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

University of Wisconsin-Milwaukee – Milwaukee Molten


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# Executive Summary

This project involved designing, casting, and validating a functional late medieval horseman's axe for the 2026 SFSA Cast in Steel Competition. The team selected an all steel, one-piece casting design to highlight casting capability and reflect historical examples from the 15th–16th centuries. Investment casting was chosen for its precision and ability to reproduce complex geometry. S5 tool steel was selected for its high impact toughness and reliable heat treatment response. SolidWorks modeling, SolidCast simulations, and FEA guided the refinements to ensure castability, minimize shrinkage, and eliminate stress concentrations. The final design showed uniform stress distribution and strong structural performance. The axe was cast at MetalTek and heat-treated at ThermTech using austenitizing at 1650° F, oil quenching, and tempering at 700° F. Chemical analysis confirmed compliance with ASTM A681, and hardness testing verified a predominantly martensitic structure suitable for impact loading. Postprocessing included surface finishing, sharpening, welding of rondels, and a leather wrapped grip. Despite significant design pivots and time constraints, the team successfully produced a historically grounded, structurally robust, and competition ready axe that met all performance and manufacturing objectives.

# Introduction

The Steel Founders' Society of America SFSA has created this competition to encourage students to learn about making steel products using the casting process and applying the latest technology available. The challenge required students to design and cast a historically accurate horseman's axe and validate its functionality through testing.

## Objective of Project

Design, model, and validate a functional horseman's axe by selecting an appropriate steel alloy and heat treatment process while developing a geometry optimized for investment casting through SolidWorks modeling and SolidCast simulation.

## Historical Background

Between the 14th and 16th centuries, the horseman's axe emerged as a specialized weapon adapted to the demands of mounted combat. Its defining feature was a shaft around two feet in length, which allowed the rider to swing effectively from the saddle without compromising balance. Some versions featured hammers or spikes opposite the cutting edge, reflecting the need for rigid, armor-piercing capabilities. Regional developments such as the German and Italian all-steel horseman's axes (ca. 1470–1550) introduced metal shafts, hand guards, and leather-wrapped grips to enhance durability and handling under wet or combat conditions.

This guided our decision to pursue an all-steel design consistent with recorded late-medieval horseman's axes. The team used the Arms & Armor Horseman's Axe as a reference to develop the final geometry of the axe. This replica is based on an original horseman's axe dated to approximately 1540 and currently housed in the Royal Armory in Madrid, Spain. The reference design includes several features commonly found in late-medieval horseman's axes, such as a short overall length suitable for one-handed use from horseback, a curved cutting blade, and a rear spike designed for penetrating armor. Additionally, the original weapon incorporates an all-steel shaft with protective rondels and a leather-wrapped grip, features that improve handling and hand protection during combat. While the manufacturing method differs—modern casting rather than traditional forging—the geometry and functional characteristics of the final axe produced for this project remain consistent with documented historical designs.

# Material Selection

The material selection process for the axe was based on both performance and manufacturability. Available options were initially provided by MetalTek, which helped narrow the selection to steels that could be realistically cast for this project. To support the selection process, CES EduPack was used to compare candidate materials based on key mechanical and physical properties. In addition, discussions with ThermTech provided insight into the expected heat treatment response of each alloy, which was an important factor in achieving the desired properties.

The main alloys considered for this project were 1015 carbon steel, 4340 alloy steel, and S5 tool steel. These materials were selected because they are commonly used in applications requiring high strength and toughness, and they are compatible with heat treatment processes.

The material selected for the axe was S5 tool steel, a shock-resistant tool steel commonly used in applications such as chisels, jackhammer bits, and other impact tools. This steel is specifically designed to absorb repeated impact without cracking, making it well-suited for this application. Compared to 1015 and 4340, S5 offers superior impact toughness while still achieving the required hardness after heat treatment. Based on discussions with ThermTech, S5 was also determined to have a favorable heat treatment response for achieving the target hardness range of 48–52 HRC without significantly compromising toughness. This was a key factor in the final decision. Additionally, S5 aligns well with the functional requirements of the axe, as it provides a balance between hardness and toughness that is critical for impact-based applications.

# Design Phase

After analyzing numerous replicas and historical references, two main designs were identified, a steel head with a wooden handle or an all-steel axe. First, the team focused on designing just the axe head. Different concepts were explored, including variations in spike placement to improve strength and mass distribution. The team met with industry sponsors to review the designs. Based on their feedback, several modifications were made to improve castability and make the design more suitable for heat treatment. This included adjusting geometry and avoiding features that could create issues during casting.

In December, the team discussed the possibility of replacing the axe design with a fully cast, all-steel axe. This idea was explored to see if it was a viable option both from a design and manufacturing standpoint. The new design was shared with sponsors for feedback, and they confirmed that the design was feasible, but changes were needed to improve manufacturability, reduce stress concentrations, and improve metal flow during casting. These included adding fillets, reducing sharp corners, and smoothing transitions between sections (Table A4).

In January, the team gathered to decide which design to move forward with. A pros and cons chart and a decision matrix were created to compare the two options based on criteria such as manufacturability, performance, and overall risk. Based on this, the team decided to proceed with the all-steel axe design. In addition, choosing a fully cast design was deemed advantageous because it aligns with the spirit of the competition, which is to demonstrate casting capabilities. Casting the entire axe as one piece would show a higher level of design complexity.

The concept decision matrix was used to compare the two design concepts (Table A5) against each other. Based on the Concept Selection Matrix analysis, the All-Steel Axe is the preferred design concept. While the traditional head only design has a better cost, an all-steel concept marks most of the CTQs, especially structural integrity and casting feasibility.

## Finite Element Analysis

Finite Element Analysis (FEA) was performed on the final axe design and several earlier iterations. A dynamic load was applied to the blade perpendicular to the handle, with the handle fixed at the bottom of the haft, to identify stress concentrations and potential failure points under impact.

Early analyses showed a major stress riser at the handle–head interface, caused by a sharp geometric transition. This area was redesigned with smoother fillets, eliminating concentration. In the final model, both the tapered handle and revised haft-to-head transition showed no concerning stress levels, indicating that the updated geometry distributes impact forces effectively. The FEA image (Figure A4) shows that the stress concentration was focused on the top of the handle. For this reason, we removed the cast handle section and went to a simpler shaft. It also showed that there wasn't a stress concentration problem where the haft meets the head (Figure A3).

# Casting Method

Casting methods available in the Milwaukee area include sand casting, investment casting, and centrifugal casting. Sand casting was considered due to its low cost and flexibility; however, its relatively poor surface finish and lower dimensional accuracy make it less suitable for the complex geometry and thin sections of the design. Centrifugal casting was also reviewed but was deemed inappropriate due to its limitations to axisymmetric components. Investment casting was ultimately selected because it provides superior surface finish, high dimensional accuracy, and the ability to produce intricate geometries with minimal post-processing. Additionally, it is well-suited for steel alloys and allows for improved control over solidification, making it the most appropriate choice for ensuring both the structural integrity and quality of the final component.

# Simulation

With the final design consisting of a fully steel component, the development of an effective rigging system became essential. Using the gating wizard in SolidCast, regions requiring gating were identified based on predicted flow and feeding requirements. Based on these results, the final rigging design incorporated two gates: one located at the head and another at the end of the haft (Figure A1).

A primary concern for the team was achieving directional solidification, particularly due to the haft's geometry as a tapered solid section. Ensuring proper feeding in this region was critical to minimizing shrinkage defects. Following the filling simulations, several key parameters were analyzed to evaluate casting quality and solidification behavior:

- **Material Density:** This parameter was used to identify potential regions of macro-porosity. Areas of lower predicted density indicate insufficient feeding, which can lead to shrinkage cavities or void formation.
- **Solidification Time:** This metric provides insight into the sequence of solidification throughout the casting. By examining which regions solidify first, the team assessed whether directional solidification was achieved as intended.
- **Critical Fraction of Solid:** This represents the point at which the metal loses its ability to flow. Understanding this threshold helps identify areas where feeding becomes restricted, increasing the risk of shrinkage defects.

# Casting Parameters at MetalTek

**Temperatures**

Preheat Shell Temperature: 1800° F, Pouring Temperature: 2850° F

**Chemical Analysis**

*Table 1:* Spectrometer Results

| | C | Si | Mn | P | S | Cr | Ni | Mo | V | Cu | Fe |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Sample1 | 0.67 | 2.09 | 0.83 | 0.02 | 0.01 | 0.30 | 0.24 | 0.33 | 0.28 | 0.02 | 95.2 |
| Sample2 | 0.63 | 2.04 | 0.81 | 0.02 | 0.01 | 0.29 | 0.23 | 0.33 | 0.27 | 0.01 | 95.3 |
| Sample3 | 0.63 | 2.04 | 0.81 | 0.02 | 0.01 | 0.29 | 0.23 | 0.32 | 0.27 | 0.01 | 95.3 |
| **Average** | **0.64** | **2.06** | **0.82** | **0.02** | **0.01** | **0.29** | **0.23** | **0.33** | **0.27** | **0.01** | **95.3** |
| Min | 0.5 | 1.8 | 0.6 | - | - | 0.1 | 0.1 | 0.2 | 0.15 | - | - |
| Max | 0.65 | 2.15 | 0.9 | 0.03 | 0.03 | 0.3 | 0.3 | 0.4 | 0.3 | - | - |

# Metallurgy

Test coupons for tensile testing, hardness testing, and microstructural analysis. We'll be able to see similar chemistry, solidification, and heat treatment and be able to remove it without damaging the axe. These samples were prepared using ASTM standards.

# Heat Treatment

Heat treatment was implemented as a critical post-processing step to achieve the required mechanical properties, including increased hardness and strength while maintaining sufficient fracture toughness. The objective was to obtain a final hardness of approximately 48–52 HRC, providing the shock resistance necessary for repeated impact loading. Because the axe was designed as a fully cast steel component, careful heat treatment was essential to prevent cracking or distortion in both the blade and handle.

Key heat treatment parameters are summarized in (Table A6) and were used to guide the final heat treatment recipe. Additional considerations included hardenability, tempering response, and the potential for distortion during quenching. Standard heat treatment practices for S5 tool steel, along with guidance from ASTM A681 and industry data for shock-resistant tool steels, were used to establish appropriate temperature ranges and processing conditions.

Although these standards are primarily developed for wrought tool steels, they were used as a reference due to the strong influence of chemical composition on heat treatment response. Factors such as carbon content and key alloying elements enabled the standards to be refined through simulation and consultation with industry partners to develop a suitable heat treatment process for the cast axe.

### Heat Treatment Simulation

To better understand the heat treatment behavior of the axe, the team collaborated with DANTE Solutions to perform heat treatment simulations. The simulation evaluated heat transfer and phase transformations throughout the heat treatment cycle. The model included heating, transfer, immersion into the quenchant, and cooling stages, while accounting for fluid flow effects and minor variations in cooling between surfaces. Results showed that martensite formation began shortly after quenching, with slight differences in transformation timing across the geometry. By the end of the quench, most of the microstructure had transformed to martensite. This simulation provided additional confidence that the selected heat treatment parameters would produce the desired microstructure. Simulation outputs, temperature profiles, and phase transformation results are provided in Appendix – Figures A7-9.

### Final Heat Treatment

The team met with ThermTech to discuss the heat treatment of the axe and presented the design geometry, material selection, and other information gathered. ThermTech helped develop a practical heat treatment recipe that would safely achieve the desired hardness. Before heat treatment, the axe was straightened with an arbor press and copper hammer.

The final process included:

- Austenitizing: 1650° F for 2 hours.
- Quenching: parts were oil quenched at 140° F for 8 minutes. The quench tank agitators were set to 25% capacity.
- Tempering: 700° F for 3 hours

During the heat treatment process, the axes were hung by the head**.** Proper racking is important to minimize distortion during heating and quenching. The atmosphere inside the furnace was set to have a carbon potential of 0.48% ± 0.10%. This allows the parts to heat up and prevent decarburization during the austenitizing cycle. After heat treatment, the parts did not appear to have experienced noticeable distortion.

# Post-Processing and Finishing

Following heat treatment, the oxidation, scale, and any remaining debris from the casting and heat treatment processes were removed using an angle grinder, allowing a smooth surface while maintaining control over material removal. Then, the blade and the spike were ground and sharpened to achieve a sharp, but strong edge.

To improve the functionality and safety of the axe, rondels were fabricated from steel stock. The steel stock was cut into disks with a hole in the center of one of them using a saw and refined using a belt sander. The rondels were carefully welded to ensure minimal distortion of the handle using a copper-coated mild steel welding wire. After welding, the axe was cleaned again to remove any welding residue.

For the handle, the team decided to wrap it with tape then with leather. The leather wrap provides a more comfortable and secure grip as well as a level of vibration damping, which can help reduce hand shock during impact.

# Results & Analysis

## Non-Destructive Testing

Non-destructive testing of the casting was performed to evaluate internal integrity and identify potential defects (Figure A5). X-ray imaging reveals contrast differences that correspond to variations in material density. Lighter regions observed in the images indicate areas of relatively higher density, while darker regions may suggest localized shrinkage or voids. Image processing techniques, including the use of a FlashCast filter, were applied to enhance contrast and improve the visibility of subtle internal features.

The circular features visible in the radiographs correspond to thicker material sections associated with vent “pop-offs.” These vents are incorporated in SLA patterns (or thicker wax regions) to relieve internal pressure and facilitate airflow during the burnout process. These features were removed during post-processing and are not present in the final component.

Additionally, faint V-shaped indications observed along the shaft were identified as centerline micro shrinkage. While these features were visually enhanced through image filtering, they represent minor density variations and are not expected to negatively impact the mechanical performance of the casting. Such indications are common in metal manufacturing processes, particularly in long, straight, solid sections where achieving perfectly uniform solidification can be challenging. Overall, the NDT results indicate that while minor shrinkage features are present, they do not compromise the structural integrity or functionality of the final component.

## Hardness Testing

Hardness testing was conducted based on ASTM E18 standards to verify the effectiveness and uniformity of heat treatment. For testing, MetalTek provided a section of the runner from the axe mold, along with two cast test bars that were placed alongside the axe, one oriented parallel to the axe head and the other parallel to the end of the handle. These samples provided material that experienced similar chemistry, solidification conditions, and heat treatment as the axe, while allowing for destructive testing without damaging the final component.

Hardness measurements from the as-cast material showed significantly lower values (Table A3). After heat treatment, the samples experienced an increase in hardness (Table A2). The results confirmed the effectiveness of heat treatment and a successful martensitic structure. Similar values between surface and core indicate an effective heat treatment penetration.

It is also important to note that the runner section had a larger cross-section than the axe itself, 2 inches for the runner, and 1 inch for axe. Since the thicker runner section achieved uniform hardness through its full thickness, it can be concluded that the thinner axe geometry achieved similar heat treatment response.

Additionally, ThermTech performed hardness testing directly on the finished axes by polishing localized areas on the surface and using a handheld Rockwell hardness tester. Measurements taken on the axe fell within the range of 50–54 HRC.

Axe specifications:

| Length | Weight | Materials |
|---|---|---|
| 20.1875" ± 0.125 | 2.889 lb. | S5 tool steel, leather |

# Challenges

Time was the greatest challenge throughout the project. The initial plan, developed in September, focused on casting only the axe head with a wooden handle. This remained the working concept until December, when the team proposed switching to a fully cast, all-steel design. Although ultimately the better engineering choice, this late design change required the axe to be completely redeveloped—new CAD models, revised material selection, updated casting simulations, and a restructured project timeline. The new design also required approval from industry partners, further compressing the schedule. Due to these constraints, metallography and some planned testing had to be removed from the scope.

Several manufacturing challenges have also emerged. Machining the test samples proved difficult, and two molds broke during pouring, reducing the number of usable castings. With only two final castings available, destructive testing was limited. In hindsight, producing multiple molds and committing to a final design earlier would have reduced risk and provided backup castings for testing and validation.

# Conclusion

The team successfully designed, casted, and validated a functional all-steel horseman's axe for the 2026 SFSA Cast in Steel Competition. The final design was a one-piece casting made from

S5 tool steel, allowing the team to demonstrate advanced casting techniques while maintaining features of a historical accurate horseman's axe. Throughout the project, simulation tools were used to guide design decisions and reduce risk of failure, by refining geometry, improving metal flow, and reducing stress concentrations. This project allowed current students to become more knowledgeable about the metal casting process and build the resilience to overcome engineering challenges.

# Appendix A

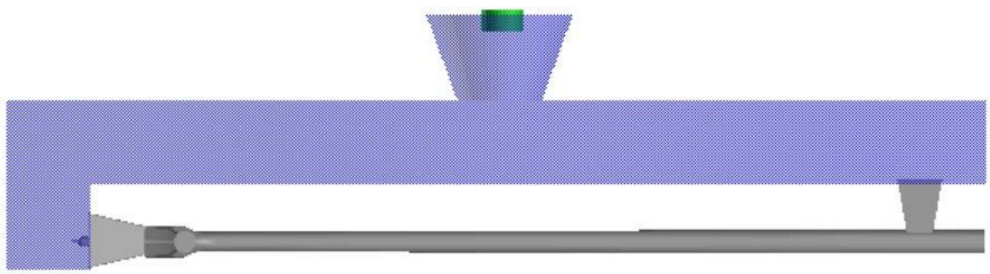


*Figure 1. Full rigging design of model*

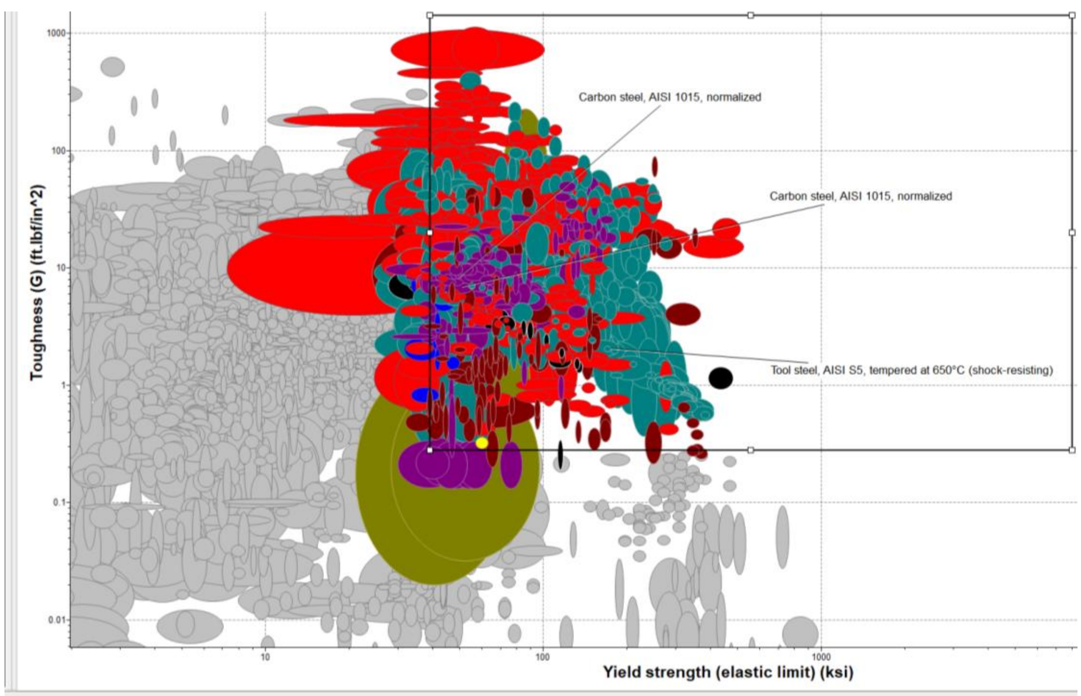



*Figure 2. Ansys EduPak*

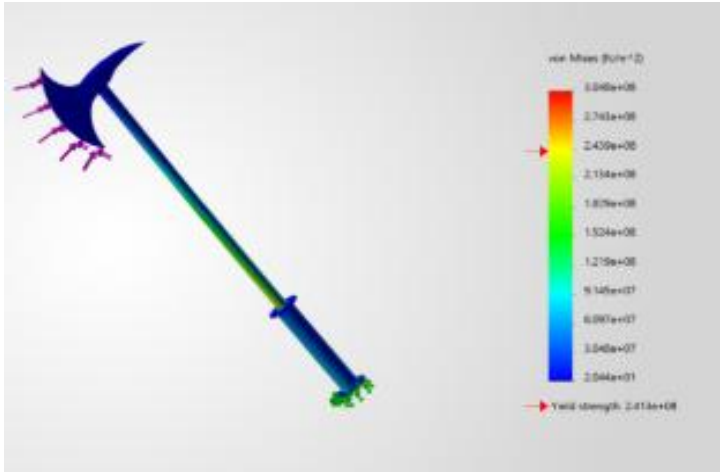


*Figure 3. Force load FEA*

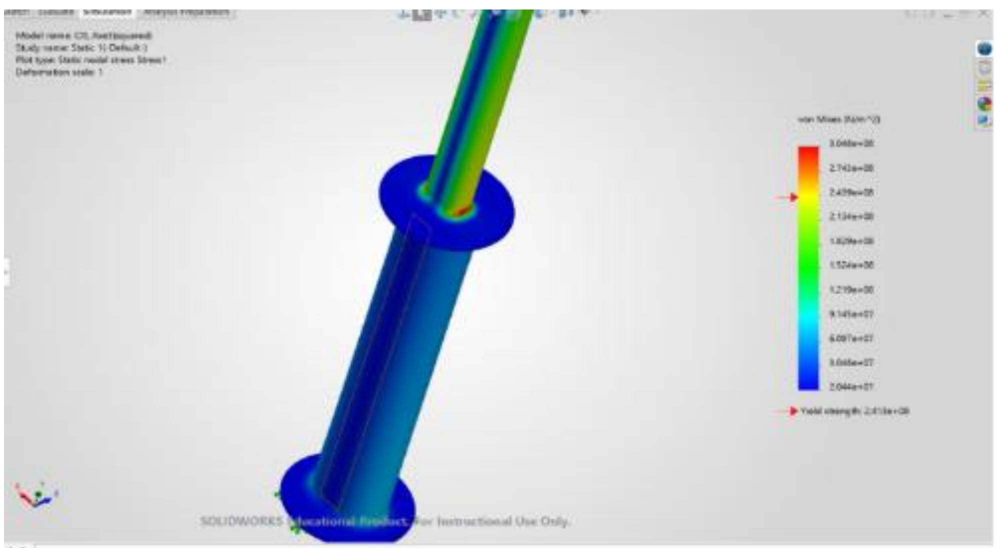


*Figure 4. Haft FEA*

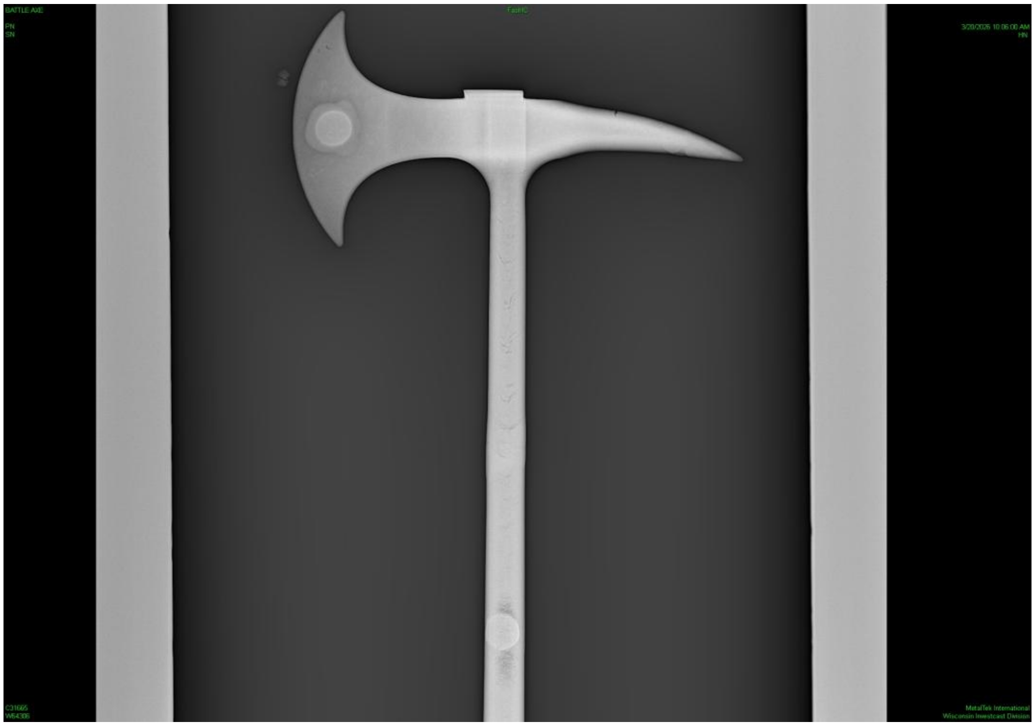



*Figure 5. NDT Results*

*Table 1: Hardness Results – Heat Treated*

| Hardness Runner (Heat Treated) | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Test | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | Ave |
| Surface HRC | 52.9 | 51.0 | 53.0 | 52.8 | 53.1 | 52.0 | 52.1 | 53.7 | 51.0 | 52.5 | 52.4 |
| Core HRC | 53.0 | 50.5 | 51.0 | 52.0 | 53.8 | 53.2 | 53.9 | 53.0 | 52.4 | 52.1 | 52.5 |

*Table 3. Hardness Results – As Cast*

| Hardness As-cast (handle) | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Test | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | Ave |
| Surface HRC | 36.4 | 36.9 | 36.2 | 37.2 | 36.7 | 35.6 | 35.9 | 36.0 | 35.7 | 35.5 | 36.2 |
| Core HRC | 33.0 | 35.3 | 35.3 | 34.7 | 32.2 | 36.8 | 34.9 | 37.8 | 35.8 | 35.8 | 35.2 |

*Table 2. SolidWorks Model Iterations*

| Version | Developments | CAD Models |
|---|---|---|

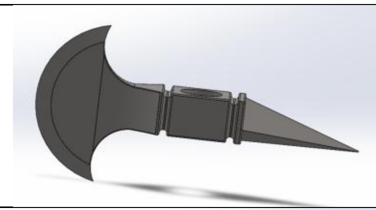
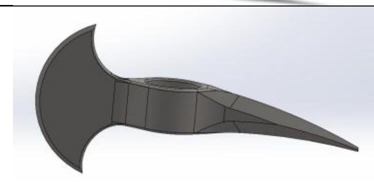
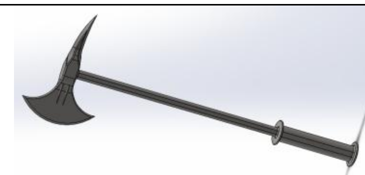
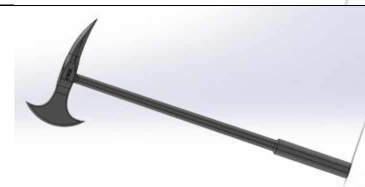
| | | |
|---|---|---|
| 1 | • First iteration of the horseman's axe. |  |
| 2 | • Removed sharp corners.<br>• Smoother transitions between the eye and blade/pick.<br>• Shallower edge geometry. |  |
| 3.1 | • Switched to full steel design.<br>• Added blade supports to maintain rigidity and lightness. |  |
| 3.2 | • Blade supports and rondels were removed for castability.<br>• UWM logo is added.<br>• Removed material from the blade and tapered the haft for weight reduction. |  |
| 3.3 | • Removed handle to be replaced by lighter material.<br>• Blade and pick thickness increased for ease of casting.<br>• Larger fillet between head and haft to reduce stress concentration. |  |

*Table 3. Decision Matric for Design*

| **Concept Selection Matrix<br>Cast in Steel (Axe)** | | **Option A** | **Option B** |
|---|---|---|---|
| | | **All Steel** | **Steel Head** |
| **Comparison Weight** | **Requirements** |  |  |
| 5 | Structural Performance & Durability | 2 | 2 |
| 5 | Weight | 2 | 1 |
| 5 | Assembly & Attachment Elimination | 2 | 2 |

| | | | |
|---|---|---|---|
| 1 | Budget | 0 | 2 |
| 2 | Printing Time | 0 | 2 |
| 2 | Aesthetic | 2 | 1 |
| 4 | Historical Background | 0 | 2 |
| 2 | Ergonomics & Handling | 2 | 1 |
| 1 | Post-Processing & Machining | 2 | 1 |
| 1 | Design Flexibility (features, carving...) | 2 | 1 |
| 5 | Casting Feasibility & Integrity | 2 | 1 |
| **Unweighted Score** | | 16 | 13 |
| **Weighted Score** | | 52 | 50 |

*Table 4. Heat Treatment Parameters and Importance*

| Parameter | Information | Why the Parameter Is Important |
|---|---|---|
| **Martensite Start Temperature (Ms)** | Approx. 525–610 °F (280–320 °C) | It defines when martensitic transformation begins during cooling. Helps select an appropriate quench medium and cooling rate to ensure sufficient martensite formation, which affects final hardness. |
| **Austenitizing Temperature** | Must exceed the $Ac_1$ temperature of ~1410 °F (766 °C); typical industrial range 1600–1700 °F (871–927 °C) for oil quenching | Proper austenitization ensures complete transformation of prior microstructure into austenite before quenching. Insufficient temperature can result in non-uniform hardness, while excessive temperature can promote grain growth and reduce impact toughness. |
| **Desired Final Hardness** | Target range 48–52 HRC | This hardness range provides a balance between wear resistance at the blade edge and fracture toughness under impact loading. |
| **Retained Austenite Content** | Typically 5–15% depending on quench severity and tempering temperature | Excess retained austenite can reduce effective hardness and dimensional stability. Controlled quenching and tempering minimize retained austenite while preserving toughness. |
| **Maximum Section Thickness** | Approximately 1 inch (25.4 mm) | Section thickness directly affects cooling rate during quenching. Thicker regions cool more slowly and may not fully transform to martensite if the heat |

| | | |
|---|---|---|
| | | treatment process is not properly designed. This consideration guided quench selection and soak time to achieve uniform properties throughout the axe. |

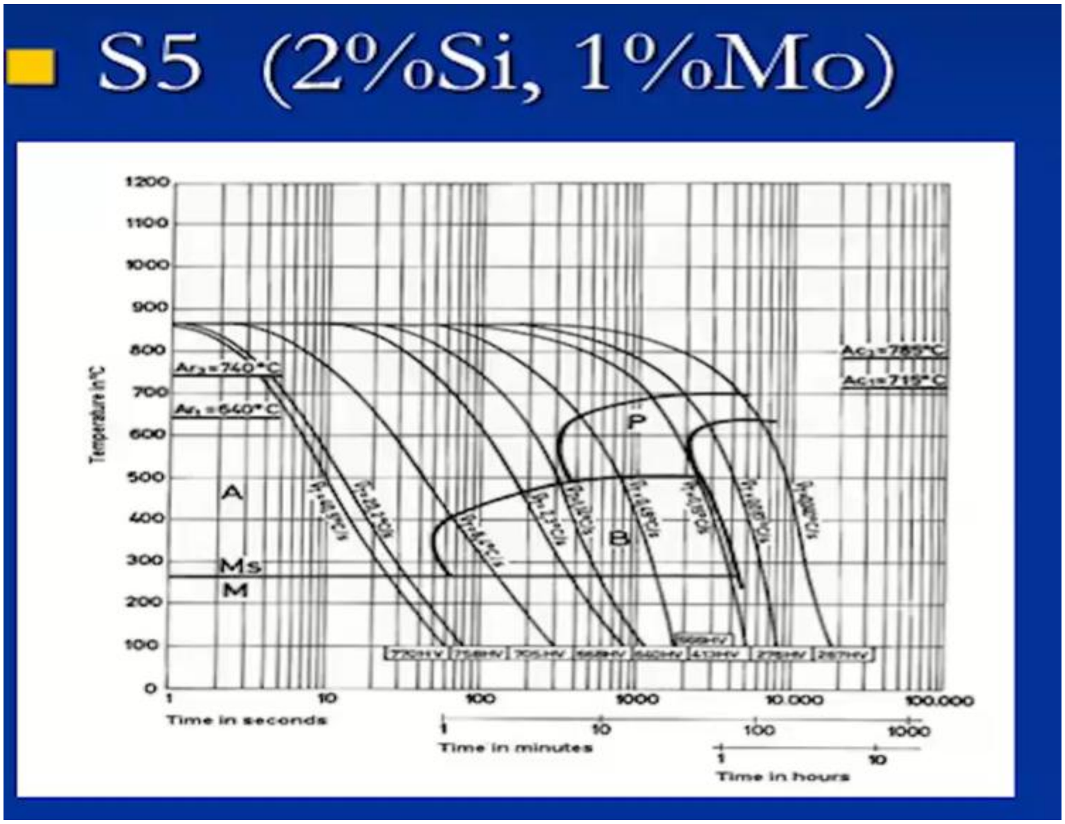



*Figure 6. S5 TTT Diagram - Literature*

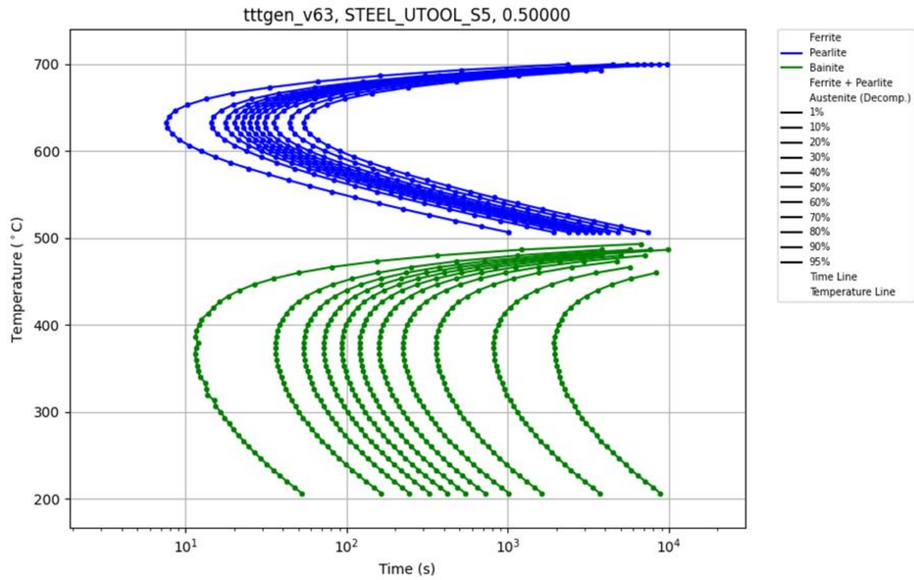



*Figure 7. Simulation TTT Diagram*

Parameters used for simulation:

Austenitizing: 950° C; Heating Rate: 5 °C/s; Soaking: 30 min; Cooling Rate: 10.0 °C/s;

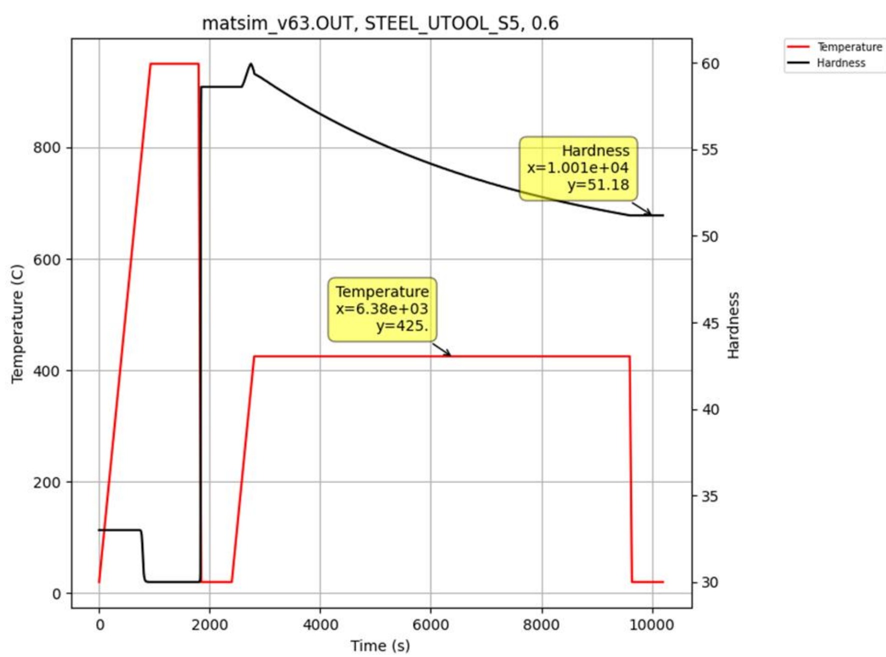



*Figure 8 - Temperature and Hardness Simulation*

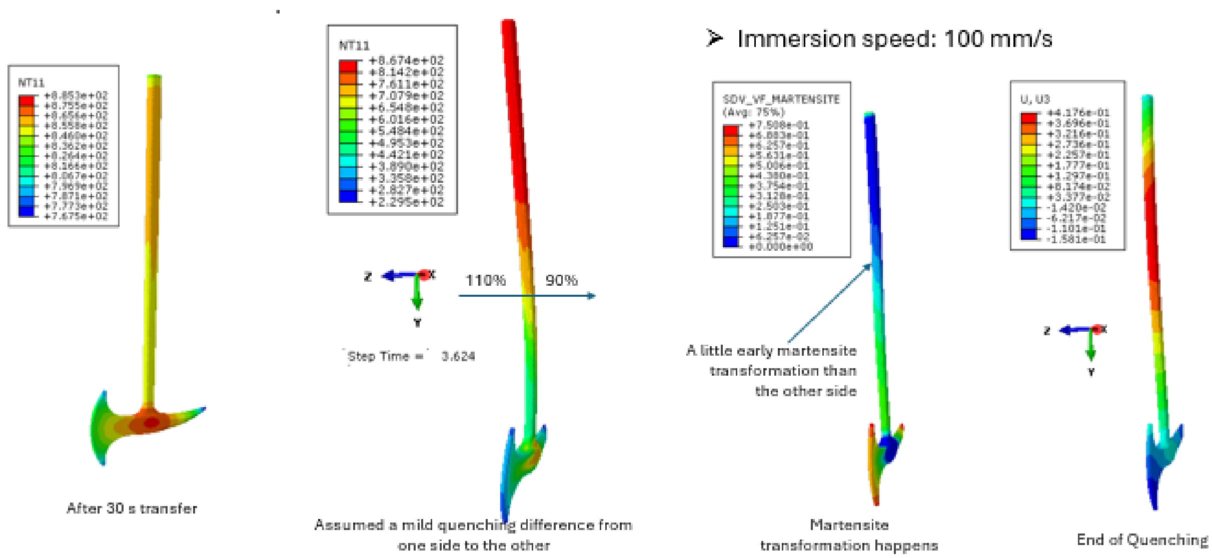



*Figure 9. Heat Treatment Model Process Steps*

# Acknowledgement

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Woodshop – Arthur Gibson