SFSA Cast in Steel 2026

Horseman's Axe

Technical Report

Purdue University - Pourdue

Team Members:

Tiansui Chu, Jack Klopfenstein, Anthony Pineda Hercules, Liliane Joan Belliveau

Advisor Names:

Maxwell Brewer, Laura McKinnon, Jake Espinosa, Clayton Kibby, Teng Lee, and Dr. Xiaoming Wang

Foundry Partner:

Kimura Foundry America

Introduction

SFSA has created this competition to encourage students to learn about making steel products using the casting process and applying the latest technology available. To achieve this, the Purdue University Pourdue team partnered with Kimura Foundry America (KFA) in Shelbyville, Indiana. KFA has experience with advanced 3D binder jet sand mold printing and rapid-turnaround prototype casting capabilities. The project began with extensive research into historical examples of horsemen's axes, which the team translated from hand sketches into refined CAD models using Autodesk Inventor and SolidWorks. Following several design reviews, a single-axe-head design was selected and further optimized. The subsequent mold development phase involved a collaborative effort between the team and KFA's engineers, with each iteration informed by fluid flow and solidification simulations conducted in MAGMASOFT in addition to years of industry experience. This simulation process led to the printing, assembly, and pouring of 16 total cast heads across four molds. KFA provided essential pre- and post-pour analysis, including chemistry reports, keel blocks for tensile testing, and X-ray radiography to inspect internal porosity.

Following the removal of gates and risers, the team performed secondary finishing operations, including grinding, glass-media bead blasting, surface polishing, and oxide finishing. This allowed for the evaluation of casting quality, which ranged from Grade A (defect-free) to Grade C (minor surface or sub-surface inclusions), establishing the baseline for subsequent heat treatment and impact testing. After testing heat treatment and impact testing, further finishing operations were conducted until an acceptable edge was ground, and the head was finally mounted to a hand-carved hickory handle before being shipped for testing in Grand Rapids, Michigan. Throughout this project, group members were exposed to various aspects of casting, including chemistry, metallurgy, gating/risering, modeling, simulation, pouring, and finishing operations. The support of Kimura Foundry America enabled the Pourdue team to achieve their goals within time constraints. Without Kimura Foundry’s assistance, this project would not have been possible. We sincerely thank them for their generosity and support.

Historical Background

The horseman’s axe, as we know it, was developed in the later years of the 15th century, just as full plate armor was at its peak. Swords were rendered useless, unable to generate enough impact to pierce armor, and thus knights turned to the horseman’s axe. While small, only around 20” and 3 pounds, when wielded one-handed from the bottom of the handle, that leverage can generate a large amount of force. The blades were semicircular and often featured a spike, pike, or back hammer for piercing armor. While, for the most part, we stayed true to historical blade and pike shapes, for aesthetic purposes, we added decorative points with a thinner blade.

Additionally, these axes were able to be decorated similarly to swords, making them a popular choice for the upper-class [1]. These decorations were mostly concentrated on the blade as intricate engravings of crests or family names, which became more popular as horsemen's axes traveled south from Scotland to Italy [2]. Thus, we chose to honor this and add Purdue’s crest featuring a griffin from Medieval lore.

However, the handle remained straight and undecorated, especially as the horseman's axe evolved into other medieval weapons like polearms, for length, weight, and so it could be reinforced with metal. These sacrificed control for distance, unlike non-battle axes that around the 1840s [3] began having curved handles for ergonomics and for additional aesthetic appeal. Thus, we chose to disregard historical precedent to create a more comfortable handle, but also to push the design to be more fantasy-like. Additionally, with the use of hickory wood, a material not available to Europe till the 17th century, for its strength and shock absorption, we figured embracing modern influences in the design would improve it. This took the visual appeal of the axe from being focused on the engravings to being shown in the overall silhouette.

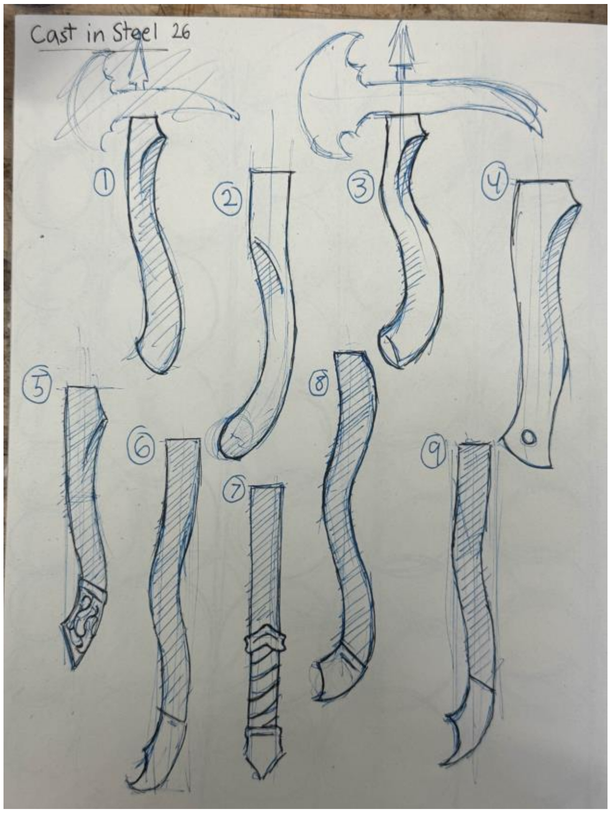

Figure 1: Hand Sketches for Handle Design

Axe Design

The first iteration of the axe head followed designs of horseman's axes found online through museum catalogs and other sources. The team originally planned to have a top spike and a pick (spike opposite the blade), with the spike extending past the blade. However, we realized that having a top spike would be challenging. If the spike were cast with the rest of the axe head, we'd have a difficult time attaching the handle. Casting the spike separately would also prove complicated due to the attachment method to the axe head, as well as the castability of such a small object. Thus, the second iteration had just the axe blade and pick.

The second iteration of the axe focused on refining the blade draft and the transition from the main body to both the blade and pick. We added multiple lofts to smooth the transition from blade to body and to give the axe a more rounded contour. There were also efforts made to cut down the weight of the axe head to around 2.25 pounds. The attachment style for the handle was also considered, with two holes being made on the sides to hot rivet the handle to the head.

The third and final iteration of the axe was focused on improving the castability of the axe head. The draft on the blade and pick was reduced to increase thickness and improve the chances of the blade tip filling during pouring. We also added the final rounds and chamfers to all edges of the axe head, as well as deciding not to hot rivet the handle, leaving just the main hole in the body for the handle. We decided to add a negative to the side of the blade, in the shape of the Purdue crest.

There were extensive drafts on the riser, vent, and runner positions on the axe head. The sizing of the risers was determined by the amount of porosity that was shown to be left in the axe through the MAGMA software. The vents were sized so that they weren't larger than ¼ the diameter of the risers. The sizing of the blade riser was fixed, as it did a good job throughout the simulations. The main middle riser was very tricky, due to small pockets of porosity in the metal, so multiple size iterations were needed. There was a riser on the pick of the axe, but simulations showed it was not needed. Instead, a larger vent was placed on the pick.

The runner system was designed with a lot of help from Maxwell Brewer of Kimura Foundry. He helped with the shape of the gates, how many axes we could have per mold, as well as sizing standards for the filter and sprue. The runner system also had many iterations, due to the amount of metal flowing to each of the axes in the mold and the cooling rate of the metal. The final runner design had four axe heads being fed through a long rectangular runner with a sub-runner and a gate into each axe head.

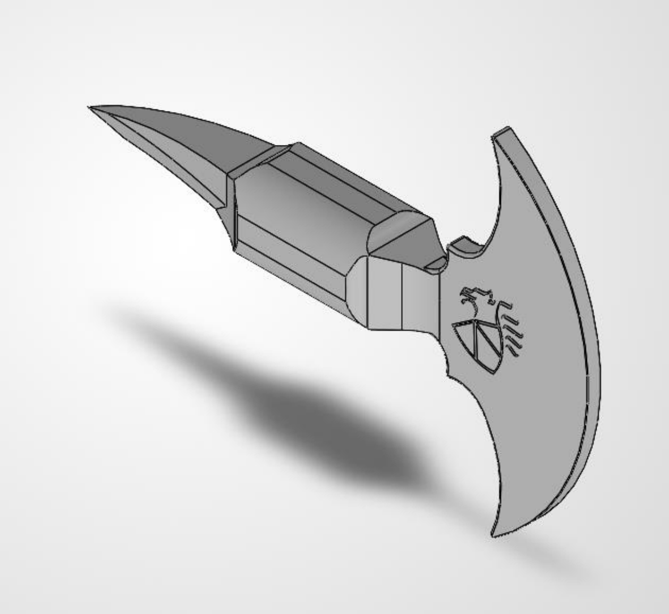

Figure 2: Final Axe Head CAD Model

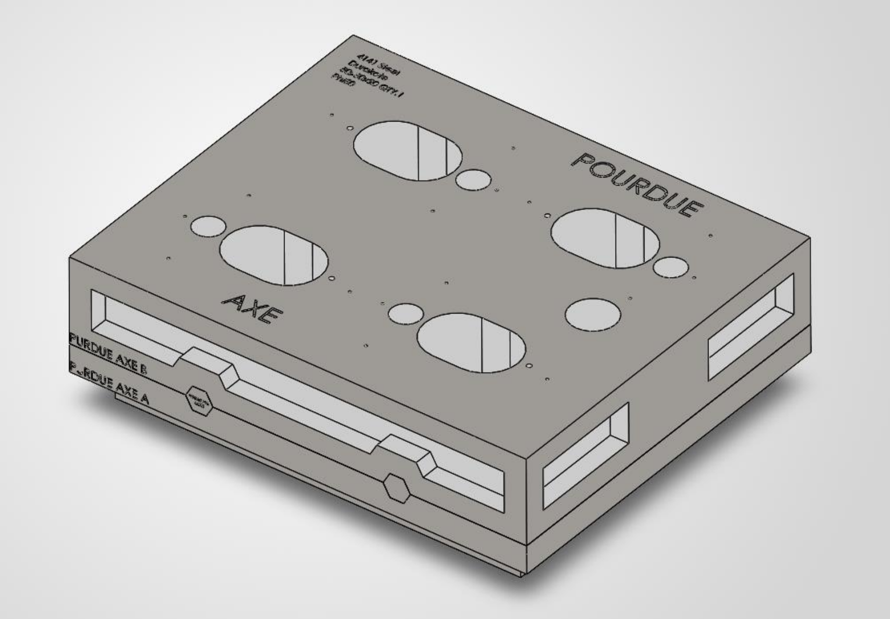

Figure 3: Final Sand Mold

Casting

To leverage the advantages of modern casting technology, the team utilized Kimura Foundry America’s (KFA) ExOne 3D binder jet sand printing to produce the molds. This additive manufacturing process works by depositing a thin layer of sand across a build platform, followed by a print head that selectively sprays a liquid binding agent to glue the sand particles together in the shape of the part's cross-section. This cycle repeats layer by layer until the entire mold is complete, after which the unbound sand is removed to reveal the finished cavity. This process was selected over traditional methods, such as using a physical pattern, because it requires no dedicated tooling, significantly reducing lead times for low-volume production. Developing a pattern and a separate core was the primary bottleneck we aimed to avoid. Creating a core for the handle through traditional means would have required significant time to create cores, and if there was no core, milling out a pocket, and the costs associated with specialized work holding and machining hours were primary concerns.

Additionally, the additive nature of sand printing allowed for the integration of an internal core and high-definition surface details, such as an engraved logo with a depth of 3–4 mm. Prior experience with the George Washington Sword project highlighted the necessity of producing a casting as close to the final near-net shape as possible to minimize the time and expense of secondary finishing. Such precision is often difficult to achieve with conventional patterns without substantial capital expense. While investment casting was considered, sand printing offered a more reliable and faster path for iteration without the complexities and risks associated with pattern burnout.

Figure 3: Binder Jet Sand Mold printed by KFA for Pourdue.

To ensure success, over 10 iterations of gating and risering were simulated, with various factors such as sizing and positioning being adjusted. Each simulation provided a better understanding of solidification behavior. Ultimately, this iterative approach led to all 16 axes being cast without serious defects or severe porosity, with most features coming out exactly as intended. Notably, the "pick" end of the head was sharp directly out of the mold, capable of piercing sheet metal without any prior grinding. The design-to-manufacture workflow followed an iterative cycle. The process initiated with the development of a CAD model, which was then submitted to KFA for technical review. This collaborative phase focused on optimizing geometry for the casting environment, incorporating design improvements based on KFA's internal specifications for mold integrity and metal flow. By aligning the CAD designs with specific mold parameters, the team ensured the final digital models were optimized for the binder jetting process, bridging the gap between historical artistic design, production feasibility, and lead time.

Heat Treatment and Alloy Selection

The steel alloy used for our axe head was AISI 4140. This alloy was chosen due to its excellent hardenability and the fact that it is a common alloy used by our partner foundry. After the axe heads were poured, they were slowly cooled for 48+ hours before shaking out, resulting in a microstructure as predicted by the Fe-Fe_3C phase diagram, ferrite and pearlite. Figure 4 shows the as-cast microstructure.

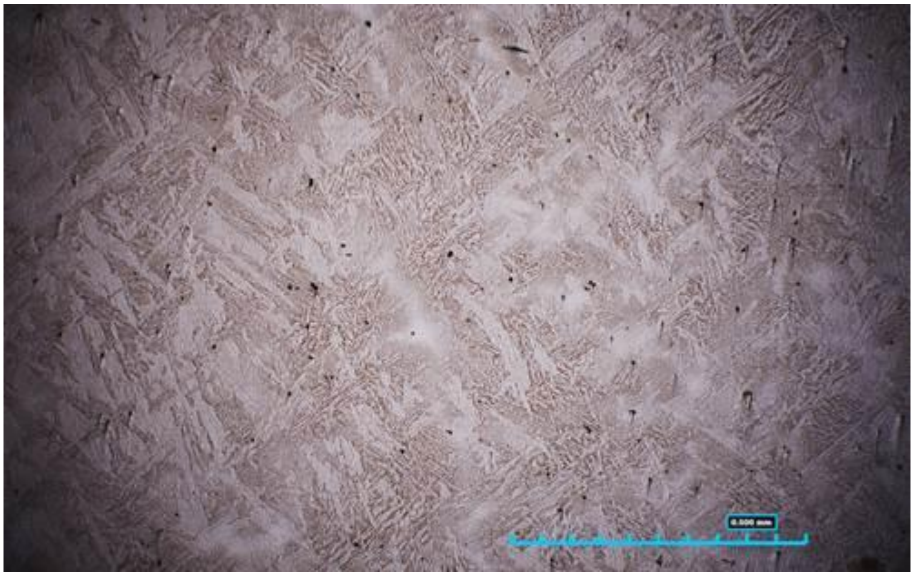

Figure 4: As-Cast Microstructure

Due to the large presence of ferrite, the axe heads were quite soft, having a Brinell hardness of approximately 297 HB. To achieve higher hardness, we decided to perform a heat treatment that would transform the axe head structure to martensite. To accomplish this, we first slowly heated the axe heads to 1200°F. This was the pre-heat, which was done so that the axe head would not experience thermal shock. After the pre-heat, the oven temperature was ramped up to 1575°F. At this temperature, the microstructure begins to transform into austenite [5]. Once the axe head reached that temperature, it was left to soak in the oven for ten minutes to allow for the microstructure to fully transform into austenite. The axe head was then quickly removed from the oven and dunked in a bucket of quenching oil to quickly cool the steel.

When steel is quickly cooled from the austenite range, there is not enough time for ferrite to form, and the carbon gets trapped in the lattice. This structure is referred to as martensite, which is much harder than ferrite and pearlite [5]. After the axe head was quenched until its temperature reached around 350°F, the axe head was transferred to a different oven set at 350°F, where it remained for one hour. The purpose of this is to temper the axe head, which relieves internal stress, decreases hardness, and increases ductility [5]. This is important as it makes the head less brittle and decreases the likelihood of breaking. After the temper, the axe head was allowed to slowly cool to room temperature, and then it was cleaned with sand blasting and grinding.

The heat treatment of the axe heads was successful, with the edge of the axe having a hardness of 49.5 HRC and the body having a hardness of 44.7 HRC. These results are slightly lower than published hardness values of 4140 with similar heat treatments [4]. This is likely since when quenching, our oil was not being stirred by an agitator and relied on us moving the axe around in the bucket. This could have caused the axe head to cool slightly slower than expected, resulting in a lower hardness.

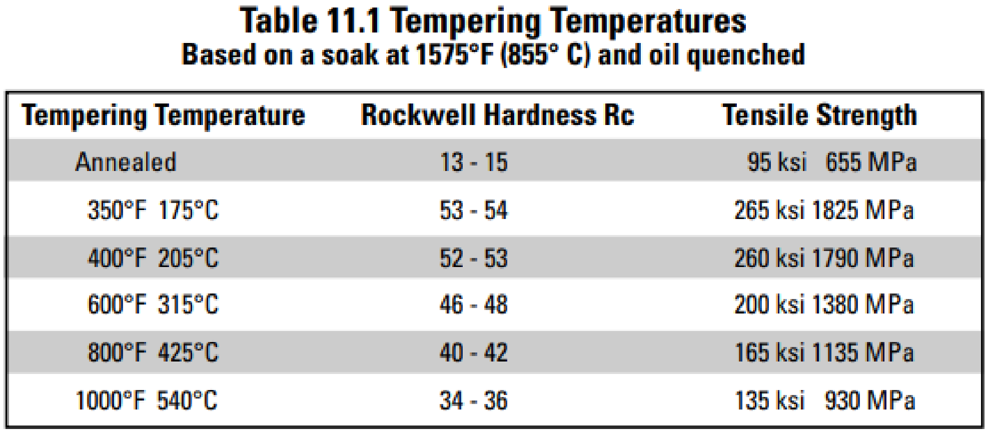

Table 11.1 Tempering Temperatures

Based on a soak at 1575°F (855° C) and oil quenched

Tempering Temperature	Rockwell Hardness Rc	Tensile Strength
Annealed	13 - 15	95 ksi 655 MPa
350°F 175°C	53 - 54	265 ksi 1825 MPa
400°F 205°C	52 - 53	260 ksi 1790 MPa
600°F 315°C	46 - 48	200 ksi 1380 MPa
800°F 425°C	40 - 42	165 ksi 1135 MPa
1000°F 540°C	34 - 36	135 ksi 930 MPa

Figure 5: Table 11.1 from [4]

Testing (Destructive & Non-Destructive)

To ensure the integrity and performance of the horseman's axe, the team employed both non-destructive (NDT) and destructive testing methods. The initial phase focused on NDT to verify internal soundness without compromising the castings. Before shipment to Purdue, KFA utilized X-ray radiography to identify subsurface porosity or inclusions, particularly in higher stress regions near the handle and the neck of the main blade. No severe porosity or inclusions were detected that would cause premature failure of the axe.

Figure 6: CT X-ray scan of a cast head provided by KFA

Once internal integrity was confirmed, the "Grade C" heat-treated axes were subjected to a series of destructive and functional tests to simulate real-world conditions. We also used a hardness tester to see the effectiveness of our heat treatment cycles, ensuring the martensitic transformation reached the desired HRC levels for optimal edge retention. To evaluate edge durability and resistance to brittle fracture, we performed high impact strikes against cinder blocks and sheet metal, including microwave housing, to test piercing capabilities. Finally, the handle-to-head interface and the overall balance of the tool were validated through chopping and shearing tests on cherry dowels and pine 2x4s.

Figure 7: Using a hardness tester to test as-cast and post-heat treatment hardness.

This round of testing with the prototype handles and heads revealed that repeated extremely heavy strikes caused the handle to loosen due to the wedge slipping. We resolved this issue by using epoxy to act as a vibration insulator and by adjusting the geometry of the slot cut into the handle. During testing, the pick remained sharp until subjected to numerous heavy blows against a concrete block. Similarly, the axe edge maintained its profile until dozens of impacts against concrete. Significant deformation did not occur on either surface until these extreme tests were conducted. These results provided evidence that our material selection and quenching produced an axe capable of withstanding the extreme mechanical loads required for the competition.

Conclusion

Throughout this project, the Pourdue team embraced both traditional methods and technological advancements, ranging from hand-carving hickory handles and manual surface polishing to utilizing automated 3D binder-jet sand mold printers. By engaging in every stage of production, from design to hand-grinding, team members gained diverse experience across numerous engineering and skilled trades fields. The result is a horseman's axe comprised of AISI 4140 steel, cast in coordination with our foundry partner, Kimura. With a total weight of **3.1 lbs (1.41 kg)** and an overall length of **21.5 inches (546 mm)**, the axe is within the competition requirements of 3.3 lbs and 31.5 inches. Advanced metallurgical controls, including a 1575°F austenitizing cycle followed by a 350°F temper, produced a microstructure with a functional edge hardness of **49.5 HRC**. These specifications, combined with the properties of the hand-carved hickory handle, ensure the axe provides the optimal balance of historical authenticity and mechanical durability required for the performance testing phase in Grand Rapids.

We would like to once again extend our deepest appreciation to **Maxwell Brewer, Laura McKinnon, Jake Espinosa, Clayton Kibby, Teng Lee, and Dr. Xiaoming Wang** for their invaluable support. Whether it was pouring a heat of 4140 specifically for our project, providing X-ray diagnostics, donating materials, sharing their expertise, or offering facility access and advice, this project would not have been possible without them. The support of these individuals was fundamental to our success.

8. References

[1] R. Ellis, “Horseman’s Axe,” myArmoury.com, 2026. https://myarmoury.com/review_aa_haxe.html

[2]“] “Horseman’s Ax of Cardinal Ippolito de’ Medici (1511–1535) | Italian,” The Metropolitan Museum of Art. https://www.metmuseum.org/art/collection/search/26548

[3] F. Test, “Get a Handle on It: Everything You Need to Know About Axe Handles,” Brant & Cochran, Oct. 20, 2023. https://www.bnctools.com/blogs/the-chop/get-a-handle-on-it-everything-you-need-to-know-about-axe-handles, https://www.bnctools.com/blogs/the-chop/get-a-handle-on-it-everything-you-need-to-know-about-axe-handles

[4] W. E. Bryson, Heat Treatment, Selection, and Application of Tool Steels, 2nd ed. München: Carl Hanser Verlag GmbH & Co. KG, 2005. doi: 10.3139/9783446436701.

[5] W. K. Dalton, The technology of metallurgy. in Merill’s international series in engineering technology. New York: Merrill [u.a.], 1994.