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Sand Casting a Viking Axe

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Abstract

A historically similar steel Viking axe was cast using a split pattern. A core was utilized to form the eye of an axe. An intricate pattern and core box was designed on Solidworks and 3D printed. MAGMASOFT solidification simulation was then implemented to minimize shrinkage for the casting. A test cast was done with green sand mold and aluminum alloy 356. The alloy chosen for the axe was steel 4340. Axes were cast at Georgia Iron Works and Missouri University of Science and Technology with chemically bonded sand. The castings were sandblasted, and machined to prepare for heat treatment. Heat treatment was done at Duramatic Products via the austempering following the parameter determined in a work by Naizil et al and the ASM handbook. Heat treatment includes austenitization at 850C for 1 hour, then quenched and isothermally held at 350C for 1 hour. A decorative handmade hickory shaft, with purple heart inlay, was created using chisel, bandsaw, lathe and then sanded with increasing grit until smooth. The shaft was finished with linseed oil and the head was fitted using wedges. An examination of the final microstructure exhibited fine lower Bainite with a hardness of 41 HRC.

Introduction

Throughout history, there were few warriors as feared for their ferocity in battle as the Vikings. Known for forged iron and steel axes, Vikings were also very religious and superstitious people. The axes were not only well made, but also very decorative with runes to specific gods and other symbols along the shaft and blade. Today, casting is a popular and effective manufacturing process. One might wonder how a steel cast axe would measure up to the forged steel axe of these ancient warriors.

Keeping with Viking craftsmanship, an intricate mold pattern of the axe head was designed on Solidworks and 3D printed. Using MAGMASOFT solidification simulation, risers were designed to limit solidification shrinkage. Chemically bonded sand was used to then create the mold and core. 4340 alloy was selected and cast. Austempering was the choice of heat treatment used to induce bainite in the phase composition of the alloy. The axe was then grinded and polished. A handmade hickory shaft with purple heart inlay was then further designed and machined with chisels, sanders, lathe and a band saw. Keeping with Viking simplicity, the shaft was finished with linseed oil and fitted using wedges. Machining was kept to a minimum as casting was desired to be the main component of the axe's features.

Procedure

Axe Design

To begin, the design of the axe was narrowed down based on the desired functions of the axe. For this specific axe, it was desired that it would not only chop, but also be able to be thrown accurately. As such, the initial design needed to include a counter weight and the position of the center of mass was taken into consideration. Among these, it also needed to be comfortable to hold and use, with safety also being a factor when considering the form of the axe.

Design considerations around the function of the axe was relatively straight forward. Since a throwing axe was desired, the shaft needed to be long enough to chop with two hands, but short enough to comfortably throw with one hand. As well, the center of mass needs to be along the handle to accurately be thrown. This was the main reason for the counter weight at the back of the axe head. The counterweight is pointed so it can double as war pick to puncture helmets, if needed. Designing the axe head in the style of a “bearded axe” was for function. A viking could swing above an enemy’s shield, grab the lip of the shield and lower it to gain an advantage in battle.

Figure 1. Axe head designed with Solidworks

On the center of the head is a symbol called the Celtic trinity knot also referred to as the Triquetra, meaning three-cornered in Latin. This is the most famous of the Celtic knots dating to around the 8th century AD. It is believed to be derived from the Norse Valknut, a symbol associated with the god Odin. This symbol was later adopted for the Christian church to represent the trinity as seen in the famous book of Kells. The Triquentra continues to be a popular symbol representing a variety of faiths and cultures. On the blade itself is the symbol of the spiral. The Celts used the spiral to represent the journey and changes of life. The spiral was a common symbol which adorned many Celtic sites and runes.

Ergonomics and safety was integral to the design process. The shaft of the axe was sized for comfort while also providing a stable grip. Adequate space in between the blade and shaft was included for a hand to be able slide up the shaft without making contact with the blade. The slight curve of the handle was implemented to help gain momentum when swinging or throwing the axe. A final, but notable addition to the design of the shaft was the "butt" of the handle. The additional mass concentration not only helped build momentum when swung, but it also juts out to protect the hand if swung too hard. It has most of the protection of a hand guard, without the bulk of one.

Pattern Making

The axe head was then modeled on Solidworks. As needed for casting, the axehead was split into a cope and drag with a 3 degree draft. Core prints and a core box were also designed to account for the axe shaft. The axe blade was also designed purposely "dull" as added protection against porosities that might occur during pouring. For simulation purposes, the axe shaft was also approximated, and used for a benchmark to determine the length of the shaft (Around 14 inches.)

After modeling the mold pattern and core/core box, the parts were 3D printed with a Stratasys J750, as can be seen below in Figure 2.

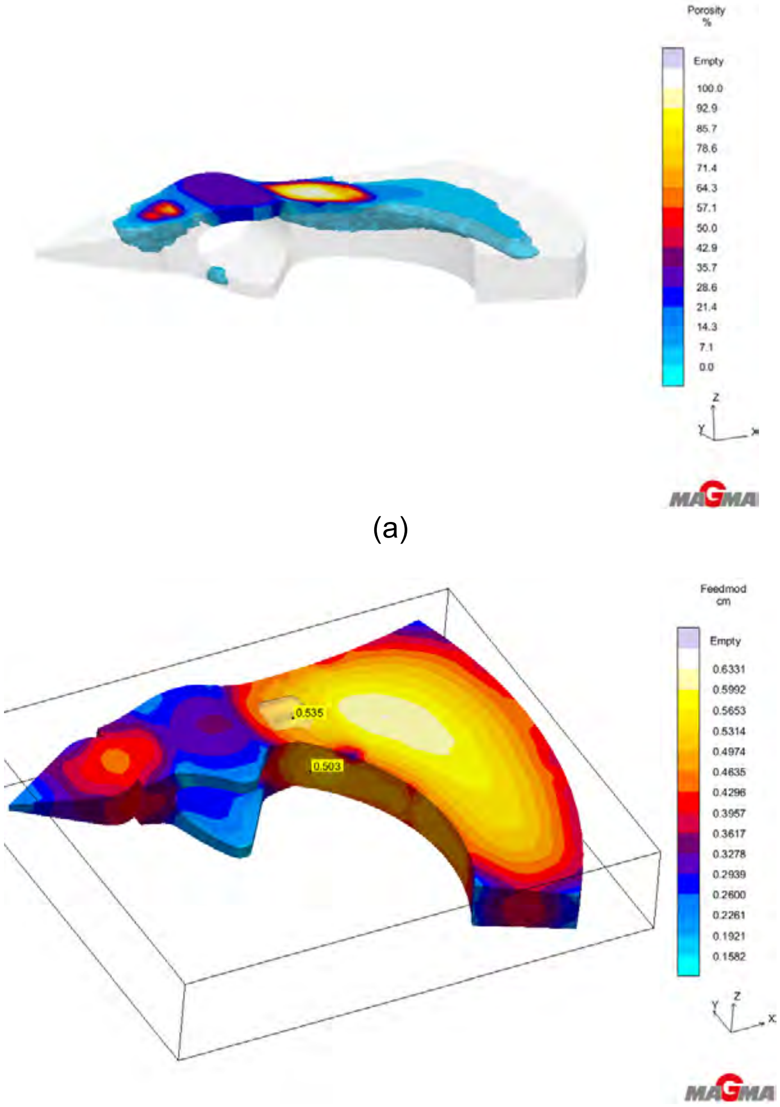
Figure 2. Finished 3D Print of the Axe head

3D printing was chosen to create the pattern and core/core box as it offers a very precise and accurate pattern, as compared to the dimensions defined in the Solidworks models. Doing so, also allowed for the potential for multiple castings as the mold pattern is permanent.

Solidification Simulation with MAGMASOFT

To decide how to create the mold, simulations were ran to predict and protect against certain flaws that can occur when casting. To compensate for any solidification shrinkage that may exist in the axe head, MAGMASOFT 5.2 was used to design a proper riser system and simulate the solidification process. The effect of the risers can be seen below. Figure 3(a) shows the porosity distribution in the axe head without any risers. In Figure 3(b), the thermal moduli of the castings where porosities are expected were found at around 0.535 cm. To make a sound casting, the riser needs to have 20% higher thermal modulus than these values (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. Initial simulation results in Figure x shows 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 3. Initial MAGMASOFT simulation shows (a) porosity distribution in the axe without any riser and (b) thermal modulus at critical points in the axe head.

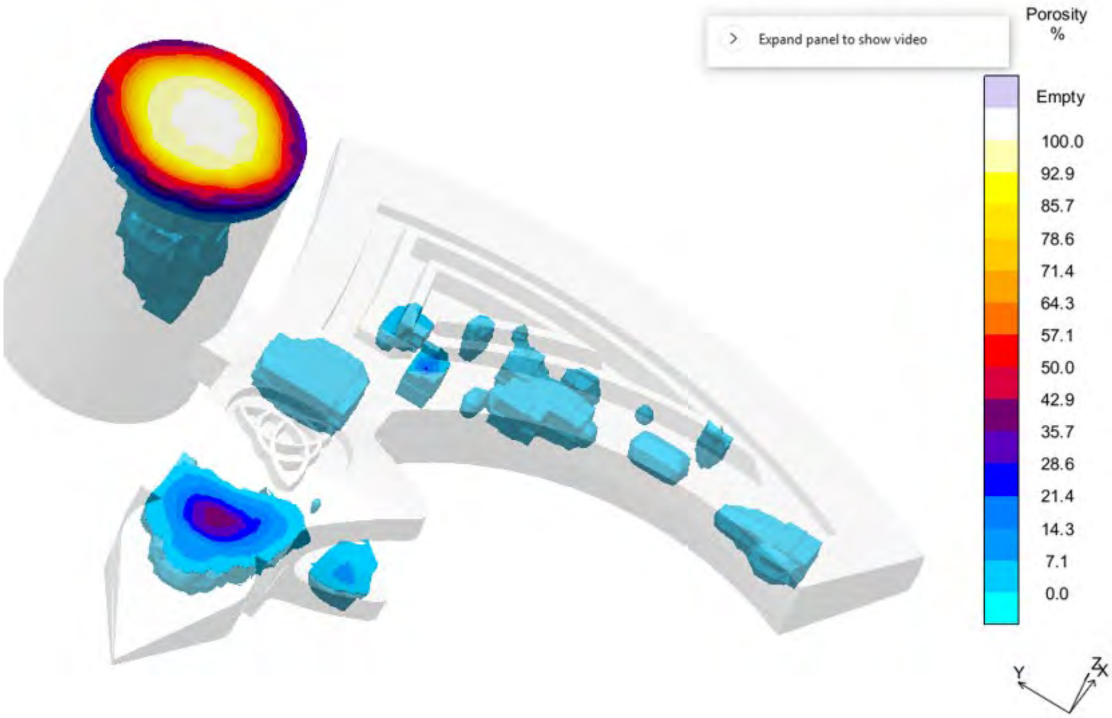


Figure 4. Initial MAGMASOFT simulation shows that a side riser is efficient to remove the porosity on one side of the casting; a second riser (not shown) was added onto the other side in the final design

<u>Molding</u>

With a “blueprint” of the parts needed to create a mold with adequate risers, the mold was then created. With the help of foundrymen in the R&D division of Georgia Iron Works (GIW), sand molds were created using chemical bonded furan sand. Two molds were created complete with risers, for redundancy. The cope of one of the finished molds can be seen in the Figure 5.

Figure 5. Completed chemically bonded sand mold before removing the patterns and risers

While the finished molds were very precise to the intricate designs on the axe head, the pouring of the axe at GIW resulted in gas porosity from dissolved oxygen that made the axe unusable. Due to this, the axe had to be recast later at Missouri University of Science and Technology. The mold patterns were the same as at GIW, but the mold was made out of chemically bonded silica sand with a particle size of AFS#60. The core was created from the same sand. The finished molds can be seen in Figure 6.

Figure 6. Completed axe head mold using chemically bonded AFS60 silica sand

ALLOY SELECTION

Keeping in mind, that the axes will be tested upon logs and mild steels before the edge sharpness testing, the team decided to use a high work hardening steel with a good combination of strength and ductility. 4340 steel was selected as it best met these requirements. 4340 has good toughness that will prevent it from chipping during testing, and any plastic deformation that may see during the chopping test will further increase the hardness of the blade. The table below lists the targeted chemistry for selected alloy. T_L represents the liquidus temperature of this alloy, which was calculated using thermodynamic software FACTSAGE.

Table 1. Liquidis of Selected Steel Allo calculated with FACTSAGE

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

With 4340 selected, the specific phase of 4340 had to be determined. Bainitic microstructure was desired due to its high strength and hardness. Austempering was the method thought best to achieve this microstructure.

CASTING

Casting was performed at Georgia Iron Works (GIW) R&D lab and the teaching/research foundry at Missouri University of Science and Technology. Both GIW and Missouri University of Science and Technology use INDUCTOTHERM coreless induction furnaces. A 50 lbs heat was produced at GIW and a 100 lbs heat was performed at Missouri S&T.

At GIW, 4140 shaft returns were used. Ni and Ferro-Mo was then added to alloy it up to 4340. Heat was covered with a small amount of argon as protection from oxidation and atmospheric gas pickup. The metal was tapped onto pure aluminum at 1680C into the ladle. It was then poured into the mold immediately afterwards. The metal was allowed to cool in the mold for 2 hours before the shakeout.

As previously mentioned, shaking out the mold revealed multiple gas porosities on the casting surfaces. This was due to the excess amount of dissolved oxygen being picked up during melting. The three factors that most likely caused the oxidation are as follows: (1) When charging the last piece of the shaft return, a “bridge” (metal solidified on top of the liquid pool) was formed and the technicians had to work to get it dissolved and pushed it down to get contact with the liquid pool. The Furnace was left uncovered during the process; (2) because the melt size was only 50 lbs, the surface-area-to-volume-ratio was quite large; (3) the argon flow rate wasn’t high enough to provide adequate protection. While some of the pattern found on the axe was immaculate, the defects were too numerous to create a viable axe.

The AFS student chapter at Missouri S&T agreed to help us to recast the axes. During this heat, fresh virgin materials were used and the charge table is listed in Table 2. Melting was carried out following the high active oxygen practice expressed in Dr. Xu’s earlier publication [1]. In short, induction iron was charged into the furnace. Once all induction iron was molten, the active oxygen in the furnace was measured at 800 ppm. This high amount of dissolved oxygen occupies the free vacancy site on the surface of the molten metal, preventing too much nitrogen from getting into the melt. Ferrous alloys and graphite were then plunged into the molten pool to achieve the desired chemistry. Once all additions are molten, calcium wire was added to remove the sulfur and modify the inclusions. Liquid metal was tapped at 1680C and killed with 0.02wt% pure aluminum then poured into the mold.

Table 2. Melt size of Steel Pour and Additives

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**

HEAT TREATING

As mentioned earlier, austempering was selected to achieve a bainitic microstructure for a good combination of hardness of toughness. An earlier work by Niazil et al. suggested that for alloy 4340, austenization occurs at 850C followed by a quench in a 350C salt bath. The quench should be held for 1 hour to yield the highest hardness at 392 BH. [2] As another reference from the ASM handbook, the Continuous Cooling Transformation diagram of 4340 is shown in Figure 7 below. At 350C, austenite to bainite transformation finishes at around 1 hour, and the hardness expected is around HRC 42, which is consistent with Niazil's work.

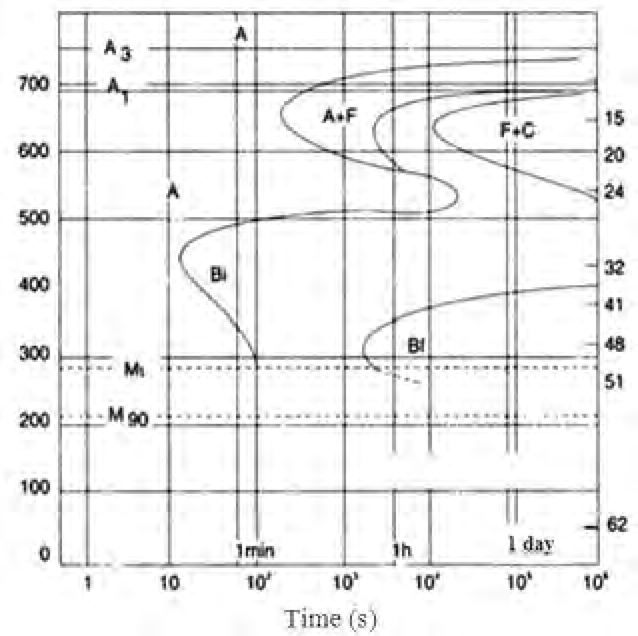


Figure. 7 Continuous Cooling Transformation diagram of 4340 [3]

Prior to the heat treating, the gatings and risers were removed from the axes. The axes were cleaned with an angle grinder, removing or reducing most surface defects. The bevels of the axes were grinded at this time. Sand/slag related porosities were plug welded using the TIG method. Most of grinding was done to avoid any major grinding after the heat treatment, as the heat generated from grinding can alter the microstructure of the axes.

The Heat treatment 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 dipped 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.

After heat treatment, the decarburization layer was removed using an angle grinder and polished. Oxide layer inside the designs was left as an aesthetic choice to give a unique contrast to the sheen of the axe.

Shaft Creation

The wood for the axe was chosen to be hickory as it is a very tough wood, perfect for the impacts that a Viking axe would be put through. A rough outline was traced in the wood, and a general profile was created using a bandsaw. Next, a more precise outline was traced, and a chisel was used to remove excess wood. An angle grinder was used to create the curves of the handle, further refining the profile. At this point, three holes (3/8", ½", ⅝" diameter, respectively) were drilled into the base of the handle to house purple heart cores, for decoration, using a drill press. The cores were made out of purple heart, and were turned using a lathe. The cores were inserted using a mallet, and a mixture of purple heart wood shavings and glue was used to plug any gaps. The finished inserts can be seen in Figure 8.

Figure 8. Purple Heart Handle Inserts on the Shaft

After it dried, a sander was used to smooth the surface of the handle to its final dimensions. The grits used were 60 and then 120. To fix the axe onto the shaft, the diameter of the poll of the axe was made to be just under .8" (the small diameter of the axe head). To ensure that the axe would sit properly on the shaft, the shoulder and heel was rounded to compensate for the fitting of the axe head**.** The rounding of the shoulder and heel of the shaft can be seen in Figure 9. Afterwards, a natural finish was desired, so linseed oil was coated evenly with a rag along the shaft.

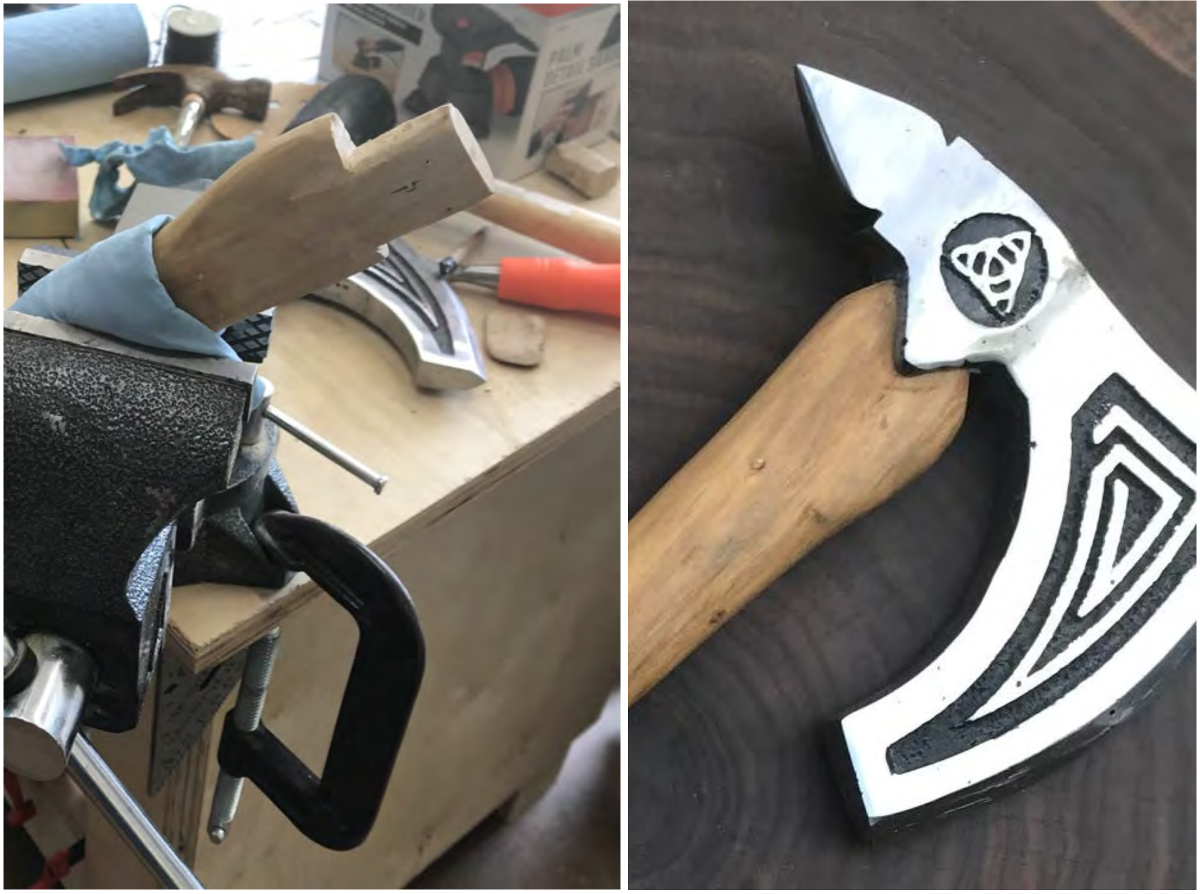


Figure 9. The shaft without the linseed oil finish and shoulder/ heel chamfer (left); The shaft with shoulder/heel chamfer and linseed oil finish (right).

Wedges were then placed around the top of the shaft and hammered in with a mallet to fix the head to the shaft. Excess wood was then removed. Hickory wood shavings and glue was used to create a uniform finish above the axe head. An ink finish was applied to the top of the axe. The axe head was then coated in oil and wrapped wax paper to prevent rusting. The finished axe can be seen in Figure 10.

Figure 10. Completed Steel Cast Viking Axe

Discussion

Chemical Composition

Chemistry of the steel was measured with an OXFORD Optical Emission Spectrometer and listed in Table 3. The chemical composition of the steel axe head was very similar to the target 4340 alloy and its additives.

Table 3. Desired Alloy Composition compared with Actual Composition

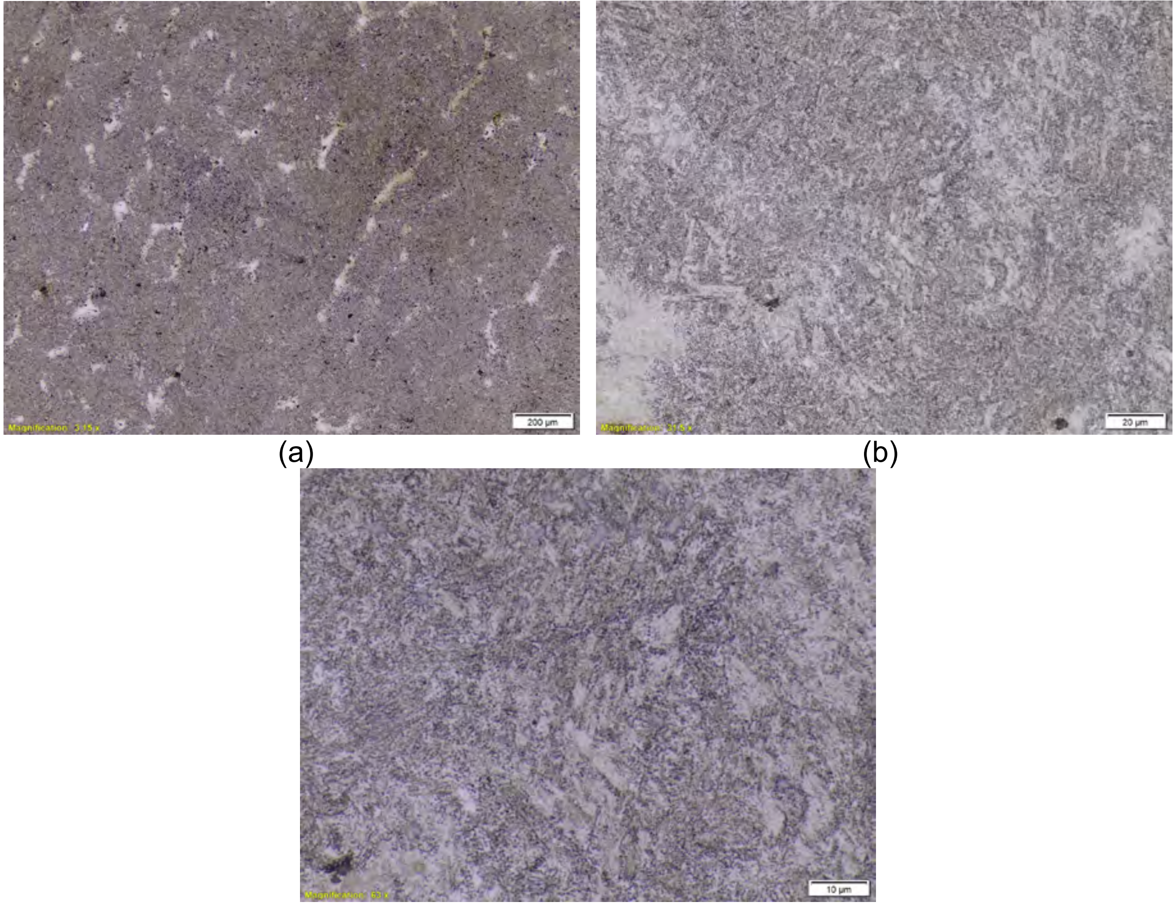
	C	Si	Mn	Cr	Mo	Ni	P	S
Target wt%	0.42	0.2	0.6	0.75	0.25	1.8	0.03max	0.03max
Actual wt%	0.45	0.21	0.66	0.80	0.27	1.91	0.011	0.015

The percent difference of the target composition vs the actual was under 10% in each case. The final percentage of Phosphorus and Sulfur of the steel Alloy came in under the .03 target as desired.

Phase Composition and Microstructure

The final microstructure of the axe head can be seen in Figure 11. After heat treating, the axes consist of mostly very fine lower bainite.

As can be seen in Figure 11(c), the typical structure of bainite is exhibited. The fine structure of the alloy indicates that it will have high strength and toughness, as desired for an axe head. This was confirmed through a Hardness test of the axe head, resulting in a hardness number of 41 HRC, which is expected based on Naizil’s work and ASM handbook.



(a) (b)

(c)

Figure 11. Phase Composition of the Axe Head at 50x (a) 500x (b) and 1000x (c)

Conclusion

The casting of the axe revealed the difficulties in trying to get a proper a cast without defect. Protecting against defect seemed to be the most difficult of the three in sand casting. This is due to the environmental factors that can affect the casting while heating the molten metal and pouring. Despite the extreme care taken when pouring, some surface gas porosities remained. The final axe, however, was protected well enough such that no porosities should affect the performance of the axe. To reduce the amount of slag related defects on the surface of the blade, one could use a filter in the gating system to remove as much slag/dross as possible. Another way to avoid defects would be to explore casting in a vacuum.

The chemical composition of the alloy was extremely close to the target values as can be seen in Table 3. The target phase composition of the alloy was bainite, which corresponded with the microstructure exhibited in Figure 11. This also supports the work done by Naizil et al. in “Austempering Heat Treatment of AISI 4340 Steel and Comparative Analysis of Various Physical Properties at Different Parameters,” which was the basis of the heat treatment process for the axe head. The final hardness of the alloy was found to be 41HRC through a harness test, which is consistent with Naizil’s work and ASM handbook. During the testing, the deformation taking places during the chopping test will work harden the blade, so an increased hardness is expected to give good edge retention.

Acknowledgment

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Reference

[1] M. Xu, D. Field, V. Athavale, J. Qing, D. Van Aken, “Controlling Nitrogen Pick-Up during Induction Melting Low Alloy Steels,” AFS transactions 2017

[2] Najeeb Niazil, Salman Nisar, Aqueel Shah, “Austempering Heat Treatment of AISI 4340 Steel and Comparative Analysis of Various Physical Properties at Different Parameters,” International Journal of Multidisciplinary Sciences and Engineering, Vol 5, No. 10, 2014

[3] ASM Handbook, 8th Edition. Volume 2: Heat Treating, Cleaning and Finishing, Hardcover – 1964