SFSA Cast in Steel 2026 - Horseman's Axe Technical Report

Colorado School of Mines - Colorado Calvary

Colorado Calvary Team Members:
Zach Plummer, Aiden McGowan, Thomas Walker, Ana Poland, & Josephine Rose

Colorado Calvary Faculty Advisor:
Sarah Harling, Hot Shop Supervisor and Foundry Educational Foundation Professor

Colorado Calvary Industry Sponsor:
Western Foundries

Abstract

This report documents the design, casting, and evaluation of a horseman’s axe developed by the Colorado School of Mines team for the 2026 Steel Founders’ Society of America (SFSA) Cast in Steel competition. The project aimed to demonstrate the feasibility of producing a historically inspired, functionally effective axe using modern steel casting techniques, overcoming traditional casting challenges such as the formation of thin structural features and high impact loading that can be disrupted by defects.

The design process integrated historical research with engineering constraints to create a weapon optimized for mounted combat and anti-armor performance. Key features included a forward-weighted blade, integrated langets for structural reinforcement, a hammer poll for armor penetration, and Celtic-inspired aesthetics. Advanced CAD modeling and PLA 3D printing were used to produce detailed patterns, including complex lattice structures, while iterative design improvements addressed manufacturability and casting defects.

Initial casting attempts using sodium silicate resin bonded sand molds with silica sand resulted in misruns and cold shuts where the metal cooled too fast and didn't completely fill the pattern and form together. This was due to a combination of our ladle not being preheated long enough and our runners and gates of the mold being too wide. This led to significant redesign of the gating and riser systems with guidance from industry partners. Subsequent aluminum test pours and a final green sand steel casting successfully produced high-quality axe heads. Post-processing involved machining, heat treatment, and finishing to achieve a balance of hardness and toughness. Metallurgical analysis confirmed improved material properties, with the final 4140 steel alloy achieving a hardness of 53 HRC after heat treatment.

Overall, the project demonstrates the successful application of modern casting methods, iterative engineering design, and interdisciplinary collaboration to produce a complex steel component with both functional and historical significance.

Introduction

The Steel Founder’s Society of America Cast in Steel 2026 competition challenges student teams to design and successfully cast a horseman’s axe. SFSA has created this competition to encourage students to learn about making steel products using the casting process and applying the latest technology available. Casting an axe runs counter to conventional manufacturing practices. Documented in the following report is the Colorado School of Mines team’s full development processes, from the beginnings of CAD design all the way to completion.

Axes are standardly forged due to the demanding combination of thin edges and high-impact loading. Thin cross-sections in castings cool rapidly, increasing the risk of misruns and incomplete mold filling, while also acting as stress concentrators that promote warping and cracking. Furthermore, cast components are inherently susceptible to defects such as porosity, inclusions, and internal cracking, all of which significantly reduce structural integrity in impact applications.

The Cast in Steel competition is designed to expose students to the possibilities of modern casting. Through the use of CAD and 3D printing, modern technology can be used to solve millennia old problems with rapid iteration and more creative freedom. This work represents not only a technical effort, but an exploration of how modern tools can be applied to overcome constraints that have shaped metalworking practices for centuries.

Historical Context

Following the deaths of King Alexander III and his heir, Scotland entered a succession crisis that destabilized the kingdom, which enabled Edward I of England to assert control, initiating the Wars of Scottish Independence. Scotland, organized around clan loyalty and constant localized conflict produced fighters who prioritized mobility, adaptability, and practical weaponry; key considerations for a durable and versatile axe design.

In contrast, the English military fielded heavily armored knights supported by disciplined infantry and longbowmen. Advances in armor including reinforced mail and the great helm, reduced the effectiveness of cutting weapons and increased the importance of concentrated, armor-penetrating force. As a result, weapons capable of delivering blunt or concentrated force, such as axes, maces, pikes, and war hammers became increasingly important for penetrating or bypassing armor.

Scottish weapons evolved accordingly. While swords remained common, axes, particularly those with elongated shafts like the Lochaber axe, offered significant advantages. Their design allowed for powerful, momentum driven strikes capable of denting armor, breaking bones beneath it, or hooking and pulling mounted knights from their horses. Other axe variants incorporating hammer or spike features further enhanced their anti-armor capabilities, allowing warriors to exploit weaknesses in plate and mail.

Tactically, English forces favored structured engagements, while Scottish forces, under leaders such as William Wallace and Robert the Bruce, relied on mobility, terrain, and ambush tactics. Development like the schiltron formation countered cavalry but required adaptability due to vulnerability to missile fire. These conditions reinforce the need for a weapon that is both robust and maneuverable (like an axe).

Bruce’s campaign culminated in victory at Bannockburn, demonstrating the effectiveness of Scottish versatility. This victory also had a great effect on his later reconciliation with the Church, which was pivotal in uniting all of the Scottish people under his banner. Thus establishes the importance of symbolic and religious elements in the weapon’s design.

Within this context, the axe must deliver concentrated impact for armor penetration, maintain durability and balance for mobile combat, and incorporate symbolic features reflecting authority and legitimacy. To meet these historical accuracy requirements, the final design reflects these defining characteristics of a horseman’s axe as used during the Wars of Scottish Independence.

The pronounced top cutting edge and rear hammer of the axe, aligns with period-appropriate weapons intended for mounted or highly mobile fighters. This configuration enables both slashing and concentrated impact, consistent with the need to engage armored opponents effectively. The handle length and balance were selected to provide maximum leverage while on horseback, a critical requirement for cavalry whose strikes hit with the strength of their charging horses. Additionally, the incorporation of symbolic detailing reflects the sociopolitical and religious context of Robert the Bruce’s era, reinforcing the weapon’s authenticity not only as a tool of war but also as a representation of authority. Collectively, these features ensure the axe is both functionally and historically consistent with an authentic Scottish horseman's axe of the 13th century. The exact justification for the design decisions are justified further in the following Axe Design section.

Axe Design

Historical Justification

The axe design process began with an evaluation of historical context to establish three primary criteria: intended function, cultural and symbolic design elements, and the identity of the wielder.

The primary function was defined as a quick secondary weapon for a mounted combatant with anti-armor capabilities. Mounted weapons require forward-weighted designs to maximize impact force during downward strikes. With swing motion being limited on horseback and the swing having enhanced power due to the momentum of the horse, the axe should be not only long enough to reach infantry effectively but also have an edge curve that promotes strong follow through. Thus a longer top edge with a more aggressive curve is favorable. This design increases cutting continuity, increases effective blade range, and minimizes the likelihood of the blade becoming lodged due to wedging rather than cutting.

Aesthetic design posed a challenge due to the largely utilitarian nature of 13th-century Scottish weaponry. Analysis of artifacts from the Trove.scot archive showed minimal ornamentation. By drawing inspiration from pendants, statues, and tombstones showed a repeating Celtic knotwork and cross motif. Its prevalence during Robert the Bruce's efforts to secure Catholic recognition reinforces its symbolic relevance, while its common use in tombstones reflects both religious and martial themes. This choice supports the axe's dual role as a functional weapon and a representation of authority.

Further inspiration was drawn from later medieval English weapon designs, particularly the incorporation of the langets, metal plating added to handles to increase durability. Although rare due to manufacturing difficulty, integrated langets provided enhanced structural integrity. The team selected this feature for its functional advantages, as an opportunity to demonstrate advanced casting capabilities (particularly the challenge of producing thin sections in sand casting), and its aesthetic benefits as it completes the cross design; thus balancing structural performance, manufacturability, and aesthetic appeal.

During the 13th century, the innovation of the great helm reduced the effectiveness of cutting strikes to the head, necessitating blunt force or piercing options. The Team evaluated both spike and hammer configurations, ultimately selecting a hammer for its superior visual integration and structural feasibility. The final concept incorporated the Colorado School of Mines logo into the hammer face, serving both as a functional striking surface and a symbolic stamp. This design choice not only enhanced visual identity but also conceptually reinforced the notion of leaving a lasting mark on armored opponents.

Design Process and Challenges

Iterative design played a critical role in refining the axe geometry. Early concepts included complex geometries inspired by sledgehammer forms and carpentry-style hammers; however, these designs proved impractical due to modeling complexity, potential structural weaknesses, and solidification limitations.

The final design represents a balance between manufacturability, structural integrity, and visual impact. Minor modifications were made during later stages, including increasing the thickness of the hammer's internal logo to improve castability following initial test pours.

Initial pattern designs resulted in poor castings, with multiple misruns, cold shuts and poor surface detail. Post-analysis identified undersized runners and insufficient riser volume as primary causes, alongside the hand carved gating being generally inconsistent and leaving poor sand surfaces.

Following this initial failure, the team restructured its workflow. Significant effort was required to refine draft angles and castability. The axe head model was redesigned multiple times to achieve proper mold release characteristics. Core design, initially developed with sponsor input, was bulky and built with maximised stability in mind. However, this design would be later simplified after testing revealed the excessive bulk was just unnecessary. This facilitated larger risers and better placed gating, which was a primary concern due to the tight corners and limited space for the gating due to part thickness.

Another key challenge involved incorporating detailed lattice structures within the cross. Initial attempts using manual string weaving affixed with wax resulted in poor quality and inconsistency. To resolve this, the team learned how to utilize Blender, manually modeling the woven structures and integrating them into the pattern design. Resin 3D printing was then used to produce high-fidelity inserts, which were placed into pre-designed recesses within the primary pattern. This approach eliminated layer lines and provided high levels of detail.

The feeding system design improved significantly following consultation with Western Foundries, where the team received guidance from a 5th generation pattern maker. Applying proven design ratios and principles, the team optimized gating and riser configurations to improve metal flow and solidification behavior. A subsequent aluminum test pour was conducted to evaluate mold performance, specifically identifying areas where sand adhesion or geometric constraints could cause defects. This allowed the team to eliminate several thin walled segments prior to the final steel casting, though some minor issues remained due to design restrictions.

As for post cast processing we started with choosing which head would be used in the competition. The decision mostly revolved around different aesthetic aspects as all the castings would have generally the same engineering qualities. We chose the one with the cleanest lattice as the patterning is hardest to replicate. However, this came at the cost of the bevel. This section of the axe froze before completely filling. This reduced the horizontal and vertical length of our axe blade, causing the center of mass to be moved non ideally. As for the bevel itself it was decided that a convex grind would be best. This would maximise the amount of material behind the edge, reinforcing it against armored strikes, alongside reducing the odds of the axe getting stuck.

Almost as important as the axe head is the handle, which must balance weight distribution, alignment, ergonomics, durability, and aesthetics. Unlike the head, handle design constraints were not fully realized until later in the process, and combined with weight issues, this led to multiple redesigns driven more by practical use than strict calculation. As a cavalry weapon, the handle needed to be nearly symmetrical to support strikes from both faces, making traditional Viking-style forms infeasible.This resulted in a fully symmetrical, but less than traditional handle.

Lastly, for both the head and handle of the axe, is the finish. As 4140 is prone to rust it was decided we would use both a patina and a wax. The wax would further deepen the color of the patina resulting in greater contrast while sealing the axehead. Our team also elected to keep the side surfaces as-cast due to its appearance feeding into the practical and aged look. The handle was treated similarly as a dark stain would match the coloring of the axe head for aesthetic purposes, then boiled linseed oil would deepen the color and protect the wood.

Structural Analysis

Mechanical performance was a primary design consideration due to the rigorous testing conditions of the competition. Finite Element Analysis (FEA) was conducted using static loading, with a 20x impact factor applied to approximate dynamic conditions, resulting in a 2000 N load at the blade edge (Figure 1). Results indicate stresses remain well below the material's yield and ultimate strengths, suggesting the axe can withstand repeated high-impact loading in the absence of casting defects.

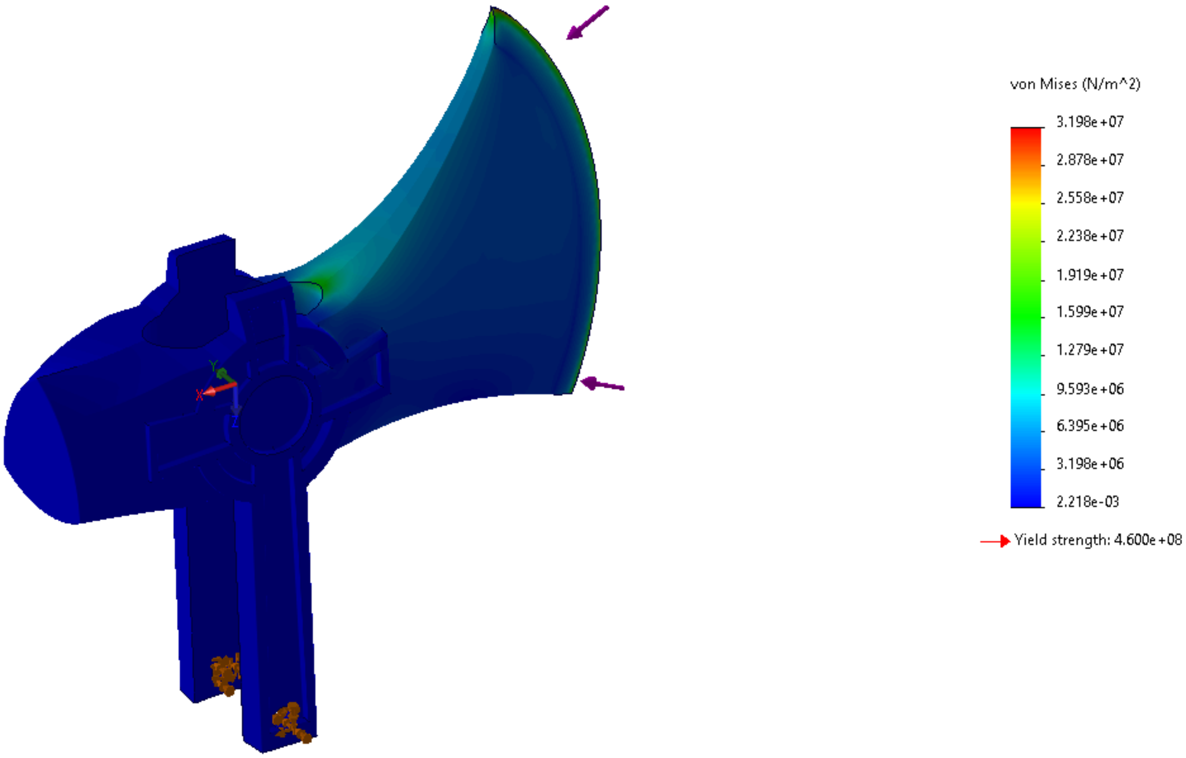

Figure 1: FEA stress analysis of final axe design.

Maximum displacement occurs at the upper tip of the axehead, where material backing is minimal; however, overall deformation remains limited under normal impact conditions. Langets play a critical role in distributing load and reducing stress transfer to the wooden handle, the most likely failure point. The addition of a pinned langet further improves structural integrity, allowing follow through on the design motivation of an axe Bruce would take to war.

Material selection for the langet pin prioritized ductility to prevent brittle failure. Brass was selected to balance mechanical performance with aesthetic considerations. Hand calculations (Appendix A) estimate a load of approximately 424 lbf during a typical swing, yielding a factor of safety of 2.3, confirming the pin meets design requirements.

Casting Process

Practice Iron Pour

Due to not all of our team members having previous experience in the foundry we conducted an initial iron pour using our cupola to give everyone more hands-on experience with a heavier and higher temperature metal compared to the typical aluminum we pour in the Mines foundry. Our cupola is capable of melting 120 lbs iron every 12 minutes allowing us to make cast iron pans through the use of 3D printed pattern boards and sodium silicate resin bonded sand molds with silica sand. This initial pour went very successfully and allowed all team members to understand the basics of tapping a furnace and pouring from the ladle into the molds.

Figure 2: Colorado Cavalry iron pour ladle.

Prototype Steel Pour

After 3D printing the prototype axe head and core boxes, molds and cores were prepared for the first steel pour. We switched from green sand to a sodium silicate–bonded silica sand due to its thermal stability, low moisture content, and improved surface finish for steel casting. However, long cure times and the lack of integrated runners, sprues, and risers required hand carving, resulting in non-ideal gating geometry. Additionally, the pattern was not split or mounted, requiring a carved parting line that reduced alignment accuracy and edge definition.

At this point in our design, our pattern was not split and mounted onto a pattern board, leading to the necessity of a parting line. This made us carve out some of the sand to allow for the pattern to be removed, causing a less defined edge on the casting, and not allowing for it to be perfectly aligned. A unique problem was presented by casting an axe in the necessity of cores to allow for an eye hole that a handle can be attached to. 3D printed core boxes were made that could be rammed up with the same silica resin sand used for the rest of the mold. Ideally, the core is not made of the exact same material as the mold and is made of a material that has high temperature resistance and compressibility allowing for the casting to shrink during solidification and deform the core, relieving stress on the casting and preventing hot tearing that would occur if the core was too rigid.

For our final steel pour, more suitable cores were produced by our industry sponsor Western Foundries. These were made of silica sand bonded with phenol-formaldehyde, a no-bake binder and treated with a zircon suspension in isopropyl alcohol to help prevent washout and improve surface finish. Once the molds and cores were formed, they were treated with graphite mixed with denatured alcohol to create a protective layer of graphite that has good thermal resistance and helps to protect the surface finish of the casting, by creating a gaseous carbon layer between the sand and molten metal preventing sand from getting stuck in the casting. An additional core had to be made in order for us to include the Colorado School of Mines logo on our hammer, as its intricate shape and design would not allow for the pattern to be pulled out cleanly if it was directly included.

As opposed to the cupola, an induction furnace, which utilizes rapid alternative magnetic fields to melt our 300 lbs of steel charge material, was used. After our safety meeting, pour teams were assigned so that everyone knew what part they were playing and who needed to step in if someone needed to sub out. After the steel had reached temperature we began our first tap of three, pouring into the ladle and then having a designated team member add in our additional charges of alloying elements, as well as scrape off the oxide slag layer that had formed. The exact alloying elements and their amounts are presented later in this report, but main additions include molybdenum and chromium that help to increase the wear resistance, toughness, and hardenability of the steel. These additions do this through the formation of high hardness carbides that impede dislocation motion, helping to strengthen the steel. The ladle was then held in the shank and carefully carried over to the molds and poured into pour cups until it was emptied. This process was repeated a total of three times in order to get all of the molten steel out from the furnace.

Both initial castings resulted in misruns and cold shuts, with incomplete filling (Figure 3). This was attributed to insufficient ladle preheating, causing premature solidification. Additionally, green sand molds used in parallel showed better surface finish than silica sand, leading to a return to green sand for subsequent pours.

Figure 3: Failed prototype casting

New Green Sand

Our old foundry green sand had not been replaced for quite a few years, so the exact composition of the remaining sand and clay was unknown. Our team deemed this was a risk that could hurt the permeability and green strength of our molds. New green sand (90% silica sand to 10% bentonite clay) would allow for us to get better green strength than the old sand, due to a more active clay content being helping to ensure that when the pattern was pulled out the mold would
stay intact and retain its shape.

Figure 4: Old vs. new green sand

Figure 5: Pattern board drag side

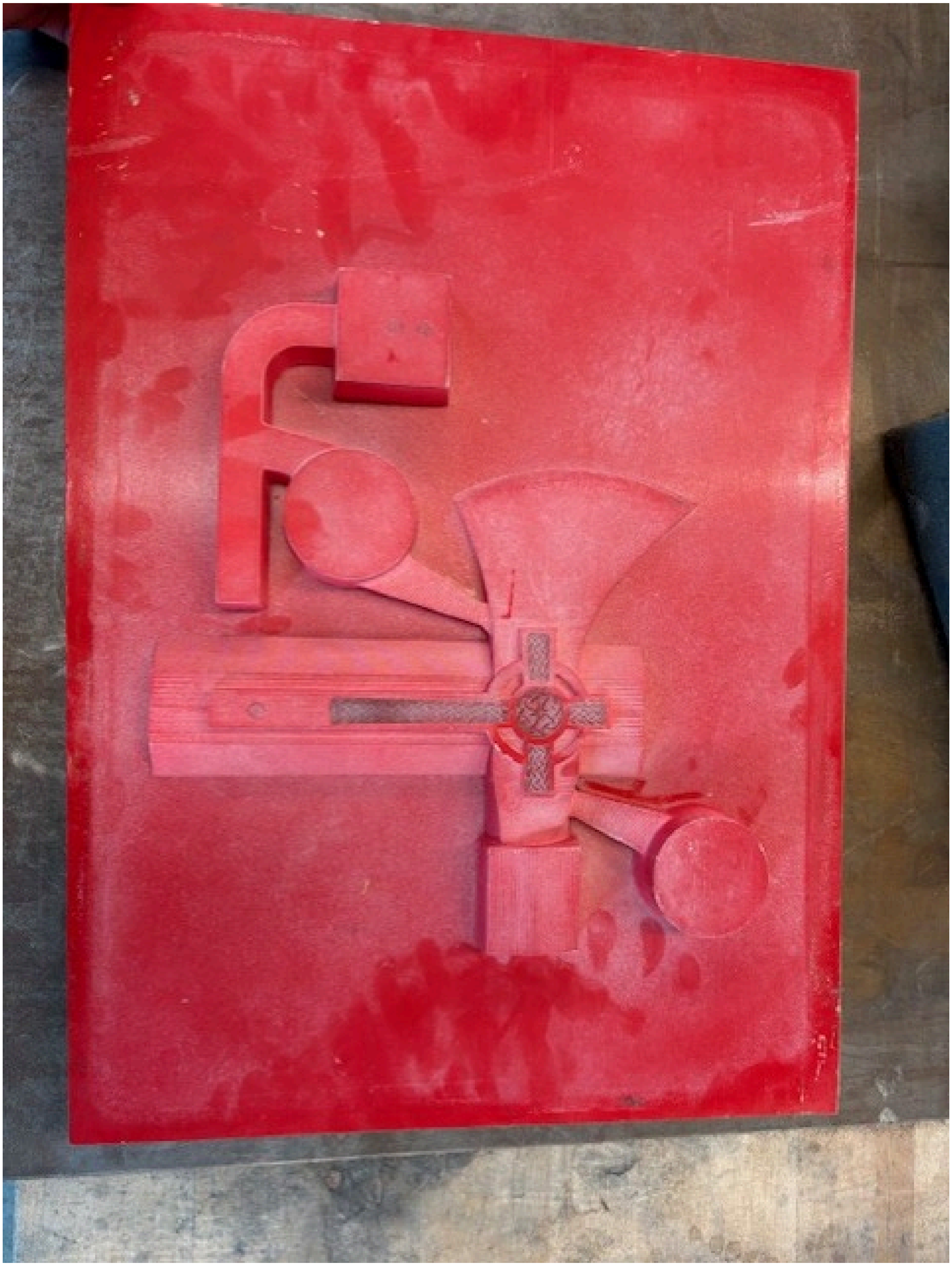

Figure 6: Pattern board cope side

Figure 6: Aluminum test cast to verify pattern board

Final Steel Pour

Now with our redesigned pattern board we were ready to do our final steel pour. The fresh green sand mold was prepared. To combat the ladle from not getting hot enough we switched over to a much larger natural gas tank to keep the ladle as hot as we could. After conducting multiple test dry runs to maximize our efficiency and prevent any cooling before the steel is poured we were ready to begin. The same general process as before was conducted as with our first steel pour but this time we were far more efficient at getting the furnace tapped and getting the ladle over to the molds with minimal heat loss.

Three taps were conducted on the furnace to remove all 300 lbs of steel and get them poured into the axe molds as well as additional molds to pour excess steel.. After the weekend the molds were again broken open to reveal a much more successful pour where all three of our axe molds were complete with all parts getting filled during the pour.

Figure 7: Successful steel pour cast on sprue

Post Processing

After allowing one day for cooling, all three steel axe head castings were successfully removed, cut from their gating systems with an angle grinder, bead blasted, and evaluated, with the best selected for final use and the worst designated for durability testing; the axes were then reshaped, normalized at 870 °C, beveled to a 30° inclusive angle, surface-finished, and drilled for pin holes prior to heat treatment. Heat treatment involved austenitizing at 850 °C, quenching in Parks 50 oil to produce a hard martensitic exterior with a tougher core, followed by liquid nitrogen treatment to eliminate retained austenite and tempering at 205 °C to restore ductility, after which the axes were cleaned, finished to 220 grit, and fitted with shaped wooden handles (oak for the prototype, ash for the final) chosen for regional relevance and shock absorption, though the prototype failed early due to lack of proper wedging and pinning. Final finishing on the completed axe included a darkened and contrasted surface treatment, sharpening and polishing of the blade, protective waxing of the head, and careful handle finishing with stain and linseed oil, culminating in assembly with wedging, brass pinning, and a leather-wrapped grip for durability and control.

Metallurgy/Quality

Micrographs were taken of the prototype and of the final casting. For the prototype pour we used 1045 steel, a simple carbon steel that resulted in ferrite and perlite. Figure 8 shows the results from the prototype casting. The grains vary quite a bit in size with large grains and clusters of small grains. This resulted in an as cast hardness of 29HRC. The final pour used 4140 steel alloy due to its increased toughness, and hardness. Figure 9 shows the as cast microstructure. Large ferrite grains with a fine perlite structure. The resulting hardness was 34HRC. After heat treatment the final hardness was 53HRC.

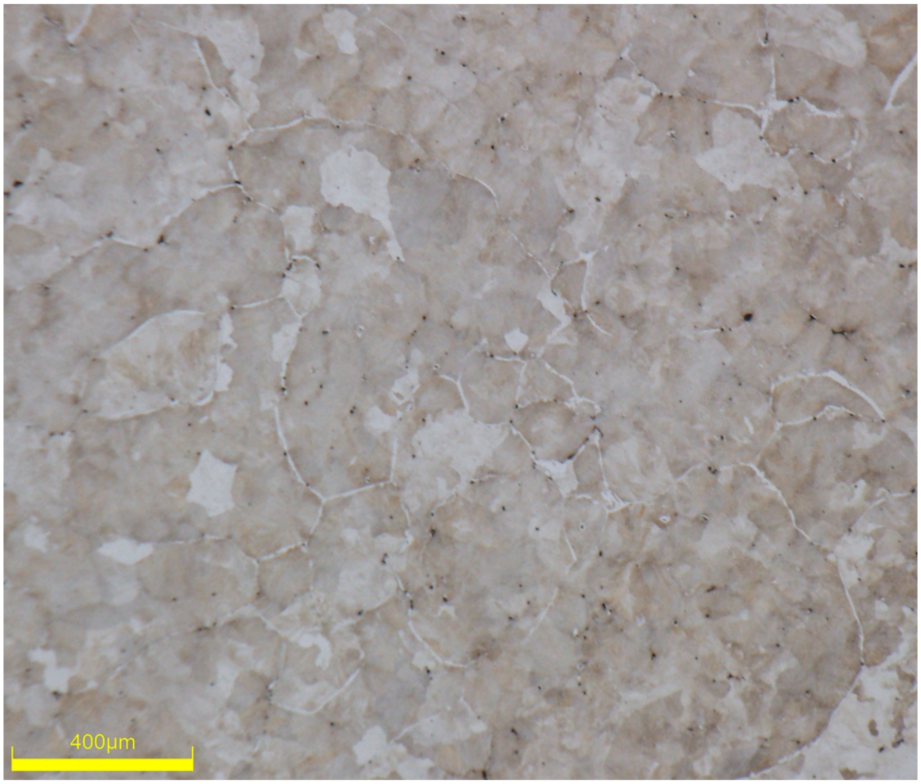

Figure 8: Micrograph of the hammer from our prototype pour.

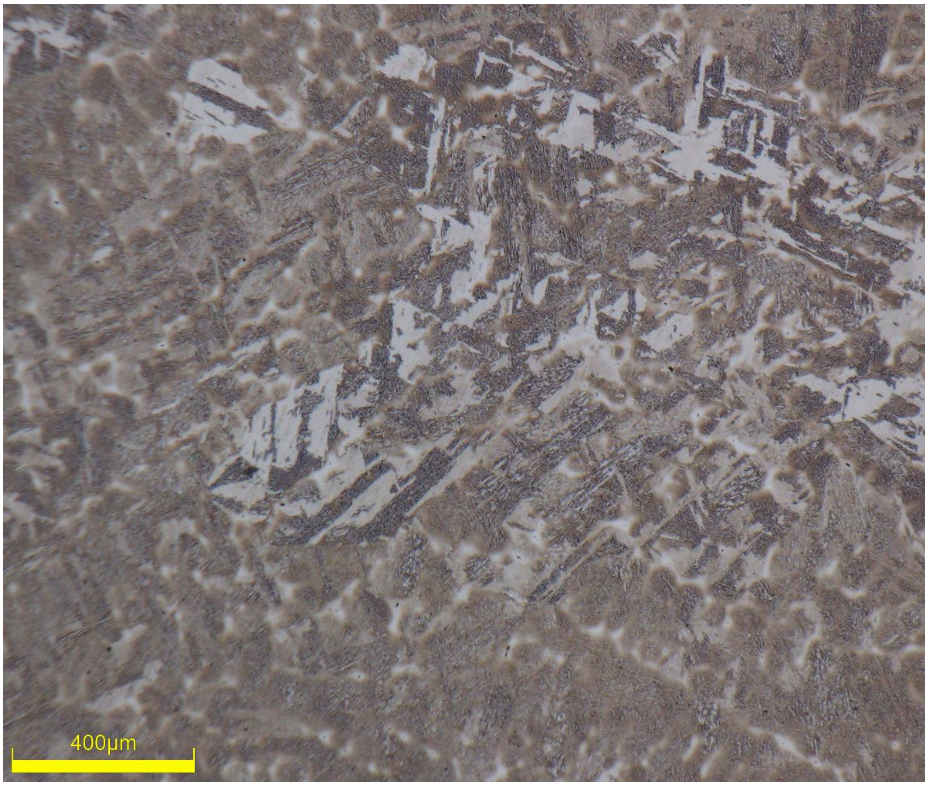

Figure 9: Micrograph of the langet from the final pour.

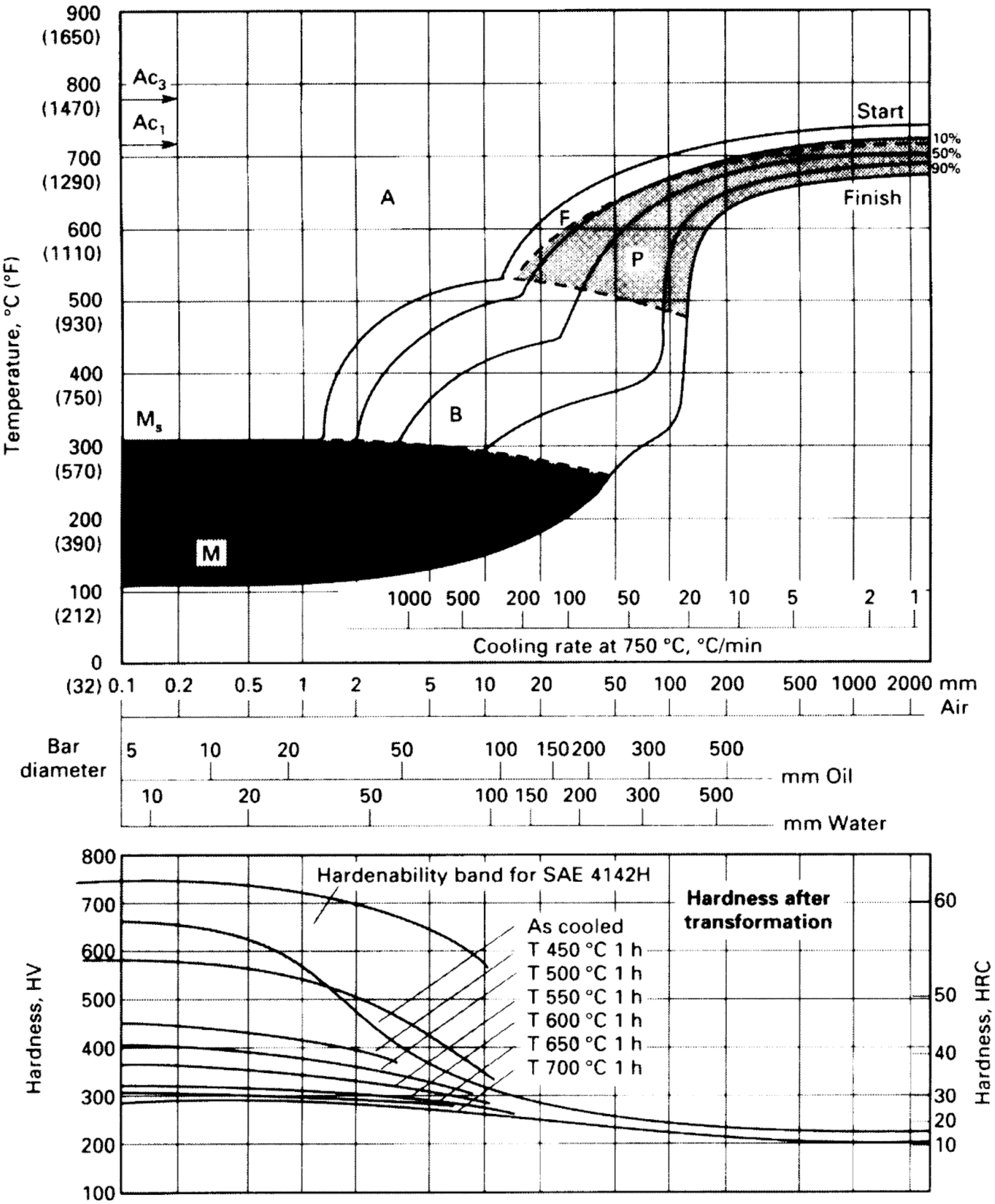

Figure 10: CCT curve and Hardness vs. Temperature curve for 4140 steel:

Chemistry samples taken from chopped riser material were analyzed using Optical Emission Spectroscopy (OES). This revealed that the alloy did not meet AISI 4140 steel specifications due to elevated carbon, chromium, molybdenum, and silicon levels. This was caused by using alloy additions intended for 300 lbs of base metal on only 250 lbs due to a last-minute furnace capacity reduction that was not communicated. This compositional shift raised concerns because 4140 was originally selected for its toughness, critical for impact resistance, but increased carbon and alloying elements promote deeper martensitic transformation and greater carbide formation. Especially chromium and molybdenum carbides, which improve strength and hardness at the expense of ductility. Although this might be somewhat counteracted by silicon as while it contributes to solid solution strengthening it also may limit carbide formation. Despite these changes, the axe still achieved the expected hardness of ~56 HRC, suggesting that while toughness may be somewhat reduced, the ductile core likely remains sufficient to prevent failure, and the increased strength may even enhance edge retention.

	C%	Cr%	Ni%	Mo%	Si%	Mn%	Cu%	S%	P%	Al%	V%	N%
W. Min	0.370	0.800	-	0.150	0.150	0.750	-	-	-	0.080	-	-
W. Max	0.440	1.10	1.000	0.250	0.350	1.000	1.000	0.040	0.035	0.120	-	-
Test 1	0.417	1.22	0.044	0.264	1.23	0.839	0.064	0.005	0.011	0.101	0.005	0.011
Test 2	0.507	1.25	0.046	0.275	1.27	0.884	0.066	0.006	0.012	0.105	0.006	0.013

Table 1: Axe alloy compositions compared to typical 4140 steel

The below figure (Figure 12) shows the locations of known problematic pores in the axehead. These were found via computed radiography defined in ASTM E2033-17, with testing performed by Team Services Inc. Gating and runners in the team’s pattern were too long and narrow, leading to premature freezing and risers ineffectively feeding. Because the cast was fed poorly there were large shrinkage pores where the casting solidified last.

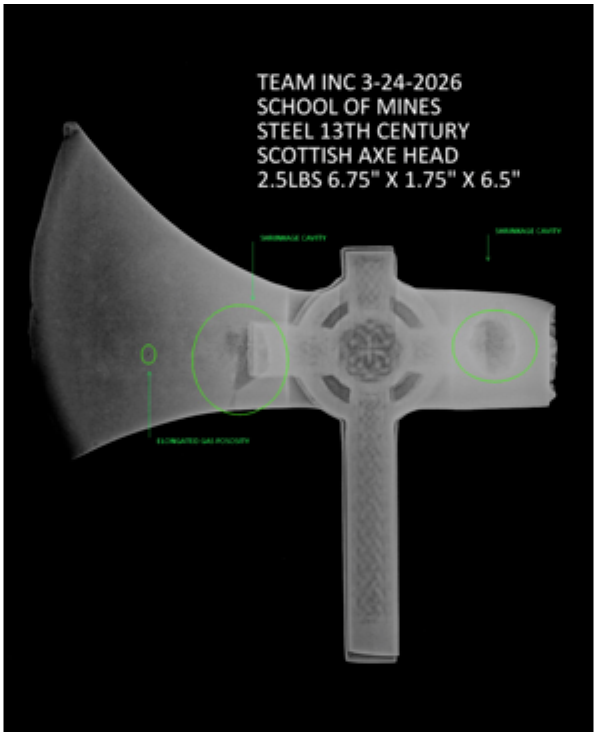

Figure 11: CT scan of axehead

These pores present a serious issue in the performance of the axe. The pores act as stress intensities. Where material would normally help dampen and dissipate stresses the pores actually concentrate it, leading to higher loading in the areas with these pores. The exact effects cannot be known, but they can be approximated in FEA. By roughly approximating the size and shape of these defects and re-running the static loading study, the below figure was made.

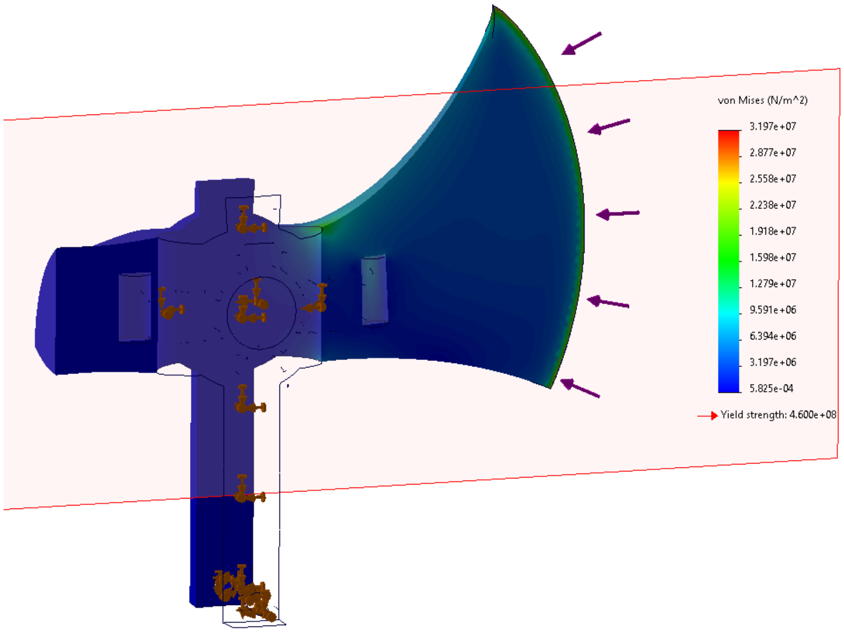

Figure 12: FEA analysis of axehead with porosity defects

The stress study shows that, although concerning, the pores do not cause a significant change in internal loading. This is good news, and supports that the performance of the axehead will be stable. However, these pores show evidence of shrinkage porosity in the axehead, and although the most severe, may not be the only porosity present. If there are more pores throughout the head the risk of fracture, internal fractures, and rapid crack propagation significantly increase.

Conclusion

We successfully demonstrated that a complex, historically inspired horseman's axe can be produced through modern steel casting methods despite the inherent challenges associated with thin sections, internal defects, and mold design. Through iterative engineering design, integration of CAD, additive manufacturing, and close collaboration with industry partners, the team was able to diagnose early casting failures, optimize gating and riser systems, and ultimately achieve a fully realized 4140 steel casting with desirable mechanical properties. The final met functional performance requirements, as supported by structural analysis and metallurgical testing, and also captured the historical and aesthetic intent of a 13th-century weapon. This project highlights the effectiveness of combining traditional metallurgical principles with modern technology, reinforcing the viability of casting as a method for producing high-performance components with both technical and cultural significance.

Acknowledgements

Dr. Gerald Bourne, Teaching Professor and Associate Department Head of Metallurgical and Materials Engineering, for use of the Colorado School of Mines Physical Metallurgy Laboratory and Bladesmithing Laboratory.

Dr. Kip Findley, Director, Advanced Steel Processing and Products Research Center and Teach Professor, Metallurgical and Materials Engineering, for generous donation of 1045 steel charge material

Dr. Stephen Midson, Research Professor of Metallurgical and Materials Engineering, for continued guidance and assistance with foundry metallurgy fundamentals.

Daniel Bourque & Tim Plamondon, Western Foundries, for continued support and assistance with melt practices during the steel pour, gating and riser systems feedback, and supplied chemistry values.

Juan Enriquez, for continued support and assistance with furnace operation and melt practices during the steel pour.

Adam Zimmer, Denver 3D Print Company, for continued support with CAD modeling and feedback.

Mason Weems, Max Marsh, Tristyn Hurd, Ally Curry, & Kennedy Veldhouse, for continued assistance with steel pours

Art Hernandez, General Manager of Accurate Metals Testing, for supplied tensile test results

Sam Urban, Team Ink Services, for supplied non destructive CR/DR Scan results

AJ, FedEX, for helping us get this unruly axe packed and shipped

References

[1] Asm International. Handbook Committee, ASM Handbook Volume 4. Materials Park, Ohio: Asm International, 1990.

[2] Asm International. Handbook Committee, ASM Handbook Volume 15. Materials Park, Ohio: Asm International, 1990.

[3] E28 Committee, *Test Methods for Rockwell Hardness of Metallic Materials*. doi: 10.1520/E0018-24.

[4] E28 Committee, *Test Methods for Vickers Hardness and Knoop Hardness of Metallic Materials*. doi: 10.1520/E0092-23.

[5] A01 Committee, *Test Methods and Definitions for Mechanical Testing of Steel Products*. doi: 10.1520/A0370-24A.

[6] A01 Committee, *Specification for Steel Castings, Carbon, for General Application*. doi: 10.1520/A0027_A0027M-20.

[7] J. Campbell, Castings Practice. Elsevier, 2004.

[8] C. W. Ammen, *The complete handbook of sand casting*. in TAB books, no. 1043. Blue Ridge Summit, Pa: TAB Books, 1979.

[9] America, “Steel Founders’ Society of America,” *Sfsa.org*, 2024. https://www.sfsa.org/

[10] “Cast in Steel,” *Cast in Steel*, 2026. https://www.castinsteel.net/ (accessed Mar. 17, 2026).

[11] “Best Wood For Axe Handles [Top 12] - Axe Adviser,” Dec. 06, 2022. https://axeadviser.com/best-wood-for-axe-handles/

[12] E07 Committee, *Practice for Liquid Penetrant Testing*. Doi: 10.1520/E1417_E1417M-21E01.

[13] “Knife Edge Grinds and Uses”, Lansky.com, 2026. https://www.lansky.com/resources/post/knife-edge-grinds-and-uses.html (accessed Mar. 27, 2026).

[14] “Welcome to trove.scot | The key to Scotland’s past,” *Trove.scot*, 2025. https://www.trove.scot

[15] “Historic Environment Scotland,” *www.historicenvironment.scot*. https://www.historicenvironment.scot

[16] Chronicle - Medieval History Documentaries, “The Ancient Origins Of Medieval Scotland’s Most Feared Military Tactics | Warriors Way | Chronicle,” *YouTube*, Dec. 02, 2023. https://www.youtube.com/watch?v=ceN8SfSkoGk (accessed Mar. 27, 2026).

[17] “Parks 50 quench oil tech data sheet”, *Knifedogs.com*, 2017. https://knifedogs.com/resources/parks-50-quench-oil-tech-data-sheet.5/download (accessed Mar. 27, 2026).

[18]“Standard Practice for Radiographic Examination Using Computed Radiography (Photostimulable Luminescence Method),” *Astm.org*, 2024. https://store.astm.org/e2033-17.html (accessed Mar. 28, 2026)

Appendix

Appendix A — Safety Factor Calculation for Axe Head Retaining Pin (Moderate–High Impact Case)

Given:

Axe head weight: $W = 2.8$ lbf
Pin diameter: $d = 0.25$ in
Material: Cartridge brass (C260)
Configuration: Double shear

Assumptions for impact:

- Swing velocity: $v = 22$ ft/s
- Stopping distance on impact: $s = 0.05$ ft (≈ 0.6 in)
- Gravitational acceleration: $g = 32.2$ ft/s^2

A1. Mass of Axe Head

$$m = W / g$$

$$m = 2.8 / 32.2 \approx 0.087 \text{ slugs}$$

A2. Impact Force from Deceleration

Using work-energy principle:

$$F \cdot s = (1/2)\, m v^2$$

$$F = (m v^2) / (2s)$$

$$F = (0.087 \times 22^2) / (2 \times 0.05)$$
$$F = (0.087 \times 484) / 0.10$$
$$F = 42.1 / 0.10$$
$$F \approx 421 \text{ lbf}$$

A3. Total Effective Load

$$F_{total} \approx 421 + 2.8 \approx 424 \text{ lbf}$$

A4. Shear Stress in Pin (Double Shear)

$$\tau = 2F / (\pi d^2)$$

$\tau = 2(424) / [\pi (0.25)^2]$
$\tau = 848 / 0.196$
$\tau \approx 4330$ psi

A5. Material Shear Strength

For cartridge brass:

S_y ≈ 18,000–25,000 psi

Shear yield strength:

S_shear ≈ 0.577 S_y

Using conservative value:

S_shear ≈ 10,000 psi

A6. Safety Factor

n = S_shear / τ

$n = 10{,}000 / 4330$
$n \approx 2.3$

A7. Final Result

$n \approx 2.3$