

SFSA Cast In Steel 2026 – Horseman’s Axe

Technical Report

Central Michigan University – The Choppewas



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1. Introduction

Central Michigan University collaborated with Bay Cast to design, cast, and evaluate a historically inspired Horseman's Axe for the 2026 Steel Founders' Society of America (SFSA) Cast in Steel Competition. This competition challenges students to reinterpret historically significant tools using modern casting technologies, integrating metallurgical understanding, CAD-based design, manufacturing processes, and performance testing. SFSA has created this competition to encourage students to learn about making steel products using the casting process and applying the latest technology available.

A five-student CMU engineering team partnered with Bay Cast, who provided casting expertise, alloy guidance, and assistance with gating and riser development. The project objective was to merge historical authenticity with modern manufacturability while meeting the competition constraints for weight, length, and functional performance.

The team used binder-jet printed sand molds, CAD modeling, nondestructive evaluation, machining, and heat treatment to recreate a 14th-century Horseman's Axe associated with King Robert the Bruce at the Battle of Bannockburn. Modern engineering tools, including finite element analysis (FEA) and computer aided design (CAD), supported the design and verification process.

Overall, the project demonstrated how modern casting technologies can produce historically grounded tools with improved dimensional control, reliability, and reproducibility compared to traditional forging.

2. Historical Background and Accuracy

The project focused on creating an accurate interpretation of a 14th-century Horseman's Axe associated with King Robert the Bruce and the Battle of Bannockburn. Historical accounts describe Bruce striking and killing Sir Henry de Bohun with a single mounted blow, illustrating both the functional and symbolic importance of axes used during this period.

To ensure authenticity, the team reviewed medieval illustrations, museum references, and common characteristics of horseman's axes from the early 1300s. These weapons were compact and balanced for rapid mounted strikes, typically featuring a crescent blade, reinforced socket, and a functional rear spike.

The initial CAD model incorporated these elements and originally included a small decorative cutout inspired by crown motifs linked to Bruce. A back spike was also designed based on documented medieval examples. Although the cutout was removed during later machining, and the spike required reshaping due to casting cleanup, the final geometry preserved the essential form and functional appearance of a 14th-century Horseman's Axe.

The use of a hickory handle, historically appropriate mass distribution, and a period-consistent blade profile ensured that the final design remained aligned with historical expectations while accommodating the practical constraints of casting and machining.

3. Casting Technology and Manufacturing Value

Casting was the main challenge of this project, and it influenced almost every decision that was made. Although forging would have been a simpler method for producing a small axe head, the competition required casting, making this a valuable learning experience for the team. This was the first time anyone on the team had worked with steel castings, so understanding how much extra material is normally added, how draft angles work, and how to plan machining around a casting became a major part of the project.

Bay Cast produced the patterns using binder-jet 3D-printed sand. This allowed draft angles, fillets, and geometric features to be incorporated directly into the CAD model. The printed molds provided consistent geometry and supported simulated fill-flow analysis prior to pouring.

The as-cast axe heads presented significant challenges. Each arrived weighing approximately 7 pounds—more than double the competition requirement. The original spike geometry was also accidentally removed during foundry cleanup, which required reshaping the spike by hand using the excess stock material.

Three of the eight castings were selected for CNC machining, nondestructive testing, and heat treatment. CNC machining reduced each selected casting to roughly 4.8 lb. Final weight reduction to the 3.2–3.8 lb range required extensive hand grinding.

Despite these setbacks, binder-jet casting still provided major advantages: consistent geometry, the ability to produce more complex features, and reduced labor compared to traditional pattern-making. The project reinforced the importance of communication, stock allowance control, and early machining planning when casting components with strict weight limits. The team learned firsthand how critical Design for Manufacturing (DFM) is when using cast steel, particularly when mass constraints and machining time are major considerations.

4. Design Process

The design process for this project began with understanding what was required for the SFSA Cast in Steel Competition. Our goal was to create a historically accurate Horseman's Axe that still met the competition's functional, dimensional, and weight requirements. From the start, we knew that balancing historical inspiration with casting limitations would guide most of our decisions. Because this was the first major engineering project for several team members, a large part of the design phase involved learning how design choices translate to manufacturability, machining needs, and final performance.

Competition Requirements

The design process was driven by requirements from the SFSA 2026 Cast in Steel competition:

- The completed axe had to weigh no more than 1.5 kg (3.3lb) and measure less than 800 mm (31.5 in)
- The team was required to submit a technical report under 10 pages, excluding appendices.
- A project video under five minutes had to accompany the submission.

Additional needs came from collaboration with Bay Cast. Since they were producing the molds and pouring the steel, the team had to consider their recommendations for draft angles, fillets, and the overall geometry of the casting. Internally, the team also prioritized:

- Maintaining the recognizable look of a Horseman's Axe
- Designing a part that could be machined with CMU's equipment
- Keeping the final assembly achievable within the timeline

These needs were later summarized in a design specification table, which is in Appendix A.

Concept Development and Initial Sketches

Several blade and spike concepts were sketched and compared using a weighted scoring matrix. Criteria included historical accuracy, castability, machining effort, stress distribution, and manufacturability. The chosen design provided a historically recognizable form while remaining feasible for steel casting and machining.

Material Selection

4340 alloy steel was selected for the axe head after reviewing mechanical property charts, heat treatable alloys, and feedback from Bay Cast. Using 4340 also kept consistency with the other Central Michigan University team. An alloy comparison table is included in Appendix A.

Hickory was selected as the handle material due to its high strength-to-weight ratio and excellent shock absorption. These properties align closely with what would have been used historically and make it easier to shape by hand and machine. The final handle profile, shown in Appendix A, was designed to balance the head properly and provide a comfortable grip. The shape was finalized after several rounds of sanding and test-fitting.

CAD Development

Once a concept was selected, the team created a detailed CAD model in Catia. This was an iterative process. Many of the design changes came from Bay Cast's feedback on casting feasibility. The team added draft angles to all appropriate surfaces, incorporated fillets to reduce stress concentrations, and adjusted wall thicknesses to prevent thin sections that could cause defects. After the design was chosen, they were put into Autodesk Fusion and dynamic simulations were performed to test the theoretical strengths and weak points of our designs.

The back spike, blade edge taper, and socket geometry were modeled based on historical references. The cutout was designed to be simple enough for machining but still tied to the

original inspiration. The internal pocket for the handle was also modeled into the CAD to ensure a tight and consistent fit after machining. Original CAD models can be found in Appendix B.

Finite Element Analysis Summary

Finite element analysis (FEA) was performed in the design phase to predict stress distribution during typical impact loading. The analysis showed acceptable stress levels across the blade and spike, with the highest stresses located near the cutting edge during a downward strike. The maximum predicted von Mises stress remained below the expected yield strength of heat-treated 4340 steel. These results can be seen in Appendix C.

5. Casting Process

The casting process was vital to turning the CAD design into a functional steel axe head. The team used binder-jet 3D-printed sand molds, which allowed drafts, fillets, and other features directly from the CAD model to be incorporated. This method eliminated the need for physical patterns and gave us consistent mold geometry for each casting.

Mold Preparation

Once the CAD files were finalized, the team provided them to Bay Cast for mold production. The foundry created binder-jet printed sand molds directly from the CAD geometry, eliminating the need for physical patterns. Each mold included additional stock to allow for material removal during post-processing. The printed sand molds were coated with zircon to protect critical surfaces from erosion and thermal damage during pouring. All mold surfaces were inspected, and the mold halves were assembled using built-in keying features to ensure proper alignment prior to casting.

Gating and Risers

Bay Cast designed the gating and riser system based on the provided CAD files. The gates were curved, and risers were placed to allow uniform filling and feeding during solidification. While the team provided recommendations, Bay Cast determined final positions. The gating system ensured the molten steel would fill the cavity completely. [Diagrams in Appendix D]

Pouring and Shakeout

After assembling the cope and drag, the mold halves were bolted together and allowed to cure for 72 hours. This curing period was longer than intended due to inclement weather conditions. The pouring took place three nights later at midnight. The molds were filled with 4340 steel melted in a 3000°F furnace. The pour was monitored for temperature and flow, and each mold was allowed to solidify undisturbed for the required duration. Once solidified, the molds were cooled to room temperature before shakeout. The as-cast axe heads arrived with significant

excess material and without the intended back spike, requiring major adaptations during post-processing.

Summary

This phase of the project emphasized the importance of careful mold design, gating strategy, and stock allowance for machining. Although the printed molds provided precision and repeatability, the as-cast weight required extensive CNC machining and hand grinding to reach the competition's target specifications. Lessons learned from this phase informed improvements in design-for-manufacturing and will guide how the team approaches future casting projects.

6. Post Processing

All eight axe heads were received weighing approximately 7.2 pounds and with the back spike accidentally removed during initial foundry cleanup. Post-processing required a combination of CNC machining and extensive hand grinding. CNC operations focused on removing bulk material from the sides of the head and machining the pocket for the wooden handle. After CNC machining, each selected head was reduced to roughly 4.8 pounds. Additional weight reduction was then completed by hand, a process that required many hours of grinding and shaping to meet the competition's requirement. Three axe heads were chosen for further processing and sent for nondestructive testing and heat treatment. Their final weights after all finishing steps were 3.2, 3.4, and 3.8 pounds. Images of this process and the resulting heads are provided in Appendix E.

Late-Stage Design Adjustments

Although the original CAD model included a decorative cutout and a defined spike, the actual casting and post-processing steps forced last minute adjustments. When the castings arrived with far more excess stock than expected, and the original spike was accidentally removed, the approach was shifted. The remaining material was reshaped by hand to form a new back spike. The cutout, which was part of early design intent, had to be eliminated due to time constraints after heat treatment. Only three castings were fully machined, and heat treated due to scheduling and resource limitations.

7. NDT and Inspection

Non-destructive testing (NDT) was performed to verify the internal and surface quality of the castings after the first round of machining but before heat treatment. Because the axe heads arrived with significant excess stock and the original back spike had been removed during early cleanup, it was essential to inspect the castings at this stage to ensure that no hidden defects would worsen during machining or the quench-and-temper cycle.

After initial CNC operations—which included machining the handle pocket and removing bulk material to reduce each head to approximately 3.5 pounds—the three selected castings were sent for visual inspection and magnetic particle testing.

Visual Inspection (VT) — ASTM A802 Level III

A 100% visual inspection was performed following ASTM A802 Level III acceptance criteria. This level allows minor cosmetic imperfections but does not permit structural defects such as open cracks, excessive porosity, or deep surface discontinuities. All three axe heads passed the evaluation, indicating no visible flaws that exceeded the allowable limits. These results demonstrated that the castings were safe to proceed through heat treatment and performance testing. VT photographs are provided in Appendix F.

Magnetic Particle Inspection (MPI) — ASTM E709

Magnetic particle testing was performed with complete coverage on each casting. The inspection followed ASTM E709 with Level I acceptance limits for cracks and Level III limits for inclusions—meaning the criteria for cracks were very strict while inclusions had more moderate limits. All three axe heads passed the MPI inspection. No surface or near-surface cracks were detected, and any inclusions present were minor and well within acceptable standards. Because MPI is more sensitive than visual inspection, passing this test provided strong confidence in the structural integrity of the castings. MPI results are shown in Appendix F.

Importance of NDT

Both VT and MPI were especially important because the blade and socket areas experience the highest thermal stresses during casting and are the most susceptible to internal flaws. Inspecting the castings at this stage prevented the risk of machining into hidden cracks or defects, ensuring that only sound components continued to heat treatment.

Due to timeline constraints, Bay Cast could not complete hardness (Rockwell) testing or additional material verification that had originally been planned. However, the heat-treatment sequence was performed correctly, and the magnet test conducted during cooling confirmed proper austenitization of the steel. Based on the temperature cycle used and the known response of 4340 steel, the final hardness and toughness were expected to fall within typical ranges for tempered 4340. As a result, NDT served as the primary verification method for internal soundness prior to heat treatment and final finishing.

8. Heat Treatment

The axe heads underwent a full heat-treatment cycle to achieve the required mechanical properties for 4340 steel. Thermistors were attached to the surface of each head, and the parts were heated in a forge until the surface temperature reached approximately 1550°F. They were held at this temperature for one hour to ensure the surface and core reached uniform temperature. The heads were then removed and oil quenched, with only the first two inches of each side submerged. The quench oil was preheated to around 150°F, and each blade was dipped for 10 seconds, starting with the cutting edges to ensure proper cooling. After quenching, the axes were allowed to cool to below 300°F, and a magnet test was performed to confirm full austenitization.

The parts were then tempered at 500°F and left to air-cool to room temperature before final grinding and assembly.

9. Testing and Performance

After heat treatment and final shaping, the axe heads were inspected and tested to verify that they met the SFSA performance requirements and that the final designs were safe, durable, and historically accurate. Because each casting arrived significantly overweight, a major part of the performance evaluation centered on confirming the final mass and balance after machining and hand grinding.

Final Grinding and Finishing

Post-heat-treatment grinding reduced the heads to final weights of:

- 3.1 lb (competition axe)
- 3.3 lb (testing axe)
- 3.8 lb (unfinished third head)

This weight reduction required a combination of CNC machining, extensive hand grinding, and careful reshaping of the back spike.

Fit and Assembly

The CNC-machined pocket provided a consistent starting geometry, but the hickory handle still required hand-sanding and shaping to achieve a tight, interference-style fit. Once the fit was finalized, the team completed the assembly using an epoxy and an aluminum wedge. The epoxy reinforced the interior of the pocket for long-term stability, while the aluminum wedge expanded the top of the handle and mechanically locked the head in position. After assembly, the head was secure with no movement during handling or light swing testing. Only one of the three axe heads could be fully assembled with a wooden handle due to the limited time remaining after heat treatment and final grinding. But an additional axe head was attached to a metal handle for additional testing.

The axe that was sent to the competition weighed in at 1.489 kg and about 608 mm from one tip of the blade to the end of the handle. Final assembly and weight can be found in Appendix G.

10. Results and Discussion

This project combined historical research, casting-based manufacturing, and hands-on machining to produce two functional Horseman's Axes inspired by early 14th-century designs. Despite challenges—including excess stock material, the accidental removal of the original spike during foundry cleanup, and a compressed schedule after heat treatment—the team successfully completed two heat-treated axe heads that aligned closely with the intended design.

Although the decorative cutout could not be completed due to time constraints, the team reshaped the back spike and preserved the most important historical features of the weapon. The final axes maintained appropriate proportions, blade geometry, and mass distribution consistent with documented Horseman's Axe examples.

Throughout the project, the team gained practical experience in how casting impacts design, manufacturability, and machining workflow. Key lessons included the importance of controlling stock allowances, planning machining operations early, and maintaining consistent communication with the foundry during mold production and post-cast cleanup.

If this project were repeated, the main improvements would include tightening casting tolerances, receiving castings closer to the intended geometry, and allocating more time after heat treatment for final shaping and assembly. Overall, the project reinforced core engineering skills and demonstrated how modern casting processes can effectively support historically inspired designs when paired with thorough planning and adaptability.

Appendix A — Tables

Table A1. Design Specifications Table

Spec. Number	Needs Met	Metric	Importance	Units	Value
1	8	Limit the overall length of the axe	4	inches	25<L<31
2	1, 4, 8	Limit the overall weight of the axe	4	pounds	W<3.3
3	1, 4, 5	The axe is one handed (reasonable hand size)	3	opinion	Yes or No
4	1, 5	Hole on handle for strap	3	inches	<=1
5	5, 8,10	The design is historically accurate	2	opinion	Yes or No
6	1	The axe consists of multiple parts	5	count	1<=N<=3
7	6, 8, 10	The axe can hold up during testing; high strength	3	ksi	
8	3, 7	Creative design engraving	2	opinion	Yes or No
9	2, 3	Large fillets for casting/manufacturing	4	inches	
10	4	Balanced Weight (filling of the axe)	3	pounds	
11	9	Limit overall cost of materials	2	\$	<=3,000

Table A2. Alloy Comparison Table

Property	AISI 4330	AISI 4340	Notes
Density (lb/in ³)	.284	.284	Same density
Machinability	Moderately machinable ~60%	Not highly machinable ~50%	4330 slightly easier
Tensile strength (ksi)	≥125	108	Similar after specific tempers
Yield strength (ksi)	≥100	68.2	Differences depend on heat treatment
Hardness (Brinell)	285	217	Both suitable for axes

Table A3. Hardwood Comparison Table (Hickory vs. alternatives)

Property	Hickory	Ash	Maple	Oak
Density (lb/in ³)	0.029	0.024	0.025	0.027
Impact Resistance	★★★★★	★★★★☆	★★★★☆	★★★★☆
Shock Absorption	★★★★★	★★★★☆	★★★★☆	★★★★☆
Workability	★★☆☆☆	★★★★☆	★★★★☆	★★★★☆
Historical Accuracy	High	Medium	Medium	Medium

Table A4. Weighted Scoring Matrix (Concept Selection)

Specification	Importance	Wood Handle		Metal Handle	
		Eval. Score	Weighted Score	Eval. Score	Weighted Score
Historical Accuracy	4	5	20	4	16
Overall Performance	5	4	20	3	15
Assembly	4	5	20	4	16
Light Weight	5	5	25	2	10
Total		19	85	13	57

Appendix B — CAD Figures

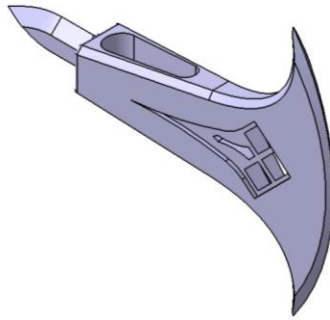
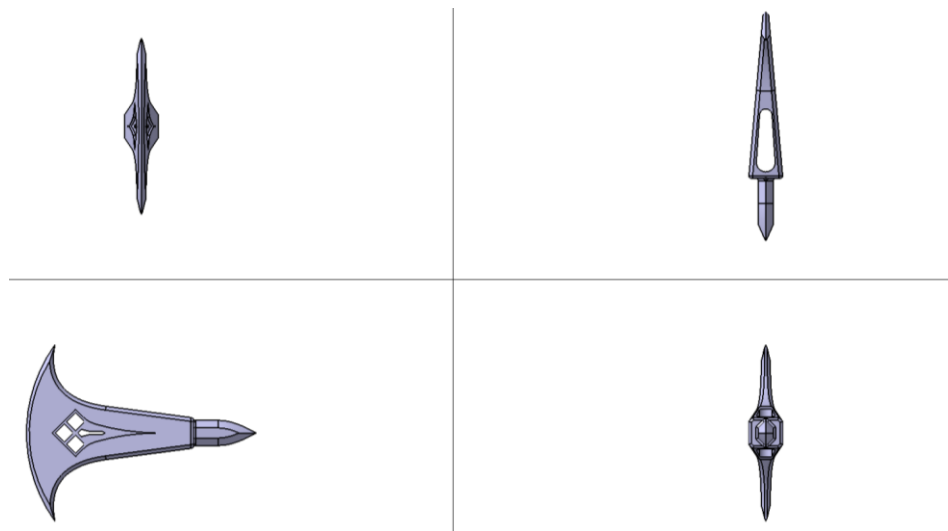


Figure B1. Isometric View of Original CAD Model



B2. Orthographic Views of Original CAD Model



Figure B3. Handle Profile Geometry

Appendix C — FEA Results

[MPa] 0.00 9462.436

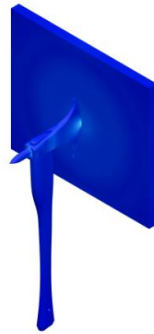


Figure C1. Von Mises at Step (Frame) 26. Axe is traveling into a titanium alloy at 30 MPH.

[mm] 0.00 1.222

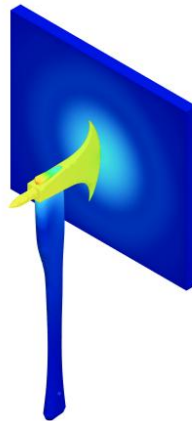


Figure C2. Displacement at Step (Frame) 26.

Appendix D — Casting Diagrams

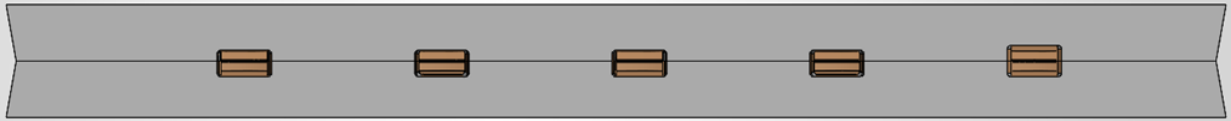


Figure D1. Draft Angle Diagram - Because the mold was 3D-printed, no draft was required on the casting itself. However, a -10° draft was added to the outer mold to securely hold the printed mold inside the flask during packing and pouring.

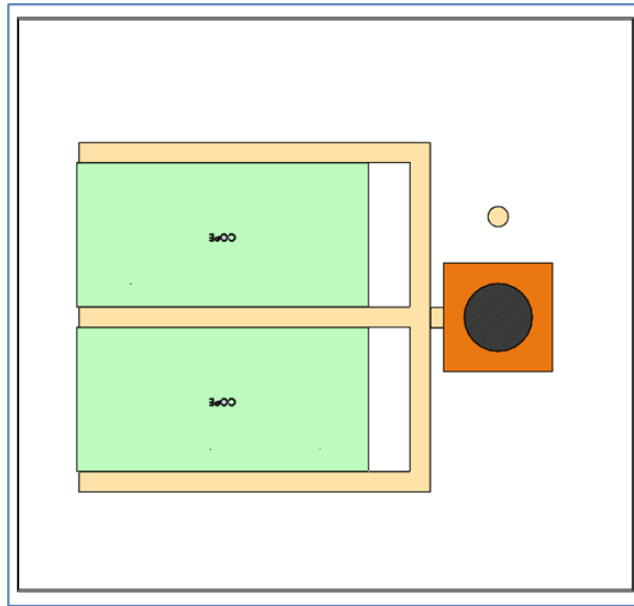


Figure D2. Gating and Riser Diagram – Cope

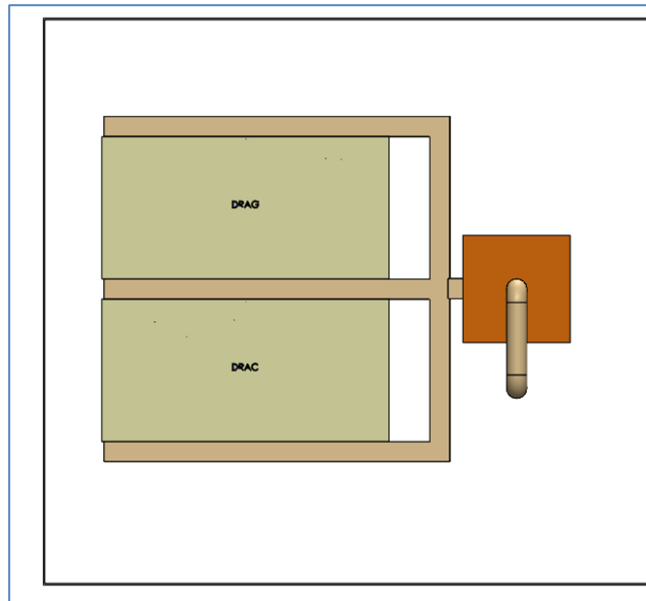


Figure D3. Gating and Riser Diagram – Drag

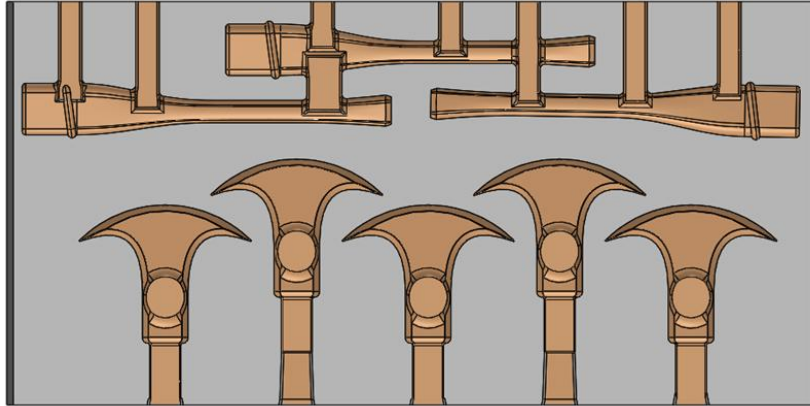


Figure D4. Printable Mold Images

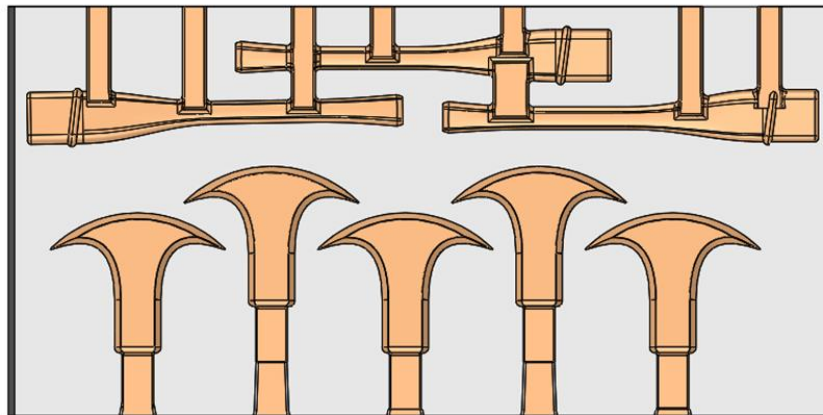


Figure D5. Printable Mold Images



Figure D6. Post Cast



Figure D7. Post Cast - Back Spike Cut Off

Appendix E — Machining & Weight Reduction



Figure E1. Machining Photos (CNC Weight Reduction)



Figure E2. Machining Photos (Planning Back Spike)



Figure E3. Machining Photos (Pocket Cut Out)

Appendix F — Testing



Figure F1. Visual Inspection



Visual Inspection Report

Customer: Central Michigan University Part Name: Axe Heads/Handles
Control No.: n/a Material: ASTM A958 SC 4340
Part No.: n/a Heat No.: 260014
P.O. No.: n/a

Inspection Specifications

Procedure: ASTM A802
Criteria: Level III

Areas Inspected:

100%

Additional Notes/Sketches:

Inspection Report for 6 Axe Heads and 2 Handles.

Inspection Date:
3-11-2026
Status of Part:
Pass

Upon passing, the above part has been inspected and certified to meet the criteria specified as:
**ASTM A802
Level III**

Signature:



Jason J. Holman
VP/QA Manager
NDT Level III

Figure F2 – Visual Inspection Report



Figure F3. NDT Images (Magnetic Particle)


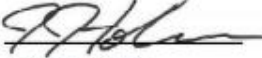
	
Magnetic Particle Inspection Report	
Customer: <u>Central Michigan University</u>	Part Name: <u>Axe Heads/Handles</u>
Control No.: <u>n/a</u>	Material: <u>ASTM A958 SC 4340</u>
Part No.: <u>n/a</u>	Heat No.: <u>260014</u>
P.O. No.: <u>n/a</u>	
Inspection Specifications	
Procedure: <u>ASTM E709</u>	Areas Inspected:
Acceptance: <u>ASTM E125 Level I for cracks level III for</u> Criteria: <u>inclusions</u>	<u>100% Accessible Areas</u>
Magnetic Particle Test Set-Up	
Machine: <u>Magnaflex</u>	Leg/Prod Spacing: <u>4"-6"</u>
Model No.: <u>Y-2</u>	Particle Type: <u>Magnavis #8A Red</u>
Serial No.: <u>N8758</u>	Current: <u>AC current</u>
Cal. Date: <u>1-27-2026</u>	Field Dir.: <u>Longitudinal</u>
Light: <u>White light</u>	Surface Condition: <u>Mechanically ground</u>
Light Meter: _____	Media App.: <u>Manual</u>
Demag.: _____	Mag. Process: <u>Continuous</u>
	Means: <u>Yoke</u>
Notes: <u>Inspection Report for 6 Axe Heads and 2 Handles.</u>	
<u>Inspection Date:</u> <u>3-11-2026</u> <u>Status of Part:</u> Pass	Upon passing, the above part has been inspected and certified to meet the criteria specified as: ASTM E709 ASTM E125 Level I for cracks level III for inclusions
Signature:  Jason J. Holman VP/QA Manager NDT Level III	DOC-WI-05 rev 0, issued 7/00

Figure F4 – Magnetic Particle Inspection Report

Appendix G – Final Axe Images



Figure G1 – Final Axe Weight at 1.482 kg



Figure G2 – Final Axe