a sand mold and the velocity of which the steel entered

the mold. Some unexpected porosity was discovered on the bottom side of the axe; this is thought to be due to the degassing of the mold glue and may have been avoided with a more liberal application of the glue in that area. Given the relatively high impact toughness of AF-96 (as evidenced by its Charpy V-notch value), this axe should have no problem retaining an edge during the testing.

## Conclusion

This Viking axe was modeled after the iconic Dane axe used by Vikings in the late 10<sup>th</sup> to early 11<sup>th</sup> century, with some minor liberties taken with the design to improve castability, reduce porosity, and decrease post-processing machining time. AF-96 was elected to be used in place of a standard low carbon steel so that our axe would have the highest impact toughness and highest hardness possible. During casting, it was found that one of the axe molds formed a cold shunt in the gate. This could have been avoided by increasing the gate size from 3mm to 6mm, and by increasing the head pressure on the main sprue. Due to its high hardness and impact resistance, this axe will most likely be able to retain a sharp edge throughout the testing process.

## References

1. Christophe Adrien. January 7, 2017. What Was the Difference Between Danish, Norwegian, and Swedish Vikings? Viking Blog. <https://cjadrien.com/2017/01/07/difference-danish-norwegian-swedish-vikings>
2. National Museum of Denmark. Viking Axes. The Viking Age: Weapons. <https://en.natmus.dk/historical-knowledge/denmark/prehistoric-period-until-1050-ad/the-viking-age/weapons/axes>
3. Wu-Singel, Joan. "Low Alloy, High Impact Toughness Steel | TechLink." *TechLink Center*, [techlinkcenter.org/technologies/low-alloy-high-impact-toughness-steel/](http://techlinkcenter.org/technologies/low-alloy-high-impact-toughness-steel/).
4. *AISI 1080 Steel, as Rolled*, [www.matweb.com/search/datasheet\\_print.aspx?matguid=37ca3458dfbe482f1efdf59d52e424](http://www.matweb.com/search/datasheet_print.aspx?matguid=37ca3458dfbe482f1efdf59d52e424).