Cast in Steel Competition

Viking Axe

2019

Pittsburg State University

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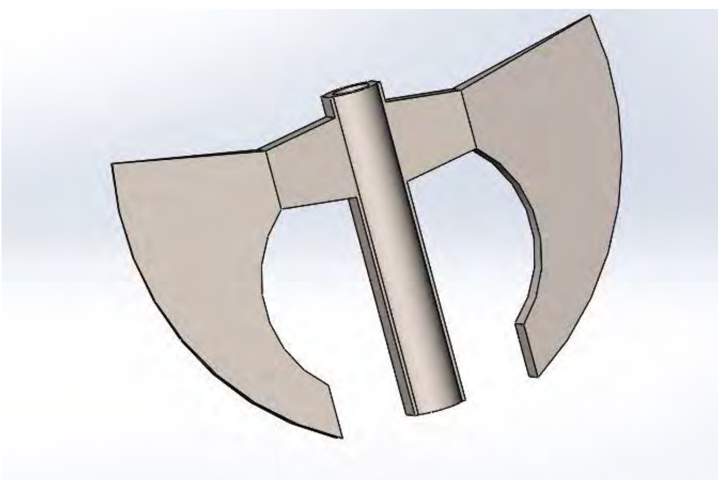
Introduction to Competition:

On August of 2018 we were informed of the SFSA Viking Axe competition. The competition was introduced to us by our Professors Jacob Lehman and Russel Rosmait. Not much thought was initially put into the competition until mid-November of 2018 when we reached out to SFSA to express interest.

Phase 1 3D Modeling the Design:

The first step in the whole process was to formulate a design and production plan. Our goal was to design an axe a Viking man would have only dreamt about. A high quality fine detailed war weapon. A weapon that could not be produced with his limited means of production by forging. We wanted to make a design that incorporated intricate features only capable of being produced in our modern times.

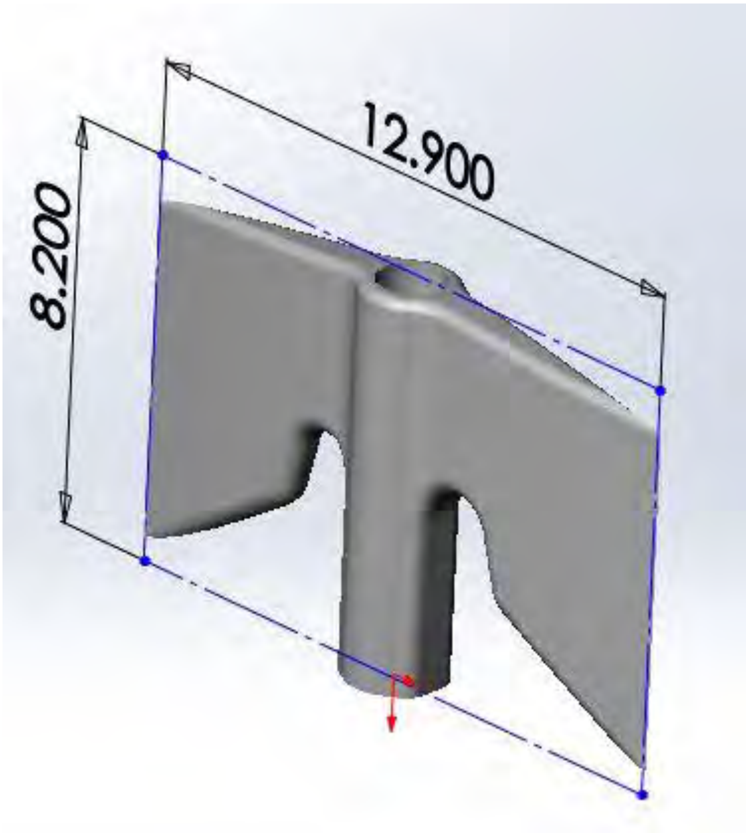
So obviously in our modern times the first step was CAD. A quick concept was designed in Solidworks.



To the left in Figure 1 was a quick design that was modeled in Solidworks. The design was based on a traditional forged Viking axe, but double headed. Going straight to CAD was also very helpful in the future because we learned a great deal about what tools we had to use within the software to produce a 3D model of an axe.

Figure 1. First quick design concept

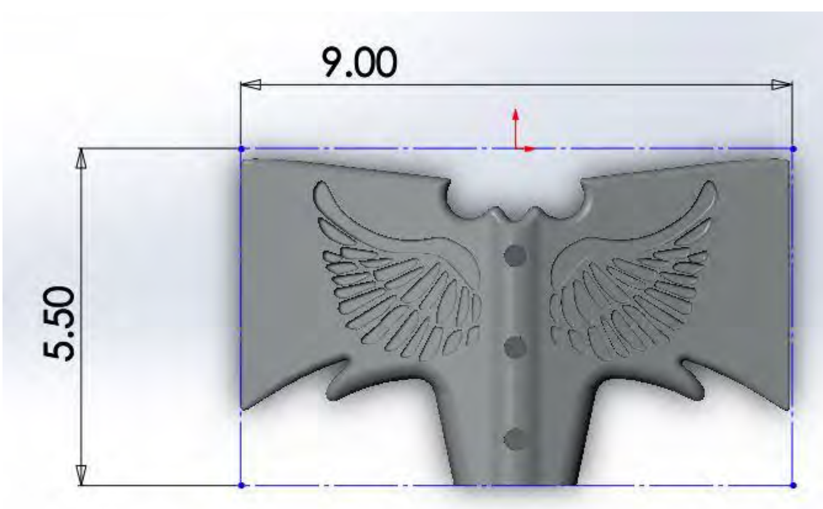
After looking at the quick 3D model created, we noticed this more traditional Viking axe design was a shape easily achievable by swinging a hammer and pounding to shape. The desired design was to be something incapable of being produced by a Viking in the tenth century. So, it was back to CAD again.



To the left is the second design iteration. More thought and time were put into this concept. Casting processes were being thought about and we added radii to the design for better solidification and fewer stress risers. Size was also considered as you can see in Figure 2. This design was going to be large and incorporate a round handle. However, the design still did not seem modern enough for our liking.

Figure 2. Design Iteration 2

After these two designs had been 3D modeled with the more traditional Viking axe shape design, we realized if we wanted to use the full capability of the metal casting process, we needed to challenge ourselves to think of something more modern. So, we got creative.



The next approach was a smaller more decorative and intricate design that included features that could not be produced by a Viking and a hammer.

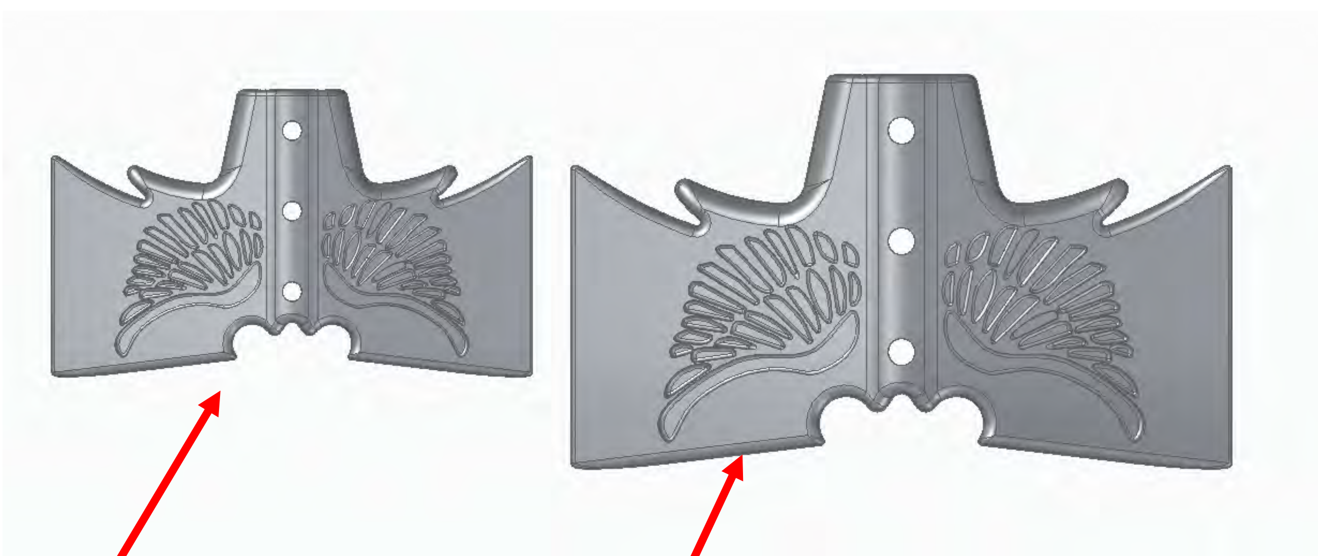
Figure 3. Design Iteration 3

After we created a CAD model we were satisfied with, the next step was 3D printing a prototype. So, we 3D printed half of the axe head for real world visualization out of PLA plastic.

To the left you can see an image of the half of an axe we printed. When the axe came off the printer, we instantly knew it was too small. This shows how deceiving CAD can be. We printed just half of the axe so it would print faster, and we could get an idea of real size quickly.

Figure 4. Design Iteration 3 3D printed

When the 3D printed model was found to be too small. The solution seemed simple. The axe just needed to be scaled up to a size of our liking. So, we scaled up the model by a factor of 1.375.



The solution was however not that simple. After scaling our design up by a factor of 1.375 our steel axe head weight changed from 4 pounds to 10.5 pounds. A 10.5-pound axe head was decided to be way too heavy to perform well. It was decided the only way to achieve a lighter, but also larger size was to redesign our geometry. So once again it was back to CAD.

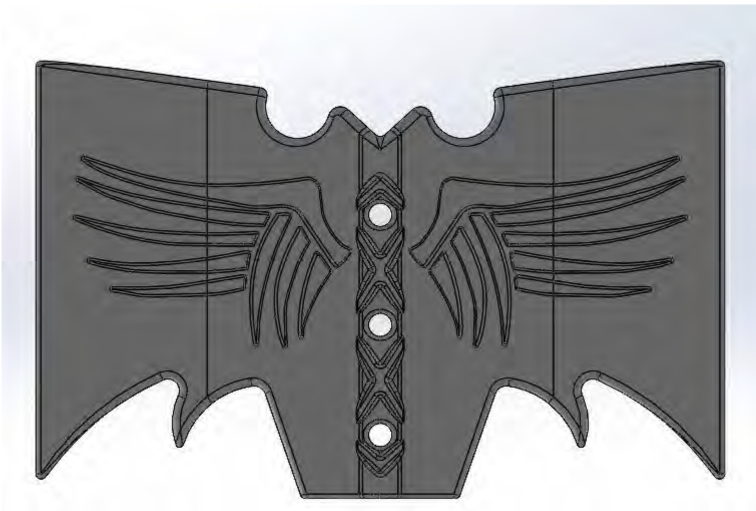


Figure 5. Final Axe Design (4th Iteration)

Four design iterations were completed in the design phase in CAD. The final design had everything we planned on. It was not overbearingly heavy but also not light. This weight would definitely be no problem for a tenth century Viking. The final weight of the design was 5.8 pounds in solid works. We thought this axe head with a handle weighing one to two pounds would be an ideal weight for a large Viking axe.

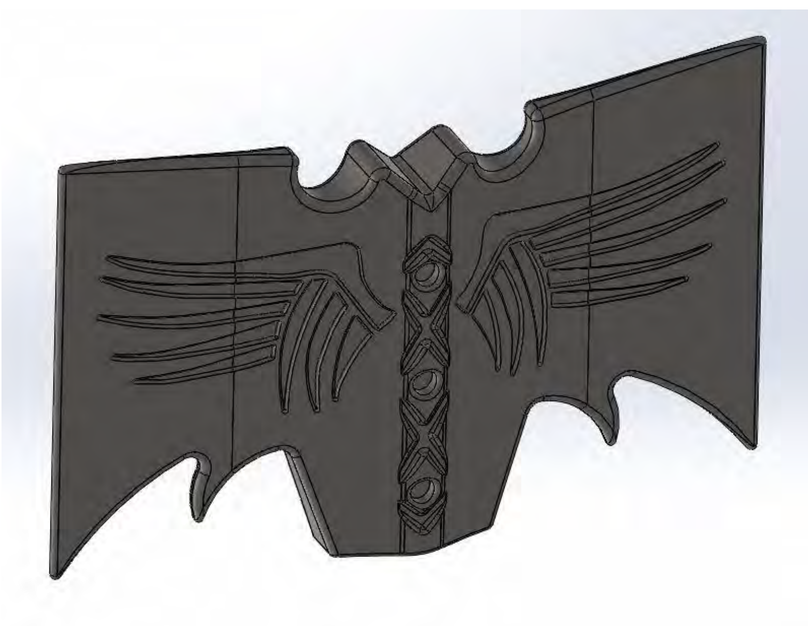


Figure 6. Iso View of Final Design

General Reference Dimensions of Axe Head (All dimensions in inches)

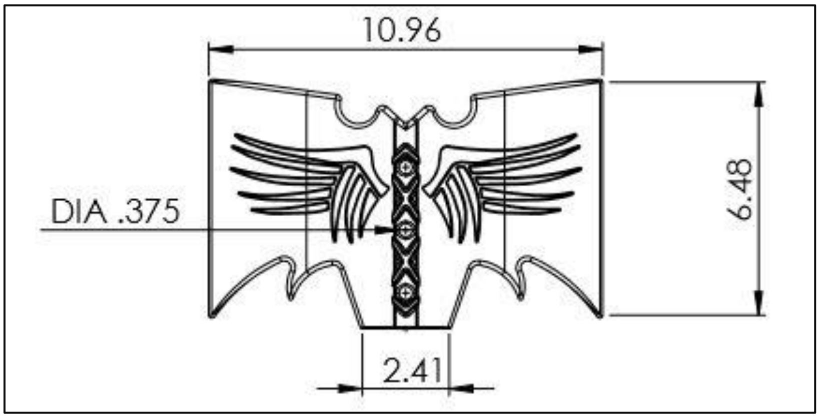


Figure 6. Front View of Axe with Reference Dimensions

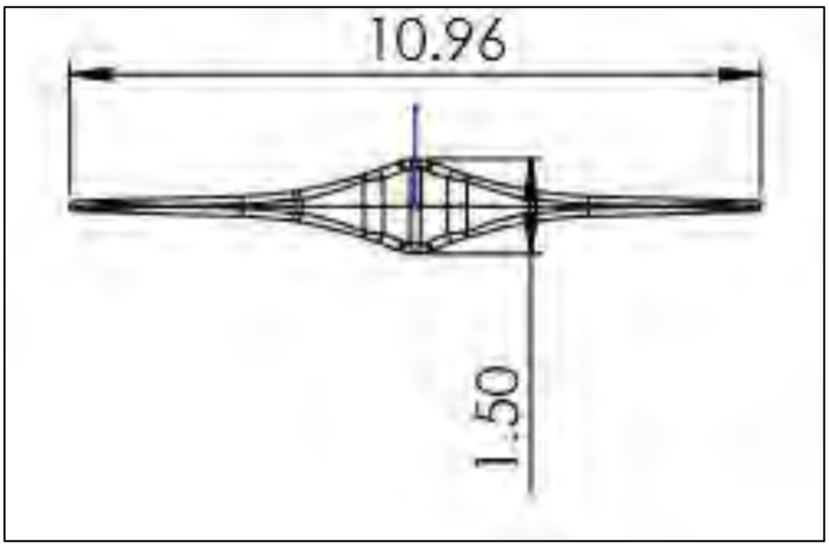


Figure 7. Top View of Axe Head

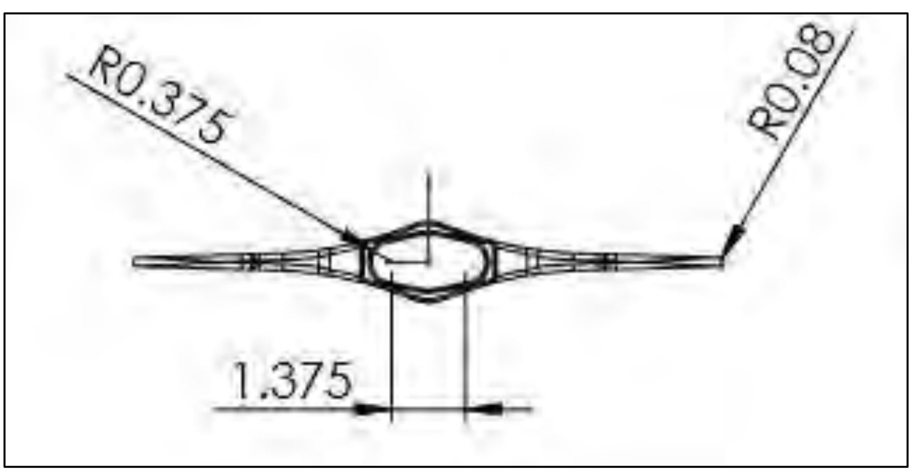


Figure 8. Bottom View of Axe Head

In figures 6-8 general reference dimensions are shown of the axe head. The axe has a minimum wall thickness of around .1875 or 3/16 of an inch. It is mostly this thin around where the handle will be inserted. The tip of the blade was designed to be .080 of an inch radius. This thickness on the end was chosen so the part would be manufacturable for casting and not have too much material to remove from the blade to sharpen it. The axe was also designed with moldability considered. All faces have draft, and everything is filleted. The axe design also implements a standard parting line right down the center as shown below and one core in the center.

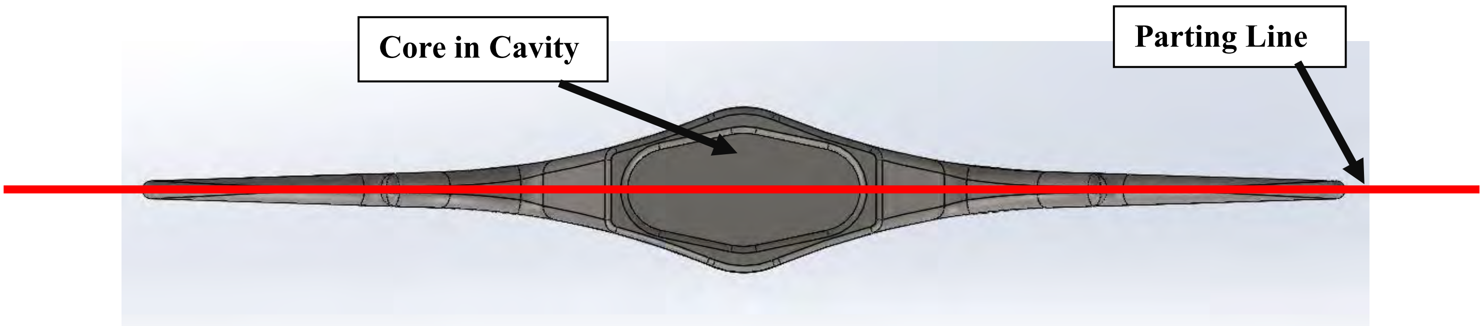


Figure 9. Standard Parting Line

The design also features three thru holes that will be used to attach the handle to the axe. The part was designed with full knowledge the dimensions would change after the part had solidified in the mold during the casting process. The reasoning behind this was because with this being a one-off part actual size or a specific tolerance was not necessary to achieve. The most crucial dimension was achieving a fully solidified casting that produced the shape.

With the design completed for the axe head work was now focused on the handle.

3D Modeling the Handle:

For the handle we started in Solid works, where the Viking man would have started in the forest. We had put some thought into the handle design and knew what size the mating component of the wooden handle would need to be. The size of the handle peg that mates with the axe would be made to fit exactly with the nominal dimensions of the axe in our 3D model. After the axe would be cast, obviously the hole in the axe would shrink due to solidification shrinkage. This would ensure the handle was a tight pressure fit with some light sanding to the handle peg. The handle was also designed with manufacturability in mind.

Figure 10. General Handle Design

Handle Reference Dimensions (All dimensions in inches)

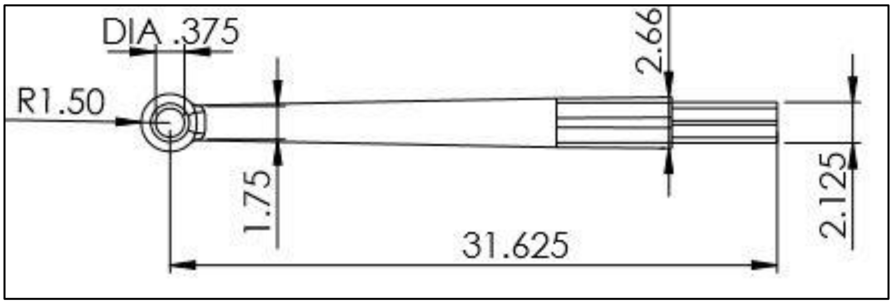


Figure 11. Front View Handle Reference Dimensions

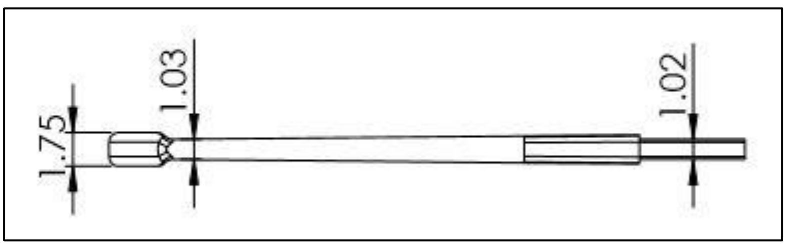


Figure 12. Top View

The total handle length was 31.625 or 31 5/8 inches. 5 and half inches of the handle is inserted into the axe head and 27.5 inches is what will be visible. The handle was designed to be wider than most generic axe handles so it would be Viking proof. It also implements a round hole in the end that acts as a base for your hand providing a strong grip point to prevent slipping. The hole also provides a place so it can be hung up when not in use. The handle was connected with three brass pins that were peened over to hold the axe head securely. Epoxy resin was also used to guarantee the axe head to stay firmly in place. The simple handle shape was designed in Solidworks, but plans to give it personal touch were in mind.

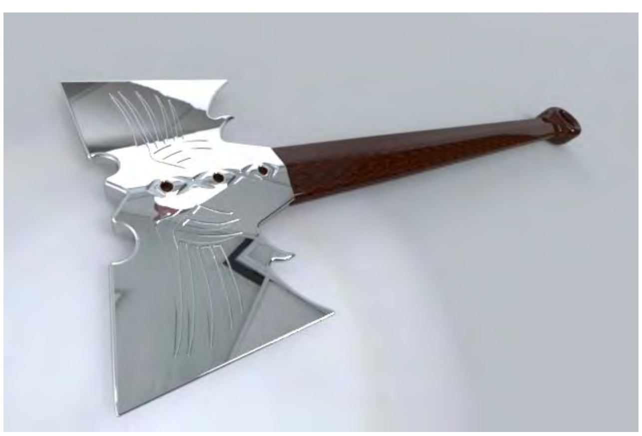


Figure 13. Final Design Rendering of Axe

Phase 2: Material Selection and Manufacturing Plan

Material Selection:

The next step was to decide what alloy of steel to select to cast the axe from. The handle material also needed to be considered.

Axe Head Material:

We reached out to Richard a metallurgist employed by EMJ Metals in Schaumburg Illinois. He suggested three different steel alloys that he has seen axes and other similar shock impact tools cast from. The first alloy he recommended was 4130 which is commonly referred to as chrome moly steel. Next, he recommended 4140 steel also a chrome moly steel. The third recommendation he gave was 6150 steel. This is a steel that has a high level of vanadium, chromium, and carbon content. This makes this steel have very high hardenability while also retaining toughness and resistance to shock and impact loads. We chose to use 6150 because we wanted a high-performance weapon. This steel contains elements a Viking man has no ability to synthesize into pure compounds and imbue into his war weapon.

Element	Content (%)
Iron, Fe	97.095 - 97.72
Chromium, Cr	0.800 - 1.10
Manganese, Mn	0.7 - 0.9
Carbon, C	0.480 - 0.530
Silicon, Si	0.150 - 0.3
Vanadium, V	≥ 0.150
Sulfur, S	≤ 0.04
Phosphorous, P	≤ 0.0350

Figure 14. Chemical Composition of 6150 Steel

Axe Handle Material:

The wood type chosen was White oak it was selected for its strength as well as its availability. It has long vertical grains that help dissipate the force from axe impact. When designing the handle, we kept in mind the grain structure would need to be oriented in the proper position to provide the most ideal mechanical properties. So, the grain structure was orientated perpendicular to the force applied during a regular axe impact. Refer to the image on the next page for a visualization of how the grain structure is orientated on the cross-sectional area of the handle.

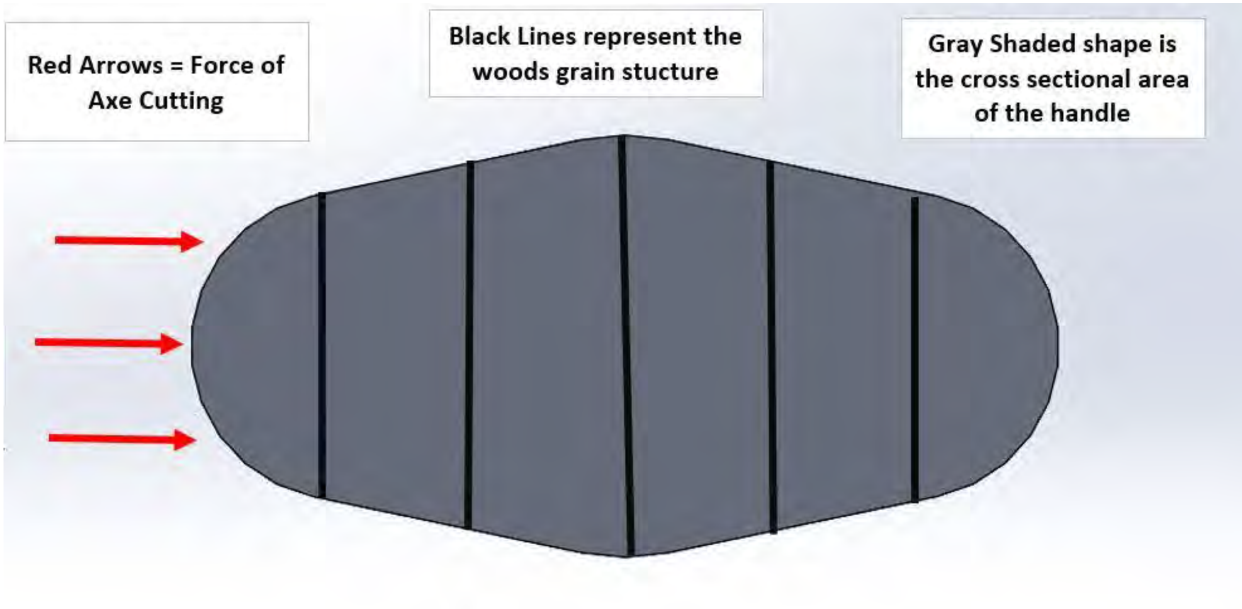


Figure 15. Cross Sectional Area of Handle

Manufacturing Plan:

Casting Process: 3D Printed Sand

The casting was designed to be molded using a split piece pattern with one core. However, early in the design stage we reached out to Emerson in Iowa, a 3D mold printing company, and they were on board to provide us a 3D printed mold. This means our gating system design was not limited to traditional molding constraints. So, we came up with the idea of a 4 axe heads in one mold concept. This would increase our odds of getting a very sound and fully formed casting. The 3D printed mold would also make it easy to orient 4 axe heads on a gating system. For the actual pouring of the mold we worked with Monett Metals our SFSA partnering foundry.

Handle Manufacturing Process:

To manufacture the handle, we planned on cutting one half of the profile out of a square block then flipping the block to cut the other half of the profile. This would be done on a CNC wood router.

Handle and Axe Assembly Process:

As discussed earlier to assemble the handle to the head of the axe, the handle would be press fit onto the axe head with epoxy. Then three holes would be drilled through the handle using the holes in the axe head as drill bushings. Three brass pins would then be press fit into the axe head and handle. The pins would then be peened over to ensure they could not fall out.

Phase 3: Gating System Design and Simulation

The plan for the gating system was to produce an ideal design that resulted in four fully formed axe head castings in just one mold. Since at Pitt State we have MAGMA licenses we utilized this software to simulate the gating systems designed. Many iterations were experimented with until desirable results were achieved.

Figure 16. Final Gating Design

Above is the 3D model of the most ideal gating system designed. Since a 3D printed mold would be utilized, we had a great deal of design freedom. Many different riser locations and sizes were tried to obtain ideal porosity and shrinkage levels. The design was directly driven by the results from the MAGMA simulations. This design was found to have the least amount of shrinkage and porosity as well as a smooth and quiet filling pattern.

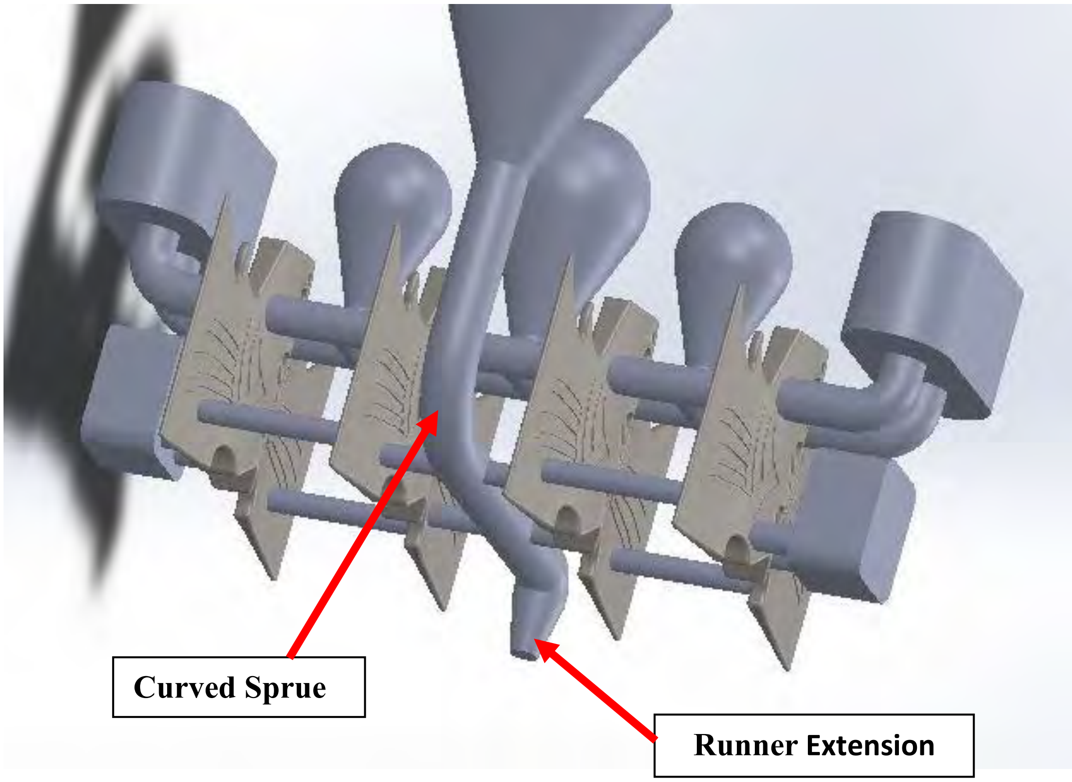


Figure 17. View of bottom of gating system

The gating system as you can see above featured a sprue that curved into the runner. This helped exponentially to produce a smooth filling pattern. Also, a curved down runner extension was used to trap the first metal down the sprue. All gating and riser feeder necks were also round to improve filling patterns. The design included a total of seven risers to feed the castings. Riser placement and size was decided by simulation results. Another feature of the gating system was a very large pouring cup to make it easy to fill the mold. Overall all the total pour weight was 126 pounds.

MAGMA Simulation Parameters:

When using simulation software, it is very important parameters set are as accurate as possible to real world conditions. For defining the steel alloy in the software, we used the exact chemical composition as seen in Figure 14, in the foundry we would also need to ensure the melt had the same chemical composition. For the pouring time MAGMA auto generated a pouring time based on the size of our pouring cup and gating system. The calculated pouring time was 11 seconds. This would also need to be accurate while pouring in the foundry. Another important parameter was the pouring temperature. From research we decided a pouring temperature of 3000 F would be appropriate. This would provide enough super heat to help the liquid steel flow better. Once again, we would need to ensure this pouring temperature was accurate in the actual pour. Sand type and initial temperature are also important parameters. The sand type chosen was cold box sodium silicate sand. This is the sand the mold would be printed from. For the temperature ambient temperature was chosen because we would not preheat the mold.

MAGMA Simulation Results:

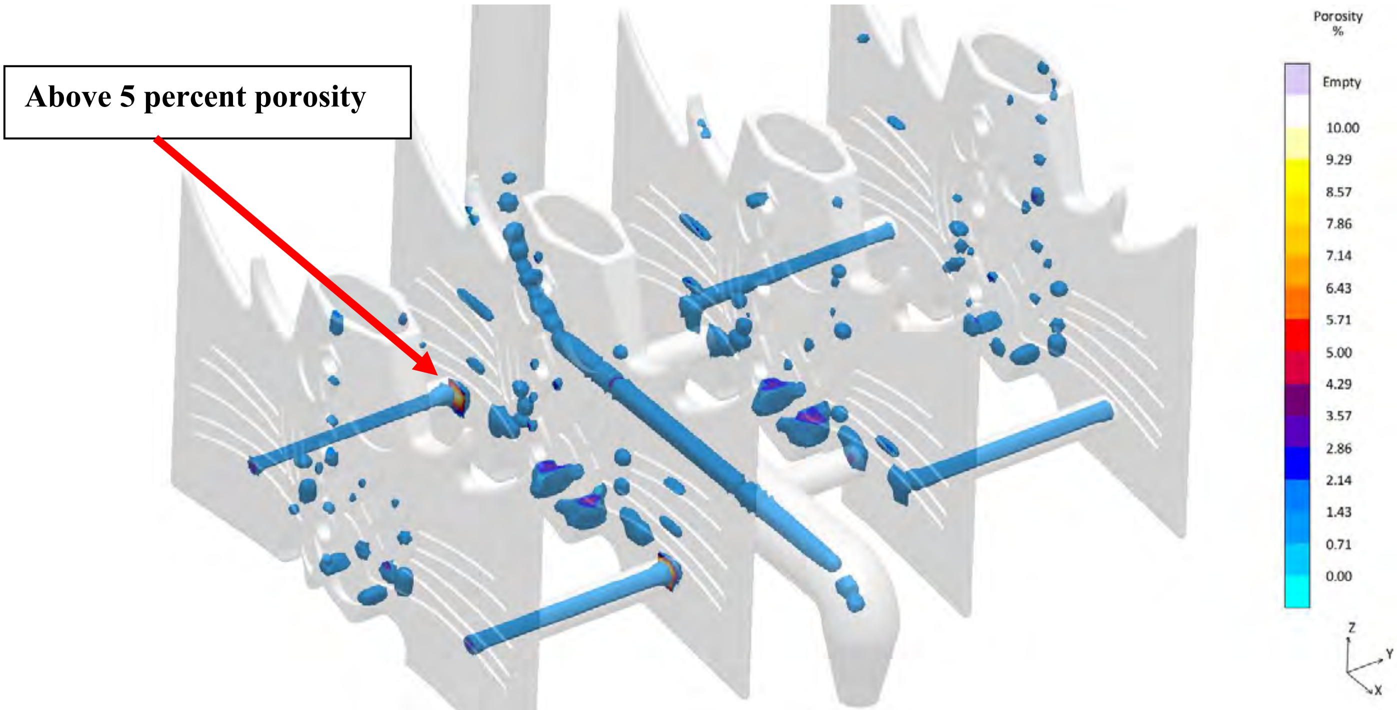


Figure 18. Porosity Results from MAGMA

Above is a porosity result generated by a MAGMA simulation. Referring to the scale on the right of the image it can be seen porosity levels are below 5 percent in all places except where noted. This seemed very ideal and the results were satisfying after many simulations we had conducted earlier resulted in horrendous amounts of porosity. Also, it should be noted that the two axe heads on the outsides had significantly less porosity as the inner axe heads.

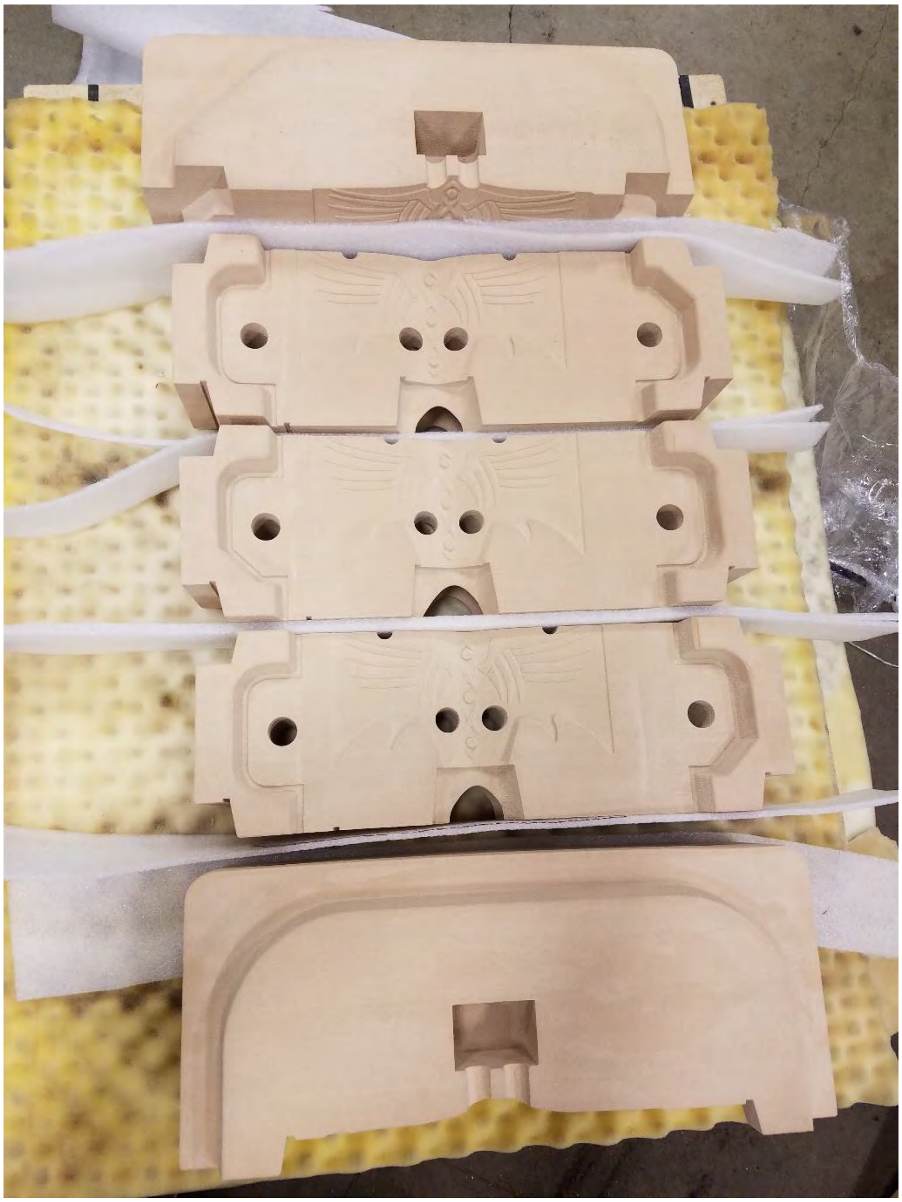
Metal velocity was also a focus in the gating design simulations. Below is a link to a video clip of a metal velocity and filling pattern simulation conducted. The video shows the metal velocity in the castings while filling is very low and calm.

https://www.youtube.com/watch?v=heBpUjZiB_k&feature=youtu.be

Phase 4: Manufacturing the Axe

3D Printed Sand Mold Preparation:

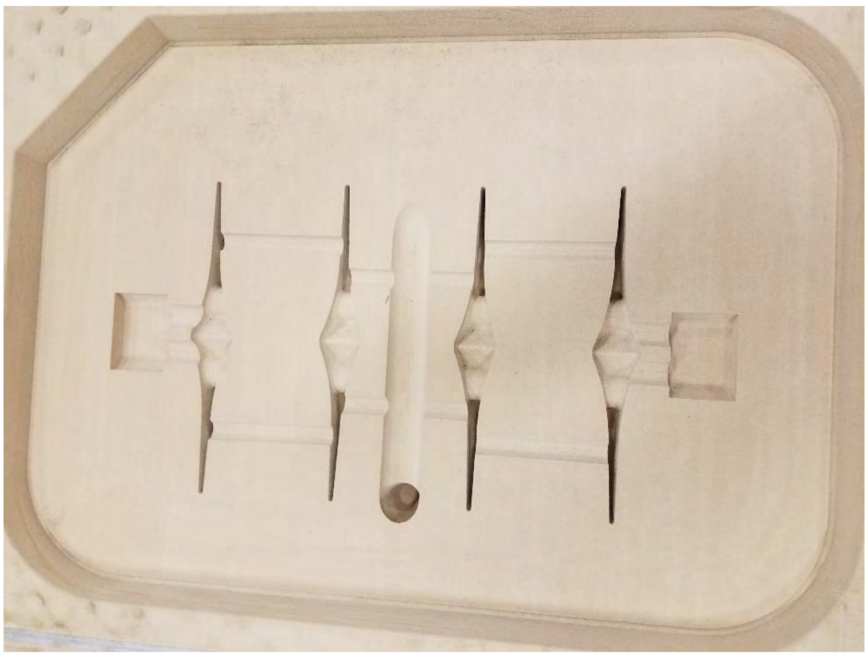
The mold was designed by Emerson. We only sent them the CAD files of our gating system and they determined how to split the mold up to make it functional. The mold was designed using seven pieces that keyed together to form the cavity of our designed gating system. Four cores were also used to produce the hollow feature where the axe head would insert. Refer to the images below for a visualization of the mold design.



To the left is the cheek section of the mold that was placed between the cope and drag. The cheek consisted of 5 pieces that all mated together. Each cheek piece had numbers 3D printed in, so the correct orientation was obvious.

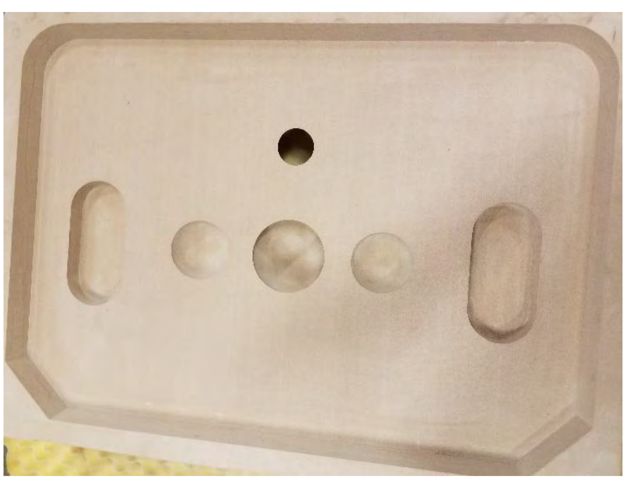
Figure 19. Cheek sections of the mold.

Figure 19 A. Cheek Numbers and Close up



To the left is a view of the drag half of the mold. It keyed together with all 5 cheek pieces to form the cavity.

Figure 20. Drag Half of the Mold



To the left is a view of the cope half of the mold. It contained the pouring cup and the tops of the risers. The cope half fits on top of the cheek and completes the mold.

Figure 21. Cope Half of Mold

After the mold had been received it was decided a zircon wash coating would be applied to all cavity surfaces on the mold. This zircon wash coating protects against mold erosion and the very high temperatures of steel casting. The zircon wash coating was applied with paint brushes and care was taken to prevent leaving behind brush marks that could potentially show in the casting.

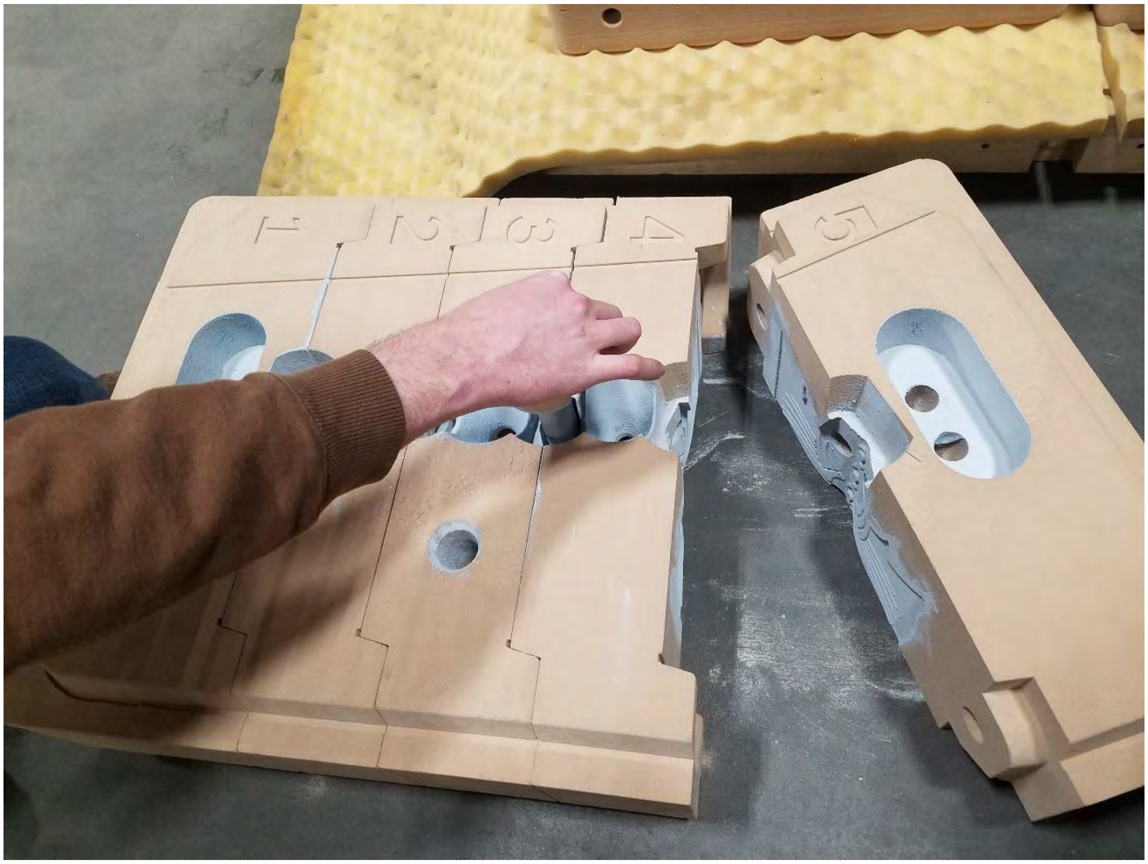


Figure 22. Zircon Washed Cheek surfaces.

Pouring the Mold:

When the mold was fully prepared, we packaged it up nicely then headed to Monett Metals. They agreed to melt and pour the 6150-steel alloy we selected. Before pouring the mold, we needed to add vent holes to the risers so we could add an exothermic material to allow the risers to feed better. The holes were crudely added with a Dremel tool with a long bit. We also were informed we should have designed vents in the mold to prevent gas build up. This was a shortcoming on our part.

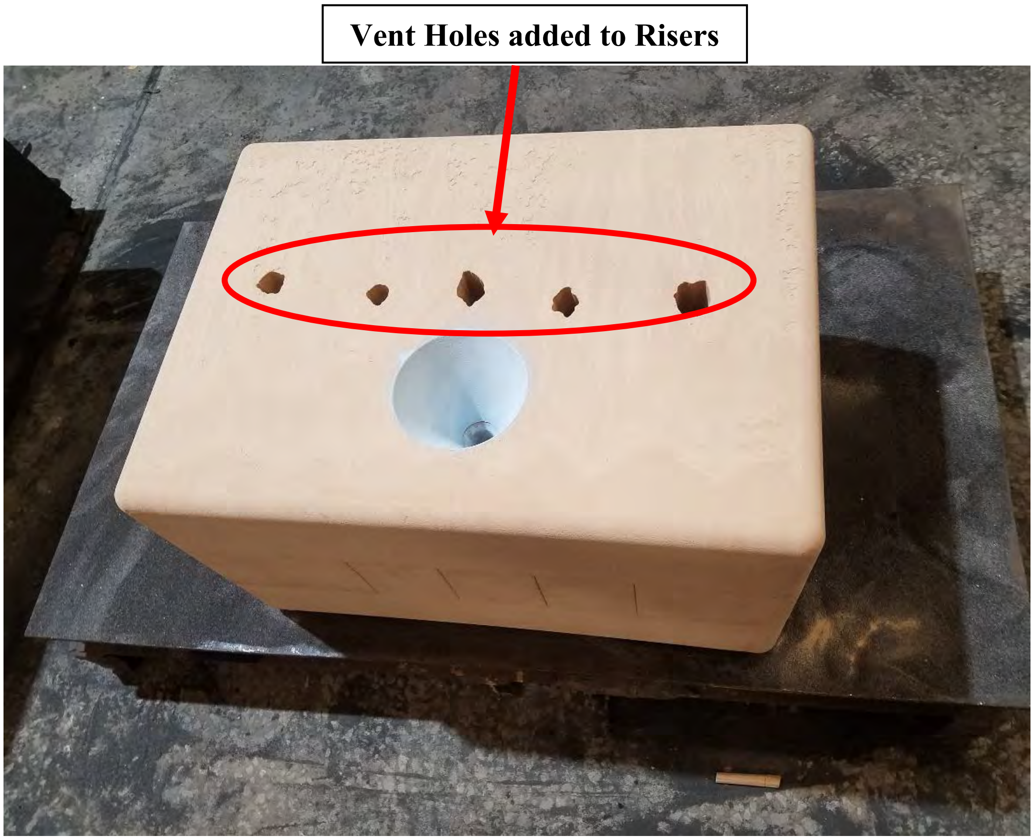


Figure 23. Vent holes added to mold

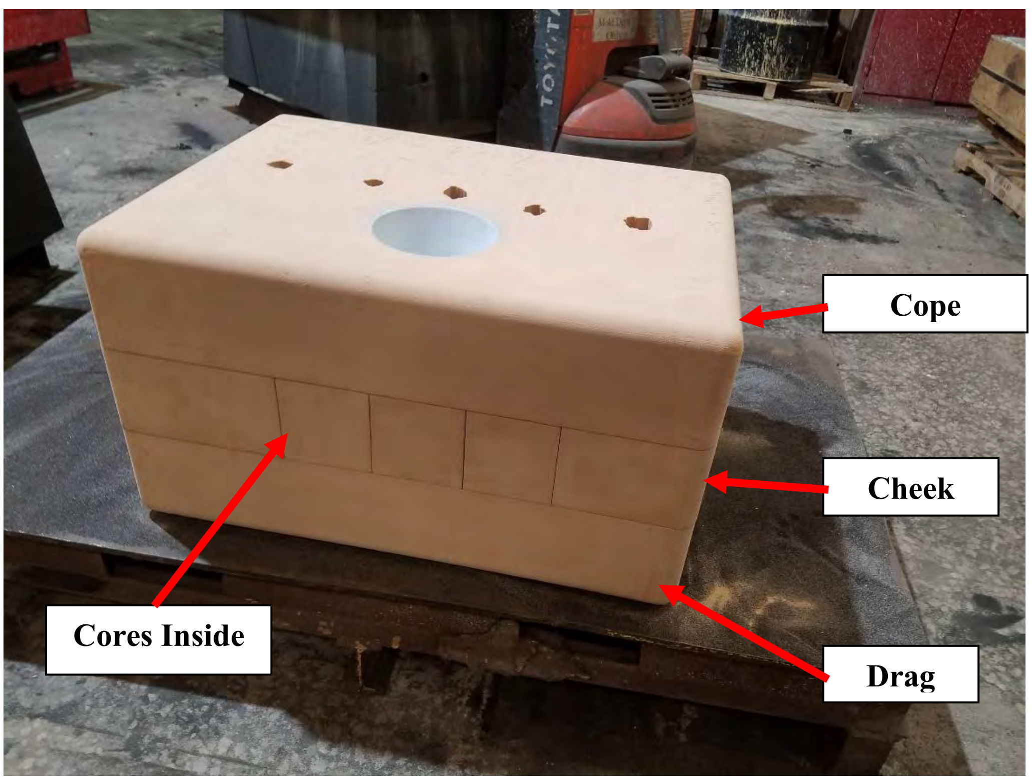
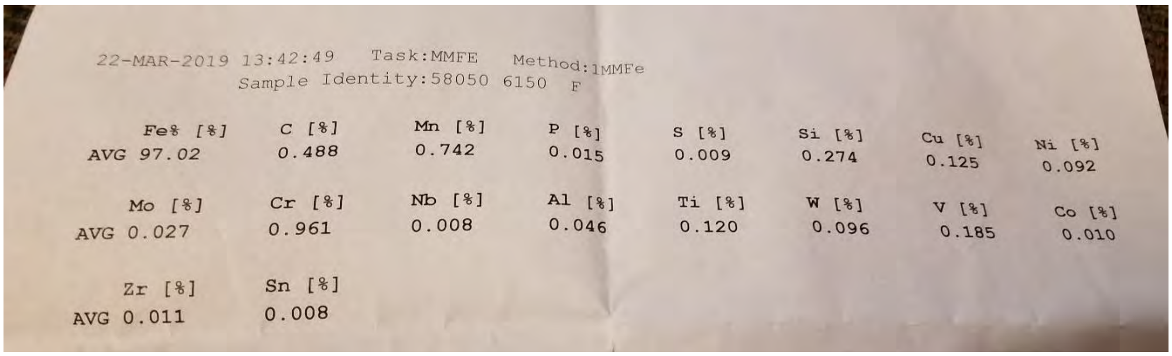


Figure 24. Ready to Pour Mold

The next step after adding final preparations to the mold was to melt the 6150 steel. An initial melt was conducted, and a small sample was poured to be chemically analyzed with a spectrometer. After the spectrometer analyzation was complete it was found our chemical composition was completely absent of chromium. This was due to none being added to the melt. So, a specified amount of chromium was added to the melt and another sample was poured. A spectrometer analysis was performed again, and the comp was right on target. The actual chemical composition can be seen below.


22-MAR-2019 13:42:49 Task:MMFE Method:1MMFe
Sample Identity:58050 6150 F

	Fe% [%]	C [%]	Mn [%]	P [%]	S [%]	Si [%]	Cu [%]	Ni [%]
AVG	97.02	0.488	0.742	0.015	0.009	0.274	0.125	0.092

	Mo [%]	Cr [%]	Nb [%]	Al [%]	Ti [%]	W [%]	V [%]	Co [%]
AVG	0.027	0.961	0.008	0.046	0.120	0.096	0.185	0.010

	Zr [%]	Sn [%]
AVG	0.011	0.008

Figure 25. Chemical composition of Poured Metal

Comparing Figure 14 the target chemical composition and Figure 25 the actual chemical comp, it can be seen we were very close and well within tolerance.

After the chemical composition was verified to be correct the next step was to pour the mold. Since we used a pouring temperature of 3000 F and a pouring time of 11 seconds in the simulations, we needed to make this happen in real life. So, the metal was 3000 F at pouring and the melt supervisor was informed to pour the mold as close to 11 seconds as possible. Before pouring weights and exotherm material were placed on the mold. Also, the metal was fluxed immediately before pouring. The pouring process was captured on video and can be viewed in the link below.

https://www.youtube.com/watch?v=ktjnMm7Nlo0

The pour went to plan. All real-world parameters matched our simulation parameters. The metal was poured at 3000 F for 10 seconds into an ambient temperature sodium silicate sand mold. MAGMA had said full solidification time would be 1 hour and 24 minutes, so we let the mold sit for that amount of time. After that time had passed the metal in the mold was still red hot but was fully solidified. So, we carefully loaded the mold up with the metal still inside and hauled it back Pittsburg. The mold was not shaken out until two days later and the metal was allowed to cool to room temp in the mold.

Figure 26. Mold After two days of cooling

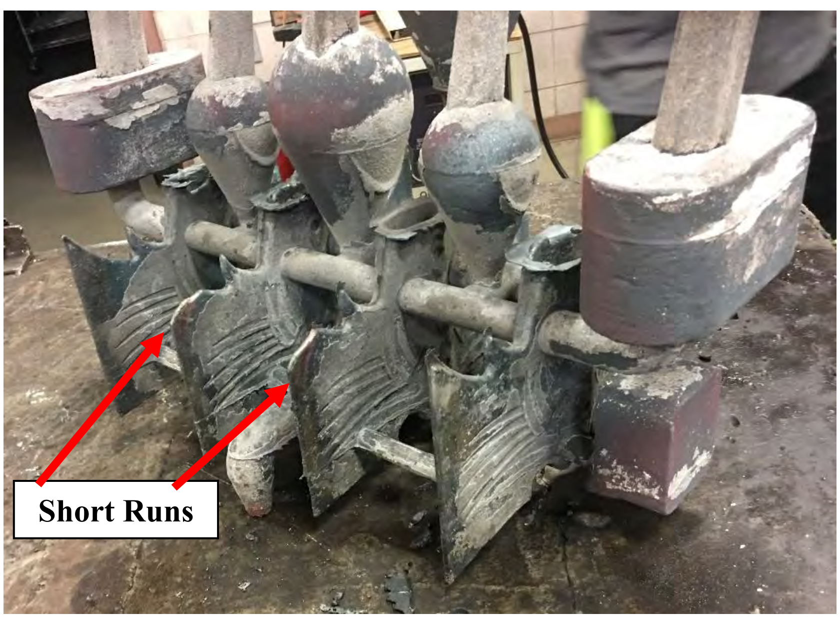


Figure 27. Breakout

When the mold was broke out it was observed the two inner axe heads resulted in short runs. This was unfortunate, but it was a good thing we decided to cast more than one. The good news was the two outside axes appeared to be relatively free of defects.

The next step in the process was removing the castings from the gating system. An oxyacetlene torch and grinders equipped with cut off wheels were utilized. The first step was to remove the two outside axes. This was achieved by using the torch to cut the lower gates in the middle. Once that had been completed the riser necks were cut with the grinder to prevent heating the axe head too much and destroying the grain structure.

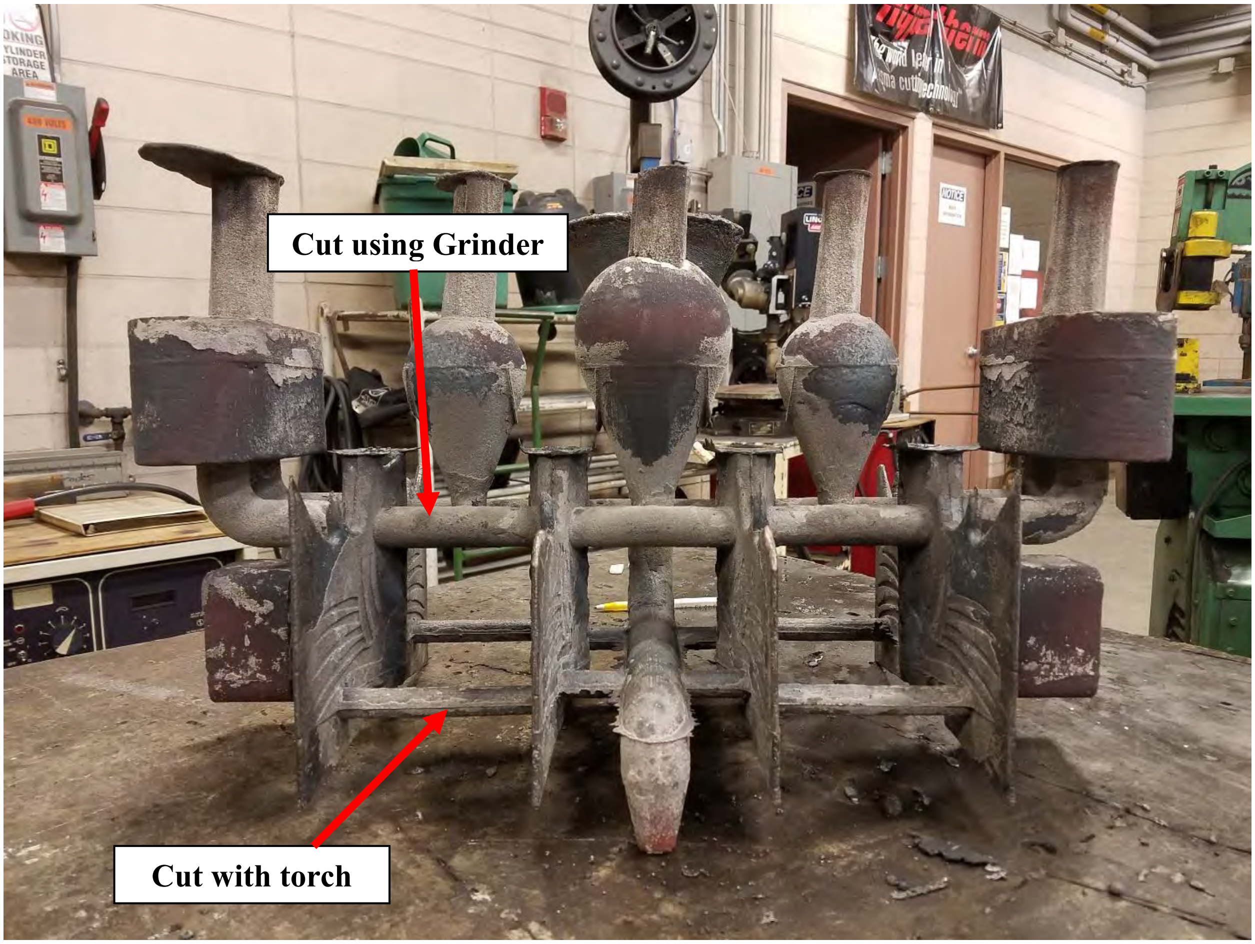


Figure 28. Cutting Visualization

With the two outer axe heads removed the two inner axe heads were much easier to remove. The grinder with the cut off wheel was used to remove the two inner axes. After all axe heads had been removed from the gating system they still had huge stubs of gates and riser necks left.

With all axe heads now being loose from the gating system the gates would need to be knocked down flush. The grinder with the cutoff wheel attached was used to cut the gates down to approximately an 1/8 inch above the casting. After this was achieved, a grinder with an actual grinding wheel was used to blend the gate into the casting. The two links below show the amount of fun we had grinding the castings. A new respect was earned for casting cleaning.

Figure 29. Axe head with Stubs

https://www.youtube.com/watch?v=aVFLyytXzHI

https://www.youtube.com/watch?v=mFnv7Zp1GoI

Figure 30. Axe Head Ready for Heat Treat

When all axes had gates removed and knocked down, they were ready for heat treat. All polishing and sharpening would be done post heat treat.

Heat Treating the Axe Heads:

For the heat treatment of the axe our target was around 45-50 Rockwell C hardness. We wanted a tool that would be hard but also not extremely brittle. Research was done into the heat treatment of 6150 Steel and a heat treat recipe was decided to produce an axe head of our target 45-50 RHC. The process was as follows.

Heat Treatment Process:

1. Place axe heads in furnace and Ramp to 1550 F
2. When 1550 F was reached, the axe heads were soaked for 1 hour
3. The axe heads were then removed from the furnace and immediately quenched in PC-108 quench oil
4. Axe heads were then placed into another furnace that was preheated to 800 F to temper
5. The heads were left to temper for 2 hours
6. Axe heads were removed from furnace and air cooled by a fan.

The heat treatment quench was video recorded and can be viewed by the link below.

https://www.youtube.com/watch?v=4uxBL1reCB8

The axes were Rockwell tested and they all came out at around 45 RHC. This was on the lower end of our target, but the results were acceptable.

Handle Manufacturing:

To manufacture the handle, we reached out to Sam Galliart, a graduate wood technology student at Pitt State, AKA the wood master. He had a machining strategy to make our handle. The first step in the process was to start with a rectangle wood blank of appropriate size. This wood blank was then secured to the router table by vacuum. Then half the handle profile was machined. Refer to Figure 31 on the next page for visualization.

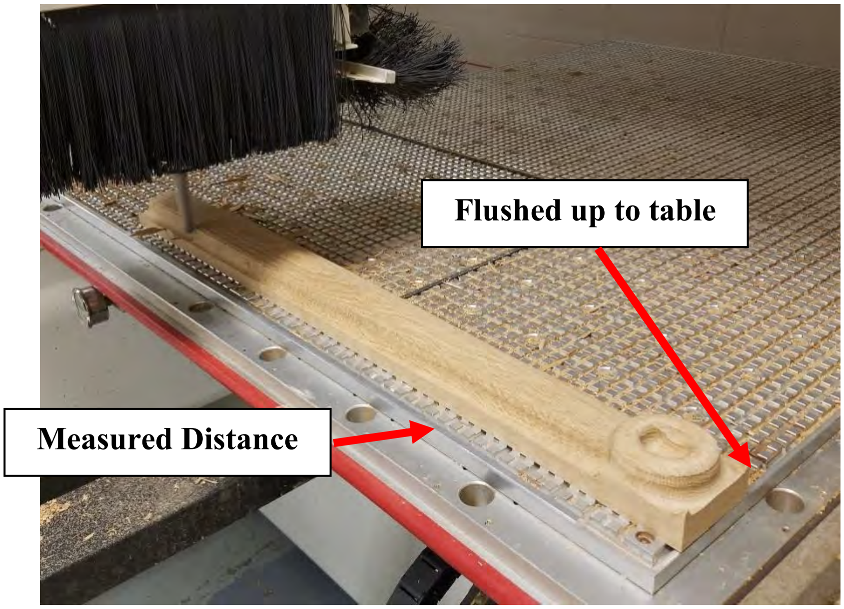


Figure 31. First Step of Proccess

As you can see to the left the wooden blank was cut to half the profile of the handle. The distance was measured from the table to the wooden blank. This would be important later. The block was flushed up to the right of the table for the other zero.

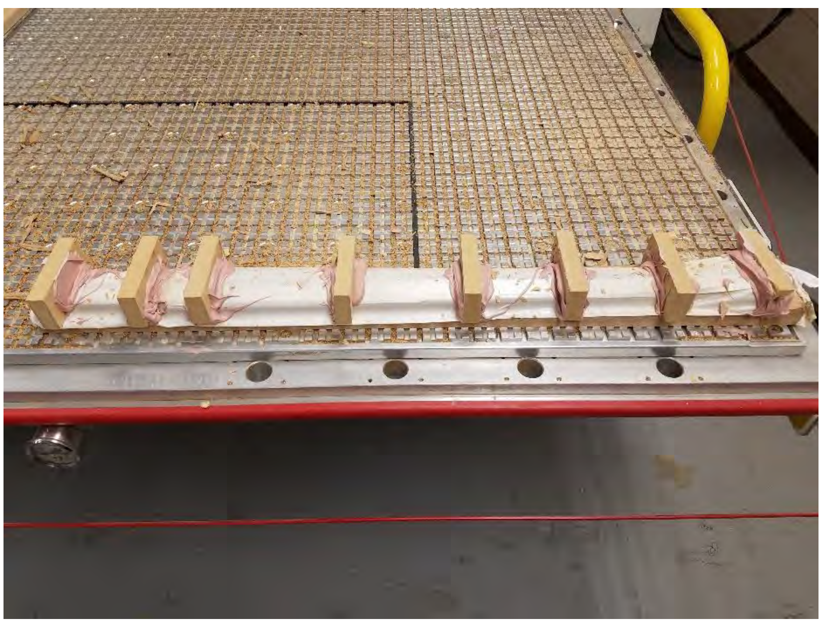


Figure 32. Second Step of Process

The next step was to apply double sided tap to the handle profile cut. This double-sided tape was used to prevent bondo from penetrating and sticking to the wood. Then blocks were cut roughly to the axe handles profile and attached with bondo. After the bondo had cured the blocks were then machined flat to all be the same height.

After cutting the full half of the profile and applying bondo to secure the riser blocks the next step was flip the handle and machine the other half of the profile.

Figure 33. Flipped axe hand

So, to flip the handle we drilled dowel pin holes in a spoil board. Then drilled mating dowel pin holes in the riser blocks attached to the axe handle. Bondo was then applied to help secure the riser blocks to the spoil board. The connected spoil board and axe handle were then attached to another spoil board that was vacuumed to the table. Since we knew the position of the axe handle before we flipped it was as simple as lining it back up and running the same router program.

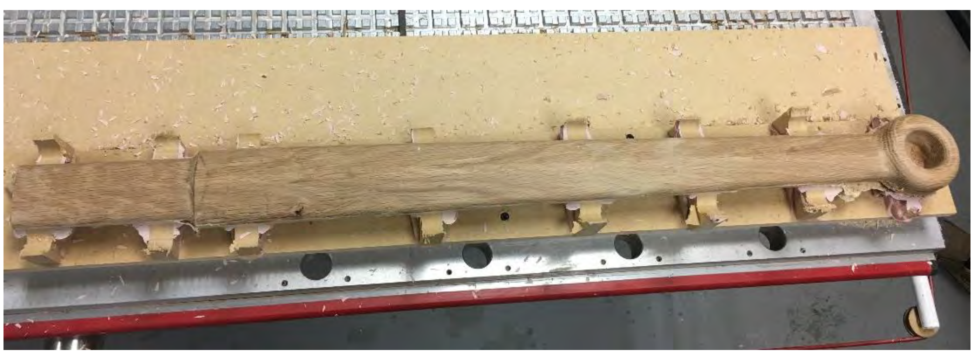


Figure 34. Second side of the axe profile machined.

The axe head in the pictures above is the process we used to produce axe handles for our axe head. Our final axe head production process for the competition was not documented besides in the video link below.

https://www.youtube.com/watch?v=AInSoOctfT4

Pictures of the final axe handle can be seen on the next page.

Figure 35. Views of Final Handle for Competition with 3D Printed Head

Polishing, Assembly, and Sharpening

Initial Polishing:

To polish the axe head the first step was to use a 40 grit flap disk wheel. From here we removed any scale from heat treatment and removed any pitting that could be removed. Then a 60-git flap wheel was used to give a finer surface finish. From here the casting was hand sanded with progressively finer grits up to 600 grit. After this we used a scotch brite wheel to begin polishing the surface. Then a finer scotch bright wheel was used. This was all the polishing that was conducted to the axe head pre-assembly.

Axe Head Assembly to Handle:

As mentioned previously the axe head would be press fit onto the handle. The handle was sanded lightly with a belt sander then epoxy was applied to the end that would be inserted into the axe head. After the epoxy was applied the handle was quickly hammered into the axe head until it seated. The epoxy was then allowed to cure. Holes were then drilled into the handle using the axe head holes as drill bushings. 3 Brass pins were then turned on a lathe to press fit into the handle. The pins were then pressed into the handle and peened over with a ball peen hammer to permanently lock the handle to the axe.

To the left is the axe head fully assembled pre final polishing

Final Polishing and Sharpening:

To put a final polish on the axe a rouge wheel was used. This polish really changed the appearance. After the axe was polished, we began sharpening. To sharpen the axe a belt sander with progressively finer grits was used. The final sharpening grit was a belt with 1500 grit. The last step was using some rouge compound and a leather belt to fully deburr the edge and apply the final edge. Also, as a last-minute addition we added paint to the SFSA logo on the handle to make it pop.

Final Axe Pictures:

Phase 5 What We Have Learned:

During the course of this project we have learned a great deal about product development and the metal casting process. In conclusion we designed an axe and designed a process to manufacture it. The axe manufacturing process was designed using 21st century technology to produce a weapon a Viking would be proud to wield. This process of design to manufacture has taught us some valuable lessons about metal casting. First lesson learned is the simulation software is not always a sure thing if parameters are incorrect and results are misinterpreted. We thought we had an ideal gating system that would produce 4 sound fully formed castings. This was not the case however with only two castings being fully formed. Even the two castings that were fully formed had some short running around the handle attachment point and some porosity. Both axe heads also had small ¼ inch holes around where the pins would attach. These holes were filled with ER80S filler rod with a TIG torch prior to heat treating. We also learned a great deal about the melting process of steel and how the chemical composition is controlled on the foundry floor. Another great aspect was performing a heat-treating process to try to achieve ideal mechanical properties. 3D printing was also utilized extensively. We 3D printed our initial design and were able to see our models come to life. Also, 3D printing was used to produce the mold cavity to pour the steel. This allowed a great deal of design flexibility allowing to cast 4 heads in one mold.

Overall this Axe competition has introduced us to modern metal casting technology. We have had some good times in this project and some bad. The casting cleaning was a hassle. This really showed how poor gating design can be a nightmare to remove. On the flip side attaching the head to handle after all the work we put in was a satisfying feeling. Starting with an idea and putting in the planning necessary to produce what you envisioned. This competition has been a blast. Thank you for the opportunity for us to compete in this year's SFSA Cast in steel competition. It's been a pleasure!

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