A Study of Different Heat Treatments on Historically Accurate Cast Viking Axe Heads and the Fabrication of an Axe

Team Members: Jacob Melvin, Raven Maccione, Vajrakaran Sachdev

Additional Contributions: Chengyang Zhang

Foundry Partner: Harrison Steel Castings Co.

Affiliated institution: Purdue University, West Lafayette

I. Abstract

Four viking axe heads subjected to different heat treatment methods were fabricated using a medium steel grade created by Harrison Steel Castings Co. for the purpose of being entered into a Steel Founders Society of America competition titled “Cast In Steel”. The shape was designed to mimic the shape of historical viking axes with a beard, and the size was designed to be usable as both a one handed and two handed axe. Dulling tests were performed on the blade edge to determine the most durable heat treat method. Optical micrographs of sectioned samples showed that martensitic structures formed under quenching, while upper and lower bainite formed for as-cast sample and normalized axe head respectively. Hardness measurements indicated that carburization introduced a shallow hardness gradient and had minimal effect on increasing the hardness. The axe head was tested for robustness as a tool via log chopping tests, and the axe submitted was determined to be the best tool/weapon hybrid made from a strong steel which displayed robustness during the applied sharpness test.

II. Introduction

Origin of viking axes

The axe was the common tool used by every farmer in Viking age Scandinavia. This tool was versatile and could be used in a variety of applications, such as building houses, smaller farm tasks such as hunting, and even in combat. Since iron tools were common and used from a young age, the axe became the personal weapon of choice for the farmer. This everyday tool was developed into the game changing viking combat axe. [1]

A viking axe is comprised of a bladed head and a long handle. When held close to the axe head, the tool could be used for more dextrous purposes such as carving wood, and when held close to the end of the handle it could be swung around and used in more high impact/lower accuracy applications such as tree cutting or war. Battle axes could be divided into two broad categories: one handed and two handed. One handed axes were more versatile and could be used for a variety of purposes including battle, but the two handed versions were exclusively designed for war. [1]

Some viking axe heads were light and thin, whereas others were thick and heavy. The smaller one handed axes were used in fast, close range combat and could even be used as a throwing weapon. The two handed axes had a longer reach, comparable to a sword, which made them a fierce counter to the more expensive alternative weapon. Typical viking axes styles are shown in *Figure 01*. [1]

Figure 01: Various examples of authentic Viking axes showing the characteristic features of their axe head including the beard, shape and mounting configuration

"*As the combat potential for the one-handed axe was realized, special axe head shapes were developed. There began to appear combat axes with a square shaped projection at the bottom of the axe head. This type of axe was called the 'Bearded Axe'. When the edge of an opponent's shield was hooked by the 'beard' of the axe, leverage could be used to control the shield with the axe. By using this technique, a shield could be forced in a direction away from the opponent, opening up attack possibilities against the opponent's body, or even pulling or forcing a shield out of an opponent's grasp."* [1]

Today, most everyday iron and steel tools are forged. This was thought to be a common method of making tools and weapons dating back to the medieval era when steel was first being worked with. However, more recent evidence of some early tools appear to show that there were cast axes as well, which do not show the markings of being forged. This would counter previously thought convention and would raise new questions as to how these heads were made [2].

This report seeks to investigate how an axe head would be made and what its properties would be if made via the casting method. While the vikings of old could very well have cast their weapons of choice, they most likely did not have the level of casting knowledge that is present today. With this in mind, the purpose of this project was to create the best possible axe using the technology of the present, while maintaining key characteristics and the spirit of the viking axes of legend.

There are many methods of these modern day processing techniques, and the ones used for this work are outlined below:

Carburizing steel involves adding carbon to the surface of a steel at a high temperature to have it diffuse into the steel, effectively hardening the steel surface. The difference in the carbon content can be observed by the change in microstructure and hardness from the outside in. This carburized outside leads to better durability and edge retention for blades. [3]

Quenching the axe heads halts carbon diffusion, and forms more martensitic and bainitic microstructures than the steel would under other circumstances. Martensite is formed when austenitized iron-carbon alloys are quenched to a relatively low temperature. This leads to material hardening and crack propagation inhibition that makes the quenched piece stronger. Directional quenching can also be utilized to create a hardness profile in the part. This was done on oil quenched trials to make a harder edge and a softer back, resulting in a harder edge will result in better edge retention at the cost of sharpenability. [3]

III. Method

The axe for this project was designed to fit the bearded viking axe style. The beard, shown in *Figure 02c*, was designed with significant length to allow for use as a hook. It’s uses include pulling enemy shields and armor as discussed previously, but also provides versatility for other applications, such as allowing the user’s hand to grasp directly behind the blade for more fine tuned blade movements. The top view in *Figure 02b* shows the wedge shape of the axe. The wedge shape is well suited for splitting both logs and skulls. With a 9.5” overall blade length, accuracy becomes less vital, and the 28” handle on the axe allows for aggressive, low accuracy sweeping swings and powerful, overhand swings for chopping and pillaging. With a 4.62 pound axe head, massive power can be displaced at the blade edge with each swing.

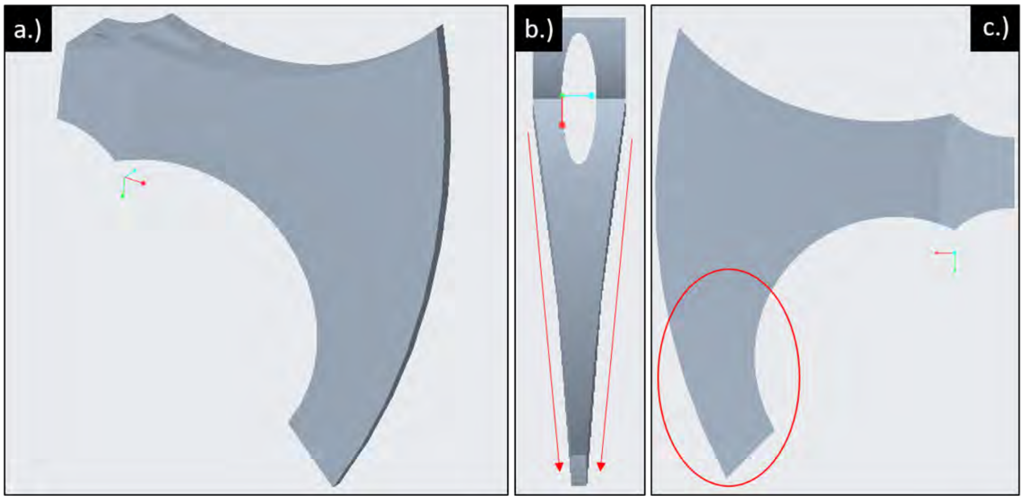

Figure 02: Isometric (a), top (b), and side (c) view of the viking axe head modeled in Creo Parametric.

The model shown had risers and gates added, and the Magmasoft program was used to model the flow and temperature of material as the mold was filled. Next, it was translated to a mahogany wood pattern via CNC router at Harrison Steel's pattern shop. The wood patterns were used to create no-bake silica sand molds. The sand mold was removed from the pattern and left to cure. The cope and drag sides of the mold were sprayed with an alcohol based zircon wash to fill any voids and create a smooth interior surface to help prevent burn on sand in the steel casting. The wash was then fired using a torch to dry completely. Metal chills and eye-hole cores were placed onto the pattern, and the cope and drag were glued together using a high temperature industrial adhesive. A pour cup was glued to the top of the mold to guide pouring therein completing the mold construction (See Appendix A for a series of images describing the process). The molten medium alloy steel was subsequently poured into the 17 molds at the end of one of Harrison Steel's batches for the chosen high strength grade. The axe heads were left to cool in the molds and were then mechanically shaken out. The risers and gates were lastly removed with acetylene torches .

Table 01: Attempted heat treat methods for axes and micro samples. The axe sections referenced are explained in *Figure 03*.

Micro Number	Axe Section	Preparation Method	Macro Hardness
90	1	Water Quench from 1650°F // 2 Hour Carburization at 1200°F	94 RWB
91	2	Normalized // Air Cooled	20 RWC
92	3	Oil Quench from 1650°F	47 RWC
93	4	As Cast	32 RWC
96	3	Oil Quench from 1650°F // Temper at 1050°F for 2 Hours	95 RWB
102	4	15.5 Hours at 1650°F in Carburization Box // Water Quench // Temper for 3 Hours at 1000°F	??

Figure 03: Photograph of the axe sectioning pattern for various heat treat attempts.

Various sections of the axe were heat treated according to Table 01 and *Figure 03*. The sections were dissected, mounted in bakelite, polished and etched using a Nital solution containing 4% Nitric acid and 96% ethanol. Following this, the samples were observed using an OLYMPUS BX41M microscope, and other optical images may be found in Appendix B.

Micro hardness tests were performed on all samples by placing them on a Wilson Hardness Tukon 1202 tester. The load was set to 1k/2k with a Vickers hardness indenter. The hardness profiles across six samples were obtained by taking measurements from the casting surface to the center of the samples at 0.0035 inch increments, measured from the center of the indentation.

Due to the competition rules requiring at least 80% of the final axe head shape being attributable to the casting process, grinding was the shaping method of choice to fashion the blade. The edge of the axes were ground to a point using a 4” wheel grinder and a cutting wheel. The axes were polished with a 40 grit flapper wheel (see Appendix C). The average weight of the finished axe head was 4.62 lbs, and the cast axe heads had an average of 5.13 lbs. As such, it was calculated that 90% of the cast axe shape was retained via this production method. They were heat treated with four different methods to determine the effect on properties.

The four heat treat methods chosen for testing were: a normalize only, normalize with carburization and temper, water quench with carburization and temper, and oil quench only. The carburization was first attempted during the temper at 1000°F; however, the carburization had very little effect as the temperature did not adequately promote carbon diffusion. Carburization was then done during the normalize stage at 1750°F in the austenitic region of the material. The heads were then directly air cooled, water quenched, or oil quenched to room temperature.

Edge dulling tests were performed to see the effect of the blade after being rubbed against an abrasive surface. The change in blade width after running the blade edge against a 220 grit sharpening stone 10, 20, 30, 40, and 60 times was observed under a stereomicroscope. The weight of the sharpening stone was the only pressure applied to the edge (8 ounces). The edge was freshly sharpened and was micrographed before the dulling tests were initiated. The edge width was measured to indicate how dull the edge was and how much it had worn down.

Since the importance of edge retention was the focus of qualification in this analysis, the heat treated axe which displayed the best durability and shear resistance under the dulling test was the heat treat method of choice for the final piece. The final piece was mounted upon a 28” axe handle. The handle was shaved down on the backside using a rotary rasp file on an impact gun to better fit the eyelet on the axe head. A wedge was hammered long ways into the top of the handle. The remaining portion of the handle was removed with a flush cut saw to complete the village pillaging tool.

IV. Results & Discussion

Razor blade sharpness is quantified by the force used to cut through a loop of thread. Since these axes are not sharpened to such a severe angle and therefore are not "razor" sharp, measuring and quantifying sharpness for an axe blade was very difficult [4]. Blade resilience was tested via the dulling test as outlined above, and the dulling test results are outlined below.

Table 02: Edge width (mm) of axe heads after successive passes against an abrasive surface to measure the dulling of the blade for different strengthening techniques. Only key data points shown.

# of Passes	Control (mm)	Oil (mm)	Carb + Oil (mm)	Carb + Water (mm)
0	0.025	0.025	0.025	0.025
20	0.2	0.13	0.1	0.12
40	0.23	0.15	0.15	0.11
60	0.25	0.21	0.15	0.12

The measurements indicate that the best blade for wear resistance was the carburized and water quenched piece, which showed the lowest amount of dulling. Photos of blade edge measurement are depicted below. The process uses a reconstructed scale bar in order to estimate the blade edge width.

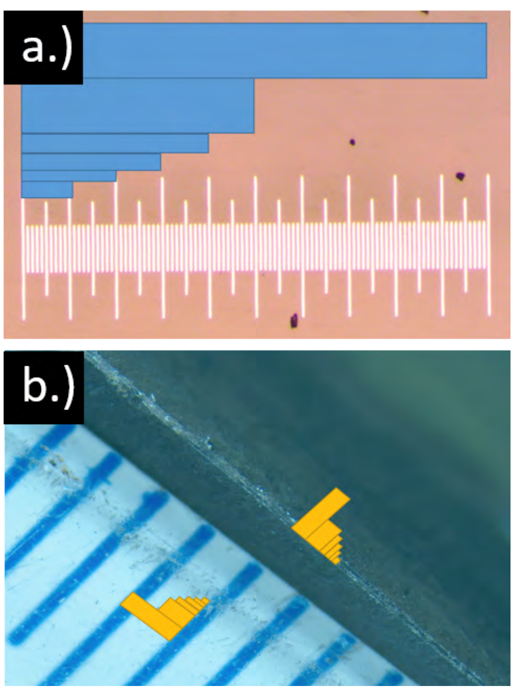

Figure 04: The scale bar (a), with a shape built comparison in order to make an overlay to more accurately measure the blade edge width, with (b), showing how scale bars were adjusted to each image and then rotated to measure the blade edge.

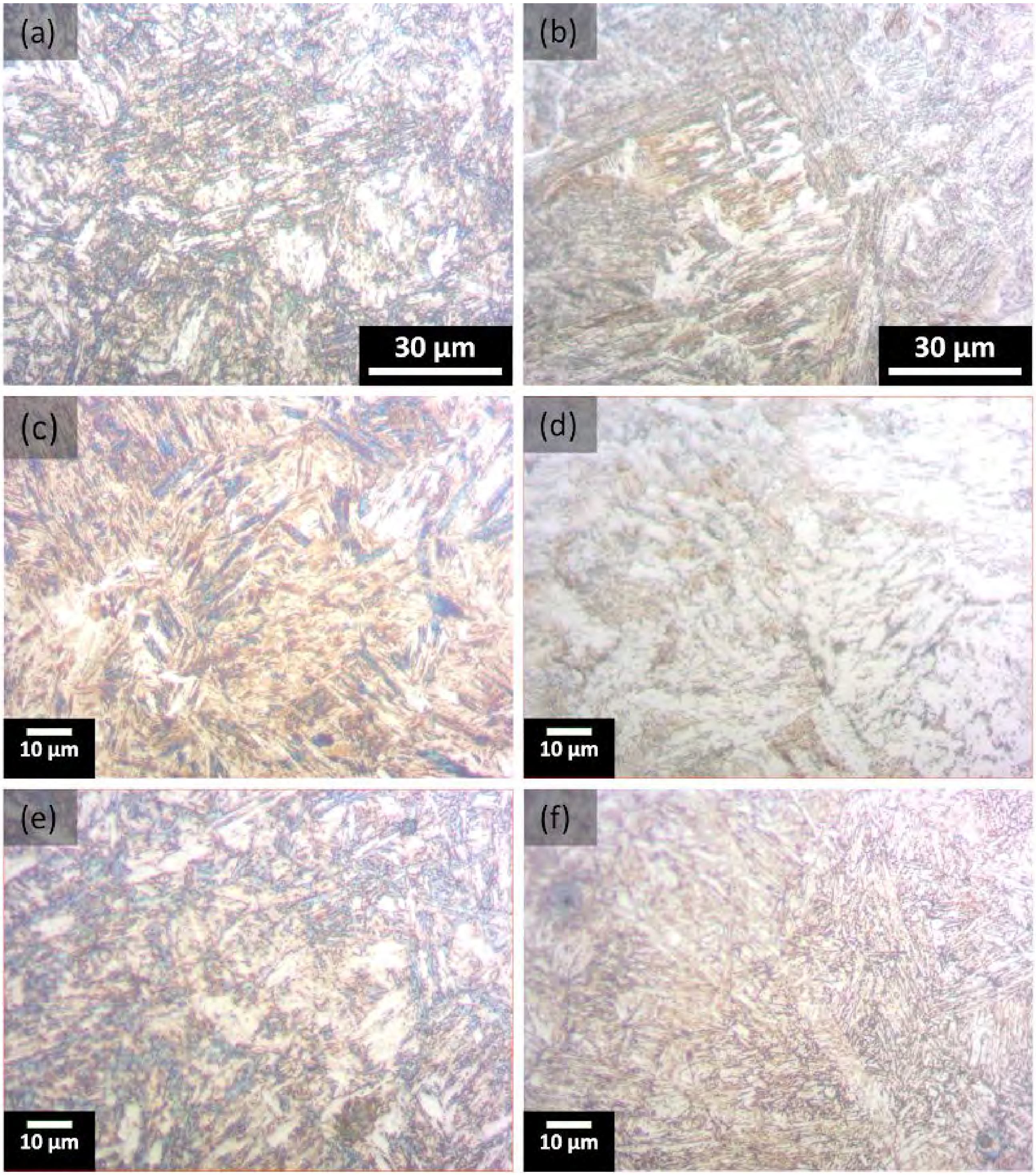

Figure 05: Optical micrographs of (a) sample 90, (b) sample 91, (c) sample 92, (d) sample 93, (e) sample 96 and (f) sample 102.

It was be observed from *Figure 05* that every sample aside from sample 93 (d) had some fraction of a martensitic structure present. Many of the needle-like grains visible in *Figure 05* (except for (d)) were super saturated, martensite twin grains; the quenched samples displayed light colored areas which are retained austenite that did not transform during the rapid quench [5]. A larger fraction of retained austenite exist in sample 90 (a) and sample 96 (e) than there was in sample 102 (f). Sample 90 (a) and 96 (e) were water quenched and oil quenched respectively. The microstructures are very similar in both samples. Both samples contain tempered martensite [6]. The twins are very cloudy due to carbon diffusion during the tempering process. The water quenched 102 (f) sample displays a very different structure from any other quenched specimen. The grains are very fine and exhibit minimal signs of tempered martensite; this was because it was tempered for one hour longer and 200°F lower than the other water quenched specimen. The twins in sample 102 (f) are much shorter and smaller than what is present in sample 90 (a), 93 (c), and 96 (e). Sample 91 (b) displays similar tempered martensite twins; however, it appears within a cloudy plate-like structure resembling lower bainite [7]. The different size in twins is explained by the severity of the quench. The resulting cooling rate for an oil quench is lower compared to the cooling rate of a water quench used on sample , showing a more coarse structure under a less severe quench.

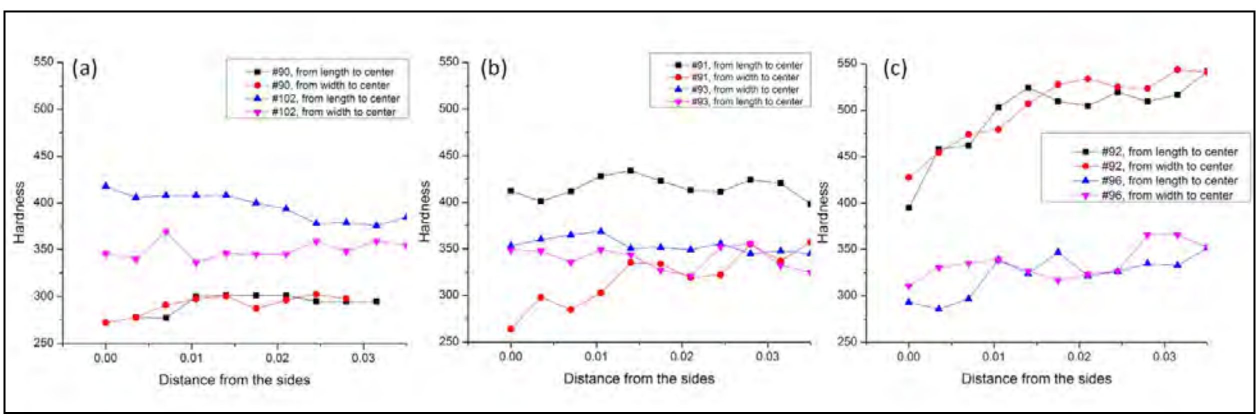

Figure 06: Micro hardness measurements from the lengths and widths towards the center of the surface for (a) sample 90 and sample 102, (b) sample 91 and sample 93, (c) sample 92 and sample 96.

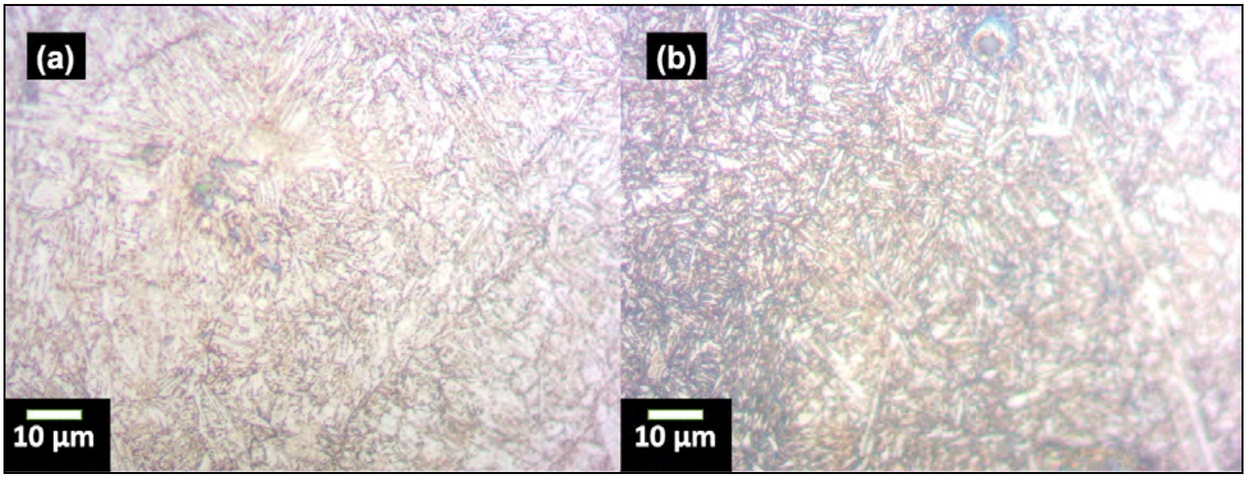

Figure 07: Example of carbon gradient from sample 102 where (a) was taken from the non-carburized edge, and (b) was taken close to the carburized edge. Note the grayscale difference due to diffusion of the carbon from (b) to (a). There may be some burning due to the etching agent and edge proximity.

The hardness gradient in the samples due to treatment methods and carbon diffusion are confirmed by *Figures 06 and 07*. Comparing the microhardness and the optical images, It appears that the blade material has smaller grains and darker, higher carbon concentration grains, leading to higher hardness. Sample 90 showed large regions of retained austenite, leading to the lowest overall hardness. It could be observed that sample 102 had the smallest grain size compared to all other samples, suggesting the highest hardness. This was also confirmed by the micro hardness tests. Even in softer regions, sample 102 had the one of the highest edge hardness values compared to the other samples. This can clearly be seen in *Figure 08*, where the tip much smaller grains and higher apparent carbon concentration. There is an anomaly with sample 92 and its hardness values as shown in *Figure 06*, where its hardness increases toward the center of the axe. No other sample does this indicating that there may have been either errors in the measurement, or may have had issues with processing leading to edge softening and center hardening. It is also worth noting the micrograph of sample 92 and 96 showed different hue compared to the other ones due to oil quenching.

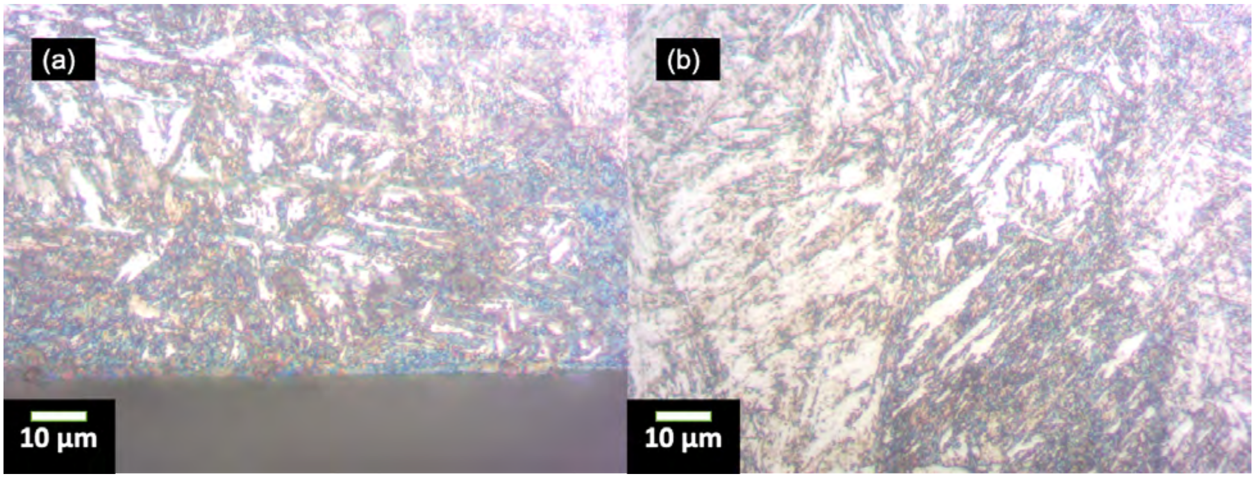

Figure 08: Comparison of grains size of the edge (a) vs the center (b) of the axe for sample 90. Note for the color that the edge may have been discolored slightly by the etchant.

Both sample 90 and sample 102 were carburized. Sample 90 was carburized for 2 hours at 1200°C and sample 102 was carburized for 15.5 hours at 1650°C. According to *Figure 07 (a)*, it was observed that sample 102 had an overall higher hardness than sample 90. This aspect was as expected because longer carburizing time and higher temperature can lead to higher penetration depth and higher carbon diffusion rate. Therefore, sample 102 was overall harder than sample 90. In *Figure 07 (a)*, A shallow hardness gradient could be observed for both samples. The gradient was as expected because at higher penetration depth, carbon concentration was lower and hence the hardness would drop from the exterior to the interior.

Sample 91 and sample 93 went through the least heat treatment steps. According to *Figure 07 (b)*, sample 93 exhibited no hardness gradient across the whole surface. This was as expected because sample 93 was an as cast sample. No treatment was applied to modify the mechanical properties. Sample 91 demonstrated an increasing hardness from the width towards the center. The hardness remained uniform measuring from the length inward. The hardness values were close as the two orientations approach towards the center.

Sample 92 and sample 96 were oil quenched. According to *Figure 07 (c)*, Both samples demonstrated significant hardness gradients. This result was as expected as oil quenching reduced the rate of heat being extracted, allowing the sample to spend more time forming the structure, generating a significant hardness gradient. However, sample 92 exhibited both a significant hardness gradient and the highest hardness among all the samples. This was not as expected because rapid quenching is more likely to produce a high hardness and result in a crack. Oil quench would typically yield a moderate hardness and less stress concentration at the case. It was possible that the property of the quenchant affected the outcome, or that there were errors in the measurement or processing method, leading to the unexpected results. It is also noted that the hard center and soft edge is poor for an axe design that needs to hold an edge and have a center that can absorb energy during use.

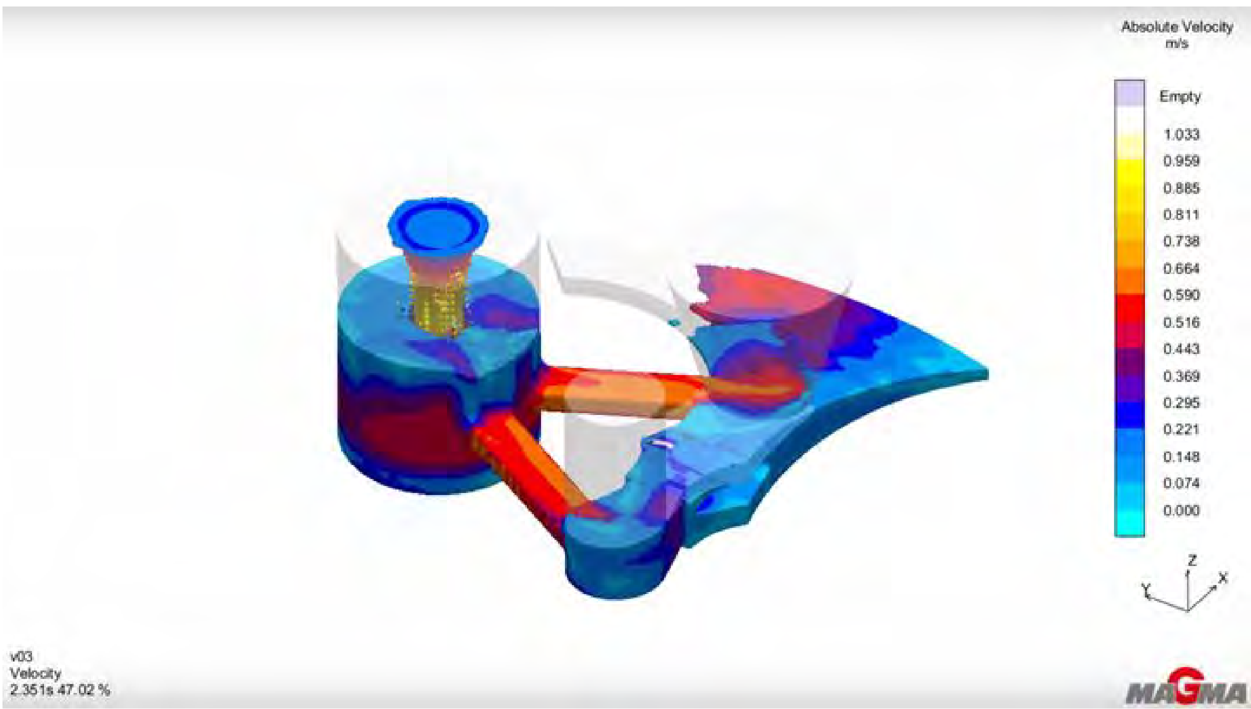

Figure 09: An image mid simulation showing velocity of the material flowing into the axe mold.

Despite the velocity predictions in the model being good, there were issues with cold shuts or splits forming on the edge of the axe. Out of 17 attempted casts, only 5 had edges without cold shuts or splits in them. This may have been avoided if another riser or gate was used, however that would have created issues with the chilled edge and the directional cooling of the initial part.

The best qualities for an axe overall were seen in sample 102 and with the water quenched and carburized axe head. It had a good microstructure gradient, better than average hardness toward the edges. We used the directional water quench and a carburized edge for the axe that was delivered.

Conclusion

The axe produced had many characteristic features of an authentic viking axe incorporated into the initial CAD model. The shape of the edge and the ratio of the length of the handle to the length of the blade edge puts this somewhere in between one handed and two handed axes, giving us a more versatile tool. The axe head was made thicker than what we would associate with a battle axe since it had to be capable of chopping wood while a beard was incorporated into the design to give the axe combat potential.

The tests performed showed us that the treatment method which gave us the sharpest axe and the best edge retention was carburization followed by water quenching and tempering (sample #102 from table 1). Throughout the dulling test, there was less blunting effect with each set of passes.(Log chopping ability demonstrated in Appendix D).

The challenges we faced during the production process included slight variance in pouring the molten steel into the molds which gave us a few axe heads with air bubbles present on the surface. We had difficulties with the cope side of the mold exhibiting porosity. We also experienced issues with some of the axe heads showing cracking on the blade edge due to the steel being at a cooler temperature than ideal. The post processing of the heads was done by hand which gave us a slight variability in the weights of the final axe heads too. Lastly, the shaping of the edges was performed by hand without any alignment setup which gave us slightly different results per axe head in terms of final shape and sharpness although all the samples fell well within the 80% as cast rule. In order to improve the consistency of the axe heads, we could have developed and built a setup that allowed us to grind the edge to the exact same specifications every time which would up the consistency in our recorded data.

Our data and real world testing indicate that our final product was an authentic replica of a viking axe consisting of several characteristic features of viking axes such as the “beard” and versatile design. Our hybrid design places our axe between a one and two handed tool which gives it increased use cases rather than tying it down to a specific purpose. Its material has also been processed in order to have a hard edge with a soft center.

References:

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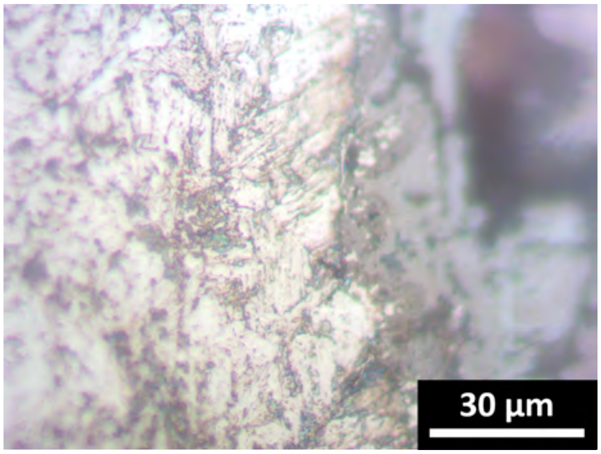
Appendix A - The Mold and Casting Process for a Single Axe Head



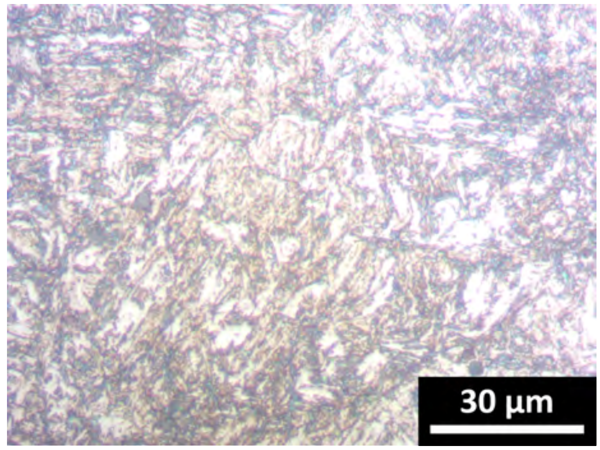

The above images show the molding and casting process for a single axe head in chronological order. After the pattern was crafted, it was packed with sand and allowed to set for two minutes. The pattern was flipped over and the mold slid out. The molds were fired and glued together with the chill and zircon core for the eyelet placed within. Weights were placed on top to prevent separation during pouring. After pouring, the casting was broken out and the heads and gates were cut off. The axe head was then ready for further fabrication and the addition of an edge.

Appendix B - Further Micro Images

Sample 90

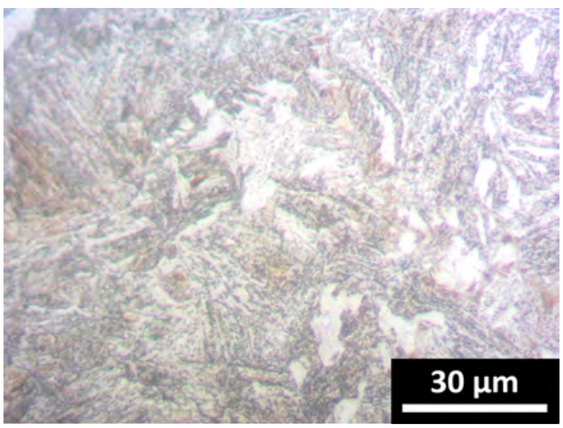


Right Edge

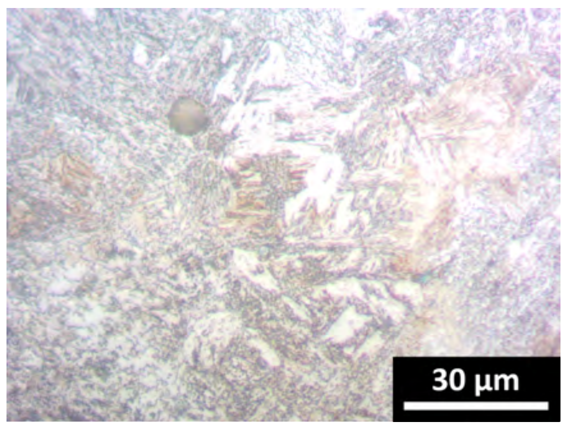


Center

Sample 91

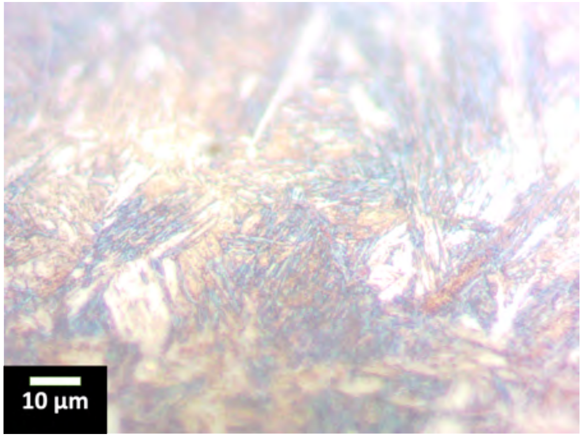


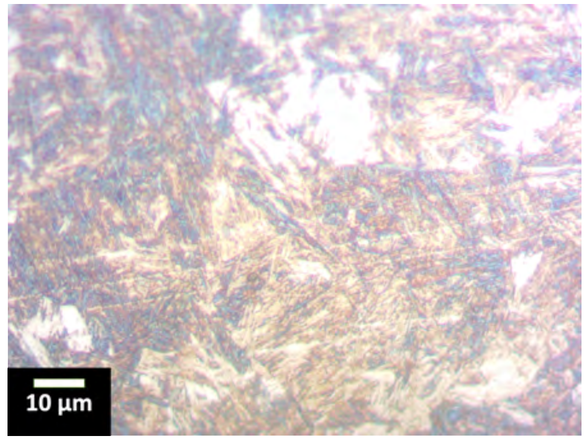
Center



Toward Left Edge

Sample 92

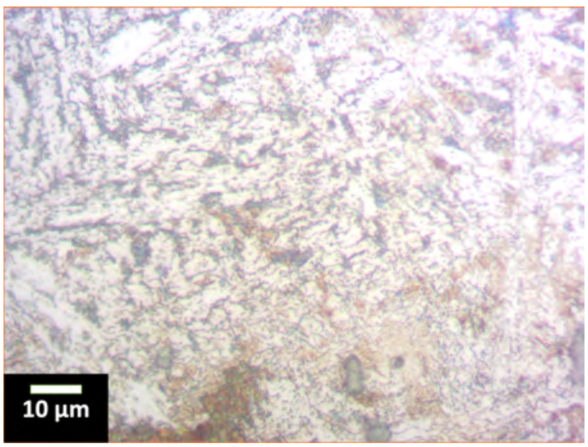


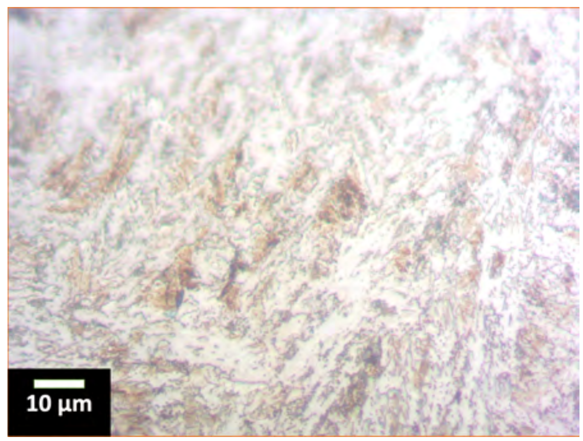


Left edge

Right edge

Sample 93

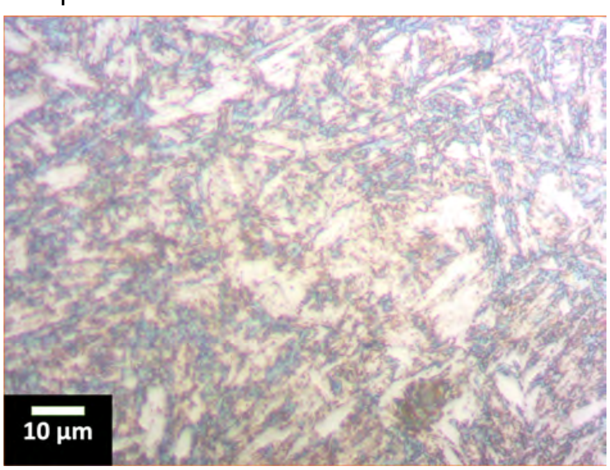


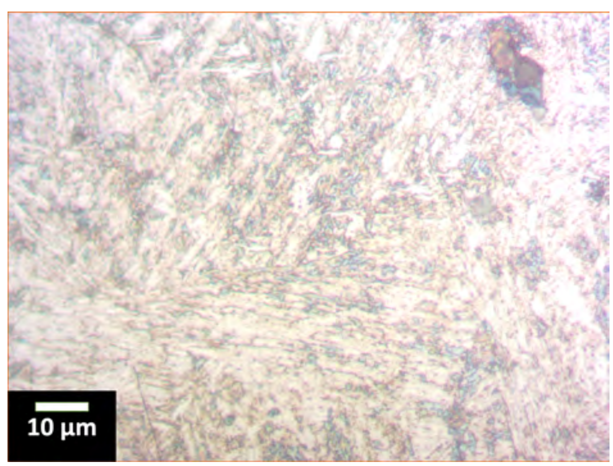


Bottom edge

Top edge

Sample 96

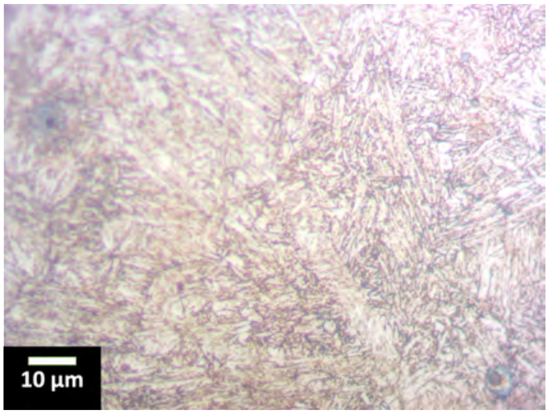


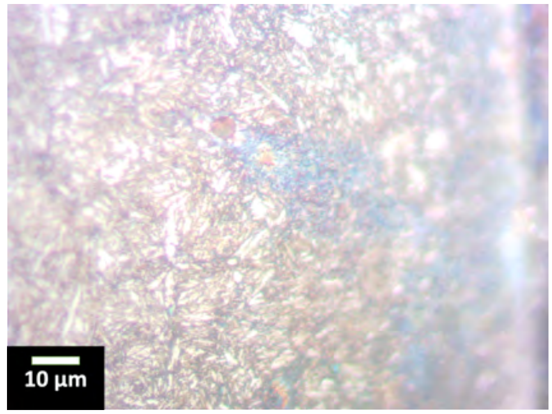


Side 3

Side 4

Sample 102





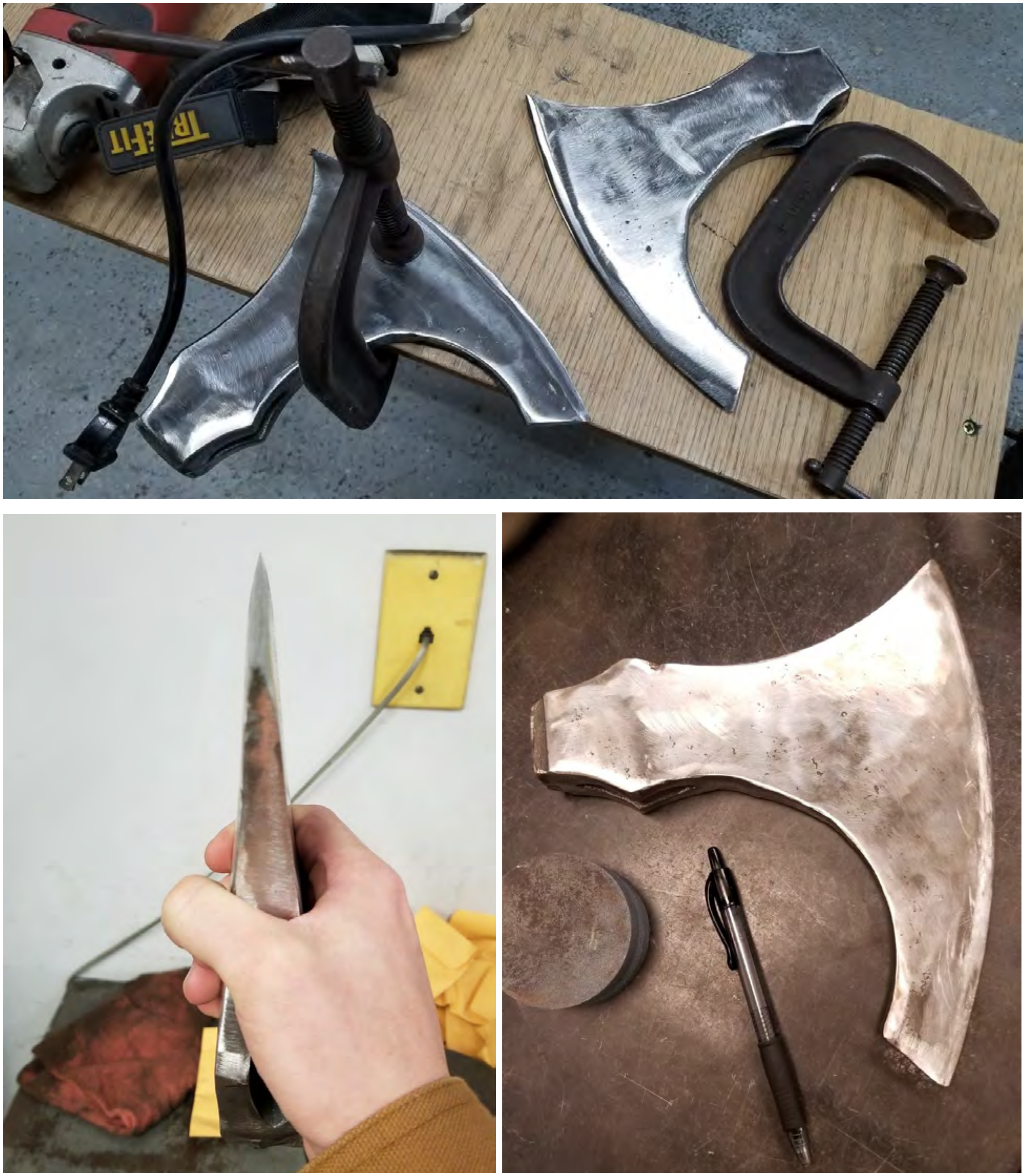
Towards center

Towards carb edge

Appendix B - Fabrication Process


TILLMAN™
1470L


1470L



The above images show the fabrication process of the blade edge. The blade edge on the axes were ground on with a 4” grinder and a cutting wheel with the taper starting 0.75” back from the end of the axe edge. The rough finish from the casting process was ground off with the 4” grinder and cutting wheel. It was polished with a 4” 40 grit flapper wheel.

Appendix C - Testing the Chopping Ability

One axe head was tested on a log. It was swung full force 100 times. The axe had good penetration into the log; however, this was an inefficient way of testing sharpness. Chopping at a log was a good measure in terms of axe ability. It chopped very well, but other means were used to further test axe sharpness.