

Mississippi State University

Cast in Steel Competition  
Steel Founders' Society of America

Foundry Partner: Southern Cast Products

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## **Abstract**

A sharpened Viking Axe was produced by a team of students at Mississippi State University for the Steel Founders' Society of America Cast in Steel Competition. The competition mandates the use of using modern casting and modeling techniques to recreate the relic axe. Working alongside a foundry sponsor, Southern Cast Products, insight was gained into the process of casting. This report outlines the logical progression of the team's efforts from the competition guidelines to the final product.

## **Introduction**

As specified by the guidelines set by The Steel Founders' Society of America (SFSA) Schumo Foundation, the axe design should be that of a traditional Viking axe. Due to the various axe dimensions in this era, the specifications required by SFSA are that the bit should be between 6 and 12 inches long, and the haft should be 18 to 30 inches. Historically, this would be considered a one-handed axe. The Vikings would forge these axes by hand; however, this competition mandates that 80% of the head shape must be attributed to the casting process. This modern approach (casting instead of forging) is required, while maintaining historical Viking axe design.

A fully functional axe must be provided by each respective team. To evaluate the axes, two rounds of testing will be completed: sharpness and edge durability in chopping and robustness as a weapon. These testing methods have been described similarly on the History Channel program "Forged in Fire."

There were two types of Viking axes: one handed and battle axe. The one handed axes featured a toe-to-heel three to six inches long and a haft as long as 32 inches [1]. The battle axe featured a nine to eighteen inch toe-to-heel and a six to seven foot haft, sometimes reinforced with iron. Iron sources were scarce, so with an axe being a common tool, the Viking axe evolved from the everyday tool of the farmer [2]. The nomenclature of various parts of a modern axe are shown below in Figure 1 for reference.

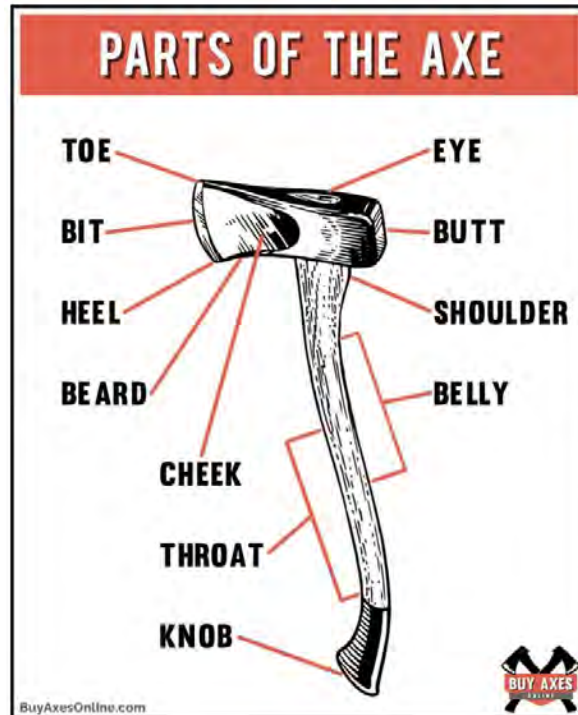


Figure 1: Components of a modern style axe [3]

Most Vikings were unable to have multiple axes dedicated to battle or farming. The same axe was commonly used as a weapon and as farm tools. As a weapon, the beard of the axe could be used to pull the opponent by hooking around their shield or even the back of the neck. The haft would commonly be longer than what is commonly imagined as a one handed axe. By having a longer haft, this allowed the Vikings to fight with the shield wall mentality; the haft allows the user to reach around their own shield and attack while still maintaining safety behind the shields. The toe of the axe was also accentuated to a point, similarly to the beard, allowing the axe to be thrust forward to attack. For axes solely used in battle, a thin cross section was used in order to efficiently split skulls. This thin profile would not be used as a farm tool due to its weakness in chopping wood. For farming and dual purpose axes, the weapon was used for tasks ranging from chopping to whittling. While the exact type of wood that was used for hafts remains uncertain, it is commonly accepted that the Vikings used hickory or a similar hardwoods to ensure its durability.

Several examples of historical artifacts were used to draw inspiration for our axe design. While Viking axes with large beards are aesthetically pleasing, the more traditional Viking axe had a longer face and a less pronounced beard. The initial model of the axe was based on a Dane axe from the National Museum of Denmark (Figure 2). This axe was discovered at a burial site dated to late Viking age to early middle ages [4]. The blade of the museum piece measured 7.24 inches toe-to-heel and was 8.6 inches from bit-to-butt.



Figure 2: Dane axe museum piece used to model our Viking axe [4]

Our axe was designed with this Dane axe in mind, as shown in Figure 3. The toe-to-heel length was increased to nine inches, and the blade section immediately in front of the eye was also lengthened to ensure more strength. The geometry and curvature were kept similar to the museum piece. The ridge before the bit was not added since the axe was cast and did not need a hardened edge forged into the blade bit.

Viking axes were often folded over to form the shape of the eye. The eyes on these axes were typically round, oval or D-shaped [5]. The eye on this axe was designed to resemble the museum piece previously mentioned, which had a D-Shape. Our axe eye was designed to have a 0.875 inch radius in the rear and 0.25 inch radius in the front, approximately 1.5 inches front to back. Viking axes were fit to the haft by sliding the head from the bottom of the haft. There were a few instances of wedging the head to the haft [5].

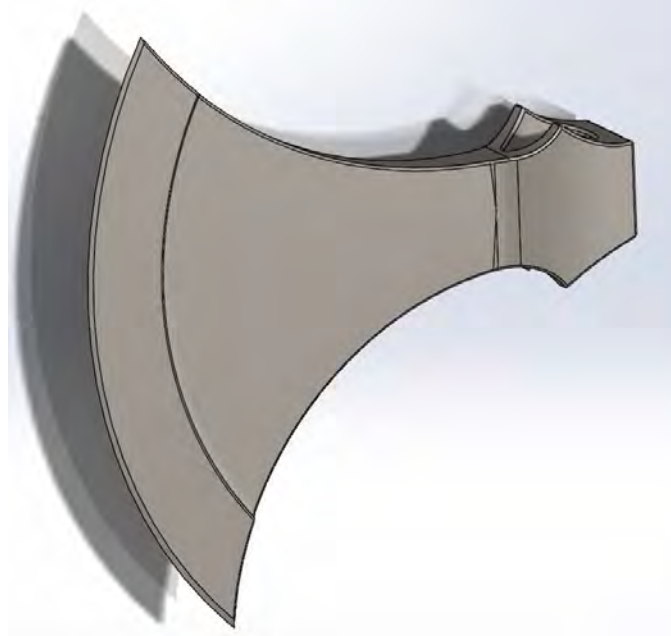


Figure 3: Initial Solidworks model of Viking axe

### **Axe Design**

Design of the pattern was crucial to creating a solid foundation for the axe. The pattern incorporates the original geometry of the design, but with several features modified to facilitate the casting and machining processes. An image of the pattern design is provided in Figure 4.

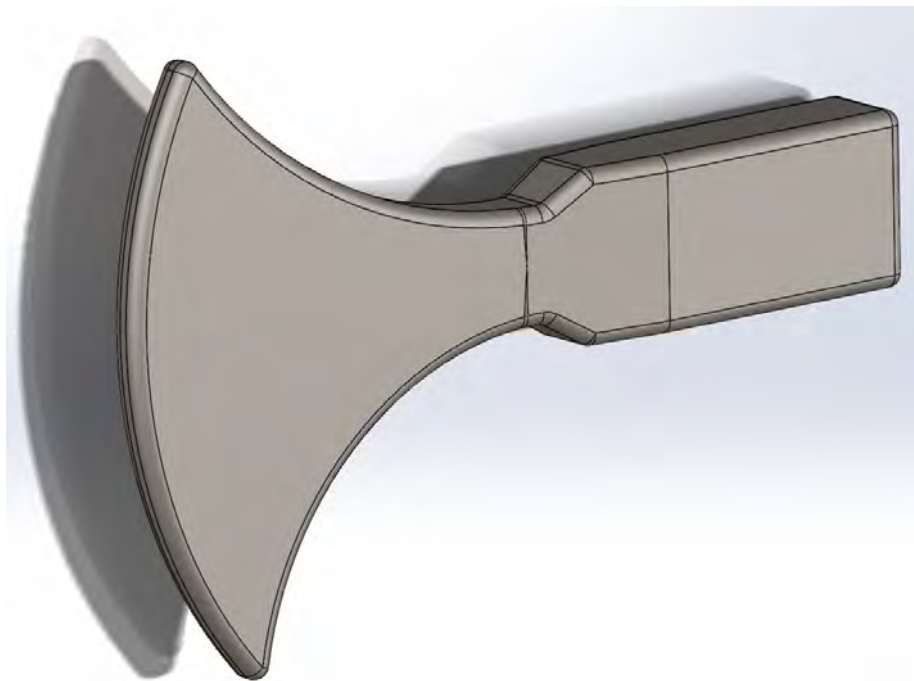


Figure 4: Solidworks model of pattern

Four notable modifications to the design of the pattern were implemented:

- The hole for the eye was omitted from the casting pattern in order not to impede the flow of metal into the casting.
- The overall thickness of the part was increased to aid the ingress of material into the part. Southern Cast Products (SCP) advised that any thickness less than 0.375 inch was a concern, so a bit thickness of 0.5 inch was chosen for the pattern.
- A gate, where the riser meets the part, was incorporated into the pattern design for ease of machining. The four inch long rectangular prism formed would easily fit in a vice and simplify the overall rigging required for the sand mold.
- The overall size of the pattern was increased due to concerns for shrinkage, following the recommendation of our foundry partner. Their general rule of thumb was that every 12 inches of travel is accompanied by shrinkage of 0.25 inch.

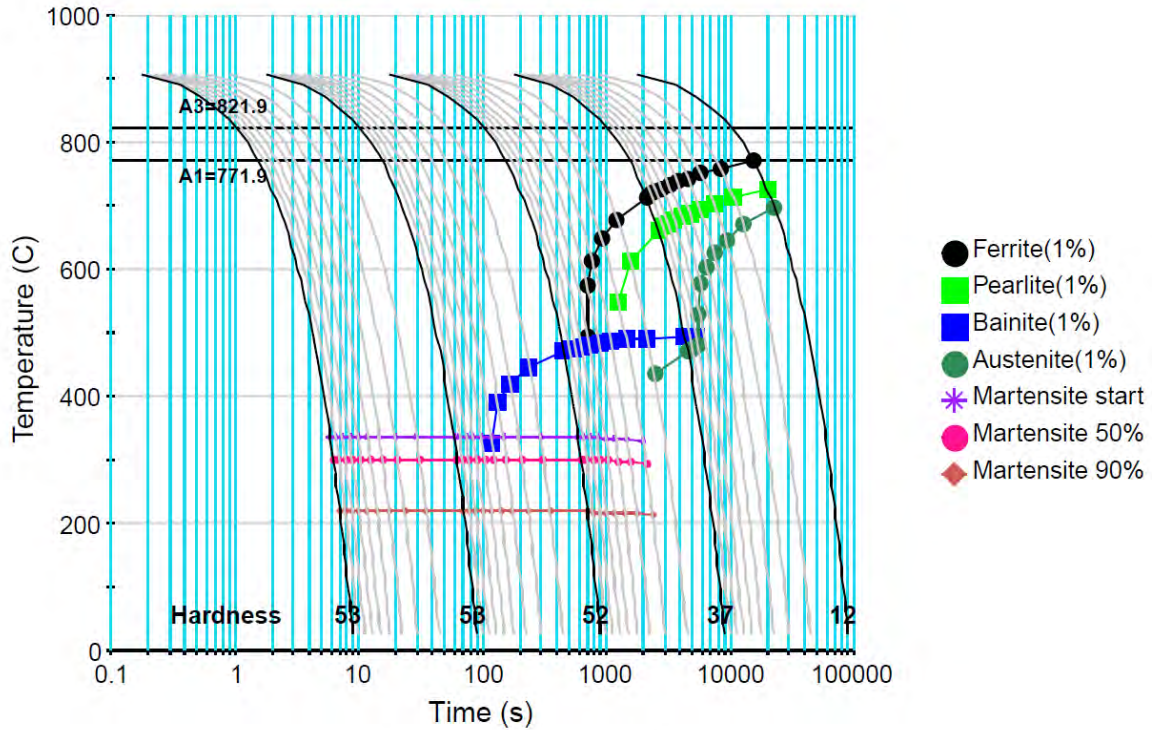
Traditional axes had thin cross section due to the forging process used. For casting, this could cause premature freezing before the mold has been filled completely; therefore, a wedge shape was used. This was completed by maintaining the side profile of the head but adding extra material to the cheeks to give a simple draft angle from haft to blade.

Due to SCP being a sizable casting operation, using a custom alloy was not feasible. However, a common alloy they use is a composition designed for mining equipment teeth. This alloy has shown to be a very hard, durable steel. To improve this steel's properties, a heat treatment consisting of a rapid quench and temper was used to further harden the axe and maintain a sharp edge as long as possible.

Table 1: Chemistry of axe obtained via spectrometer and carbon-sulfur analyzer

<b>Element</b>	<b>C</b>	<b>Mn</b>	<b>Si</b>	<b>Cr</b>	<b>Ni</b>	<b>Mo</b>	<b>S</b>	<b>P</b>	<b>Al</b>	<b>V</b>	<b>Cu</b>
<b>Spectrometer</b>	0.27	0.86	1.13	1.62	0.26	0.33	0.004	0.010	0.025	0.006	0.03
<b>Carbon/Sulfur Analyzer</b>	0.295	X	X	X	X	X	0.004	X	X	X	X

To confirm the material properties that were originally desired, the chemistry in Table 1 was fed into JMATPro software. The constant cooling transformation (CCT) curves (Figure 5) as well as a martensitic hardness value were simulated.



Austenitisation temperature (C) : 925.0  
 Grain size : 6.0 ASTM

Figure 5: CCT curve generated with JMATPro

The CCT curve predicted the cooling rate required to obtain the martensitic microstructure desired to harden the material during quenching. A grain size of 6.0 ASTM was input from the “Austenite Grain Size Estimation” tool in JMATPro.

### Axe Manufacturing

SCP required symmetrical axe halves in order to produce a sand mold, so mirrored half-axe patterns were cut out of 0.75 inch thick pine boards. The patterns were then connected with dowel rods shown in Figure 6, then milled (Figure 7) to produce the two halves with angled cheeks. These halves were belt sanded to refine their shape.





Figure 6: Split positive pattern with dowel pins



Figure 7: Milling wooden positive

Due to the relatively small amount of steel required for a single axe, pouring into a single axe mold was not recommended. It would be difficult for the ladle operator to retract the pour quickly. Therefore, 4 axe patterns were made to increase the mold size, giving the operator more reaction time. This also provided backup axe heads in case of any defects. The 4 axe patterns were arranged in a radial pattern around a single, central riser. Each individual pattern had a smaller, secondary riser on the cheek of the axe and 3 vents near the bit for the evacuation of air from the part cavity. Figure 8 shows the positive completed patterns for both the cope and the drag. A releasing agent called Zip-Slip was applied [6].



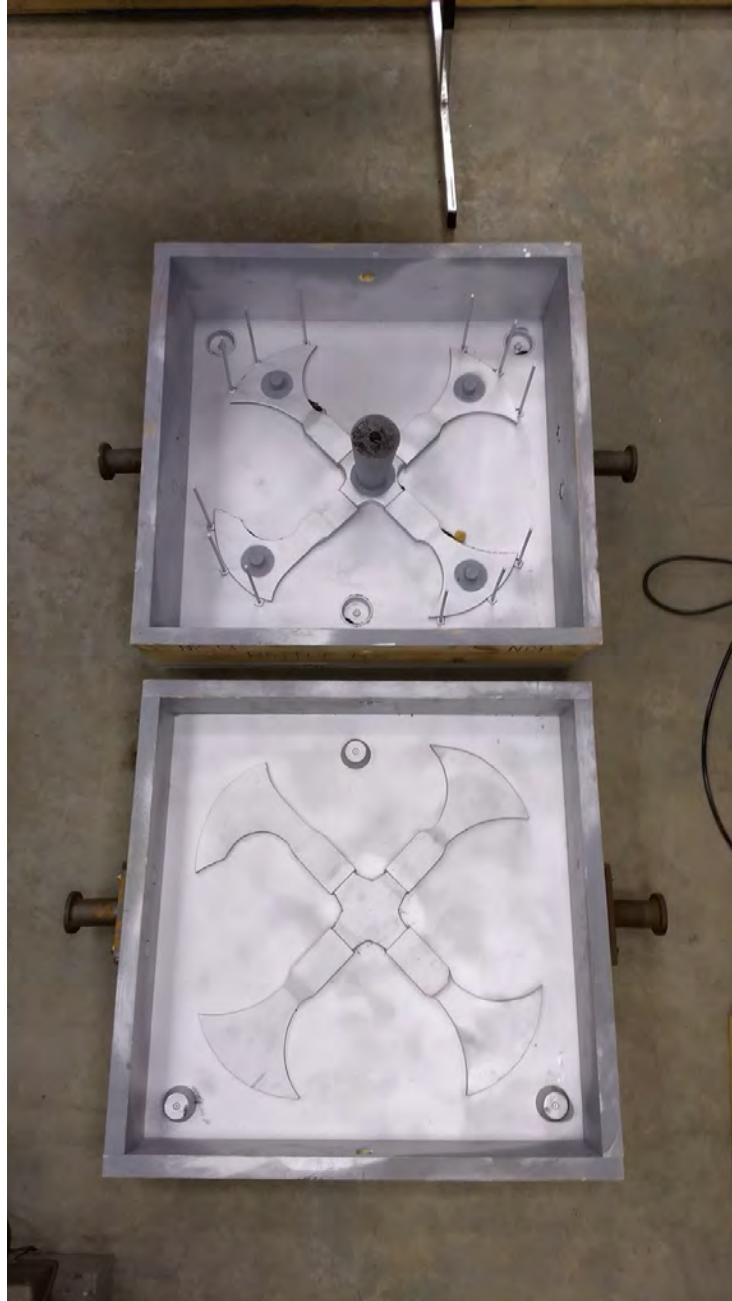


Figure 8: Positive made by SCP

The sand molds were made using American Foundry Society Grain Fineness Number (AFS-GFN) 50 silica sand from Illinois. Phenolic Urethane No-Bake (PUNB) type chemical binder was mixed with the silica sand to accelerate curing time. Once the cope and drag were cured, they were assembled together and used to cast.

Casting was performed by SCP alongside their regular castings using an alloy composition designed for mining equipment teeth. A central riser feeding the four patterns affords the casting operator more control while pouring to prevent spills. The alloy was melted in a 5,000 pound

Inductotherm furnace with liquid argon to displace the atmosphere. After melt was achieved and lollipop samples confirmed the target chemical composition, a portion of the melt was poured into a smaller, more manageable ladle for pouring the melt into the molds. Figure 9 shows a casting ladle used at SCP.



Figure 9: Pouring into a mold at SCP [7]

The casting was extracted from the sand after sufficient cooling time. Figure 10 shows the resulting cast of the four axe heads. Thanks to the constant dialog between the axe team and SCP, the design of the pattern rendered a successfully filled casting. All features of the pattern were formed.



Figure 10: Cast axes in circular pattern

The axe heads were freed from the risers and vents using a cutting torch. The cast heads were normalized at 925°C and slow cooled prior to machining, in order to homogenize and to soften the material. Afterwards, the faces of the runners on the axe were milled to provide reference surfaces for the subsequent machining.

Next the cheeks of the axe were machined to a thickness of 0.0625 inch at the bit (Figure 11), with a 2° rise along each face while moving away from the bit. The second taper connecting the cheek to the eye was partially milled to reduce the amount of surface grinding needed in the upcoming steps.



Figure 11: Planing faces of axe (left), milling cheeks (right)

The holes for the front and rear of the eye were drilled on a manual mill. A CNC mill was then used to remove the intermediate material between both holes. Excess material on the butt end of the axe head was cut off prior to final shaping using a belt sander as shown in Figure 12. The extra material on the butt of the axe was cut off at the latest time possible, just before final shaping using a belt sander.



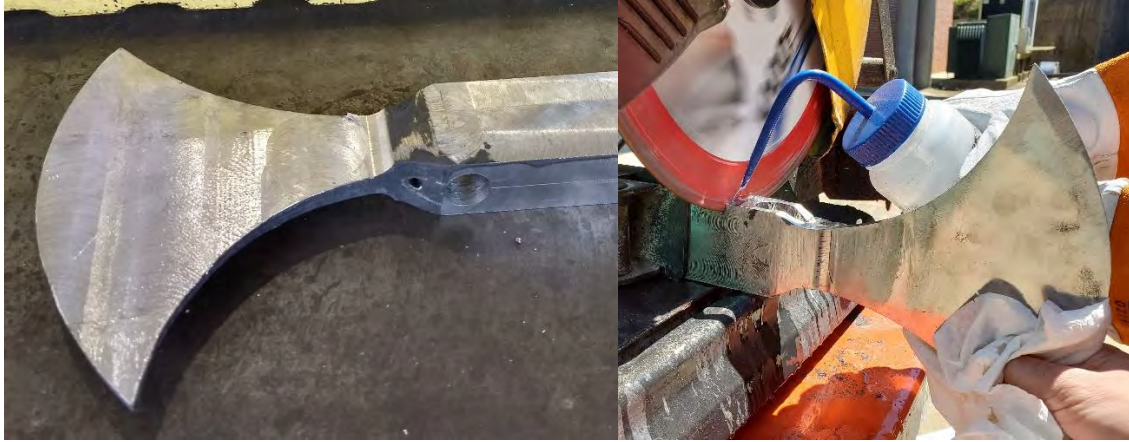


Figure 12: Holes drilled through head for eye and removal of the gate (left), cutting the excess material from the back of the head (right)

After all machining was completed on the head, a quench and temper cycle was performed to produce a martensitic microstructure. This was achieved by slowly heating the head to 900°C, and rapidly quenching in a large water bath with circulation pumps. To relieve residual stresses caused by the quench, the head was tempered at 200°C for approximately one hour, then allowed to cool at room temperature. The JMatPro simulated as-quenched hardness was 53.17 HRC. Once the axe was quenched, the hardness was measured to be 534 Brinell, or approximately 54 Rockwell C (1.55% difference).

X-ray Computed Tomography (CT) scans were conducted to check for voids and inclusions inside the axe casting. Figure 13 shows the head mounted in the CT machine.

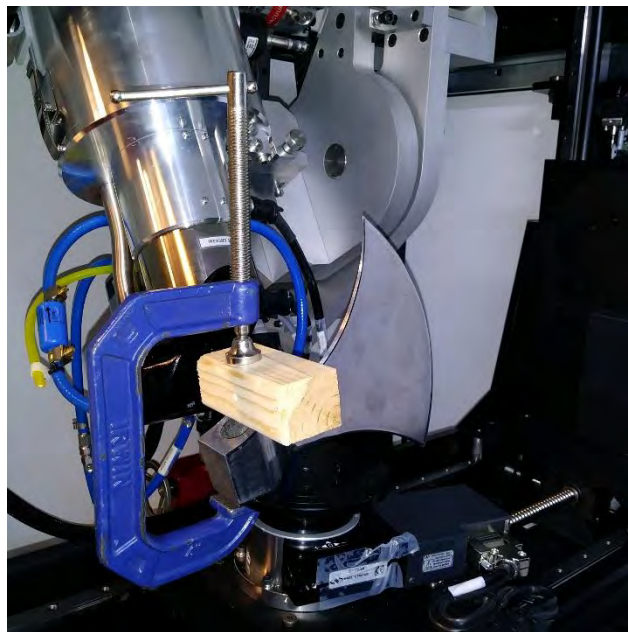


Figure 13: Axe head mounted in CT machine

The scans showed the presence of some voids within the cast. Figure 14 shows the CT images of just forward of the eye, where the highest concentrations of voids are located. Due to their location, the voids were not deemed to be a concern for the structural integrity of the axe head.

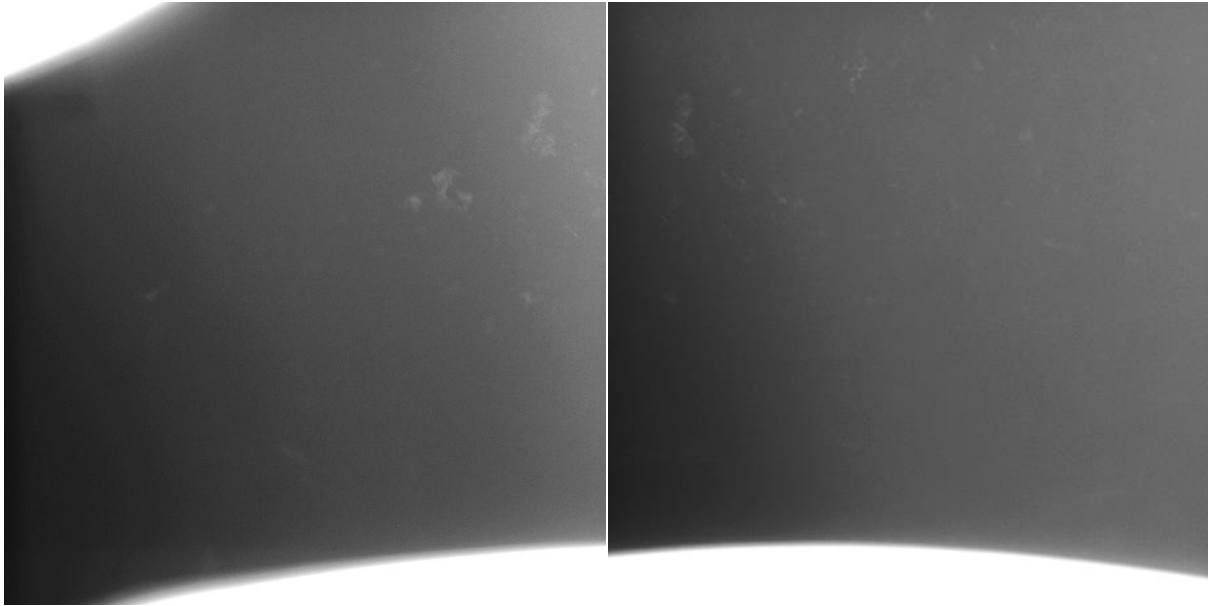


Figure 14: CT images of axe

To achieve a sharp cutting edge, a dedicated sharpening system was fashioned. It consisted of two rods attached to Heim joints, which were mounted onto adjustable ratcheting rails to allow for independent control of sharpening angle on each side. Water stones were attached to tubes that could slide along the rods to maintain a uniform angle across the bit. The primary edge from belt sanding was sharpened at a  $26^\circ$  degree angle with sharpening stones starting at 180 grit and progressing to 3000 grit, with careful consideration for producing a consistent wire edge at each grit level, before advancing to a finer one. Final stropping of the edge was performed using newspaper to hone the cutting surfaces. The cheeks of the sharpened axe were then wet sanded using a dual action polisher with progressively finer silicon carbide abrasive sheets, with the goal of reducing marks and blemishes introduced during material removal while milling and belt sanding. The final axe head is shown in Figure 15.



Figure 15. Final resulting axe head

### **Haft Design**

In designing a haft, there are two important features necessary in order to improve the robustness of the axe: indexing for blade edge location and the knob to locate the end of the shaft. These are modern design queues, but it was decided that this design would result in a more comfortable, effective weapon as a whole. Overall, an oval cross section was chosen for the haft. By giving the haft a belly and throat, as well as a slightly smaller radius on the front side of the haft, the axe wielder can intuitively tell how the bit is oriented without having to look at the axe. The knob of the haft also lets the wielder know where the end is.

In keeping with the Viking axe theme, an elongated cross section was given to the shoulder of the axe to facilitate whittling. The wielder can slide their hand to the shoulder and get better control of the axe angle.

In order to produce a haft that can withstand the abuse that an axe experiences, a long, straight-grained hardwood is used. Due to its reputation for producing excellent axe handles as well as its availability in our location, we opted to use hickory.

A wedge fitting for the haft was chosen to guarantee a tight fit. For wedging, a kerf is cut into the haft typically about  $\frac{2}{3}$  to  $\frac{3}{4}$  the depth of the eye [8]. Some suggest the use of linseed oil, glue, or epoxy to help seat haft and wedge into the eye.

### **Haft Manufacturing**

Starting with a quarter log of hickory, a cut was made to ensure that only the white wood outside the core was incorporated in the haft as shown in Figure 16.





Figure 16: Cutting the haft material from a hickory log

Keeping in mind that a throat and belly were desired in the haft, as well as a knob at the bottom end of the haft, a 2 inch offset cylinder was turned on a lathe, leaving a large square end for the knob (Figure 17). Once the lathe work was completed, the eye and the seat for the shoulder were made with a rotary tool and belt sander.



Figure 17: Haft machining on lathe (left), making eye and shoulder (right)

Both belt and hand sanding were used to produce the final contours of the haft (Figure 18). Hand sanding up to 1200 grit sandpaper was also used to provide the haft with a smooth, splinterless finish.



Figure 18: Sanding final contours of the handle

### Assembly

With the axe head polished and the haft completed, the final assembly could begin. For a secure fit, it was decided that a driven wedge along with epoxy would together yield a more robust mating. A kerf was cut front to back 75% down the depth of the eye as shown in Figure 19.

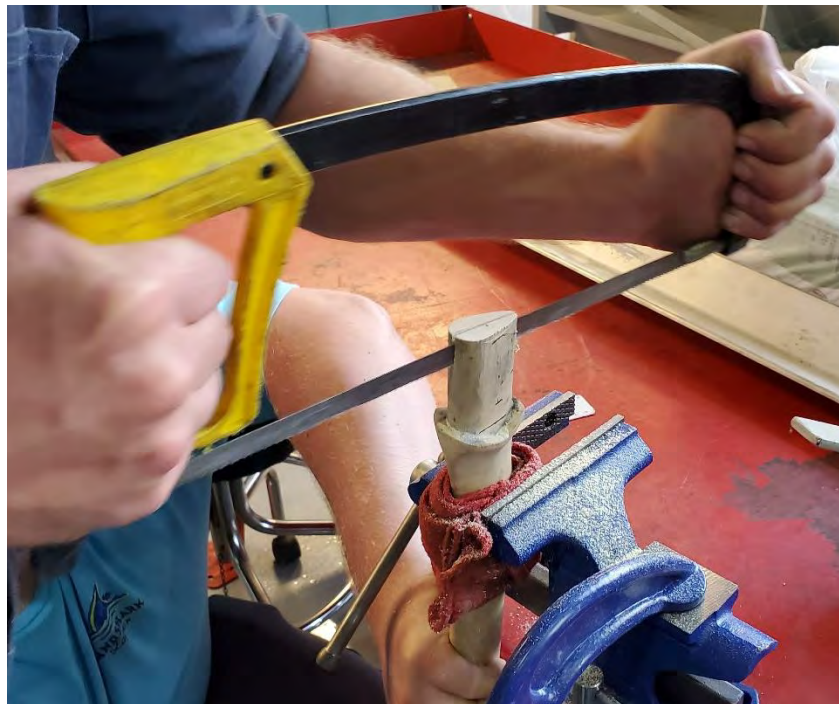


Figure 19: Cutting the wedge groove in the eye

A 12° wedge around 2 inches deep was made from the same hickory log as the haft. A multipurpose clear epoxy was mixed and used to coat the eye and the hole of the head, while



using masking tape shielding surfaces where epoxy was not needed. After sliding the head onto the haft, the wedge was driven into the kerf and hammered to obtain a tight fit. Approximately 4 hours after and the epoxy had cured, the excess epoxy was cleared away by removing the masking tape and by sanding. Three layers of shellac were rubbed into the exposed surfaces of the haft to protect and seal the haft from moisture and oil, preserving the natural hickory finish. The surface of the axe head was also coated with Premier Rust Inhibitor by LPS to prevent corrosion. The final overall weight of the axe is 2.81 lb. Figure 20 shows the axe as completed.



Figure 20: The completed axe

### **Acknowledgements**

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