SFSA Cast In Steel 2026

Horseman's Axe

Technical Report

California State Polytechnic University, Pomona

Team: License to Steel

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1.0 Introduction

1.1 Executive Summary

SFSA has created this competition to encourage students to learn about making steel products using the casting process and applying the latest technology available [1]. For the 2026 season, the SFSA challenged university teams to design, cast, and test a fully functional horseman's axe. California State Polytechnic University, Pomona's team, License to Steel, embraced this challenge to engineer a weapon that bridges historical authenticity with modern manufacturing innovation.

Our axe drew heavily on documented historical artifacts, primarily the 1475 German horseman's axe and the 1530 Italian horseman's axe of Cardinal Ippolito de' Medici, both housed at the Metropolitan Museum of Art. We preserved the essential functional elements of the period, specifically an agile and lightweight profile paired with a rear spike capable of piercing armor. To reflect the German armory tradition where these weapons were actively deployed, we incorporated a pommel inspired by the Habsburg coat of arms.

Investment casting was selected as our primary manufacturing method to capture intricate surface details directly in the mold, significantly reducing the need for post-process machining. The single-piece axe head was cast from 4140 chromium-molybdenum steel. For the shaft, we cast A356 aluminum, integrating complex Roman pillar motifs and German-inspired spiral geometry. To reduce weight without compromising structural integrity, we developed a unique hollow shaft by 3D printing patterns with internal cavities and through-wall openings. During shell building, these cavities were filled with ceramic slurry to form an internal core, while the through-wall openings served as core supports to keep the core in place throughout the casting process. In the final product, both cavities and through-wall openings also serve as weight-reduction features. Skeletonizing the axe blade further optimized the weapon's strength-to-weight ratio. Throughout the development phase, Finite Element Analysis (FEA) and SolidCast solidification simulations informed our design optimization choices. These tools directly led to gating placement and geometry adjustments, allowing us to address areas prone to high-stress concentrations and preemptively reduce porosity.

The final prototype underwent rigorous measurement to verify strict adherence to the SFSA Cast in Steel competition constraints. The final specifications are detailed below:

Parameter	Requirement	Actual Result	Status
Overall Length	≤ 800 mm (31.5 in.)	**612 mm (24.1 in.)**	***Pass***
Total Weight	≤ 1.5 kg (3.3 lbs.)	**1.27 kg (2.7 lbs.)**	***Pass***
Axe Head Material	Cast Steel	**AISI 4140**	***Pass***
Shaft Material	No restriction	**A356 Aluminum**	***Pass***
Grip Material	No restriction	**SirayaTech Foaming TPU (3D Printed)**	***Pass***

1.2 Historical Detail of the Horseman’s Axe

In the summer of 1314, Robert the Bruce was not supposed to win. His army was outnumbered, outfitted with inferior equipment, and facing the full weight of English heavy cavalry on the fields of Bannockburn. When the English knight Henry de Bohun spotted the Scottish King mounted on a small, unarmored pony, he saw an easy kill. De Bohun lowered his lance, spurred his warhorse into a full charge, and closed the distance. Bruce did not run. He did not draw a sword. He waited, sidestepped the lance at the last possible moment, and brought his horseman's axe down with a force so hard it split de Bohun's helmet and skull. When his commanders scolded him afterward for risking his life, Bruce's only complaint was that he had broken his favorite axe.

The horseman's axe was a weapon born out of necessity in the late medieval period. It represented a direct and lethal response to the rise of full plate armor on the battlefields of the 14th and 15th centuries [2]. By the early 1400s, advances in metallurgy produced suits of armor that made steel swords glance off a knight's plate. Knights required a new class of weapon that could concentrate the massive kinetic energy of a mounted charge into a curved blade. It needed to focus force at the point of impact, making it capable of denting, piercing, or penetrating the thickest plate armor of that era [4]. The horseman's axe was that answer.

From the early 1300s through the 1500s, the horseman's axe saw sustained use among heavily armored equestrian combatants across Europe. It was not a weapon confined to a single battle or army. Kings carried them. The weapon endured for two centuries because it solved a problem no sword could: defeating the full plate armor of the late Middle Ages. Our goal was to create a horseman's axe from scratch while incorporating authenticity and historical context, practicality, and aesthetics.

2.0 Axe Authenticity and Design Basis

2.1 Horseman's Axe Authenticity

To ensure historical accuracy, our team researched surviving examples in museum collections and academic sources. The primary design inspiration for our design came from a German horseman's axe dating to the late 15th century, a 1475 German axe, and the 1530 Italian horseman's axe of Cardinal Ippolito de' Medici held by the Metropolitan Museum of Art [6]. We selected these specimens because they were forged at the absolute peak of cavalry warfare, providing definitive examples of the weapon's essential functions. Blending these two artifacts allowed us to capture a highly distinct visual profile while honoring the distinct manufacturing of the horseman's axe.

2.2 Design Basis

The historical specimens in Section 2.1 defined the proportions of our axe. The axe head's curved blade profile is smooth, and the top portion of the shaft's spiralized design draws directly from the German horseman's axe design. The shaft midsection takes a different direction, incorporating an intricate Roman pillar motif. We aimed to represent structural stability and the engineering authority of Roman culture, the foundation of modern German culture. Roman and Germanic military cultures were intertwined for centuries, from Caesar's earliest campaigns against the Germanic tribes [14] through the entire lifespan of the Holy Roman Empire, which styled itself as the direct successor to ancient Rome and governed the German-speaking lands where horseman's axes were forged and carried into battle.

During the Schmalkaldic War (1546–1547), the horseman's axe was a primary weapon used by forces of the Holy Roman Empire against their Protestant Schmalkaldic opponents [2]. To account for this historical detail, we decided to add decorative engravings to the pommel, inspired by the Habsburg Coat of Arms and the Habsburg double-headed eagle. These emblems trace their lineage directly to the Roman imperial eagle and became synonymous with Habsburg authority over the Holy Roman Empire. By choosing this symbol for our pommel, we connected the Roman pillar motif on the shaft to the German-derived heraldry on the pommel and a German-inspired shaft spiral, tying the entire axe together under a single design narrative. A visual comparison of our decorative elements against their historical sources is provided in Appendix D. While many surviving museum examples have modern wooden replacement shafts, historical sources confirm that all-metal shafts became increasingly common by the mid-15th century [2]. Our decision to use an aluminum shaft is consistent with this historical trajectory toward all-metal construction, while leveraging aluminum's favorable strength-to-weight ratio to keep the axe within competition weight limits.

3.0 Alloy Selection

3.1 Steel Alloy Selection

The performance of the horseman's axe is determined by the materials from which it is made. After evaluating several candidate alloys, our team selected AISI 4140 chromium-molybdenum low-alloy steel for the axe head.

Plain carbon steels such as AISI 1045 were evaluated but rejected due to insufficient hardenability. Lacking secondary alloying elements, these steels cannot achieve consistent martensitic transformation across the varying thicknesses of the axe head. Stainless steels were similarly dismissed. The elevated chromium content required to prevent oxidation severely reduces impact toughness at the hardness levels necessary for a functional cutting edge. At the same time, the corrosion resistance itself offers zero mechanical benefit for this specific application. Finally, while tool steels provide superior edge retention, their heavily alloyed compositions create severe castability issues. During solidification, these alloys suffer extensive carbide segregation. Because investment casting produces a near-net shape, the metal never receives the subsequent mechanical forging required to break up those brittle carbide networks, making tool steel entirely unsuitable for this manufacturing strategy.

AISI 4140 steel delivered the exact balance of deep hardenability, impact toughness, and material availability required for our manufacturing parameters. The specific chromium content of 0.80 to 1.10 percent, paired with a molybdenum concentration of 0.15 to 0.25 percent, allows the alloy to achieve high hardness during quenching while preserving a tough internal structure highly resistant to shock after tempering. Furthermore, the 0.38 to 0.43 percent carbon concentration provides the precise carbon matrix required to form a hard, durable cutting edge. This alloy is widely used in modern axe manufacturing and in heavy industrial applications that demand surface hardness combined with core toughness, including gears, drive shafts, and tooling. For a kinetic impact weapon, this mechanical equilibrium is mandatory. The primary blade and the rear spike must absorb the massive kinetic energy of striking an armored target without fracturing, while the cutting edge remains sharp and resists structural deformation. The consistent hardening behavior of AISI 4140 ensures these mechanical properties are reliably maintained across the varying cross-sectional thicknesses of our cast geometry [9,10].

3.2 Aluminum Alloy Selection

For the shaft and handle assembly, our team selected A356 aluminum, a silicon and magnesium casting alloy featuring approximately 7.0 percent silicon and 0.25 to 0.45 percent magnesium. Three specific engineering requirements drove this selection.

The first requirement was weight reduction. With a density of 2.68 grams per cubic centimeter, roughly one third the density of steel, A356 allowed us to design a robust full metal shaft while minimizing overall mass. This low density specifically shifts the center of gravity forward toward the steel head, optimizing the mass distribution to maximize the kinetic energy and striking force of the weapon. The second requirement was optimal castability. Our shaft geometry is highly complex, requiring good fluidity for a successful pour. The high silicon content of A356 provides the fluidity required to fill these intricate mold cavities without misruns. The final requirement was structural integrity under impact. Because handle fractures represent a primary failure mode in axe construction, we prioritized an alloy that can absorb repeated shock loading without propagating cracks. A356 offers excellent toughness alongside strong resistance to corrosion, and it responds exceptionally well to heat treatment. To achieve the maximum mechanical potential of the material, the shaft underwent a complete heat-treatment and quenching, followed by artificial aging to reach the T6 temper. This specific processing significantly improves yield strength, tensile strength, and overall hardness compared to the raw cast condition by approximately 40%. By selecting A356, we successfully modernized the historical full-metal shaft with a material perfectly optimized for investment casting. A comprehensive table detailing all alloy properties and our specific heat treatment parameters is located in Appendix B, Figure 3.

4.0 Design and Manufacturing Process

4.1 Design

The manufacturing process began with a historically driven design phase. Initial concept sketches were based on the c. 1475 German axe and informed by examples from competition shows such as Forged in Fire (Appendix F, Figure 1). These concepts were translated into a three-dimensional CAD model in Autodesk Fusion 360, enabling precise control over geometry, volume, and final weight. (Appendix D)

Our original concept called for a spiral pattern running along an oval-profile shaft. The oval cross-section was intended to concentrate material along the axis of highest bending stress while reducing weight elsewhere, similar to how an I-beam distributes material for maximum stiffness with minimum mass. When we modeled the spiral geometry in CAD, we discovered that it appeared uneven on the oval cross-section and introduced significant weak points in the geometry. After deliberation, the team changed the shaft to a circular profile. This preserved the spiral aesthetic while producing a much cleaner design that also aligned more closely with the historical record [4].

To ensure that our axe's weight was directed toward the blade, we checked the center of mass. We found it to be 10.52 inches forward of the grip along the longitudinal axis, as shown in our CAD Drawing, confirming the head-biased mass distribution needed for striking performance (Appendix F, Figure 3). One of the most complex design challenges was hollowing the shaft. With a hollow section 20 inches long, we needed the ceramic core inside the mold to maintain its exact position throughout shell building, pattern burnout, and pouring. This is a similar core-stability issue that aerospace foundries face when investment-casting hollow turbine blades, but at a much larger scale. After burnout, the wax is gone, and nothing is physically holding the ceramic core in place. Any shift or fracture of the core would ruin the wall thickness and geometry of the finished casting. Our solution was to design support features along the entire length of the core that would bridge between the core and the outer shell, keeping it locked in place throughout the process. This meant the cast shaft would have holes at the locations of the supports. This created two design challenges: maintaining structural integrity in a load-bearing shaft with perforations along its length, and integrating those holes into the visual design so they reinforced the aesthetic rather than interrupting it. After weeks of iteration, we arrived at a solution that supported the core reliably while maintaining the elegance of the overall design.

4.2 Simulation

Finite Element Analysis was used to validate the design before committing to casting. FEA also revealed a critical stress concentration at the corners of our skeletonized design near the blade, where the fillets were insufficient for a worst-case load of 10,000 N (approximately 2,248 lbf). We increased the corner fillet radius from 0.09 to 0.15 inches, which lowered the peak stress and reduced the probability of fracture in simulation (Appendix F, Figure 4).

SolidCast was used to analyze solidification behavior and predict shrinkage zones. The results directly drove our gating design. We identified shrinkage in our first axe-head gating iteration and corrected it by adding a second gate in the affected area. For the shaft, small shrinkage points appeared throughout the bottom of the spiral. After consulting with our industry partner, we raised the pouring cup height, transferring all shrinkage into the runner system. Because the runner system is cut away from the finished casting after solidification, this approach ensured that all shrinkage porosity would only exist in the runners. Gates were positioned on surfaces designated for post-processing so that gate removal would not compromise aesthetic or structural features (Appendix F, Figures 8-11).

4.3 Physical Prototyping

A key part of our prototyping was the use of 3D-printed replicas of the axe head and shaft. Using a Bambu Lab H2D, we were able to physically see what our design would look like in real life. We focused on making the handle portion feel perfect in the hand. The foaming TPU material we used allowed us to adjust the part's softness to ensure a perfect hand feel after multiple attempts. We also gathered feedback from engineering students and faculty to evaluate whether our axe was sufficiently ergonomic for the intended application in this Cast in Steel project.

4.4 Casting Methodology

The selection of a casting process was a fundamental decision that directly influenced the project's ability to achieve both historical authenticity, structural integrity, and precise physical details. After evaluating available methods such as sand casting, die casting, and investment casting (also known as the lost-wax process). Among all casting methodologies, our team agreed that investment casting was the most optimal approach for our design. Our decision was mainly based on its renowned ability to produce parts with exceptional dimensional accuracy, intricate surface detail, and a superior as-cast surface finish [15]. This was critical for our project because we wanted to replicate fine historical details, such as the decorative engravings and spiral geometry, directly into the casting itself rather than machining them after casting [1] (Appendix G). Achieving these details as-cast added significant value by minimizing secondary operations and yielding a more authentic final product.

4.5 Execution of the Casting Process

The casting was done in partnership with our industry sponsor, Miller Castings. We planned for two axe heads, two shafts, and four pommels to provide backup components for both final assembly and performance testing. Master patterns of the axe head and shaft, including integrated gating and riser systems, were produced using high-resolution fused filament fabrication (FFF) 3D printing. Because metal contracts during solidification, we used tolerance based on the SFSA Supplement 3 dimensional capabilities guidelines for steel castings. The shrink factor for the AISI 4140 steel axe head was approximately 1.020 to 1.025, while the A356 aluminum shaft used a shrink factor of approximately 1.010 to 1.015 [17]. These allowances were built directly into our CAD models before printing, ensuring the final casting dimensions matched our design targets. From the master patterns, plaster molds were made from Hydrostone. Molten sprue wax was hand-poured into the stone dies to produce the runners and gates. These wax components were attached to our 3D printed patterns and assembled onto a central wax sprue to form a tree. The tree was repeatedly dipped in ceramic slurry and coated with fine ceramic stucco, with each layer dried before the next. A total of 12 layers were applied, consisting of primer coats, backup coats including wire reinforcement, and final seal coats, until a self-supporting shell of approximately 3/8" thickness encased the entire assembly.

The completed shells were placed in a high-temperature furnace at 1600°F to burn out the wax and 3D printed patterns, leaving a hollow mold cavity. This firing also cured the ceramic shell to withstand the thermal shock of receiving molten metal. For the AISI 4140 axe head, the steel was melted in our industry partner's induction furnace. Once the melt reached a pouring temperature of 2900°F and the chemistry was verified, it was poured into the preheated ceramic mold at 1800°F. A layer of hot topping sand is added over the molten metal, then proprietary material is added in foil. The entire mold is then covered in an inert environment under a steel drum during cooling. A layer of hot topping compound was added over the molten metal, followed by a proprietary material applied in foil. The entire mold was then covered with a steel drum to maintain an inert environment during cooling. Based on our team's previous casting experience, this drum method significantly improves surface finish by preventing the oxidation-related pitting and surface irregularities that would otherwise develop during solidification. The A356 aluminum shaft was poured separately at 1200°F into a mold preheated to 900°F, following the same procedures as for the AISI 4140 axe head, except for an aluminum degassing operation performed prior to pouring. After solidification and cooling, the ceramic shells were broken using mechanical vibration. The castings were cut from the gating system, gate stubs were ground down, and the raw castings proceeded to heat treatment and finishing.

5.0 Quality Assurance and Integrity Verification

5.1 Non-Destructive Testing (NDT) Protocol

To ensure the structural integrity of our final product, a rigorous quality assurance protocol of non-destructive testing (NDT) was implemented. This process verifies that the casting is free from critical defects internally and externally that could compromise its performance under impact loading.

Liquid Penetrant Inspection (LPI): LPI was the primary method used to identify surface and near-surface defects on our axe head and aluminum shaft. Minor surface defects were found on the corner of our skeletonized design near the back spike, the tip of our back spike, and the direct center of the blade. As for our aluminum shaft, we found various defects on the very top of the shaft, the top of our Roman pillar, and a couple on the handles. Due to these findings, our Industry Partner, Miller Castings, repaired the axe head and shaft through a repair cycle consisting of cutting out the defective material, verifying full defect removal, and welding. All repairs were performed before final heat treating to provide uniform material properties throughout the repaired areas [12].

Radiographic Testing (RT): RT was used to detect subsurface defects, such as internal porosity, that could not be identified solely through surface inspection methods. X-ray examination was performed on both our AISI 4140 axe head and our A356 aluminum shaft. After careful review of the radiographs by our industry partner and the team, we determined that no internal post-processing beyond the standardized heat treatment procedures would be required. However, minimal subsurface defects were found in our shaft (Appendix E, Figure 2).

Using NDT, we successfully mitigated internal and external defects, further improving and optimizing the performance, durability, and reliability of our horseman's axe.

6.0 Finishing and Axe Testing

6.1 Heat Treatment for Functional Performance

AISI 4140 Axe Head

The heat treatment of the AISI 4140 Axe Head was completed at Continental Heat Treating, Inc. It consisted of a five-stage process. First, normalizing was performed at 1650°F under vacuum. This step refines the coarse as-cast grain structure, relieves internal stresses from solidification, and produces a more homogeneous microstructure that responds predictably to subsequent hardening [9]. A preliminary temper at 1050°F followed normalization to further condition the microstructure before hardening. The axe head was then austenitized at 1550°F and held until the part reached uniform temperature, transforming the steel's crystal structure into austenite. The part was then quenched in oil, rapidly cooling it to form martensite throughout the cross-section [11]. Tempering was performed at 950°F, followed by a re-temper at 1025°F. These tempering stages relieve the extreme internal stresses of the quenched martensite and develop the final balance of hardness and toughness. The higher tempering temperatures used here prioritize toughness and impact resistance over maximum hardness, which is the correct approach for a weapon that must absorb repeated high-energy strikes without fracturing [20]. The final measured hardness was 34–35 HRC across both tested specimens, within the target range of 33–38 HRC. This hardness level provides excellent impact toughness while maintaining a functional cutting edge, making it well-suited to the performance demands of a horseman's axe. (Appendix B, Figure 3)

A356 Aluminum Shaft

Our A356 aluminum shaft and pommel were heat-treated at Coast Heat Treating Co. The shaft underwent a T4 solution treatment, consisting of a three-stage ramp: 945°F for 2 hours, 975°F for 2 hours, and 1000°F for 10 hours, followed by a water quench at 100°F. Parts were then packed in dry ice to prevent natural aging and returned to Miller Castings for any straightening required before the final aging step. T6 artificial aging was then performed at 310°F for at least 5 hours. The resulting hardness was 88.5-89.4 HRE, corresponding to the full T6 condition for A356 and providing significantly improved yield strength, tensile strength, and fatigue resistance compared to the as-cast state. (Appendix B, Figure 3)

6.2 Assembly

Final assembly was performed using a series of press-fit and pinned connections. The axe head was first pressed onto the aluminum shaft using a hydraulic press. A hole slightly undersized for a ¼" stainless steel pin was then drilled through both the axe head and shaft. The pin was driven into the hole using the same press, creating a tight interference fit that permanently secures the joint. The 3D printed foaming TPU grip was then slid onto the handle section of the shaft. Finally, the cast pommel was pressed into the open cavity at the base of the shaft, and a second stainless steel pin was drilled and pressed through the shaft and pommel to lock it in place. This pinned press-fit approach was chosen over adhesive-only methods to ensure that every joint can withstand the repeated shock loading of impact testing without loosening or separating. After assembling our horseman's axe, we decided to test the center of mass and compare it with our anticipated center of mass value of 10.52 inches, determined using our CAD Software. The center of mass point that was found on our assembled axe was 9.5 inches longitudinally.

6.3 Post Processing

The goal of this phase was to make our horseman's axe as aesthetically pleasing as possible. The operations conducted at our industry partner's foundry for our post-processing included welding, sandblasting, and grinding. The majority of our grinding was done on our pommel, since the features of our Habsburg Coat of Arms did not come out clean enough; our shaft and axe also required some further grinding to improve the surface finish. The other post-processing methods conducted by our team were to optimize the final surface finish through polishing. We used a drill polishing wheel for both our Steel Axe Head and Aluminum Shaft. While we consulted with industry experts on our sharpening process, we were advised to use V-Grind Sharpening to achieve the sharpness that tears through various metals, fabrics, and other materials required for performance testing. Due to our post-processing, our work culminated in the final result in Appendix H.

6.4 Performance Testing

For the performance testing portion of this project, we had a great time chopping and striking various fruits, wooden planks, plastic components, a bicycle tire, and a sheet of metal (Appendix I). Our team wanted to test a wide variety of materials to see whether our axe could truly cut through "flesh and bone." Fruits simulated weaker targets that a knight's steel armor would not protect. We then tested our axe with plastic components and a rubber tire with more structure to simulate a shield or other protective padding that a knight would use to protect their body in battle. Our final test was to see if our axe could truly penetrate through the armor of a knight. As a result, all tests went very well and we were able to penetrate about ⅛ of an inch into this sheet metal (Appendix I, Figure 3). Analysis of our performance testing provided important feedback. Specifically, we recognized the need to reduce the sharpness of the pick. This adjustment is necessary to prevent the bending observed when the component was tested against sheet metal

7.0 Conclusion

This project took everything our team had. Some setbacks cost us weeks, simulations that stalled at the worst possible time, design problems we did not see coming, and late nights spent grinding, planning, and grinding some more. Every member of Team License to Steel poured themselves into this axe, and the moment we finally held the finished product in our hands, every one of those hours was worth it. We set out to build something that had not been done before, a piece that combined real history with real engineering in a way that was entirely ours. This team made every decision in this report, from alloy selection to engraving motif to our hollow ceramic core,, debated by this team, and executed by this team. That process, more than any single result, is what made this project special. Win or lose, we are proud of what we accomplished together. We are Cal Poly Pomona, and we have a License to Steel.

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Appendix A: Project Design Targets

Table A1 summarizes the key design parameters for the horseman's axe, including competition compliance requirements and the justification for each target value.

Parameter	Design Target	Justification / Reference
Overall Length	612 mm (24.09 in.)	Within historical range for one- or two-handed horseback use. Complies with a competition limit of ≤ 800 mm.
Axe Head Length	230 mm (9.05 in.)	Proportioned for balance with the back-spike and overall head weight.
Total Weight	1.27 kg (2.80 lbs)	Sufficient momentum for effective strikes while remaining agile. Complies with ≤ 1.5 kg limit.
Key Features	Back-spike, spiral shaft, Roman pillar motif	Core functional and carrying features incorporated. Cultural motifs from the German armory tradition and Roman influence added for historical authenticity.

Appendix B: Alloy Properties and Heat Treatment Specifications

B1. AISI 4140 Steel Alloy Chemistry/Properties

Parameter	Specification Ranges	Our Specifications
Iron (Fe)	Balance	Balance
Chromium (Cr)	0.80–1.10%	1.07%
Manganese (Mn)	0.75–1.00%	0.87%
Silicon (Si)	0.20–0.80%	0.61%
Carbon (C)	0.35–0.45%	0.37%
Molybdenum (Mo)	0.15–0.25%	0.22%
Nickel (N)	<0.25%	0.06%
Copper (Cu)	<0.35%	0.06%
Phosphorus (P)	<0.04%	0.01%
Sulfur (S)	<0.04%	<0.01%
Final Hardness	33–38 HRC	34-35 HRC

B2. A356 Aluminum Alloy Chemistry/Properties

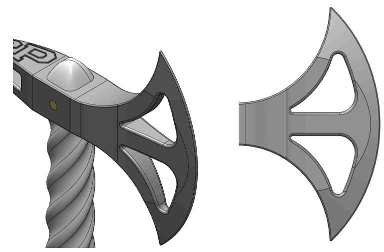
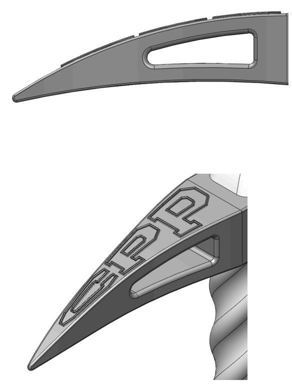
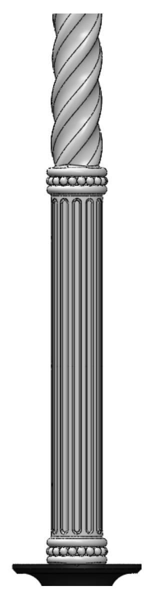
Parameter	Specification Ranges	Our Specifications
Aluminum (Al)	Balance	Balance
Silicon (Si)	6.5–7.5%	6.8%
Magnesium (Mg)	0.25–0.45%	0.41%
Ethoxy group (OET)	<0.15%	<0.15%
Titanium (Ti)	<0.20%	0.13%
Iron (Fe)	<0.20%	0.07%
Oxygen-Enriched (OE)	<0.05%	<0.05%
Copper (Cu)	<0.20%	<0.01%
Manganese (Mn)	<0.10%	<0.01%
Zinc (Zn)	<0.10%	<0.01%
Final Hardness	80–90 HRE	88.5–89.4 HRE

B3. Heat Treatment Summary

Facility	Component	Heat Treatment Process
Continental Heat Treating, Inc.	AISI 4140 Axe Head	1. Normalize at 1650°F (vacuum atmosphere) 2. Preliminary temper at 1050°F 3. Austenitize at 1550°F, oil quench 4. Temper at 950°F 5. Re-temper at 1025°F
Coast Heat Treating Co.	A356 Aluminum Shaft & Pommel	T4 Solution Treatment (3-stage ramp per AMS 2771 Rev. F): 1. 945°F for 2 hours 2. 975°F for 2 hours 3. 1000°F for 10 hours Water quench at 100°F; dry ice pack T6 Artificial Aging: 310°F for 5 hours minimum

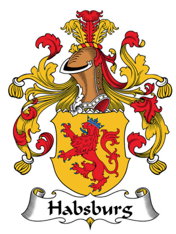
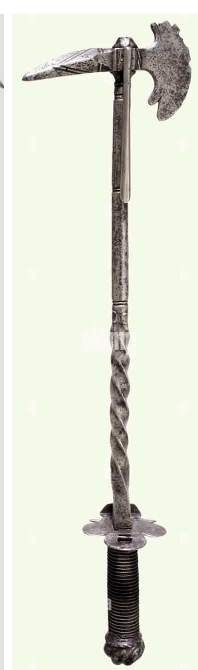
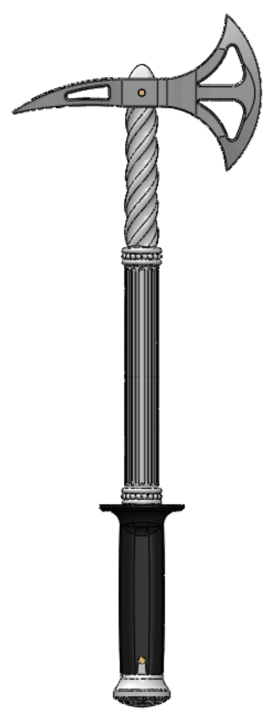
Appendix C: Horseman's Axe Features

The three main components of a historical horseman's axe are summarized below, with descriptions drawn from period sources and modern analysis.

Feature	Design	Our Axe
Blade	Typically a thin, convex blade designed for slicing through gaps in armor, mail, or leather, delivering deep, grievous wounds. Its lighter weight compared to a utility axe allowed for quicker manipulation and repeated strikes from horseback.	
Pick	The rear of the axe head was extended into a sharp, hardened spike or a concentrated hammer face. This element acted as a force multiplier, focusing the entire energy of a mounted blow onto a tiny contact point capable of puncturing or catastrophically deforming thick plate armor, something a broader cutting edge could not reliably achieve. Historical reproductions and modern analysis confirm that the back-spike was the primary armor-defeating feature of the weapon.	
Shaft	A horseman's axe shaft was typically between 2 to 3 feet in length, optimized for wielding with one or two hands from the saddle. Early shafts were hardwood reinforced with steel strips called langets, riveted to the head and extending down the shaft to prevent the handle from being severed in combat. By the mid-15th century, some specimens transitioned to all-metal shafts in cylindrical and polygonal forms, providing superior durability and eliminating the vulnerability of a wooden handle entirely. This historical precedent for all-metal construction directly informed our material choices for the shaft.	

Appendix D: Historical Compliance

A visual comparison of our decorative elements against their historical sources is provided below, demonstrating the direct lineage between period artifacts and our design choices.

Component	Historical Connection	Our Horseman's Axe
Pommel	 	 
Shaft	 	

Appendix E: NDT and Inspection Results

Non-destructive testing was performed on all critical castings to verify structural integrity prior to heat treatment and final assembly.

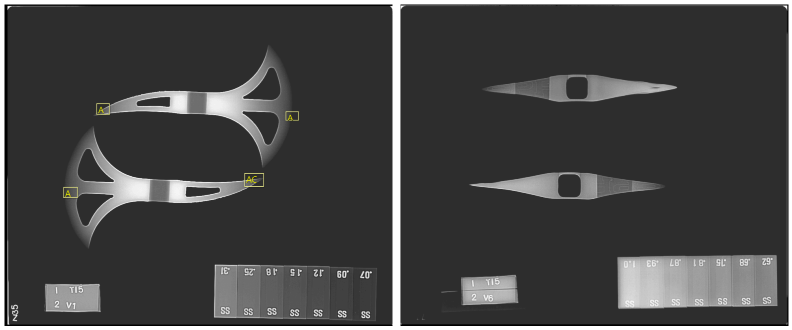


Figure E1: Steel Axe Head Radiographic Testing

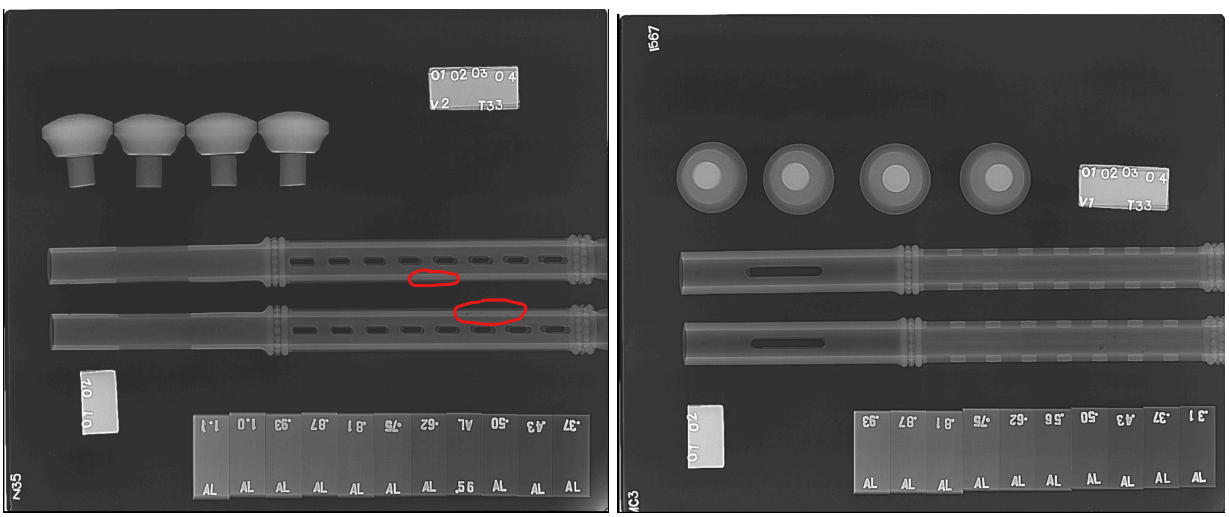


Figure E2: Aluminum Shaft Radiographic Testing

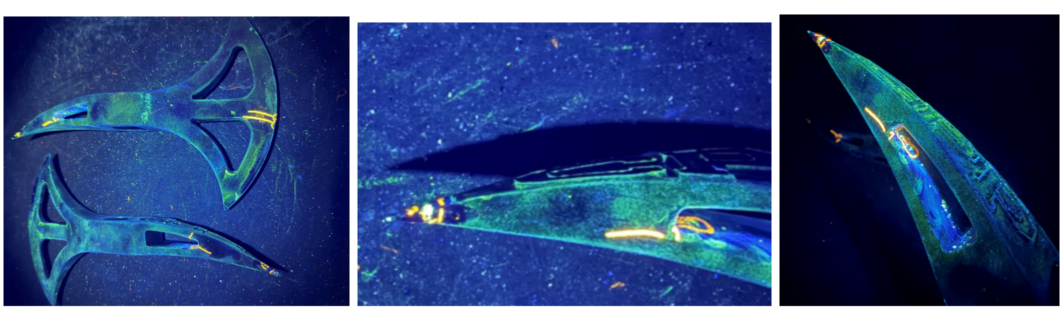


Figure E3: Steel Axe Head Liquid Penetrant Inspection

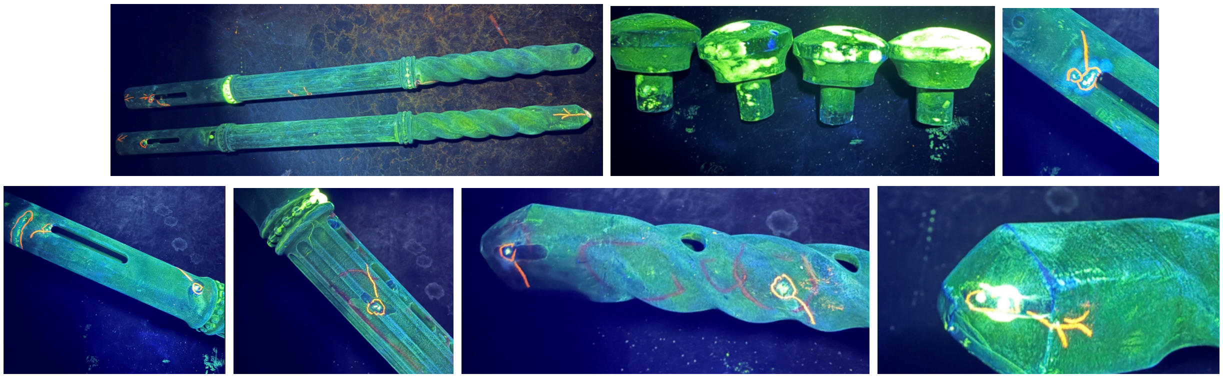


Figure E4: Aluminum Shaft Liquid Penetrant Inspection

Appendix F: Engineering Drawings and Simulation Results

This appendix presents the design references, CAD drawings, mass properties, and simulation results that drove our engineering decisions throughout the project.

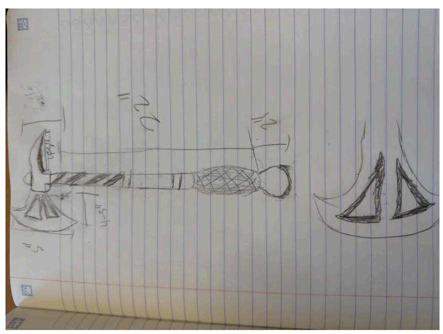


Figure F1: Axe Design Initial Sketch

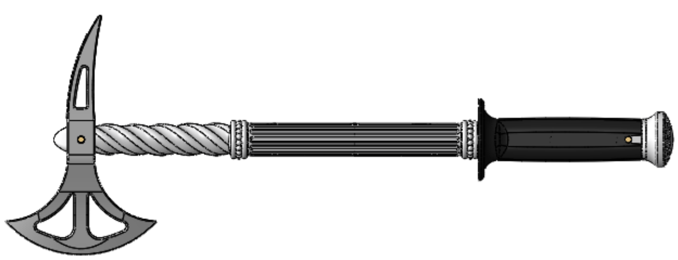


Figure F2: Final Assembly CAD Drawing

F4. Finite Element Analysis

FEA revealed a critical stress concentration at the corners of the skeletonized design near the blade, where the original fillets were insufficient for a worst-case load of 10,000 N. Increasing the corner fillet radius from 0.09 to 0.15 inches lowered the peak stress, reducing the probability of fracture in simulation.

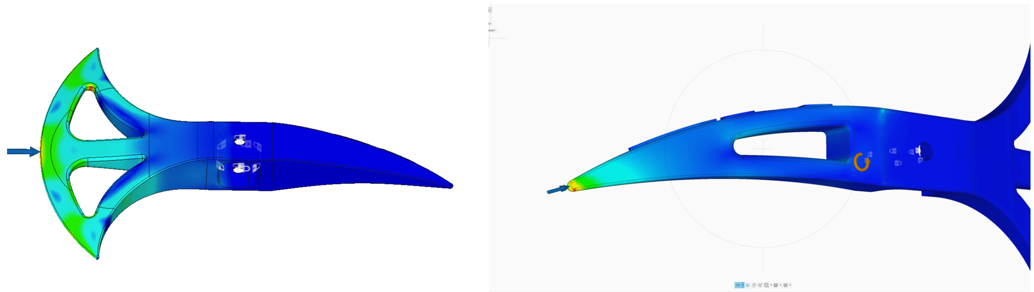


Figure F4: FEA Simulation Results (Before and After Fillet Optimization)

F5. SolidCast Solidification Simulation

SolidCast was used to analyze solidification behavior and predict shrinkage zones. The results directly drove gating design improvements for both the axe head and shaft.

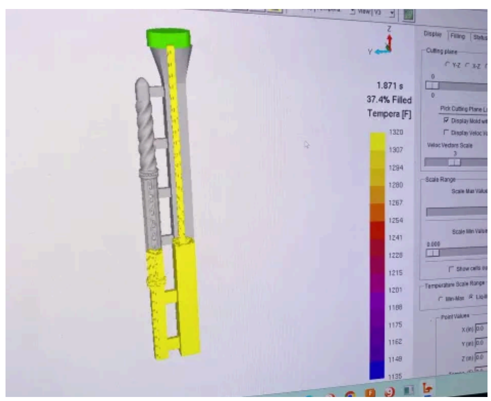


Figure F5: SolidCast Simulation

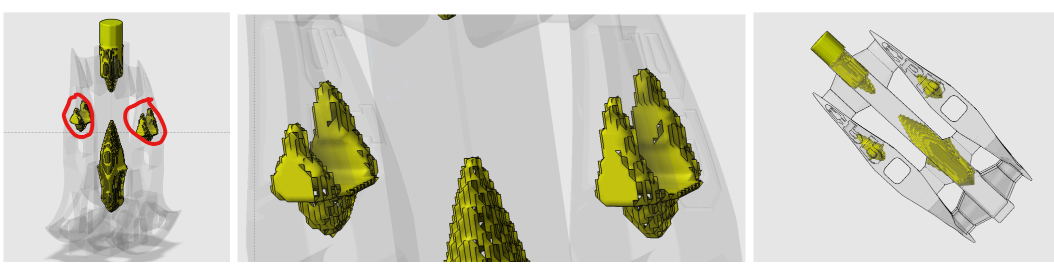


Figure F6: SolidCast Results, Axe Head (Before Iterations)

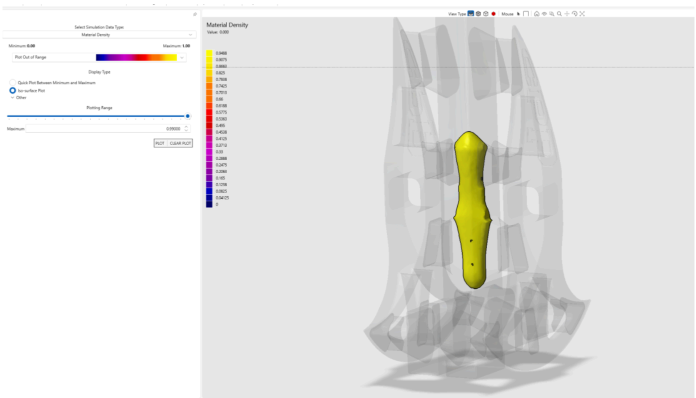


Figure F7: SolidCast Results, Axe Head (After Iterations)

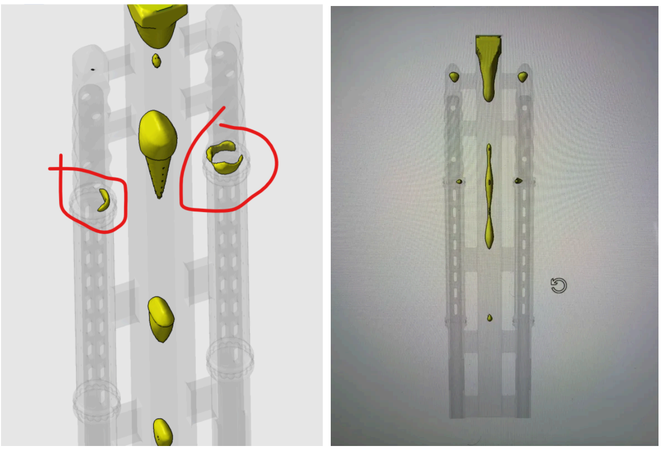


Figure F8: SolidCast Results, Axe Shaft (Before Iterations)

Figure F9: SolidCast Results, Axe Shaft (After Iterations)

Appendix G: Manufacturing Process Photographs

The following photographs document the full manufacturing sequence, from 3D printed master patterns through final post-processing.

Figure G1: 3D Printed Full-Scale Prototype Assembly

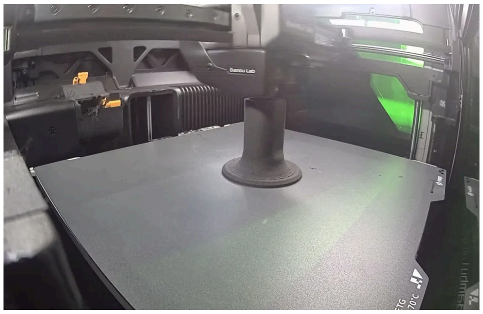


Figure G2: 3D Printed SirayaTech Foaming TPU

Figure G3: Wax Tree Assembly

Figure G4: Ceramic Shell Mold Before Pouring

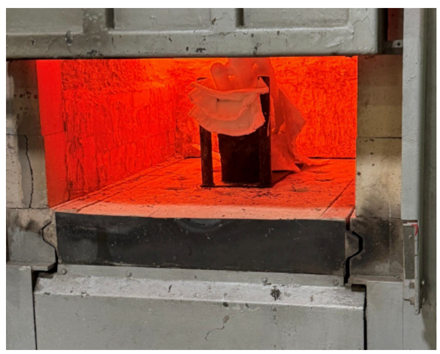


Figure G5: Pattern Burnout

Figure G6: AISI 4140 Steel Metal Pouring

Figure G7: A356 Aluminum Metal Pouring

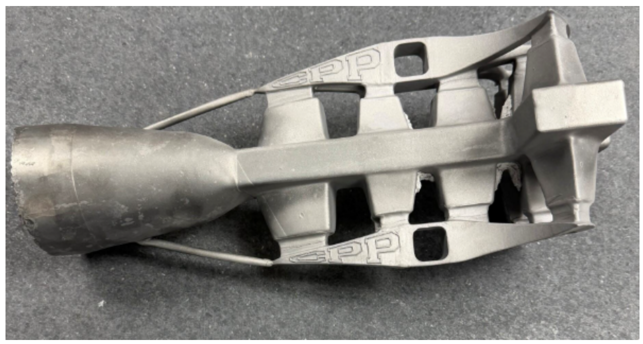


Figure G8: Raw Axe Head Casting After Knockout

Figure G9: Raw Shaft Casting After Knockout

Figure G10: Post Processing (Drilling, Grinding out Defects, Before Welding, After Welding)

Figure G11: Finished Axe Head After Heat Treatment

Figure G12: Finished Shaft After Heat Treatment

Appendix H: Final Finished Axe Photographs

The completed Horseman's Axe following all post-processing, polishing, and final assembly.

Figure H1: Completed Horseman's Axe, Full View

Figure H2: Detail of Engravings and Fine Details

Figure H3: Detail of Axe Head and Back-Spike

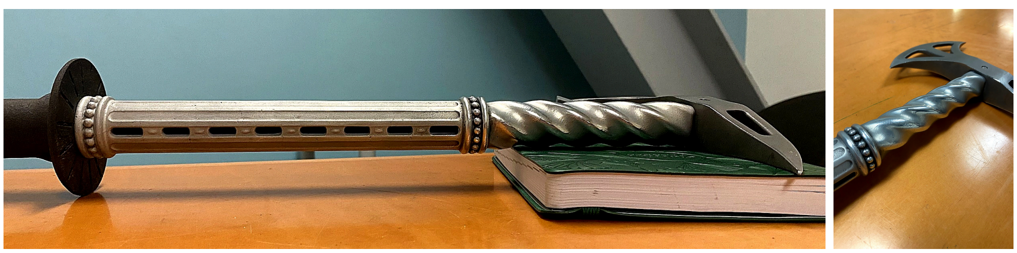


Figure H4: Detail of Shaft

Figure H5: Detail of TPU Grip and Pommel

Appendix I: Performance Testing Photographs

Performance testing was conducted on a range of target materials to evaluate the axe's cutting, piercing, and impact capabilities.

Figure I1: Performance Testing Team

Figure I2: Testing on Various Target Materials

Figure I3: Back-Spike Penetration on 14-Gauge Sheet Metal

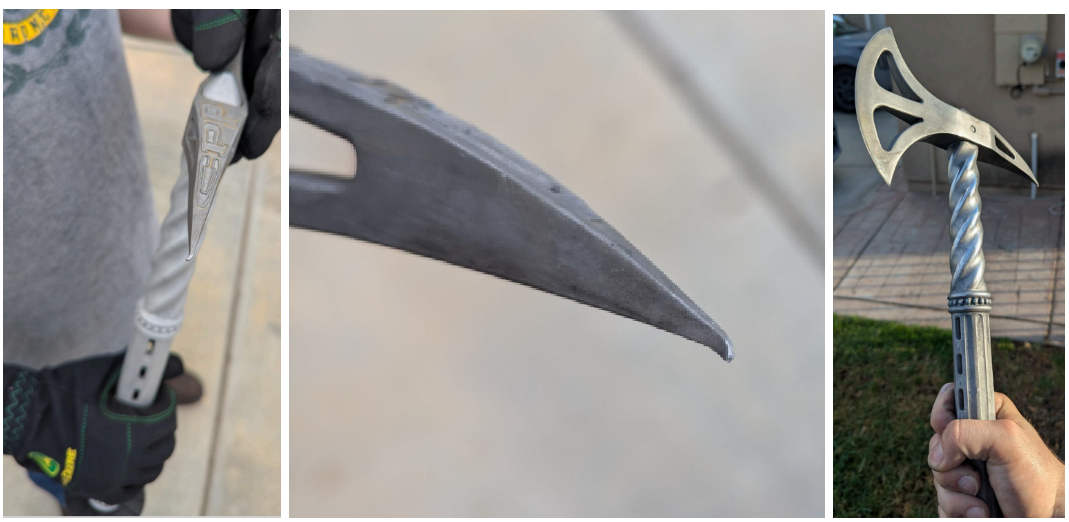


Figure I4: Post-Test Axe Condition

Appendix J: Cost Analysis

A complete breakdown of project costs is provided below. All foundry service costs were documented through Miller Castings' IFS Cloud ERP system. This analysis uses a 2 parts per mold setup. All costs are reported on a per-piece basis unless otherwise noted. These figures represent manufacturing cost to build each piece and do not reflect selling price, which would require additional markup to generate profit.

Item / Operation	Description	Cost/pc ($)	Notes
3D Printing (Patterns & Prototypes)	Master patterns for investment casting (FDM, Bambu Lab H2D)	$21.54	Team-supplied; 2 axe head + 2 shaft patterns in PLA (2 pieces)
3D Printing (TPU Grip)	SirayaTech Foaming TPU grip wrap	$48.48	Team-supplied; multiple iterations
Wax Material	Sprue wax for gating, hand poured into Hydrostone stone dies	$7.13	Per Miller Castings IFS Cloud ERP (1 mold)
Ceramic Shell Materials	Slurry, stucco, shell building overhead	$2.28	Costed by set burden overhead rate; slurry consumption cannot be directly tracked per mold
Steel Alloy (AISI 4140)	46 lbs raw material for axe head	$89.24	$1.94/lb; 43.35 lbs gating scrap
Aluminum (A356)	20 lbs raw material for shaft	$44.38	$2.37/lb; net of scrap credit
Foundry Services / Labor	Melting, pouring, cutoff, overhead	$355.09	Miller Castings; axe head + shaft combined (per mold)
Heat Treatment (4140)	Normalize, harden, temper per AMS 2759/1	$285.00	$285/pc ($570 total for 2 pcs); Continental Heat Treating, Inc.
Heat Treatment (A356)	T4 + T6 per AMS 2771 Rev. F	$200.00	$200/pc ($400 total for 2 pcs); Coast Heat Treating Co.
Powder Coat	Powder coating for all cast components	$16.67	$100 total for all parts (2 handles, 2 pommels, 2 heads)
Assembly	Labor to fit pin sizes, press pins, pin material	$35.00	Estimated: ~30 min shop labor + pin hardware
Finishing & Grinding	Surface prep, polishing, sharpening	$20.00	Consumables
Shipping	UPS to Crystal Lake, IL	$50.00	Packaging + insurance
Subtotal (Miller Castings)	**Combined foundry cost**	**$783.12**	**Documented in cost reports**
TOTAL PROJECT COST	**All operations (Miller + team costs)**	**$1,174.81**	

Note: *The cost data provided by Miller Castings is based on estimated labor times for each routing step, as no formal time study was completed. Estimated times typically trend low, which also causes applied overheads to be understated. Additionally, NDT repair work (cutting, verifying defect removal, and welding) is not included in the main part routing and would appear on the shop order cost as a variance. In a production environment, cost variance from repairs is undesirable as it directly reduces profit margin.*

Future Cost Reduction Strategies

To transition this design into a production environment, several strategies could be implemented to reduce per-piece cost:

First, heat treatment furnace loads should be maximized. Running only two parts in a furnace is not cost effective, and batching more parts per cycle would significantly reduce the per-piece heat treatment cost. Second, total alloy pour weight should be reduced by exploring how light the gating and runner system can be made while still yielding a sound part, since raw material and melt costs scale directly with pour weight. Third, repairs identified during penetrant inspection and radiographic testing can be reduced through tighter process control and improved gating design. All process parameters affect defect rates, including pouring temperature, ambient humidity, slurry pH, and shell building conditions. Fourth, a recycler should be identified to purchase the cut off gating alloy, converting what is currently waste material into a cost offset. Finally, formal time studies should be performed across all routing steps to identify methods that reduce labor time and bring estimated costs in line with actual production costs.

Acknowledgements

This project would not have been possible without the extraordinary support of Eric Cramer at Miller Castings. From the earliest stages of planning through the final cast, Eric gave our team far more of his time, expertise, and patience than we had any right to ask for. He treated a student competition project with the same professionalism and attention to detail that he brings to production aerospace castings, and that standard elevated everything we produced.