Technical Report

Viking Axe Competition

By SFSA

Sand casting group from Iowa State University

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1. Introduction

Our entrance in this year's Cast in Steel competition is one of two from Iowa State, and all members are graduate students aiding in steel casting research in the Industrial and Manufacturing Systems Engineering department at Iowa State University. Dr. Frank Peters and Ryan Horak, a recent Industrial Engineering graduate from Iowa State, advised us throughout this project. This year's Cast in Steel Competition provided an in-depth and hands-on learning experience about the steel casting process from design to finished product. Being able to produce a high-performance piece of equipment through modern manufacturing processes as opposed to forging made for an exciting and challenging project.

Our approach for this competition was to utilize additive manufacturing in conjunction with sand molding to produce a functional axe. Fused deposition modeling (FDM) was the additive method used to fabricate our patterns and core box, and no-bake resin bonded sand molding was used to create the final axe. Grinding was used as a finishing procedure for the axe blade.

The quality of our axe was analyzed via finite element analysis (FEA), magnetic particle inspection (MPI), surface roughness classification, and hardness testing. MPI and surface roughness classifications go hand-in-hand with our research at Iowa State, leading us to take advantage of those inspection techniques for the competition.

2. Materials and Methods

2.1 Rationale behind the design

The axe shape is based on some ancient Nordic/Viking axes, and was selected due to its uniqueness and recognizability. Since Viking axes were traditionally large (up to 5' in height), we opted for a longer axe. That led to our axe head weighing around six pounds, which is heavier for an axe by today's standards but most likely the average for a Viking axe. Including symbology on the side of the axe allowed us to showcase the capabilities of steel casting and add our own touch to the finished product. The Triquetra was selected for its intricacy and historical significance. There have been many Viking artifacts that showcase this symbol, but the real meaning of the symbol to ancient Vikings is unknown. For an additional challenge, we also included Iowa State lettering and our own modern Viking symbol. Our axe was also designed with manufacturability in mind;

many decisions were made during the design process to ensure a high-quality casting. Things like flow, gating, and risers were all considered while designing our axe from the very beginning.

Figure 1. Axe Design

2.2 Gating/Riser Design

We went through about 14 revisions for the gating/riser design with help and feedback from Ryan Horak from Eagle Alloy. In this section, we highlighted some of the issues we faced with initial designs and how we fixed them.

2.2.1 Initial gating/riser design issues

Our first design of the gating/riser system as shown in Figure 2 had many flaws. Through communication with Ryan, we learned that the rectangular cylinders were not as efficient as cylindrical ones and the size needed to be about 2.5 times the thickest section of the part. Additionally, the risers were not feeding the thickest section of the part. Having 3 gates attached to each part also cause an increase in post processing time.

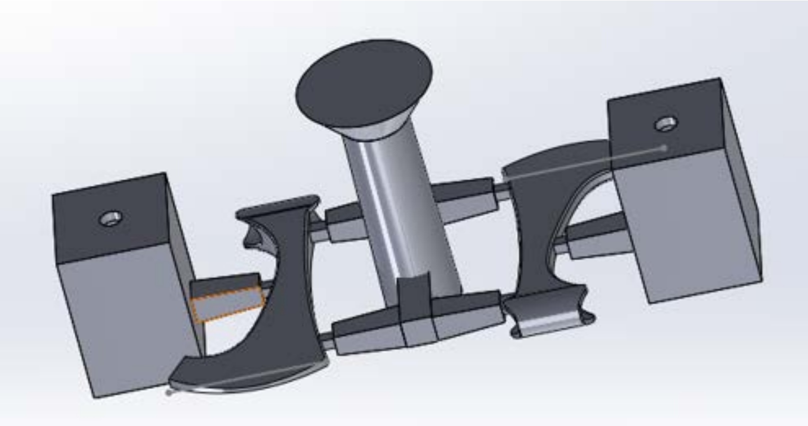

Figure 2. Revision 1 of the gating/riser system

Using MAGMASOFT software available at Iowa State University, we ran simulations to test the design. Figure 3 shows during flow simulation that the areas near the blade were not filling in as well as the other areas. This also showed up in the porosity simulation with high porosity in the area close to the blade. A major issue here was having the blade section too thin hence under filling in that area. However, the downside to increasing the blade area thickness would be the increase in post processing time to get the final sharp edge.

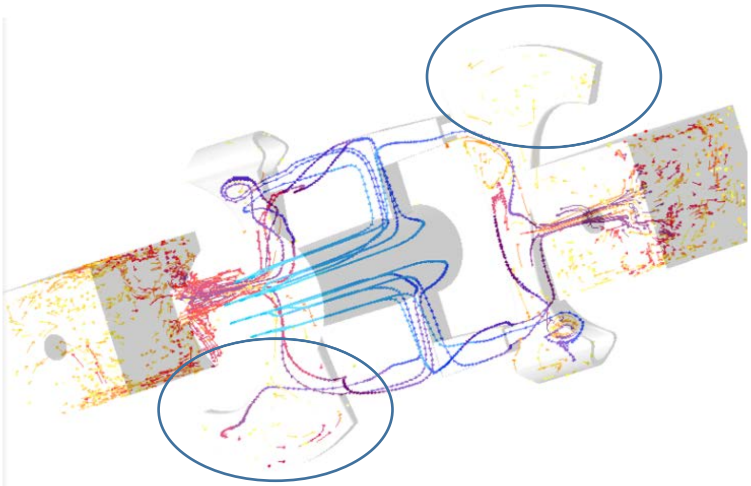

Figure 3. Flow of material simulated using MAGMASOFT

2.2.2 Final gating/riser design revision

The final gating/riser designs utilized a riser contact as an in-gate which reduces post-processing. An exothermic sleeve used by Eagle Alloy was added to the riser was added to the riser design to improve the feeding effectivity of the molten metal. Final MAGMA simulations were performed by was done by Eagle Alloy to optimize the design to their specific process and parameters. The in-gate size was increased as a result of shrinkage behind the contact from previous simulations. Figure 5 shows that increasing in-gate size eliminated the shrinkage in area. The simulation also indicates that there will be shrink in the handle and the area towards the blade but it will be minimal and should not affect the properties of the axe. Figure 4 shows porosity in the middle and near the handle of the blade. The porosity size and location are not a concern as it is not close to the blade which is the critical area.

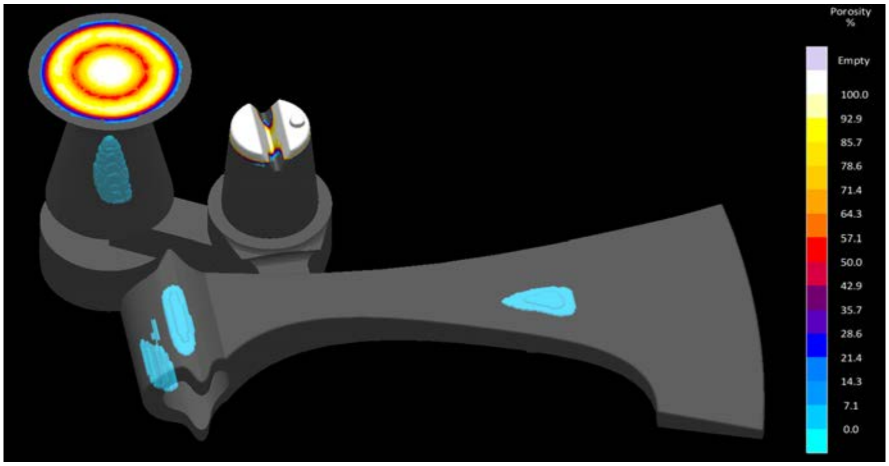

Figure 4. Porosity Simulation

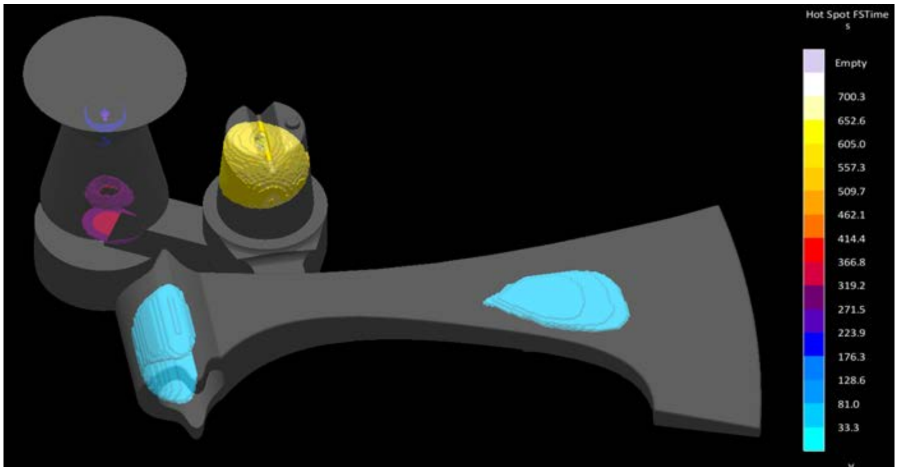

Figure 5. Hot Spot FS Time

2.3 Pattern Fabrication

2.3.1 Initial idea and pattern design

While Iowa State has two teams competing in this competition, we also wanted to compete against each other and have two completely different axes made using two varying sand casting techniques. At Iowa State, our team has access to a 5-axis hybrid manufacturing machine. This machine is a 5- axis HAAS milling machine with built in Big Area Additive Manufacturing (BAAM) capabilities. This allows for layers to be printed just like that of standard fuse deposition modeling (FDM) machines then machined to the desired surface finished. Our team originally wanted to use this hybrid machine to create our pattern and gating system in one process as it would be unique in comparison to the other Iowa State team and other teams. It would also be unique in that it is not a readily used process to make patterns currently in the casting industry.

Figure 6. Drag side of the pattern

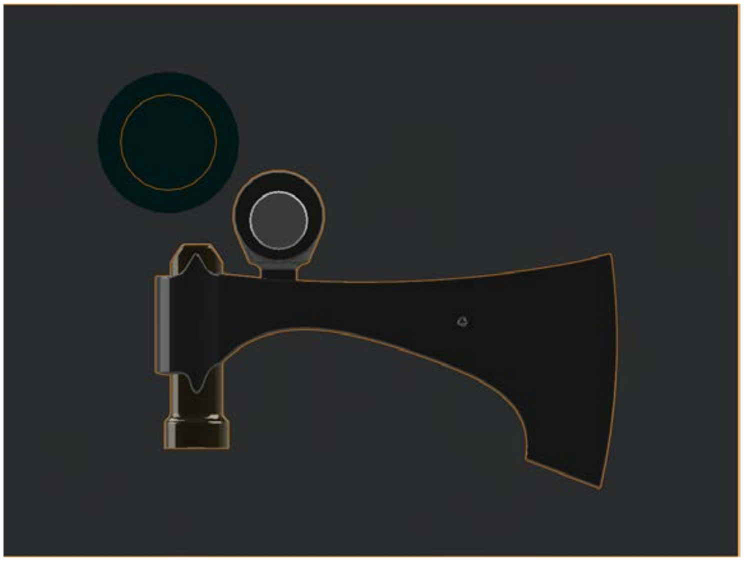

Figure 7. Cope side of the pattern

2.3.2 Problems faced

While our team had high aspirations to use the hybrid machine, the lack of experience with it turned into some major challenges. As our design iteration count increased, our time window to print and mill decreased. With the long, tapered features from the handle to the blade of the axe it would have led to a large amount of machining time to get the desired surface finish on either a hybrid process or standard milling process. Because this taper is perpendicular to the spindle axis, a ball mill would have to be used, causing the longer machining time. Another concern with the hybrid machine is the interface between the build plate and the printed part. While the bond between the two is strong enough for printing, there were concerns that it was not strong enough to withstand the shear force applied during the milling process and that the part would break off of the build plate. The benefits of printing the part on the hybrid machine was the removal of the roughing operations required when milling from a block of material. When we discovered that we would be unable to print and mill the geometry, we looked into just machining out of stock material. While it would have been possible, because of how long it would have taken and the short time window we had to make it before it had to ship to Eagle Alloy, it made it infeasible to mill the pattern.

2.3.3 Revised Method

As a result of the challenges discussed above, our team decided to resort to other methods. We ended up printing the pattern on a standard FDM machine and sanded the layers down to get our desired surface finish. To mount these parts, locator pins were printed on them. These pins were then inserted into holes that were milled into a piece of plexiglass. The pattern parts were then glued into place via a two-part epoxy and bolted into place. The finished pattern can be seen below.

Figure 8. Printed and sanded parts on the plexiglass mounting plate

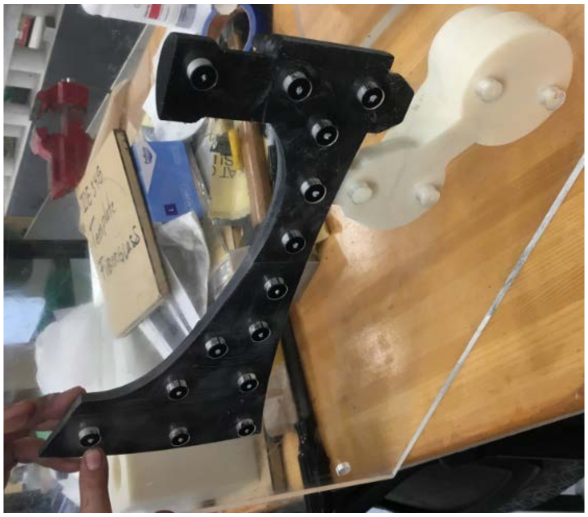

Figure 9. Back part of pattern where bolts would go

Figure 10. Finished drag side of the pattern

2.4 Materials and processing

The alloy for the axe was chosen to be 8640 steel. 8640 steel with heat treatment was recommended by Jason Bergman, from Eagle Alloy and an Iowa State graduate in metallurgy, since strength, toughness and wear resistance are of prime importance in this project. The alloy has good hardenability, strength and toughness properties.

2.5 Process Overview

2.5.1 Sand Casting

Eagle Alloy utilized chemically bonded sand to make the mold from the pattern fabricated at Iowa State University. Figures 11 through 13 show the drag pattern in wooden flask, drag mold made from the pattern and the pouring of the part. Figure 14 shows the poured part after removing the in-gate.

Figure 11. Drag pattern in wooden flask

Figure 12. Drag mold

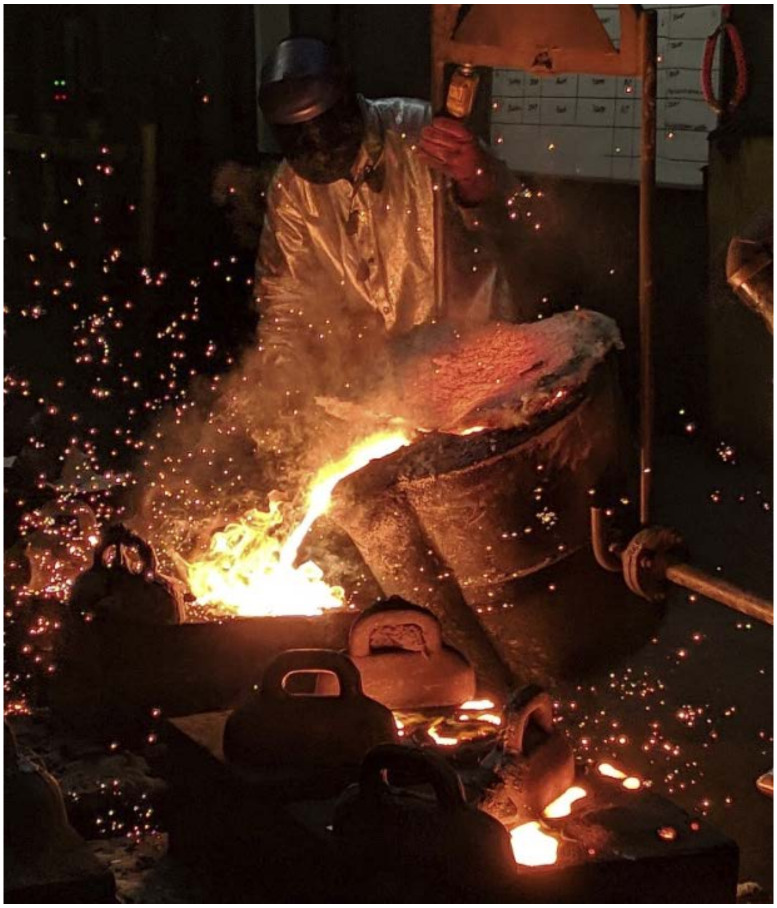

Figure 13. Pouring

Figure 14. Part after in-gate removed

2.5.2 Post Processing

Once we received the part from Eagle Alloy, we ground the blade area. Since the blade was about 0.4 inches thick (to avoid under filling due to material fluidity) it took about 3 hours of grinding to obtain a sharp edge. We then sandblasted the blade area to achieve a better blend of surfaces from the grinded surface to the cast surface. Next, we used a sharpening stone to further sharpen the blade. And finally we used a flap wheel to reduce grinding marks for a smoother surface finish.

Figure 15. Grinding process

Figure 16. Final product

3. Test Results for Quality and Properties

For testing, we scanned the final part to do a computer aided design (CAD) design to final part comparison in terms of shrinkage. We then used a section of the scanned point clouds to run a surface roughness analysis using a software being developed at Iowa State. The ASTM A802 comparator plates were also used to classify the surface finish on our axe. Finite element analysis (FEA) was done to determine where the stress areas are and if the part will be able to withstand the force applied. Additionally, to test for indications that are surface breaking or near-surface, magnetic particle inspection was performed. Lastly, hardness testing was done to obtain the resistance to indention which will give us an estimate of how the axe will perform during the competition.

2.5.1 CAD file comparison to final part

A Faro Arm was used to scan the part and the scanned point cloud was loaded into the Geomagic software. Then, the CAD model of the original drawing was loaded as well. Figure 17 shows the CAD (green) and scanned part (dark blue) before being aligned. The two models were aligned (Figure 18) by picking 4 points from each model that is in the same location as the other model. Dimensional deviation due to shrinkage can be seen on the top part and the handle of the axe which are the red points shown in Figure 19. Ryan added a quarter inch per foot to the original CAD file to account for shrinkage from solidification. Using the volume measurements from Cloud Compare, we found that the part shrinkage was minimal at slightly under 1%.

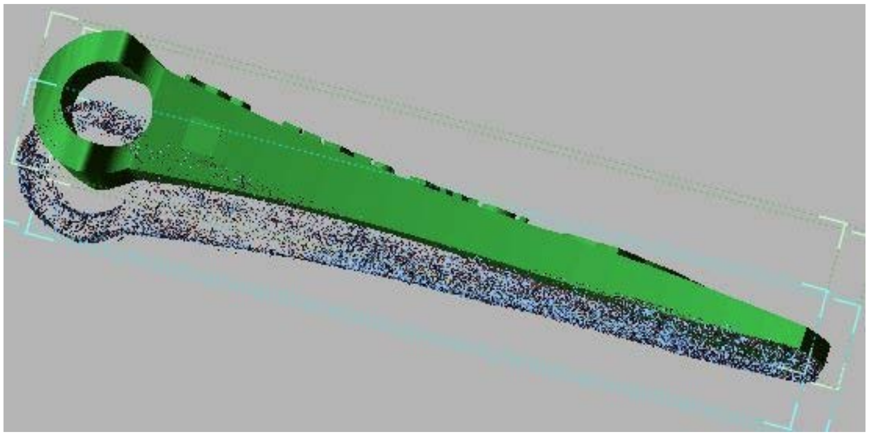

Figure 17. The CAD (green) and scanned part (dark blue)

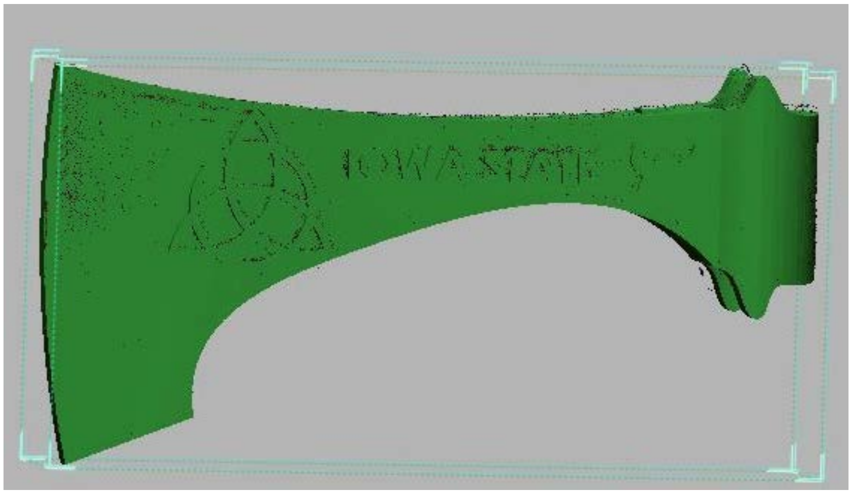

Figure 18. Aligned model

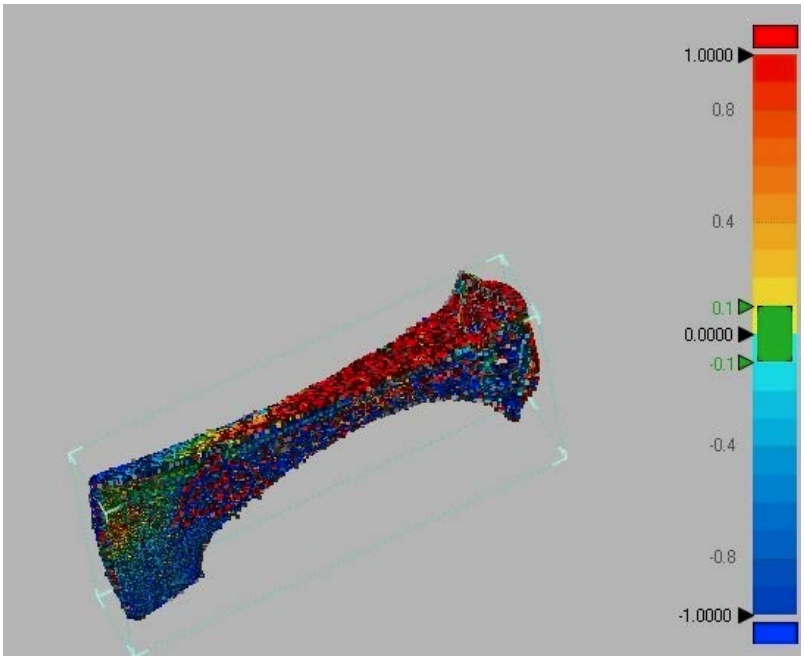

Figure 19. Shrinkage of final part compared to the original CAD drawing

2.5.2 Surface Roughness

We evaluated the surface marked by a red rectangle for our surface roughness classifications as shown in Figure 20. Based on ASTM A802's surface texture plates (A plates) we found the surface roughness to be A1. A point cloud of the area (Figure 21) was then used to be evaluated through a program created by a PhD student at Iowa State University. The program use variograms to describe the spatial continuity of the peaks and valleys in the surface texture. It is a discrete function that measures the variability between pairs of points at a distance determined by the user.

The variogram average for the area of the axe we tested (Figure 20) was 0.043 mm and for comparison the variogram average for the A1 plate was 0.058. Hence, numerically the area of the axe we tested had smoother texture than the A1 comparator plate.

Figure 20. Area evaluated for surface roughness

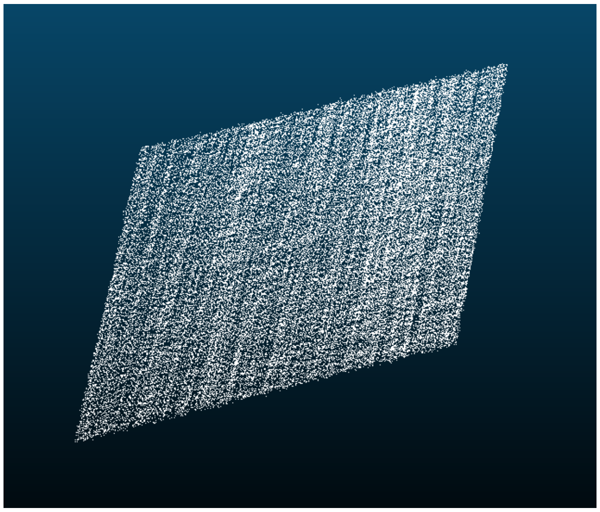

Figure 21. Point cloud of area

2.5.3 Finite element analysis (FEA)

Using simulation in SolidWorks, we ran a static load test on the CAD model to determine the stress distribution of the part. Not surprising to us, the stress map in Figure 22 shows that the first area to break will be the smallest section of the part. However, this is not a concern as the force induced by a person hitting an object with the axe is well below the point where it would break.

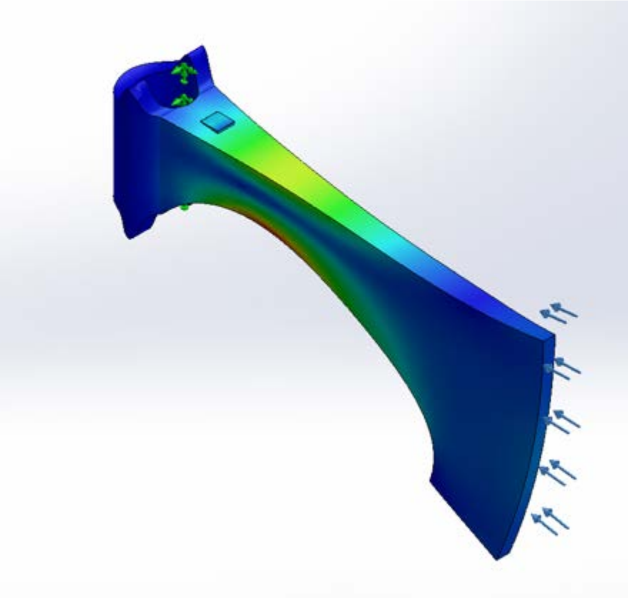

Figure 22. FEA stress map

2.5.4 Magnetic Particle Inspection (MPI)

Wet Magnetic Particle Inspection (MPI) was used to check for any indications on or close to the surface of our axe. Two orientations were tested and no indications were found on the part. There were collections of particles along the top and bottom parts of the extruded features which made sense as the ridges blocked the flow of the solution (Figure 23).

Figure 23. MPI

2.5.5 Hardness

The Rockwell hardness test method using HRC scale was used to obtain the indentation hardness value of our part. We measured a HRC value of 22.1 and the estimated hardness for AISI 8640 Steel is 28. The difference could be a result of the taper on the axe which led to measurement error.

4. Axe Handle

The handle was made by Dr. Peters. We cut a slot through the top section of the handle and drove a wedge through the slot to secure the handle in the axe. The final length of the handle was 30’’ to balance the weight of the head.

Figure 24. Axe handle

5. Key Takeaways

One of our main takeaway from this project is a better understanding of the design process for making patterns. Our team had about 14 iterations of the gating design alone, not to mention the different designs of the axe itself. Additionally, transparency of the project when working with teams across the country and with other responsibilities occurring at the same time of the project. With good communication and accurate estimates of task durations, better planning can occur for the project as a whole.