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

<u>Marauders of McNutt</u>
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1. Abstract

The Missouri S&T team, the *Marauders of McNutt*, created a horseman's axe boasting a curved blade with a top and back spike. The objective of this year's competition was to produce a lightweight, durable, and ergonomic axe capable of both cutting and thrusting applications. The manufacturing of this axe consisted of casting AISI 4340 steel into a binder jetting sand mold. The final design reflects both historical accuracy and modern manufacturing considerations. Final machining, heat treatment, and testing are applied to ensure the axe is up to the levels needed to withstand physical testing.

2. Introduction

The Steel Founders' Society of America (SFSA) has created this competition to encourage students to learn about what goes into making steel products using the casting process and applying modern technology to it. The SFSA Cast in Steel competition challenges students to design and manufacture historically accurate weapons using modern technology.

For the 2026 competition, the weapon selected is the horseman's axe. This is a historically lightweight and versatile weapon and tool used in combat. A traditional horseman's axe typically features a curved cutting edge and a rear spike. The curved blade allows for effective downward strikes while mounted, and the spike is designed for penetrating armor or delivering concentrated and accurate impacts.

The axe designed in this project maintains all the defining characteristics, including a curved edge and rear spike, ensuring historical authenticity while incorporating modern design and manufacturing processes. The team worked within competition constraints of a maximum weight of 3.3 pounds and a maximum length of 31.5 inches.

3. Design Considerations

Within the Missouri S&T foundry, we have the capability to create molds using various methods. The team initially decided on doing investment casting due to its high surface quality and fine detail. However, after significant shell cracking during the kiln burnout, the team transitioned to a binder jetting sand mold process.

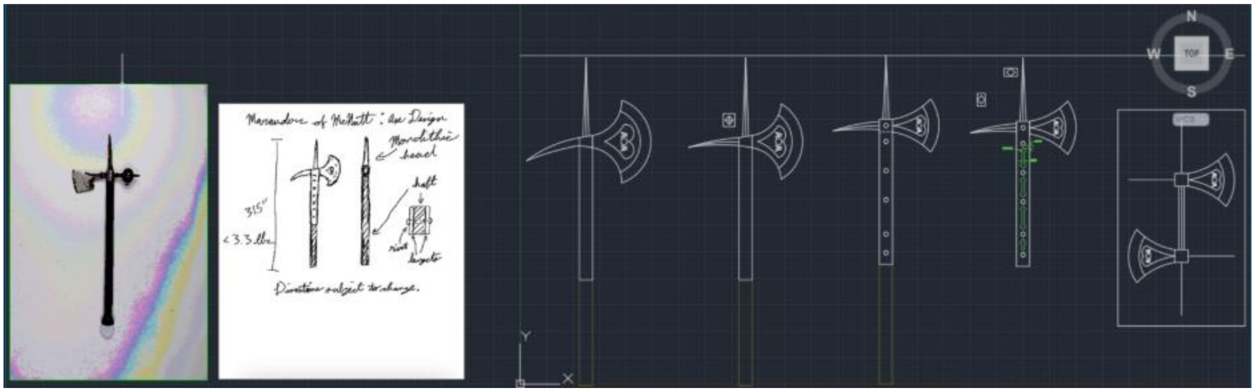


Figure 1. (From left to right) Historical size reference, original design sketch, initial CAD iterations (drafts 1&2), final design sketch (drafts 3&4), and sand mold layout.

The axe geometry was developed using CAD modeling with consideration for both performance and manufacturability. Attention was given to handle mounting throughout the process, ensuring proper room would be available to mount the wooden haft. It was decided to attach langets to the axe to mount the haft as a variation on the traditional “eye” or u-shaped bracket methods employed in the production of historical axes and polearms.

The largest constraints were the weight requirement and castability. Iterative revision resulted in continually smaller iterations to meet the 3.3lb weight requirement. Some features had to be dropped in favor of castability. Our initial intent was to cast the head, spikes, and langets as a monolithic part, but the langets were too thin and long for casting using the investment casting method we had chosen.

The design incorporates a curved blade and rear spike consistent with historical horseman’s axes. Smooth transitions and controlled section thicknesses were implemented to reduce stress concentrations and improve casting quality. The handle material selected was hickory wood because of its high strength, flexibility, and impact resistance, making it suitable for repeated use and physical tests.

3.1 Material Selection

Material selection was a critical step in the development of the axe. The team selected AISI 4340 steel due to its excellent balance of hardenability, toughness, and wear resistance.

4340 steel contains approximately 1.8% nickel, which significantly improves toughness and fracture resistance under repeated loads. Chromium is present at approximately 0.8%, enhancing hardenability and wear resistance. Molybdenum content around 0.25% reduces the steel’s susceptibility to temper embrittlement and improves high-temperature strength. These alloying elements allow for deep hardening during quenching, enabling the formation of a hard, wear-resistant edge while maintaining a tough core. This combination of properties is essential for an axe subjected to repeated impact.

3.2 AISI-Certified 4340 Chemistry and Mechanical Properties

Table 1. Certified AISI 4340 Chemistry and Material Properties (Data from AZo Materials Journal, 2012).

Element	**Content (wt%)**
Fe	95.195 - 96.33
Ni	1.65 - 2.00
Cr	0.700 - 0.900
Mn	0.600 - 0.800
C	0.370 - 0.430
Mo	0.200 - 0.300
Si	0.150 - 0.300
S	0.0400 (max)
P	0.0350 (max)

Properties	**Metric (Imperial)**
Tensile strength	745 MPa (108000 psi)
Yield strength	470 MPa (68200 psi)
Bulk modulus (typical for steel)	140 GPa (20300 ksi)
Shear modulus (typical for steel)	80 GPa (11600 ksi)
Elastic modulus	190-210 GPa (27557-30458 ksi)
Poisson's ratio	0.27-0.30
Elongation at break	22%
Reduction of area	50%
Hardness, Brinell	217
Hardness, Rockwell B	95
Hardness, Rockwell C	17

3.3 Advised Post-Processing Procedures:

Heat Treatment: AISI 4340 alloy steel is heat treated at 830°C (1525°F) followed by quenching in oil.
Forging: AISI 4340 alloy steel is forged at 427 to 1233°C (1800 to 2250°F).
Tempering: AISI 4340 alloy steel should be in the heat treated or normalized and heat-treated condition before tempering. Tempering temperatures depend upon the desired strength level.

4. Casting Process

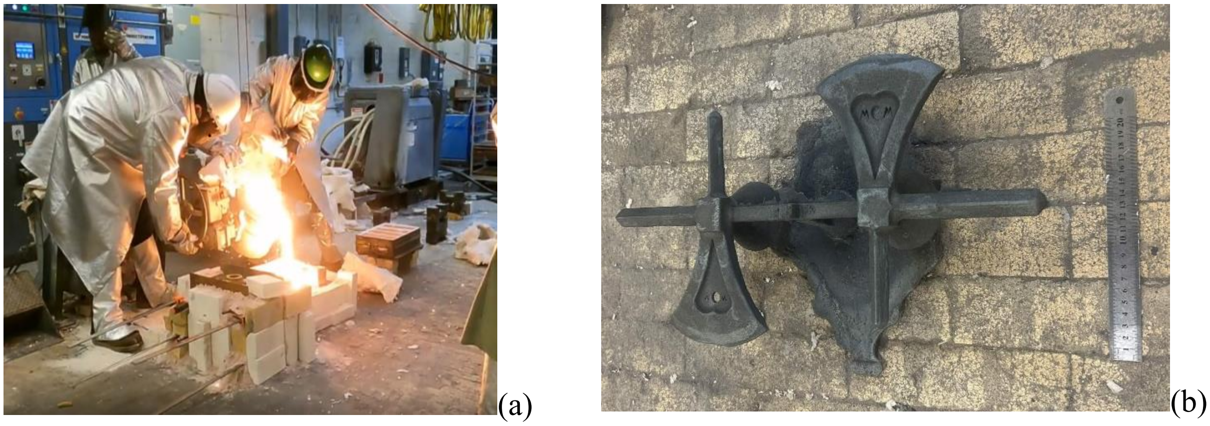


Figure 2. Casting process: (a) S&T foundry casting 3D printing molds with axes, and (b) final cast axes after breaking the sand mold.

4.1 Mold Development

The team initially pursued an investment casting approach to achieve a high-resolution surface finish and dimensional precision. Ceramic molds were created around a 3D printed burnout resin filament. However, shell cracking occurred during kiln firing, likely due to variances in shell thermal expansion, uneven shell thickness, or residual stresses during burnout. Due to time and reliability constraints, the team transitioned to a binder jetting sand mold process, which provided a more robust and repeatable manufacturing route.

4.2 Binder Jetting Sand Mold

Using an ExOne® *S-Print* 3D sand printer, the binder jetting additive manufacturing process was utilized to produce the new mold. This is a layer-by-layer deposition of sand with binder and removes the need for traditional pattern tooling. This process is able to create complex internal geometries and fine features in a short amount of printing time.

Compared to investment casting, binder jetting offers reduced lead time and increased reliability, though at the expense of an inferior surface finish and mold strength. The increased permeability of the sand mold assists in gas escape during pouring, reducing gas-related defects

4.3 Mold Design, Gating, and Risering

The gating system was designed to reduce turbulence and promote smooth mold filling, thereby minimizing defects such as oxide inclusions and shrinkage porosity. The design was developed in CAD and analyzed using MAGMA simulation software to predict solidification behavior and identify potential defect locations.

Risers were placed near the eye of the axe to promote directional solidification and compensate for shrinkage in thicker sections. Initial simulations indicated potential porosity near the blade region. To address this, additional small risers were incorporated above the blade prior to final mold printing. Porosity in the spike regions was considered less critical, as these areas will undergo forging during subsequent processing, which can close internal voids.

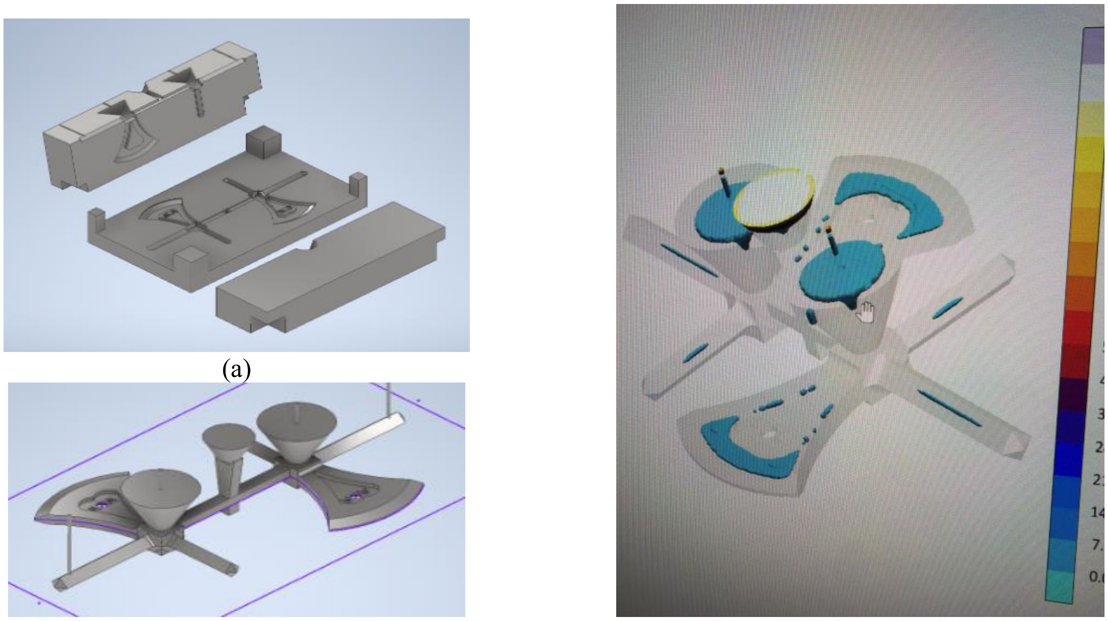

(a)
(b)
(c)

Figure 3. (a) 3-Part sand mold CAD design, (b) Sand mold gating and riser design, and (c) MAGMA simulation for the sand mold gating.

4.4 Purpose and Mold Design of the *Y-Block*

The *Y-block* presents a single-casting solution to the acquisition of multiple samples used for chemical and structural analyses, as well as specimens required for mechanical testing. The casting consists of a 2-part mold with a pouring basin, sloped gating, and a vortexing cup, reducing sand entrainment during casting. The mold incorporates integrated recesses for a ceramic filter, steel chill blocks, and a riser sleeve to insulate the riser during cooling. Our team procured all OES chemical analysis samples, microstructural analysis samples, CVN testing bars, and HRC testing samples from this casting.

Figure 4. Image of the Y-Block casting sand mold. Note the filter, chill blocks, and riser sleeve

5. Casting Process

Our team intended to melt a series of charge materials and microalloying additions in a 100lb tilting induction furnace to pour our axe molds, y-block mold, as well as thermal analysis (ATAS) samples.

Our charge materials were 50.71# AISI 4340 steel reruns, 33.07# 3”x3”x6” induction iron, with various microalloying additions. These include: 0.18# 75%Si ferrosilicon, 0.15# Desulco 9018 graphite, 0.07# ferromolybdenum chip, 0.40# electrolytic manganese, 0.07# aluminum shot, 0.33# metallic chromium, and an amount of vermiculite as deemed necessary to prevent oxidation of the melt during heating.

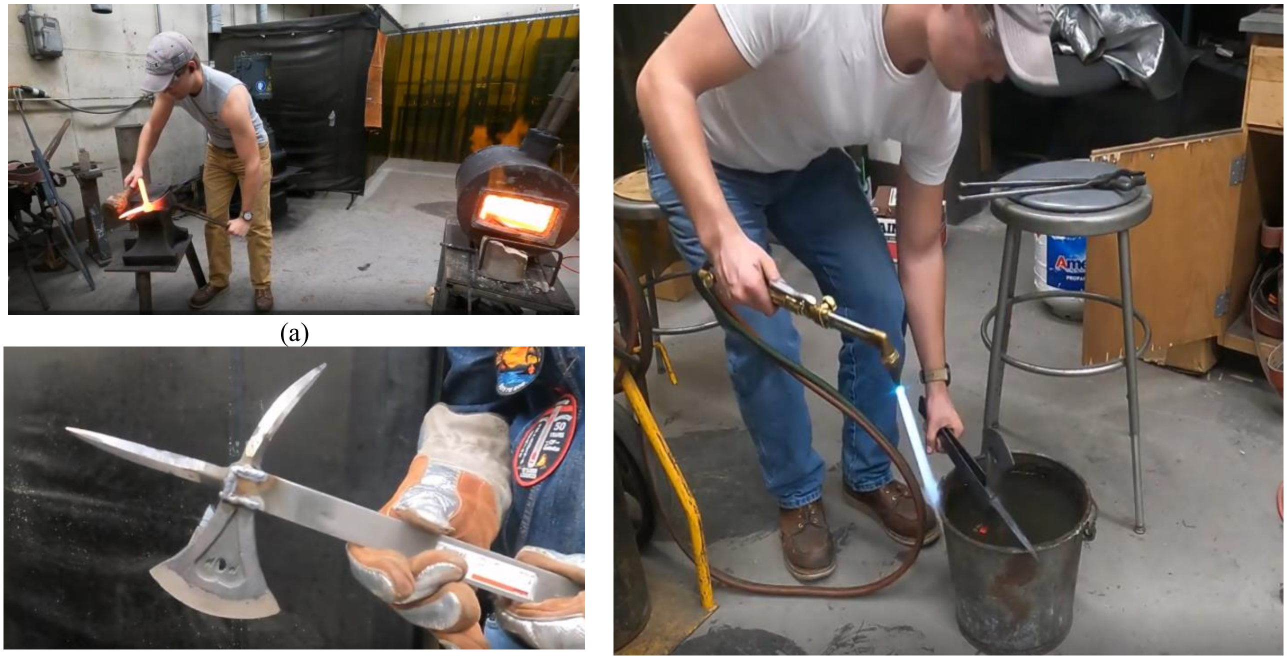
The charge materials and metallic Cr were melted in our furnace, insulated by constant argon gas, with the microalloying additions being added in the following order: Electrolytic Mn, ferrosilicon, graphite, and ferromolybdenum. Vermiculite was added throughout the process as deemed necessary by the furnace operator.

Once a superheat of 1640°C was achieved, the argon line was removed and an amount of the melt was tapped into a 25lb hand ladle to pour the axe molds, with a small portion of aluminum shot being added to the tap stream. However, during tapping, the bottom of the ladle broke, spilling 10-15lbs of the melt onto the foundry floor. The spilled metal was quickly covered with sand, and no injuries were sustained. Without the hand ladle, the ATAS cups were abandoned, and a large, crane-mounted tilting ladle was used to pour the axe molds, as well as the y-block mold. After pouring, the castings were insulted with kaowool and permitted to cool for a period of 27 hours before breaking the molds. Both the hand ladle, the crane ladle, and the furnace were inspected the day prior and showed no signs of compromise.

6. Post Processing

6.1 Forging

After casting, the axe was cut from the gating and forged to its final shape. The spikes were both shortened by an inch to fit in the investment slurry bucket and drawn out to their proper shape and length. The bevels of the bit were also forged to deepen them and improve mechanical properties. Once rough shaping was finished, the axe was put through three normalizing cycles from forging temperatures to room temperature. It was then rough ground before heat treatment.



(a)

(b)

(c)

Figure 5.: Sequence of axe processing: (a) forging, (b) welding of the langets and (c) quenching of the spikes.

6.2 Heat Treatment

Due to prior experience with this alloy, it was expected that a water quench would be required to obtain a martensitic structure, but it posed a notable risk of cracking. This is why an oil quench was tested first but predictably had too slow of a cooling rate to harden the steel. This is why the bit and spikes were brought to their Curie temperature before being quenched in heated water. The axe was finally tempered in two 400°F, one-hour cycles.

6.3 Attaching Handle

The handle was attached using five quarter-inch rivets along the length of the langets. The head was also fixed with a rivet after welding to guarantee a strong fixture and to reflect more historical construction methods. Designs were milled into the langets to reduce weight and add historical and aesthetic appeal.

6.4 Polishing and Sharpening

The axe was sanded with low grit sanding belts to efficiently shape the head and reduce weight. The bevels were refined, and the bit was reduced in thickness by one-third while the spikes were more moderately sanded. Once the rough shape was cemented, the surfaces were brought to a 120-grit finish to maintain a rugged appearance and hold oil to prevent rusting.

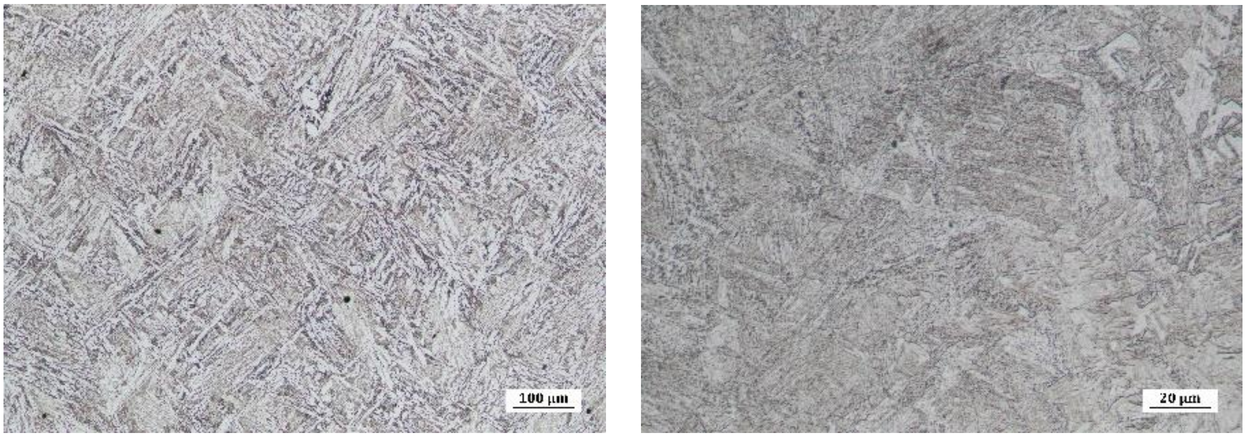
7. Results, Testing, and Observations

7.1 Hardness Testing

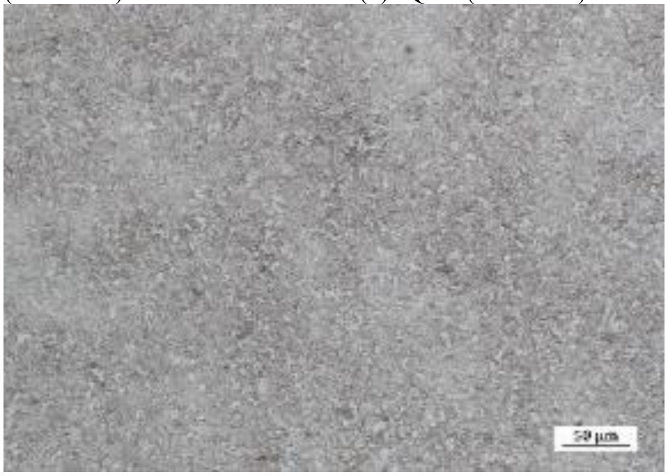
Hardness testing performed in accordance with ASTM E18 shows a clear progression in mechanical properties. The as-cast material was softer at 15.33HRC, but normalization refined the structure resulting in an HRC of 26.45. The final quenched and tempered condition had an average of 47.08 HRC, striking a good balance between strength and toughness for functional use.

7.2 Microstructural Analysis

Microstructural analysis samples were sectioned from the Y-block, mounted in Bakelite, progressively ground and polished to a final 0.05-micron surface finish, then etched using a 2% nital solution etchant. Images were taken via an optical microscope.



(a) As-cast (26.5 HRC) (b) Q&T (47.1 HRC)



(c) Quenched and Tempered (47.1 HRC)

Figure 6: Microstructure of the 4340-steel developed for this project in three different conditions: (a) As-cast, (b) Normalized and (c) Quench and tempered (Q&T).

The as-cast condition shows an inhomogeneous acicular ferrite microstructure. Typically, a dendritic structure would be expected in this type of cast steel. This difference may have been caused by quick cooling on the outside of our casting. After normalizing, the structure appears more evenly distributed. However, it is likely that the sample did not completely undergo austenitization during the normalization cycles due to some presence of bulk ferrite in the microstructure. In the fully quenched and tempered state, the microstructure consists of lath martensite, which is consistent with the observed increase in hardness versus the normalized and as-cast conditions.

7.3 CVN Impact Resistance Testing

Charpy V-Notch (CVN) samples are used to determine a material's impact resistance. 12 bar samples were cut via waterjet from a plate derived from the Y-block casting. These samples were milled to rough specifications (10mm x 10mm x 55mm) using a 5-flute carbide shell mill without coolant. The milled bars were then broached to create the 2mm "v" notch. Four of these bars were left as-is, in the "As-Cast (Milled)" condition, four more underwent normalization in a furnace, while the final group of 4 underwent normalization and subsequent quenching and tempering. These CVN results are shown below, with the average for each condition labeled.

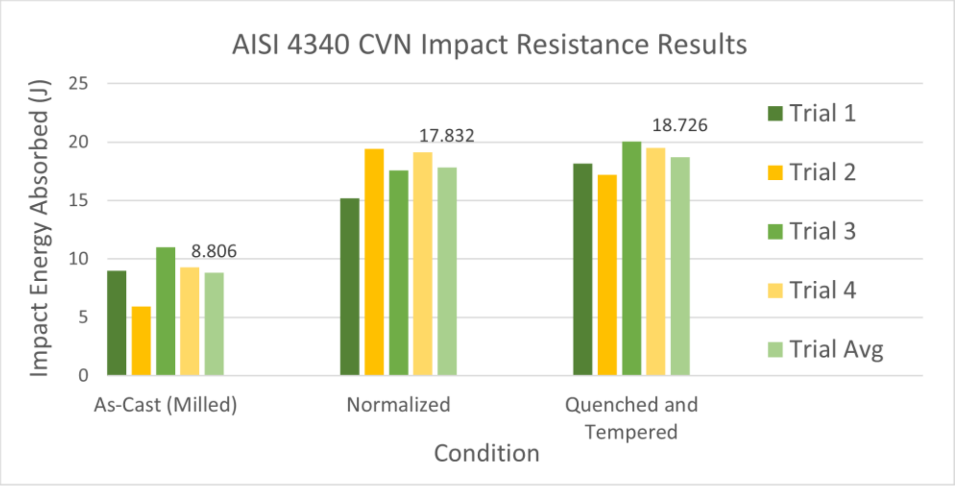


Figure 7. Impact energy results: Per-condition CVN results of the produced 4340 steel.

7.4 Summary of Mechanical Testing Results

We observed increasing impact resistance in the normalized and quenched samples versus those in the as-cast condition. As shown above (Fig.7) , the as-cast samples averaged 8.8 J, while the normalized and quenched specimens averaged 17.8 J and 18.7 J respectively.

These observations correspond with the results of our hardness tests, which showed distinct improvements in hardness after normalization and greater improvement after quenching and tempering. Likewise, this result is supported by our microstructural observations, in which the martensitic structure of the quenched samples provides superior hardness versus the softer ferritic structure of the as-cast or the mixture of microstructures (bainitic/pearlitic) found in the normalized samples.

8. Chemical Analyses

After casting, samples were taken from the Y-block for analysis via Optical Emission Spectroscopy (OES). After calibrating the machine using several standards providing reference values close to the 'ideal' AISI-certified 4340 chemistry, a series of chemical measurements were taken of the as-cast condition. These results were averaged and compared against a "target" chemistry previously determined in accordance with our charge calculations. This reveals whether our team, in broad strokes, was successful in creating a steel chemistry analogous to AISI 4340. These results are shown below:

Chemistry (wt%)										
	C	**Si**	**S**	**Mn**	**P**	**Cr**	**Al**	**Mg**	**Mo**	**Ni**
Target	0.414	0.316	0.003	0.960	0.003	1.006	0.099	-	0.240	0.995
As-Cast	0.411	0.192	0.015	0.811	0.020	0.999	0.080	0.005	0.267	0.932
Error (%)	0.725	39.241	**400**	15.521	**566.67**	0.695	19.192	-	11.25	6.332

Please note that the OES machine used is not intended for high accuracy of sulfur or phosphorus, and as such those results should be given very little consideration.

9. Conclusion

After completing post-processing steps and attaching the handle to the axe head, the final axe meets the dimensional and weight constraints specified by the competition.

The final weight of the axe is 3.28 pounds, within the limit of 3.3 pounds, while the final length of 31.25" SFSA's maximum length of 31.5 inches.

The OES analysis done in the as-cast material was in agreement with the AISI-certified composition, shown in Table 1. Broadly, this shows that we were able to accomplish the goal of creating a chemistry similar to our target and analogous to AISI 4340 steel. However, the steel produced during our heat is notably lower in silicon.

Our practical testing against wood, metal, and polymer rope instills our team with confidence that we have created an axe worthy of the Cast in Steel competition.

10. Acknowledgements

We would like to thank several individuals for assisting with the creation of our axes. Without their assistance, we would not be making a competition submission.

- Our non-Marauder foundrymen: Naziru Fuseini (furnace operator), Dr. Mario Buchely (Team advisor, heat supervisor), and William Kirk (ladle operator)
- Our industry sponsor, Southern Cast Products of Jonesboro, Arkansas. Special thanks to Henry Selig and President Douglas Imrie
- Individuals and fellow Cast in Steel competitors who provided advice and assistance: Alex Schumacher, Ben Hilgers, and Justin Singleton

11. References

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