

# Steel Founders' Society of America Cast In Steel Competition 2019



**Kent State University AFS**

# Team Information



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# Design Inspiration

When the team first began to design a shape for our casting we looked at historical examples of Viking axes focusing on 8<sup>th</sup> century Scandinavia, also called a Dane axe. The shape of these axes with the large beard protruding down from the main body seemed to have the shape we thought would work best in the test laid out by the Steel Founders' Society of America (SFSA). Research showed this shape was designed to allow large amounts of strength when chopping, but remain light enough to swing quickly



*Viking ax heads (photo by Incitatus)*

and slice through various other material while also proving helpful as a secondary war weapon. In an attempt to improve the balance and striking force of the axe, we chose add a hammer to the back side pulling in a 13<sup>th</sup> century European and 14<sup>th</sup> century French element. The team also felt that the hammer fit well into the spirit of Norse mythology and the tales of the god of thunder, Thor. Where the beard meets the handle we chose to add modern improvements by bulking up the cheek of the axe and continuing a more round contour into the the beard of the blade. We felt this would improve the structural strength of the axe and provide a more efficient separation for chopping wood. Final details such as a leather blade sheath and Viking imagery burned into the handel rounded out our design process. Combining these key design styles together we feel we have presented a casting that will do justice to the challenge presented and persevere through the rigorous testing of this competition. This is a blade any modern Viking would be proud to carry.

# Modeling for Process and Performance

The process of modeling our axe began in Inventor (shown in Figure 1) where a model was drawn based on our initial team design drawings. We then ran an initial static simulation in Magmasoft (shown in Figures 2 and 3) to determine any fill issues and discuss how to fix them before proceeding to the CNC machine.

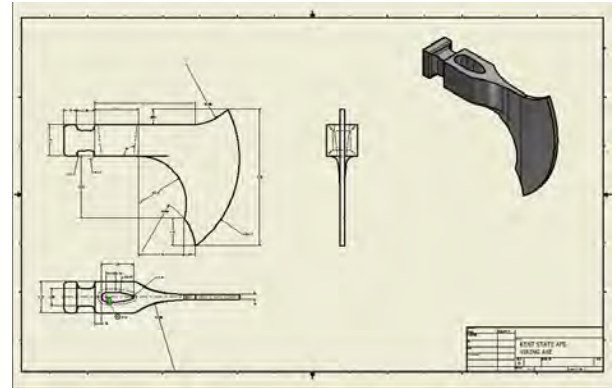


Figure 1: Dimensions of Axe

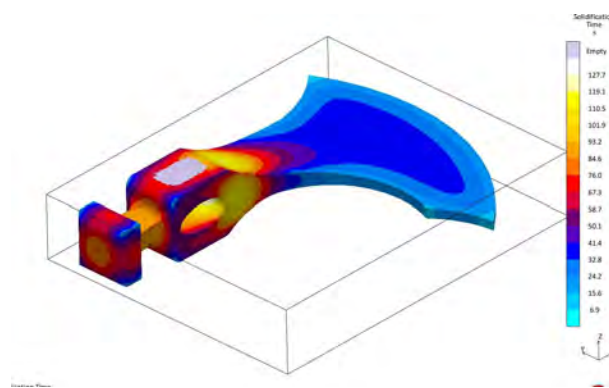


Figure 2 shows the solidification time results of the initial simulation

Figure 2: Initial Axe Solid Model

Figure 3 shows a cross section with the initial liquidus to solidus rate.

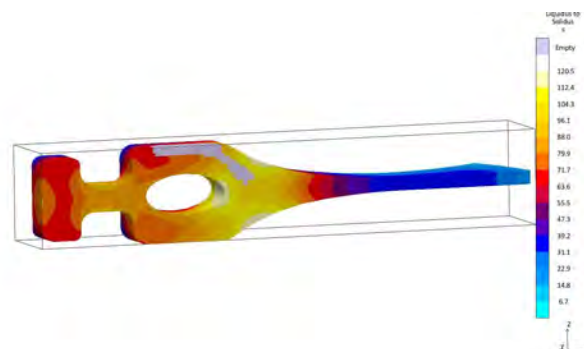


Figure 3: Initial Cross Section of Axe

Results of the initial simulation showed that the hammer head on the back of the axe created a large hot spot resulting in shrinkage and solidification issues, the eye of the axe created another large hotspot with the top portion of the axe showing no metal fill.

After several trials of riser, chill placement and sizing were run in Magma, we decided upon the final rigging (shown in Figures 4 and 5) which best eliminated all of the fill issues present in our casting. In order to combat the hotspots and shrinkage issues present in our axe, risers were placed both behind the hammer and on the top of the axe, moving the hot spot and pulling the shrinkage up out of the casting. In addition to the riser, a chill was placed on the bottom of the axe below the eye to force solidification from the bottom of the casting to move around the core in the eye of the axe and upwards into the riser above the eye. Two more chills were added on the top and bottom sides of the hammer neck, causing the solidification to close in between the two risers, so that the risers could work independently of each other. Figure 6 shows the final rigging and gating of the axe with the gating system shown in dark gray, risers in red, chills in blue, core in green, and final casting in light gray.

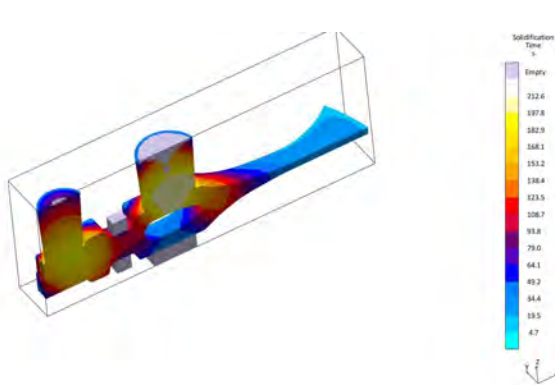


Figure 4: Cross Section of Axe with Final Rigging

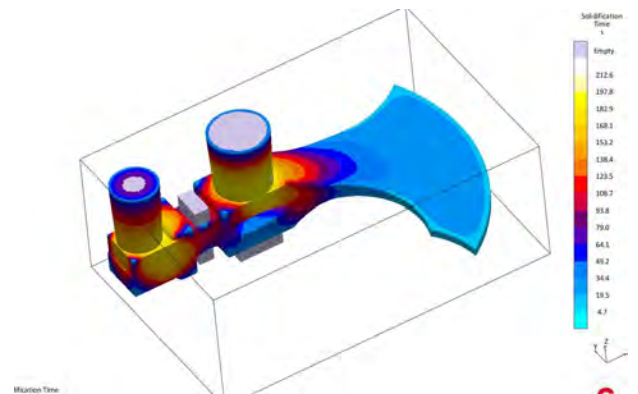


Figure 5: Solid Model with Final Rigging

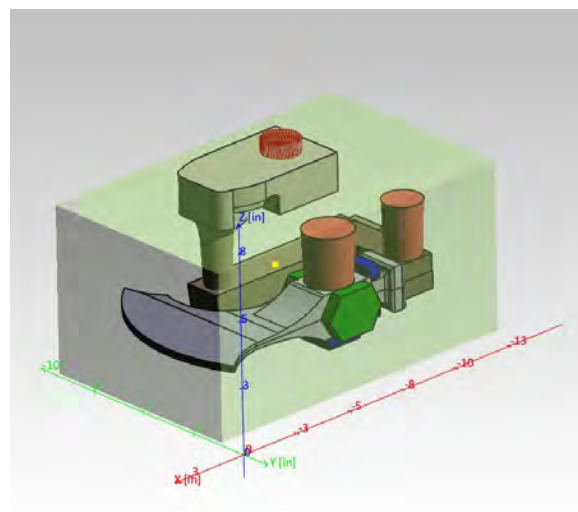


Figure 6: Solid Model with Rigging and Gating

# Alloy and Processing

Through extensive research, trial pours and errors, we ended up settling with AISI 9260 steel for the final casting. The nominal composition of the major elements are 2% Silicon, 0.8% Carbon, 0.8% Manganese and the balance being Iron. We had originally chosen A128 A Steel for the axe due to its extreme toughness and abrasion wear resistance, as well as its ability to work harden under extensive loads. In the end, this metal did not work for various reasons. The primary reason being that of safety. This metal ate our alumina crucible inside of our furnace, and melted through 2 of our fiber liners for our handheld pouring ladles during testing. After further research and online communication with commercial foundries around the world, we found that the proper crucible material is Magnesia (MgO). We were unable to acquire MgO crucibles on such short notice, so with the materials we had on hand from creating A128 A Steel we were able to create 9260 Steel very rapidly. 9260 Steel, also known as Silicon-Manganese steel or Spring Steel is widely used in applications where high toughness and edge durabilities are required. The toughness aspect of this metal comes from the high Silicon content at 2% also assisted by the >1% Manganese. This grade of steel would typically be seen in the production of swords due to its ability to bend to near 90 degrees and spring back to 0 degrees with no visible distortion, which is in part where it gets its name.

These properties do not come without their own accompanying difficulties. The high Silicon content of this Steel presents some challenges when it comes to hardening the axe. If the axe does not reach a high enough temperature before quenching, the axe will be extremely susceptible to micro cracking. This is due to the Silicon content assisting with the decarburization of the Steel while heat treating. However, the high Carbon content in this Steel allows for far superior edge retention which other similar alloys with the same or lower Carbon contents do not achieve.

Once we knew that we were going to be melting 9260 Steel we had to quickly rebuild our furnace with a new alumina liner. This Alumina liner was the last one we had on hand, as we work with donated materials, it was necessary to get this right. Not only was the Steel itself challenging to bring up to spec rapidly, the Alumina liner added some inclusions of other elements that we were not expecting to have. Also with the Alumina liner, slag buildup around the edge of the melt face was unavoidable. In order to bring the metal up to the exact spec that we wanted, we would tap the melt and pour a small test sample to run on our spectrometer. This method ended up proving useful as it gave us the historical data we needed to collect to determine our melt fades. The issue came with individual pours where even when a single test sample was taken, the metal chemistry would change drastically after sampling, most likely due to the melt face's exposure to atmosphere. With the historical data gathered from all the samples of the 9260 melts, we were able to determine very accurate fade rates for all of the

elements in our melt bath. With the rates calculated, on our last melt we added the proper amount of alloying elements and did not take any samples during the melt. However we were able to run a sample of part of the pouring basin and the metal met specifications within a few percent.

With two castings that turned out satisfactory, and with the correct metallurgy, we then turned to grinding and heat treatment. To easily rough the casting shape down to a workable surface, various forms of sanding and grinding tools were used. Once ground to a rough edge, the casting would then move on to heat treatment. This was done in our gas powered forge, and the casting was heated to a cherry red color along the contour of the cheek until the eye of the axe. Once sufficiently heated and tested to see if magnetic, the casting was fully immersed in quenching oil. After cooled completely, the final finishing edge was ground into the casting using a vertical belt sander and progressively finer grit sandpaper.

# Testing for Quality and Performance

## Quantitative Testing:

The main components that concerned us when it came to our casting were: the final shape, surface defects such as cold shuts, shrink or gas issues, and the chemistry of the metal. Our first test starts during the melting process; when the initial charge is melted and homogenized, we pour a sample into our copper sample ladle which rapidly cools the metal. We then take the sample to our spectrometer where the results from several tests are averaged together to tell us what elements are present in the sample. We then compare the results to the proper values we are shooting for, and adjust as needed and repeat the testing if needed. After the casting is poured and solidified it is then examined for defects, specifically coldlaps and non-fill. Both of these defects would make the axe unusable immediately. Once the gating and risering is removed from the casting, we examine the axe for any noticeable shrink or gas issues. Finally we do a rockwell hardness test on the axe before and after heat treating the blade. This test is done to ensure we are meeting the proper specifications for the blade.

### **Final alloy specs:**

**Fe: 95%**

**C: .64%**

**Mn: .8%**

**Si: 2%**

**Rockwell Hardness before Heat Treat: 39 C**

**Rockwell Hardness after Heat Treat: 65 C**

## Qualitative Testing:

Once the axe was fully assembled with handle and the final shape of the edge was ground in, we put it through a series of durability tests to try and force deformation to the edge. We begin by chopping wood, primarily focusing on the function of the axe with this test. IE: How the axe chops, is the blade angle we chose performing as expected, does the blade deflect in any direction? The next test carried out was chopping at raw Steel. Here we are looking for rolling of the blade edge and for any chipping that may occur on the edge. Happy with the results we observed, the final submission casting was cleaned up, mounted on the finished handle, blade guard installed and packed for shipment to SFSA.



# How to Manufacture a Viking Battle Axe Pattern

## Materials Needed

- Perfect Plank Mahogany™
- CNC wood router
- CNC code from 3-D model of axe
- Wood lacquer
- Brushes
- Drill bits
- Cutting tools
- Measuring tools
- Flask
- Parting Compound

*As with all manufacturing processes, be sure to wear proper PPE (personal protective equipment) the entire time*

## Section 1: Cutting the Pattern

1. Place the mahogany Perfect Plank on the mill table and secure it with the provided clamps.
  - a. Be sure the plank is secure and that the clamps are a safe distance from any of the cutting patterns.
2. Import the CNC code into the computer using a flash drive.
3. Insert the cutting tool and zero the mill to the starting position of the code.
  - a. When selecting a tool, make sure the cutting tool has a cutting depth that always exceeds the depth of the plank. If the cutting depth is too short, the top of the tool can scorch the plank and cause damage or break the pattern.
4. Start the machine and let the mill run the code.
  - a. Make sure to turn on the air supply to keep the cutting tool cool and to blow away wood cuttings and dust.
5. Repeat steps 1 through 4 for the second side of the pattern.

## Section 2: Drilling Flask Alignment Holes

1. Select the flask you will be using to make the mold.
  - a. Be sure to select a flask that leaves enough room around the edges of the pattern to ensure a solid mold.

2. Using appropriate measuring tools, define the centers of the holes of the flask pins on the pattern.
3. Secure the pattern on the table of the CNC wood router with the provided clamps.
  - a. A CNC wood router ensures the drilled holes will be exactly where they were specified and straight as opposed to a handheld drill, which could create an unintended angle.
4. Insert the bit and carefully drill the previously marked holes.
  - a. Choose a drill bit that is big enough to allow the pattern to slide in and out of the flask without much force, but is also small enough to align the pattern in the same spot every time a mold is made.
    - i. Using holes .005 of an inch bigger than the flask pins is a good choice.

### Section 3: Finishing the Wood Stock

1. Perfect Plank Mahogany™ must be lacquered before it is used as a pattern.
  - a. Lacquering also gives the wood a smooth surface finish and prevents the pattern from being porous, which helps prevent sand from sticking to the pattern during molding and gives the final casting a cleaner surface finish.
2. Use brushes to apply a thin layer of wood lacquer to one side of the pattern.
  - a. Let the lacquer dry and cure as directed by the manufacturer then apply a second layer.
3. When one side is completely dried and cured, repeat steps 1 and 2 for the other side of the pattern.

### Section 4: Preparing the Pattern for Molding

1. Coating the pattern with parting compound is essential to a good mold.
  - a. Without parting compound, the sand will stick to the pattern and break off upon removal of the pattern.
2. Spray an even layer of parting compound over the entire pattern.
3. Let the compound dry and spray again.
  - a. Repeat this process until no wood color can be seen.
  - b. Make sure to thoroughly coat problem spots in the pattern such as hard turns, corners, and small details.

# How to Cast and Clean a Viking Battle Axe

## Materials and Tools Needed

- Viking Axe Matchplate Pattern
- Flask
- Pep-set silica sand
- Chills
- Risers
- Core box
- Wire Rebar
- Pouring basin
- Olivine wash
- Drill
- PPE
- Cut off wheel
- Grinder
- Forge
- Tongs
- Quenching oil
- Polishing wheel

## Section 1: How to Make the Mold

1. Place the pattern in the flask making sure the risers are in the cope side of the flask.
2. Starting with the drag, place two chills in the specified areas.
3. Pour in pep-set sand.
4. Using a combination of a vibrating table and your hands, pack the sand around the mold.
5. Use a flat stick or metal piece to strike away any excess sand at the top of the flask.
6. After 8 minutes (time varies based on pep-set properties), carefully pull the pattern out of the sand. Make sure to pull the pattern out as straight as possible to avoid damaging the mold.
7. Check the sand for defects and repair as necessary.
8. To make the cope, place one chill at the specified area and the two risers on the locating pins.
9. Using a combination of a vibrating table and your hands, pack the sand around the mold.

10. Cut the sprue at the designated area.
11. After 5 minutes (time varies based on pep-set properties), use a magnet to pull the two risers out of the sand, carefully and as straight as possible so as not to disturb the sand.
  - a. This is so the risers do not get stuck inside the mold.
12. After 8 minutes (time varies based on pep-set properties), carefully pull the pattern out of the cope. Make sure to pull the pattern out as straight as possible to avoid damaging the mold.
13. Check the sand for any defects and repair as necessary.
14. Place the riser's upside down in the holes.
15. Build up the risers with more sand, and let it harden.
  - a. This allows more room for the risers to fill and feed the pattern during the pour to reduce shrink.
16. Using the same technique, fill the core box with sand. Put two small rods in the neck of each side to help with strength. Fill the pouring basin mold at the same time.
  - a. Cores take up space in the mold, allowing for hollow cavities.
  - b. Pouring basins allow metal to flow into the mold with the least amount of turbulence.
17. After 8 minutes (time varies based on pep-set properties), use the vibrating table remove the cores and the pouring basin from the molds.
  - a. Place the boxes upside down on the vibrating table, to allow the cores and the pouring basin to fall out of the molds.
18. Using a scribe, scratch a vent line through the middle of the flat inside of each side of the core, going long ways. Using core glue, glue both sides together.
  - a. This allows for a vent to help with gas defects.
19. Using a drill and a ¼ inch masonry bit, drill 7 vent holes at the specified areas in the cope side of the mold.
  - a. Vent holes allow gas to escape the mold, preventing defects.
20. Using an acetylene torch, with a feathery sooty flame. Lightly wave the flame over the molds, until the core and pouring basin turn black.
  - a. This allows a carbon barrier to help reduce the chilling effect of the silica sand, and allows the metal to flow with less turbulence.
21. Place the core in the designated area in the drag. Place the cope on the drag, connect using the pins and slots.
  - a. There are two different size slots for the core to be placed into.
22. Clamp the cope and the drag together.
  - a. This stops metal from escaping the mold during the pour.
23. Glue the pouring basin so that it will feed into the sprue.
  - a. This stops metal from escaping where the pouring basin and the mold connect.
  - b. Make sure not to cover any of the vents with the pouring basin.

## Section 2: Pouring the Metal

1. When dealing with liquid metal, always wear proper personal protective equipment (PPE).
2. Measure out desired weights of the 9260 steel, electrolytic manganese, SiMe and DESULCO 9001.
  - a. This is to make the specific alloy of metal desired.
  - b. SiMe is Silicon metal.
  - c. DELSULCO 9001 is desulfurized Carbon.
3. Load the furnace with the weighed out charge material placing the smaller, lighter additions in the bottom of the crucible.
4. Turn on the water-cooling system.
5. Turn on the furnace, making sure that you have no errors.
6. Begin to heat the metal until a bath of liquid metal forms at the bottom of the crucible.
7. Continue feeding metal into the bath until you have the desired amount of liquid metal in the crucible.
8. Heat the liquid metal to 3100 degrees F.
9. Tilt the furnace using the hydraulic controls.
10. Pour the metal from the furnace into the ladle to transfer metal to the mold.
11. Carefully pour the metal into the mold through the pouring basin.
  - a. Continue to pour until the risers are completely full.
12. Pour leftover metal into an ingot mold.
13. Cut power to the furnace.
14. Scrape the inside of the crucible to clean.
15. Let the casting sit in the mold overnight to anneal.
16. Shake out the casting the next day and clean off excess sand.

## Section 3: How to Finish the Axe

1. Using a cutoff wheel, remove the gating system and vents.
2. Using an angle grinder, grind excess metal left from the risers and the gating system.
3. Using a belt grinder, shape the casting to its final form.
4. To harden, heat the casting in the forge until it is cherry red.
5. Remove it using tongs and let it air cool to a dull grey. Repeat 2 more times.
6. Heat the casting a fourth time until it is cherry red.
7. Remove the casting and fully immerse it in the quenching oil to cool and harden.
8. Using the polishing wheel, polish to users desired finish.
9. Using the belt grinder, grind the now hardened axe to its final edge geometry.

# Problems That Occurred Throughout Our Process

## Pattern

The first issue we faced came shortly after we cut our pattern. The cope and drag sides of the match plate were offset  $1/8^{\text{th}}$  of an inch. A second match plate was cut after making changes to the CNC Code. While cutting the second plate, the CNC router caught a rough edge while making finishing passes and ripped a hole in the pattern. A small section of the gating system was also damaged. This occurred because the cutting section in our bit was smaller than the height of the wood. During the first pass, the smooth section of the bit burned the top of the wood, causing it to harden. The next pass, the bit caught the hardened section of the wood and dug into it, causing our pattern to be rotated and get damaged. We resolved this dilemma by cutting out that portion of the second match plate and replacing it with the same section from the first pattern. We tacked it in, filled the seams with bondo, and sanded it to surface.

## Molding

The next challenge arose when we started making molds for a test pour. Our Tinker Omega sand mixer had not been used in a while and we could not get the sand to mix properly. We spent two work sessions troubleshooting our binder and catalyst ratios and cleaning hoses out. The final sand mixture we used was 5% binder per pound of sand and 20% catalyst per weight of binder. This ratio gave us approximately a four-minute work time and eight-minute strip time.

Another issue we faced while making molds was a tendency for sand to stick to sections of the pattern when we removed it. We tried pulling the pattern a minute earlier and applying extra mold release to those sections. The solution to this problem was scrubbing the pattern with a scrub pad after making each mold and re-applying the mold release. There would still be some sand stuck to the pattern after stripping it from the mold, however, not a significant amount.

## Pouring

Over the course of eight pours and fifteen molds we ran into multiple issues with our casting. For our initial test pours we used virgin spring steel without any additives that we had available on hand. The first pour of two molds yielded one full casting and a short pour. We also noted that the core was misaligned, requiring an adjustment and a new core box to be cut. For the second pour we had two molds made, unfortunately both ended up only being approximately 50% to 60% filled. After cross sectioning one of the failed castings we discovered gas defects. Three vents of 1/8<sup>th</sup> inch diameter were added to the edge of the casting to eliminate this issue moving forward. Additionally we determined that the temperature when we tapped from the furnace was too low at 2850°F and we lost too much heat before the pouring team made it to the mold. To prevent this from happening in the future we decided that we would take out the liner of our pouring yoke and use it to cover the furnace to pre-heat it. This would prevent heat sap from the steel, additionally it was decided to superheat the steel to 3100°F.

Our third pour was intended as a test to determine the effects of an olivine coating of the mold, which is required for the pouring of high manganese steel. Pouring two molds, we over poured our first mold and the second mold did not fill completely because we poured it too slow after overfilling the first mold. The overpoured casting showed an unforeseen amount of shrinkage and both castings continued to show gas defects. Instead of making new riser inserts for our pattern we decided to make them taller by forming sand around the inserts after the mold had been made to accommodate for the shrinkage issues. These extensions added approximately two inches to the risers and successfully eliminated the shrink defect in future pours. To address the gas defects we placed three additional vents of the same diameter staggered between the original vents. We also found that the core was not breaking down properly and that it was causing gas defects in the eye of the axe. Two more additional vents were drilled into the cope on either end of the core and a channel was scratched down the middle of both sides of the core connecting these two vents. These vents proved successful in eliminating gas defects in future pours.

Our fourth pour was our first attempt at melting our high manganese alloy steel. This test melt was uneventful and did not produce any glaring issues that needed addressed. For all intents it was a successful test of all the improvements we had made to our pattern, molding, melting and pouring process. It was then that the team moved on to a larger run of castings for this competition.

## Alloy

Our fifth pour had four molds this time, all of which filled completely; however, all the castings had cold lapping. We determined the cause to be the olivine sand coating of the mold. After some discussion, it was determined that the olivine coating was not properly thinned down before use. We retained two of the better castings from this run to practice grinding our blade edge and do a test run of our heat treat process. Eventually all of the castings from this run were deemed inadequate for this competition.

We attempted a sixth pour, which was the third attempt with the high manganese alloy. Unfortunately this pour did not go as expected and yielded no castings at all. After tapping the furnace the liquid steel ate a hole in the liner of our yoke ladle. The ladle and furnace liners we use are Alumina Silicate which when in contact with higher concentrations of Manganese becomes acidic. Realizing this, we quickly inserted a new liner in the ladle and resumed our attempts to pour off the metal. Before we made it to the mold, the metal again ate through the ladle liner and spilled onto the pouring deck causing substantial safety concerns. As discussed in the Alloy Properties section of this document, our team reevaluated our metal recipe with our advisor to combat any further interactions with our foundry materials. We then replaced our furnace liner and repaired our yoke ladle during this period. The team decided that the risk of a furnace meltdown while using high manganese steel was too high of a safety risk, and that we would pour our final axe out of AISI 9260 steel.

Our seventh pour in this final recipe again showed gas defects because we unfortunately forgot to add the Aluminum to degas the liquid bath before pouring. The single mold from this melt was unusable.

Our eighth pour on our last available work day posed yet another issue, this time stemming from a lack of communication. The furnace was not charged properly and no alloying elements (C, Mn, and Si) were loaded into it before we started the melt. Without the charge placed ahead of time we were worried that the carbon addition would float and not mix into the bath, or burn off more than we anticipated. We poured the unalloyed steel into ingot molds and started a new melt with the alloying elements loaded properly. This ninth and final melt yielded two successful axes. As we are a student chapter, our foundry time is limited by classroom and advisor availability, thus this final work week saw us burning the candle at both ends and working into the later hours of the night. Thankfully we were able to work each casting simultaneously giving us the best chance to have two successfully finished axes.



## Heat treat

With only two castings available, we attempted a differential heat treat on one casting by only quenching the edge of the blade. After cleaning the oil from the axe we discovered microscopic fractures at the quench line as a result of the difference in temperature and cooling rates. Leaving us one final casting to work with, the heat treat of this axe was a full heat and quench submerging the entire axe in the quench oil once brought to temperature. This proved to be a good decision as the final result tested well on our Rockwell hardness test and a file skated smoothly across the edge of the axe blade.

## Wrap Up Comments

Over the last 82 days, our casting team has learned quite a bit more than we bargained for. We signed up for this competition thinking that it would be fun and a great way to get our University name out there and visible in the industry. Little did we know that working through the problems we faced in finishing this casting we would be learning valuable lessons we had not previously learned in class. We are lucky in that our College has a fully functional foundry complete with forge, CNC router and various manufacturing machinery. As such we were able to completely design, create, mold and cast this axe in house. We also learned a bit about leather crafting and wood burning. Additionally, we need to acknowledge our Faculty Advisor. Without the generosity of his time, understanding and on the job experience there is no way we would have been able to troubleshoot all the hurdles we faced. He kept the lab open extra hours in the evenings, came in on multiple weekends and feed us when needed to keep us going. He also made sure to send us home when sleep was needed and we could no longer work safely.

As for safety, the problems we ran into with the Alumina Silicate were handled as best as possible in the moment. We were then able to step back, discuss and evaluate the whole of the problem, as well as how close we actually came to a catastrophic problem. As such, we had a safety briefing with the whole of our AFS student chapter and set up a emergency response process for future use, should anything ever happen in our foundry. This is real hands on growth that we could have never envisioned when applying to compete. Thank you SFSA for this opportunity!

**Link to Video**

<https://drive.google.com/open?id=1tD0V6FwI9GvTNmcU9fkxdcc-JIbHI4qK>

