

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

Missouri University of Science and Technology – MSteel



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Introduction

The horseman's axe represents a refined balance between utility, durability, and mobility as both a practical tool and a reliable weapon for riders in demanding conditions. This compact axe combines a robust cutting edge with a mighty pick suitable for use on horseback. Its design emphasizes efficiency, power, and control, allowing the user to deliver effective strikes while maintaining balance in motion. The project detailed in this report focuses on the design and fabrication of a modern interpretation of the horseman's axe by drawing on historical examples and utilizing current manufacturing techniques.

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. Through this initiative, SFSA aims to create an environment where students not only acquire theoretical knowledge but also develop practical skills in steel product creation. Additionally, the competition provides a platform for students to explore and apply the most recent advancements in steel casting technology. SFSA acknowledges the importance of keeping pace with technological progress and seeks to instill this forward-thinking approach in the participants, equipping them for success in the evolving industrial world.

Axe Design

The horseman's axe is defined by its dual-purpose head, consisting of a blade on one side and a pick on the other, allowing it to serve both as a cutting and penetrating weapon. This year, the team took inspiration from Robert the Bruce, more specifically the legend of his performance against English knight Henry de Bohun at the Battle of Bannockburn. As the legend goes, Henry de Bohun spotted Robert the Bruce riding ahead of his army and charged with a lance. At the last second Robert the Bruce calmly swerved his horse, stood in his stirrups, and struck down Henry de Bohun with a single blow of his axe [1]. The story of Robert the Bruce and Henry de Bohun exemplifies the deadly effectiveness and legendary reputation of the horseman's axe, inspiring the team to capture both its functionality and historical character.



Figure 1: Final axe head design

Axe Blade

The axe blade was designed for powerful chopping strikes, capable of cleaving through armor, shields, or limbs with a single, accurate blow. Its weight and momentum, especially when swung from horseback, made it a devastating weapon in close combat. The team took inspiration for the profile of the axe blade from the axe depicted in the statue of Robert the Bruce at Bannockburn Visitor Centre. Additionally, the advice from the competition judges provided during their podcasts posted on the SFSA YouTube channel was a great help during the design process. The examples and ideas presented, most notably the thought to reduce the cross section of the blade to help manage overall weight, were very impactful on the final design. Adding a final touch, a Celtic knot and trinity knot were added on the face of the axe blade to honor Robert the Bruce and add a bit of unique flair.

Pick

The pick complements the blade by providing a concentrated point of force capable of penetrating tougher materials such as armor or shields. In battle, the pick could be used to puncture armor, hook or pull an opponent, or deliver focused blows where cutting alone would be ineffective. Again, the team took inspiration from the advice provided by the competition judges. The design includes fullers along each side of the pick to reduce weight without significantly compromising structural integrity as well as a slight curvature intended to follow the natural arc of the user's swing and improve overall fluidity of motion during use.

Mold Design

An initial axe head was cast utilizing a simple 3D printed match plate pattern with a down sprue connected to one face of the axe blade. The purpose of this iteration was to provide an initial casting test of the axe head design in a chemically bonded no-bake sand mold. This "draft 0" axe revealed that, should the team choose to proceed with no-bake sand molds, it would be necessary to increase the blade thickness as the corners of the blade could shut and never fully formed. However, this increased blade thickness was likely to put a strain on the already difficult to match weight requirement of the competition. So, this initial trial helped push the team toward the decision to make use of ceramic investment shell molds.

Designing the investment casting mold involved multiple iterations. Each step consisted of designing a pattern, simulating shrinkage and potential hot tearing in MagmaSoft, and adjusting the design accordingly. This iterative process produced the final mold geometry, shown in Figure 2, which minimized problematic areas. Some minor porosity remained, but all major defects observed in earlier designs were resolved. The final design was 3D printed using PolyCast filament.



Figure 2: Final mold design

The investment casting shells were composed of three main components: a colloidal silica binder, milled 200 mesh zircon flour, and zircon stucco. Small amounts of antifoam and wetting agent were added to aid in slurry application. Shell formation was achieved by dipping the 3D-printed pattern into the slurry, allowing excess to drain, and then sprinkling zircon sand over the wet surface. This process was repeated to create a total of eight layers, with the final layer left free of additional zircon to facilitate cleaner transport to the foundry. The shells were left to dry for up to 24 hours between layers. This caused the slurry to need to be rehydrated periodically to maintain an appropriate viscosity. Lastly, the shells were baked overnight at 1000°C to ensure a complete burnout.

Handle Design

The initial stage of the handle design consisted of research into both historical and modern examples of horseman's axes to guide design decisions. Inspiration was drawn broadly from 15th and 16th century axes, with two notable references influencing the final design. The first was the Horseman's Axe of Cardinal Ippolito de' Medici, housed in the Metropolitan Museum of Art, whose ornate detailing inspired the inclusion of carved elements in the handle [2]. The second was a modern interpretation by Ben Abbott (a competition judge) that he posted on his Facebook profile on June 27, 2023. This specific example inspired the use of a steel swell and leather wrapping. Dimensional guidance for the handle was derived from One Moving Part: The Forest Service Ax Manual [3], specifically the geometry of a 28-inch double-bit cruiser-style handle. Based on these combined references and competition requirements, a balanced and functional handle design was established.

Material selection for the handle considered several traditional options, including hickory, black locust, and ash, all of which offer favorable strength and shock resistance. However, Purpleheart wood was ultimately selected due to its exceptional density, strength, and natural resistance to

wear and decay. While this choice may exceed typical functional requirements, it aligns with the project's emphasis on durability and performance. Additionally, the wood's distinct purple coloration provides a unique visual characteristic that complements the overall design.

Upon finalization of the design and material selection, fabrication of the handle began. The handle was shaped using a combination of saws, knives, files, and sanders to achieve the desired form. The final design features a hand-and-a-half handle, providing versatility in grip and control. A leather wrap was applied to improve handling and reduce vibration during use. Decorative elements were also incorporated, including burned-in Dwarvish runes inspired by *The Lord of the Rings*, adding a personalized aesthetic element to the handle. The runes translate to "This is a cool axe" and "MSTeel for the win." The handle is finished with a 1:1 mixture of beeswax and boiled linseed oil to protect the wood and give it a dark purple look. The handle was fitted to the axe head and secured using a wooden wedge, a metal wedge, and a light epoxy coating to ensure a stable and durable assembly.

Casting Process

Every iteration of the axe head was cast on campus at Missouri University of Science and Technology in the Robert V. Wolf foundry with input and training from the team's advisor. Due to the slow turnaround of producing investment casting shells on campus, the team was able to perform only two heats in the timeframe of the project.

Alloy Selection

The selection of an appropriate alloy required careful consideration of both performance requirements and manufacturing constraints. The primary factors influencing this decision were mechanical properties, specifically toughness, hardness, and wear resistance, as well as compatibility with available equipment and processing capabilities. To guide this process, comparable industrial applications were reviewed, particularly those requiring high impact resistance and durability. This led to the identification of tool steels as a suitable material class, with particular focus on the S-series due to their well-known shock resistance. Within this family, S7 tool steel was selected as the optimal candidate. S7 is commonly used in applications such as shears and dies, where components are subjected to repeated high-impact loading. Its combination of high toughness and good hardness made it well suited for the functional demands of a horseman's axe.

After selecting the alloy, the target chemical composition was established using the specifications outlined in ASTM A681-24 [4]. The selected composition falls near the midpoint of most specified ranges, with deliberate adjustments toward the upper limits of manganese and molybdenum content to further enhance toughness. A comparison of the standard composition ranges and the final target chemistry is provided below.

Table 1: S7 chemistry range and selected chemistry

	C		Mn		P	S	Si		Cr		V	Mo		
ASTM A681-24	0.45<	>0.55	0.20<	>0.9	0.03>	0.03>	0.2<	>1.0	3.00<	>3.5		>0.35	1.30<	>1.80
Target	0.50		0.85		0.006	0.003	0.85		3.25		0.200	1.60		

Initial Heat Procedure

The pouring procedure was developed to produce approximately 90 lbs of steel while maintaining the target chemistry. A simulation was conducted using JMatPro to estimate the liquidus temperature, which was determined to be 1468°C (see Appendix Figure 1). Based on this, the required charge materials were selected, with their exact weights and specifications provided in Appendix Table XXX. Prior to melting, all charge materials were baked overnight in an air-recirculating furnace at 360 °C to remove residual moisture and cutting fluids. After baking, the charge materials were arranged within the induction furnace crucible. Chromium and molybdenum were added early in the process to promote the formation of a molten heel during initial melting.

A separate sample mold was assembled to produce a large block, approximately 4" × 4" × 6", for the purpose of heat treatment evaluation. Prior to initiating the melt, the team conducted a full procedural walkthrough, including a detailed safety review and verification of proper personal protective equipment. The induction furnace was activated and the melting process began with a gradual increase in power to the induction coils, generating eddy currents that raised the temperature of the charge material. As the metal liquefied, the remaining induction iron was added to establish the bulk molten mass. Once fully molten, secondary alloying elements including vanadium, manganese, carbon, and a partial silicon addition were introduced. The interrupted addition of silicon was used to promote deoxidation before the final carbon adjustment. The melt temperature was then increased to approximately 1620 °C, providing a superheat of about 150 °C above the liquidus temperature. Upon reaching the target pouring temperature, the remaining silicon was added, and pouring operations began. Molten metal was first transferred into a preheated hand ladle containing 2 grams of aluminum for deoxidation and then poured into the investment shell molds positioned in a sand pit. This process was repeated for the second investment mold. The third mold, used for the sample block, was filled using a crane-assisted ladle with 5 grams of aluminum added.

Following pouring, all molds were covered with thermal insulation blankets and allowed to cool undisturbed. After complete solidification, the castings were removed and inspected. During this evaluation, significant surface defects were observed on the axe castings.

Initial Heat Results

Following the initial heat, several critical defects were observed that required investigation before proceeding with subsequent pours. The primary concerns were the failure of one investment shell, which split during casting, and the presence of extensive surface pitting across all axe castings. An initial hypothesis, proposed during the pour, was that elevated nitrogen levels potentially introduced through the ferrochrome addition may have contributed to the observed defects. To evaluate this possibility, samples were prepared for LECO analysis to measure nitrogen, hydrogen, and oxygen content. However, the internal condition of the selected sample, which contained significant porosity, rendered the results unreliable. As an alternative, a section of the separately cast test block was examined for internal porosity typically associated with nitrogen contamination. No such defects were observed, suggesting that nitrogen was not the primary cause of the casting issues.

With nitrogen contamination deemed unlikely, attention shifted to mold related factors. Reference to the Investment Casting Institute defect atlas [5] indicated that the observed surface pitting and shell failure could result from inadequate shell permeability, insufficient mold or metal temperature, or improper feeding during solidification. Based on these findings, several process modifications were implemented. The pouring procedure was adjusted to increase superheat and a polymer additive was incorporated into the shell formula to enhance both strength and permeability. These changes were intended to mitigate defect formation and improve casting quality in the subsequent heat.



Figure 3: Initial casting with heavy surface pitting

Revised Heat Procedure

Following the defect analysis, several targeted modifications were implemented to improve casting performance. As previously discussed, the investment shell fabrication process was adjusted to increase permeability, promoting more effective gas escape during pouring and solidification. In addition, changes were made to the alloying materials. The chromium source

was switched from ferrochrome to high-purity metallic chromium to reduce impurity levels and minimize nitrogen pickup in the melt. Further refinements were made to the melt procedure by adjusting the sequence of alloying additions to limit slag formation and improve overall melt cleanliness. Thermal conditions during pouring were also modified. The tapping temperature was increased from 1620°C to 1650°C to provide additional superheat, improving metal flow during hand ladling and reducing the likelihood of solidification defects. Finally, the aluminum addition was increased to 3 grams to promote more effective deoxidation, resulting in a more fully killed steel and improved casting quality.

Heat Treatment and Testing

Heat treatment procedures began with preparation of the sample block, which was sectioned to remove the riser and sprue. Using thermodynamic data generated from JMatPro (see Appendix Figure 2 and 3), the dissolution temperature required to place carbides and precipitates back into solution was determined to be approximately 1000°C. The sample block was then heated in a kiln at a rate of 100°C per hour to 1050°C and held for four hours to ensure complete thermal homogenization. Following this, a controlled cooling rate of 14°C per hour was calculated and applied to transform the material into a fully pearlitic microstructure. This condition was specifically targeted to improve machinability and reduce costs during specimen preparation.

From the annealed block, three slices approximately 0.5 inches thick were sectioned and machined down to a uniform thickness of 11 mm with parallel faces. Charpy bar blanks measuring 11 mm × 11 mm × 55 mm were then produced on campus via abrasive waterjet cutting. These samples were prepared to evaluate the effects of quenching media and tempering conditions on mechanical properties, with hardness and toughness identified as the primary response variables. The two quenching media investigated were air and canola oil. Although S7 tool steel is typically air hardened, oil quenching was explored to reduce hardness and increase toughness through the promotion of retained austenite.

The samples were divided into two groups for heat treatment. The first stage involved heating all specimens to 725°C for 30 minutes, followed by transfer to a second furnace at 1100°C for an additional 30 minutes to ensure uniform austenitization. After reaching temperature, one group was placed in a thermal blanket to achieve an air-cooled condition, while the second group underwent an intermittent oil quench to simulate the intended quenching process for the axe heads. Following quenching, three samples from each condition were tempered at 205°C, 315°C, 425°C, 550°C, and 650°C for two hours. After heat treatment, all samples were surface ground to a final thickness of 10 mm with parallel sides to ensure consistency for testing. Hardness measurements were then conducted, with each sample tested five times, resulting in 15 measurements per quenching and tempering condition (see Appendix Figure 5).

Although toughness testing was initially planned for all samples, this was not fully achievable due to the high hardness of the majority of specimens. Specifically, 27 out of 30 samples

exceeded 50 HRC, which prevented proper notch preparation due to limitations of the available broaching equipment. As a result, only one condition, the oil-quenched sample tempered at 650°C, was successfully tested. This sample exhibited a room-temperature V-notch Charpy toughness of 12.67 ft-lbs at a hardness of 45.6 HRC. While this toughness value is relatively low, it is consistent with expectations for S7 tool steel, which is often evaluated using notched or C-notch specimens.

Based on these results, the same heat treatment condition was applied to one of the initial axe heads, which was mounted to an oak handle for functional testing. This axe demonstrated strong performance under practical conditions. Following this evaluation, full-scale heat treatment of the remaining axe heads was initiated using the same annealing procedure and cooling rate as the sample blocks. However, a significant challenge encountered during this stage was decarburization. This phenomenon occurs when carbon at the surface reacts with oxygen to form carbon monoxide, reducing surface carbon content and, consequently, hardness.

To mitigate decarburization, an argon atmosphere was introduced into the kiln at a constant pressure of approximately 3 PSI. Despite this precaution, the argon supply was depleted during processing, resulting in significant decarburization to a depth of approximately 1.0 to 1.2 mm. Attempts were made to restore the carbon content through pack carburization using graphite. Samples were sealed in stainless steel bags and exposed to carburizing conditions for durations ranging from 1 to 5 hours, as well as a 24 hour cycle at 925°C. However, due to the absence of a controlled atmosphere furnace with a carbon-rich environment, these attempts were unsuccessful.

Following these challenges, three axe heads with varying heat treatment conditions were available for final evaluation: a 5 hour carburized sample with an air quench and 425°C temper, a 24 hour carburized sample with a 315°C temper, and an oil quenched sample tempered at 650°C from the initial casting. These axes were tested against a variety of materials, including low-carbon steel rods, armor plate, cinder blocks, and rope. Based on a balance of performance, edge retention, and consistency in casting quality, the final competition axe was selected to be the one heat treated in an air-quenched condition with a 425°C temper for two hours.

Conclusion

The final axe submitted for the Cast in Steel 2026 competition is shown in Appendix Figure 6. The axe is an S7 steel that was cast by the MSteel team of Missouri University of Science and Technology on campus in the Robert V. Wolf foundry. Ceramic investment shells created on campus were utilized in the team's casting procedure. The axe successfully completed rigorous physical testing before being shipped to compete in the competition. The axe is 28.5 in. long and weighs 2.75 lb.

References

- [1] Mysterium Tours, “Robert the Bruce and his battle axe,” Mysterium Tours. [Online]. Available: <https://www.mysteriumtours.com/robert-the-bruce-and-his-battle-axe/>. [Accessed: 27-Mar-2026].
- [2] The Metropolitan Museum of Art, “Horseman’s Axe of Cardinal Ippolito de’ Medici,” The Met. [Online]. Available: <https://www.metmuseum.org/art/collection/search/26548>. [Accessed: 27-Mar-2026].
- [3] Forest Service, One Moving Part: The Forest Service Ax Manual, [City: Publisher, Year].
- [4] ASTM International, ASTM A681-24: Standard Specification for Tool Steels, West Conshohocken, PA: ASTM International, 2024.
- [5] Investment Casting Institute, Casting Defects Atlas, [City: Investment Casting Institute, Year].

Appendix: Additional Figures and Tables

Table 1: Charge table

In Charge	Weight (kg.)	Weight (lb.)
Induction Iron	33.000	72.753
Fe75Si	0.358	0.789
Desulco 9001 Graphite	0.072	0.159
FeMo	1.030	2.271
Bar Addition	3.500	7.720
Electrolytic Mn	0.270	0.602
FeV	0.162	0.357
Low C FeCr	2.290	5.049
Total	40.69	89.70

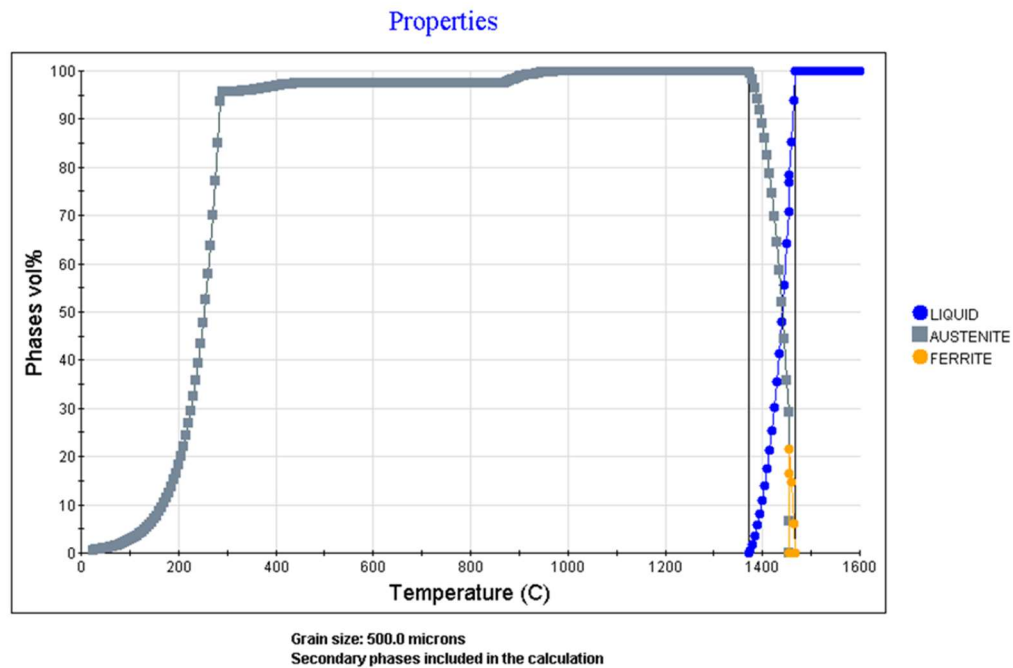


Figure 1: This graph represents the Phase volume% by Temperature Which was used for calculating the liquidus temperature

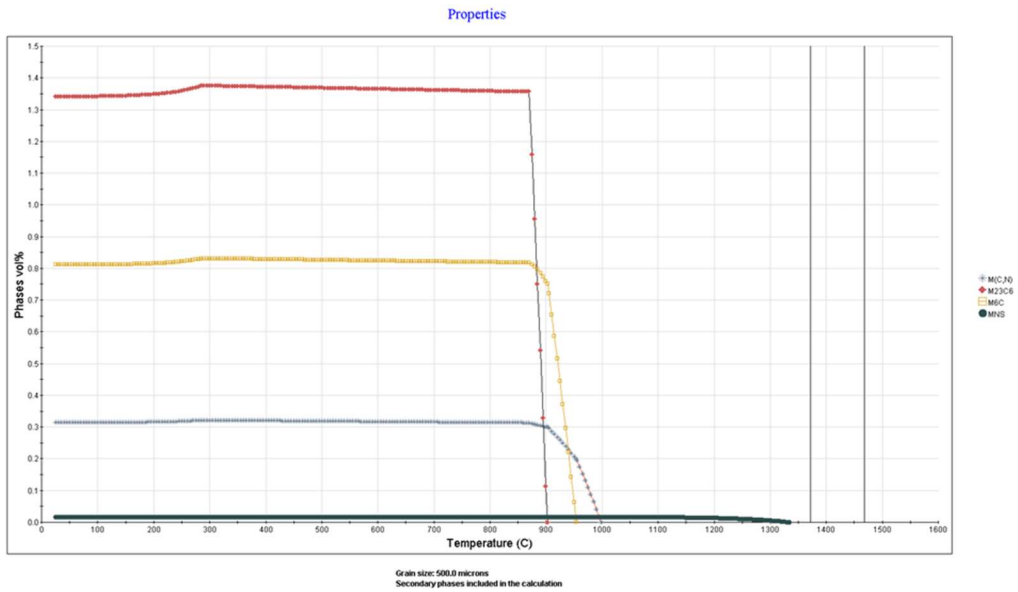


Figure 2: This graph shows the metallic carbides and Precipitates that are present in the steel

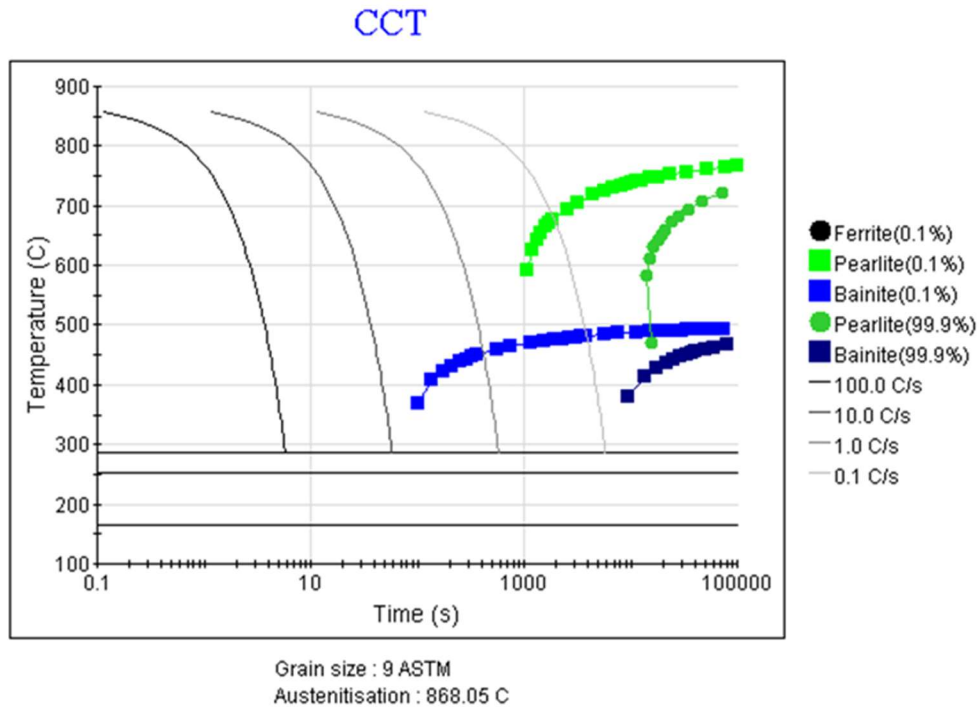


Figure 3: This Continuous cooling curve was used to define the cooling rates required for the annealing of the sample block

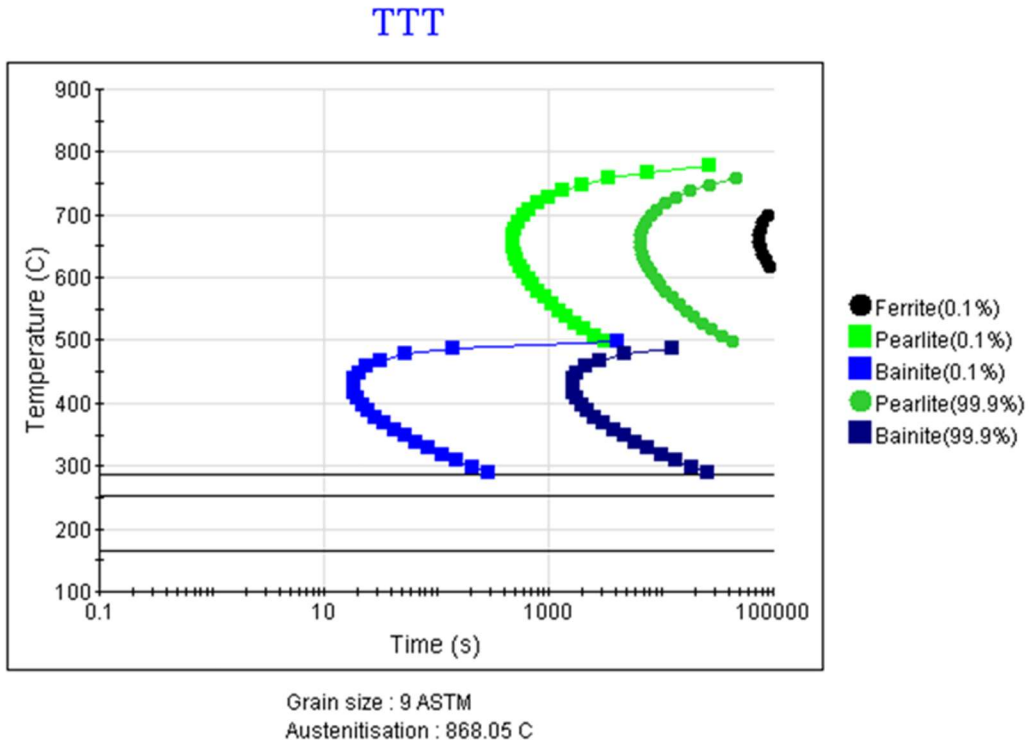


Figure 4: This time and Temperature graph was used to assist in calculating the anneal

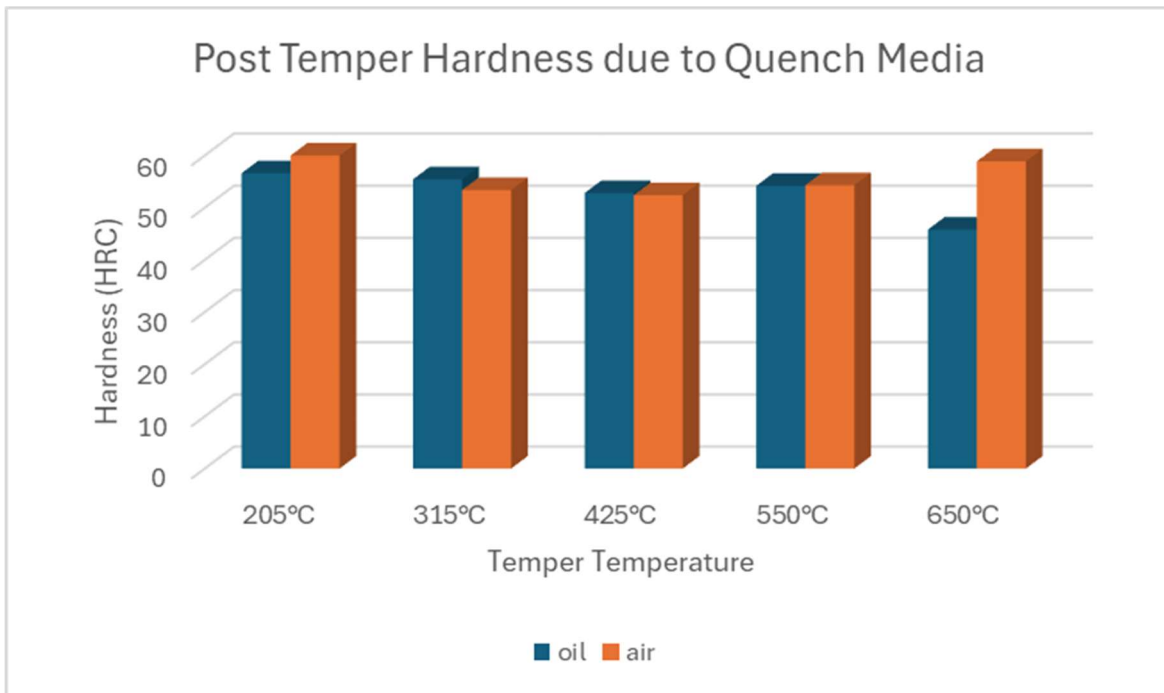


Figure 5: This graph represents the hardness measured due to the temper the samples received after they were quenched



Figure 6: Final axe sent to competition