SFSA Cast in Steel 2026 – Horseman's Axe

Technical Report

Central Michigan University Group A – The Horseless Axe-men

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Foundry Partner:

Bay Cast, Bay City, Michigan

Introduction and Historical Background

Forging is one of the earliest and most used forms of metalworking in history, due to its efficiency while maintaining proper balances of strength, ductility, and hardness. However, modern improvements in manufacturing have allowed other material processes to become more prevalent, and even more efficient or cost effective depending on the direct application of said process. One commonly used process is known as casting, where molten material is poured into a mold and holds its shape throughout the solidification process.[1] The Steel Founders' Society of America holds a yearly university-based competition known as Cast in Steel, requiring the use of the casting process to recreate a historical weapon of their choosing. The SFSA has created this competition to encourage students to learn about making steel products using the casting process and applying the latest technology available.[2]

In 2026, teams were tasked with producing a horseman's axe akin to that of the axe Robert de Bruce, King of Scotland, used in the Battle of Bannockburn in 1314 to defeat Henry de Bohun in battle.[2] The axe, such as shown in Figure A.1, was traditionally one-handed weapons, used on horseback and popular throughout Europe through the next several centuries. They often were created with key features such as an axe head and pike used for attack through plate armor and chainmail, as well as a top spike used for close. For this competition in particular, the requirements of the axe included a weight limit of 1.5 kg and a length limit of 800 mm. References used for concept design, such as the axe shown in Figure A.1 found through historical research, that of axes shown in the SFSA Cast in Steel 2026 Expert Discussion[4] and other modern sources of inspiration such as Forged in Fire[5], were used to reference the eventual design of our axe to that of historically accurate European one-handed horseman's axes, through the inclusion of similar features into our unique design.

Axe Design

Each team member did their own research regarding how the horseman's axe should be designed, based on different sources such as Dalton using the SFSA Cast in Steel 2026 Expert Discussion, Tim using personal experiences with interests in weapons and weapon design, Ashton using both historical weapons and modern recreations of horseman's axes, etc. Each team member drew their own model, all of which are shown in Figure A.2. The team created a product needs table for the project, which was used to create a design specification table with weighted factors for each need and scored appropriately. Due to the similarity of multiple designs, two main designs were chosen to be designed in CAD, with a third less traditional design being chosen for FEA simulation comparison and manufacturing feasibility. The product needs, design specifications, and scoring matrix tables are all shown in Table A.1, A.2, and A.3 respectively.

Before modeling the axes, both CMU Cast in Steel teams spoke with our advisor, our industry partner Bay Cast, and did our own literature review regarding steel and metallurgy to determine which steel alloy would be the best for our axes. Bay Cast had the recommendation of looking into 4330 and 4340 steels, due to using them with success for past Cast in Steel competitions. While working with the other CMU team, we agreed to use 4340 steel for the competition. 4340 steel is a nickel-chromium-molybdenum steel, which Table A.4 shows has a positive impact on the toughness, hardness, and oxidation resistance of the steel. Bay Cast had the capabilities to provide both annealing and heat treatment of the steel after casting, allowing us to machine the axes despite the hardness of 4340 steel and to improve the strength and hardness of the axes post-machining for competition. A chemical analysis was done by Bay Cast for the specific batch of 4340 steel that was used for the pouring of the CMU group's axes, which is shown in Figure A.3. It is important to note the steel is categorized as SC 4340 steel under the ASTM A958 standard, and that the carbon content of the steel (0.35%) is under the minimum carbon requirement for SC 4340 steel for this standard (0.38%).

<u>3D Modeling</u>

Three team members modeled their own designs of the axe using Autodesk Fusion, Catia, and Siemens NX, based on personal preference and experience. Each axe was modeled using the competition requirements and final design criteria, but each team member was able to include their own personal preferences in the design, such as fuller for weight reduction, blade length, pike thickness, handle style, etc., if they justified it to the team. Preliminary CAD designs are shown in Figure A.4. It is important to note the flexibility that casting gave our design as a process compared to forging. Because of the desire to target complex shapes, curves and thicknesses, on the blade, pike and spike; the casting process allowed for more design freedom than machining from a block of steel or trying to accurately forge them. In turn, we were able to use the casting process to add value and reduce machining time. The casting process allowed for fillets on edges, and junctions in the body of the axe head, that otherwise would take much longer to do in a machine. This did raise some challenges as the casting process does create restrictions in large junctions, small fillets, or radii. This is where we were able to design with our intended manufacturing process in mind by keeping consistent radii and junctions throughout all designs.

After the preliminary models were made, our advisor suggested that we try to use generative designs to modify our designs based on load constraints, weight requirements, etc. A separate, more generic design, was placed into Autodesk Fusion, and topology optimization was used to modify the axe's design. Figure A.5 shows the model including its added input parameters, as well as the resulting generatively designed model. While this model wasn't intended to be used for the competition, it helped with determining where material could be added or removed from the axe to not ruin the axe's structural integrity. This allowed us to make informed decisions regarding the other models being designed that would result in positive CAE testing results.

After the preliminary modeling phase, the team met to discuss any changes that we wanted to make to the overall design. First, the team discussed having a wooden handle versus a steel handle. The team decided between a wooden handle that would allow for a larger axe head, or a steel handle that would be more structurally sound and historically accurate despite requiring an overall smaller design.

In discussions regarding shaft and handle design, different teammates offered diverse opinions regarding the shaft length and design. These include Gavin's idea of a hexagonal-shaped shaft to add uniqueness to our axe compared to a standard round shaft, or a discussion centered around Dalton's suggestion of a longer shaft. In the end, a steel shaft was chosen with the use of a hidden tang design for the handle. The shaft/handle assembly weighed approximately 1.8 pounds and was 18" long, a shorter length to compensate for the weight of the steel.

Once all four models were created, non-linear impact testing was completed through Autodesk Fusion to verify the strength of the axes while observing simulations for any high stress points that could be of concern during testing. Velocity estimates used were 30 MPH and were estimated using the analysis of a replica hammer-swinging video taken by the team in Logger Pro 3 software. Non-linear impact simulations were done using this velocity to accelerate the blade and pike-tip into modeled plate armor made of A36 steel. Images of the blade and pike non-linear impact simulations for one axe design are shown in Figure A.6. Analysis of the normal stresses in comparison to the tensile strength of 4340 steel, is shown in Table A.5.

As stated previously, the axes were designed to be manufactured using the casting process. One example of this, is once the final designs were agreed upon between the team and Bay Cast, extra stock was added to the models to avoid imperfections in the cast. This included removing sharp corners and points, and making sure the minimum thickness at any point was 3/8" to ensure successful flow in the casting. Fluid flow simulations were then done on the stock models to verify castability and establish the placement of risers and gates within the mold for the casting, which is shown in Figure A.7.

Casting

Using our stock models, our foundry partner Bay Cast worked with the company Voxeljet to create Binder Jet 3D printed sand molds, which would be used for the sand-casting process. These molds, which are shown in Figure A.8, were created through 3D printing alternating layers of sand and a binder material until the desired shape of the mold was created. Bay Cast, who typically applied casting to large industry applications, had a requirement of a minimum of 3000 pounds of steel poured at once in their foundry, despite the maximum weight of our axe being 1.5 kg. To help reduce waste, two measures were taken. First, multiple axe head designs (12 total, 3 of each of our 4 designs) and 6 handles were cast to ensure efficient use of the extra material that was being poured. Second, both CMU teams poured together using the same batch of 4340 steel in order to be time and cost efficient.

Both CMU Cast in Steel teams then traveled to Bay Cast to build the sand molds by hand. This process started with building the first half of the sand mold, called the drag. The 3D printed molds were placed at the bottom of the drag, and separate styrofoam pieces were connected to the molds to create what would become the runners, sprue, etc. Once built, support rods were placed into the mold before sand was poured in and packed tightly within the mold container. This sand was allowed to cure for 3 hours, before the surface was cleaned and sanded down to remove any sharp edges. The same process was used to build the cope directly on top of the drag to ensure symmetry in the casting. Once the cope cured, the surface of both halves of the mold were coated with a blue wash that prevented the steel from penetrating any holes in the surface of the mold during the casting. Images of the mold/runner system and the surface of the finished drag are shown in Figures A.9 and A.10 respectively.

Once the pouring was complete, the axes were shaken out and removed from the molds. The castings came out well for our main two designs and our secondary non-traditional design, though the topology optimization axes were not cast successfully due to their overly complex geometry.

Fabrication – Axe Heads

In order to make the axes easier to work on, Bay Cast annealed the axe heads and handles. The team picked up the axes from Bay Cast, and the initial axe heads and handles are shown in Figure A.11. Upon picking up the axes, we noticed issues with the casting on several of the axe heads. Many axe heads had holes almost all the way through the center of the head, perpendicular to the blade. Our second design had several issues with the casting as well, including the center line of multiple being uncentered, one blade being bent off center, and the main body of the axe head was too small to be used due to being cut-off during the demolding process. In the end, we chose three axe heads, one of each design, to be finished and heat treated at Bay Cast for testing. These are the same three axe heads that are shown in Figure A.11. The traditional design with the larger pike is referenced as “Design One”, the other traditional design with the smaller pike and larger blade is referenced as “Design Two” while the “Non-traditional Design” will be referenced as so for the rest of the paper.

The main priority of the fabrication phase of the axe heads was to remove excess material to meet the weight requirement of the competition. The method of doing so was debated heavily amongst the team, as each team member had a different method or tool to be used for removing said material. Gavin attempted to use the CNC machine to remove material due to its efficiency and accuracy, while Tim argued that using hand tools such as the belt sander and file would result in a more clean, uniform look for the axe head. Gavin moved forward working on Design One with the CNC, and Tim began to work on Design Two.

Focusing on Design One, Gavin used the oxyacetylene torch and then followed with the angle grinder to remove finer imperfections and material from the axe head. The next step was to create soft jaws to be able to use the mill to remove excess material. This was done by creating PETG soft jaws to hold the axe head. Although this method of creating soft jaws is not traditional, it is much more time efficient for a one-off part and is something that has been proven as an effective method through Gavin's past experiences with manufacturing.

Using Autodesk Fusion, CAM tool paths were created for the removal of material on the axe head in the CNC machine. After several attempts of changing the soft jaw geometry and work holding locations, it was determined that the inaccuracies in the casting process of our axe head created issues accurately making soft jaws with enough clamping force for work holding in the vise and therefore eliminated the CNC machine as an appropriate means of machining our axe heads. To counteract this, an angle grinder was used to remove the bulk material from all areas of the axe head, ensuring that the dimensions of the axe head stayed consistent with those expected from our CAD models. Once the dimensions of the axe head were accurate, a Bridgeport mill was used for two purposes; To mill out pockets and machine cleaner, straighter edges where necessary and to open the hole in the axe head to allow for a plug to be welded in. To fill the hole in the side of the axe heads, a slightly larger but uniform hole was milled out, and filled with a steel plug that could be welded in to provide strength and uniformness. A picture of Design One's axe head after the milling process is shown in Figure A.12. This plug was then welded in place, and the surface was machined flat once more to ensure an even uniform surface free of any defects.

Design Two was done entirely by hand, using various tools, including but not limited to a file, angle grinder, and belt sander. Although this created a bit more uncertainty and risk with dimensional inaccuracies, this axe design was created with manufacturability in this way, in mind. This includes large faces, corners rather than radii and fillets, and the design allowing for most of the geometry to be captured in the cast rather than it being "hidden" by excess stock. Design Two captured a true cast product, where the final product is minimally distinguishable from its cast shape.

The Non-traditional Design was also done by hand, using primarily the angle grinder and belt sander. This design posed its own difficulties, being designed with a very fluid shape and the intent to be the most structurally sound. This axe was very difficult to replicate the desired profile while also meeting the weight requirement.

During the excess material removal of all 3 designs, a scale was consistently used to ensure we could target the appropriate weights for the individual head components. 1.3 lbs for Design One, 1.5 lbs for Design Two, and 1.5 lbs for the Non -traditional Design. Due to the imperfect comparison and material properties on CAD software, our physical axe heads did require extra material removal than intended. For example, Design Two required the spike to be smaller than designed to accurately hit the weight requirement.

Fabrication – Shafts

The casting process with the shafts introduced an interesting problem that was not anticipated by the team. Due to the location of the gates and runners in the mold. Much of the desired hexagonal geometry of the shaft was hidden or altered. This required much more workmanship to maintain the desired profile and get the axe down to its final correct weight. This also created a difference in opinion for methods between team members. Tim wanted to use the belt sander, while Gavin wanted to use the lathe. Ashton determined that a mix of both would be a good solution to maintain dimensional accuracy while still allowing us to save the desired geometry.

First, the angle grinder was used to remove the bulk of the excess material, then once more with a grinding disc to flatten out some of the high spots on the hexagonal planes. Now the axe was ready to be put in the lathe, centering on 3 of the 6 cast surfaces. This was done to reduce the 1" long section that would be welded into the axe head to a 5/8" diameter, while reducing the 5" for the handle below the shaft to a ½" diameter (smaller due to the addition of wood in the handle assembly). Due to the desired shape of the shaft, the lathe was not an option for the rest of the shaft, so the angle grinder was used once more to flatten and square these surfaces to each other. Although a piece of hex-stock could have been used to achieve this result easiest, it was not in the best spirit of the competition. Our two options would be to cast a full cylinder shaft, and then machine the hexagonal shape, or to cast the shape from the get-go and clean up what was required. Since the goal was to use and benefit from the casting process, we chose the latter, which allowed us to save machine time as well as utilize the casting process to create the intended geometry.

An image of the Design One and Design Two axe heads with their respective shafts prior to heat treatment and welding is shown in Figure A.13. Once the initial fabrication phase was completed, the team went to Bay Cast, who assisted the team with welding, heat treatment, and non-destructive testing of the axes.

Fabrication – Rondels, Wooden Handel & Leather Grip

The rondels were plasma cut out of 0.25" 6061 aluminum and milled down to be the correct thickness (0.15"). The dimensions of these rondels, which are shown in Figure A.14 were 3.00" outer diameter, with a hole for the shaft at 0.55".

The wooden handle was created out of a 2" x 2" x 6" block of ash and was done by drilling a 0.55" hole to allow for shaft clearance and the epoxy to be applied later. Next two 13/64" holes were drilled into the wood perpendicular to the 0.55" hole. This was to make a spot to put two brass support pins in later to help reduce the handle from spinning. The test 3D printed handles were then centered with the 0.55" hole as shown in Figure A.15 and using the bandsaw to cut to length and shape. The final outer finish of the wood was done by a belt sander to get a smooth finish.

Next, the leather grip was cut to size to properly wrap around the wooden handle. Next, the holes were punched along the edge with a spacing of 0.2" between each, and a cross stitch with wax coated stitching was used to sinch the entire piece around the handle. An image of the leather stitched around the wooden handle addition is shown in Figure A.16.

Non-Destructive Testing

While at Bay Cast, non-destructive testing was done to analyze the quality of the axe heads and handles prior to heat treatment and welding. First, a visual inspection of the axe heads and handles was done using the standard ASTM A802: Standard Practice for Steel Castings, Surface Acceptance Standards, Visual Examination. An analysis of the axe heads and handles was done to determine acceptable levels of different possible deformations and surface conditions, including surface textures, gas porosity, etc. A report based on this standard is shown in Figure A.17 and shows that the axe heads and handles were accepted based on Level III acceptance criteria under the standard. The axe heads and handles were also tested using magnetic particle testing under the standard ASTM E709: Standard Guide for Magnetic Particle Testing. Magnetic particle testing works by magnetizing a ferromagnetic material and introducing magnetic particles to the surfaces of the material[8]. Where discontinuities exist on the material's surface, there is a break in the magnetic field and the particles will be attracted to that area, highlighting that discontinuity on the material's surface. This testing was done using a Magnaflux AC Yoke Visible Magnetic Particle Kit to create the magnetic field. A Magnetic Particle Inspection Report was created, which is shown in Figure A.18, and shows that the axe heads and handles passed the inspection within the criteria of ASTM E125, passing within Level I for cracks and Level III for inclusions.

Heat Treatment & Quenching

After non-destructive testing was done, the axes underwent heat treatment. Bay Cast built a forge to keep the axes heated to a high temperature. Thermistors were put on the surface of the axes to monitor temperature, before the axes were heated up to 1550° F and left in the forge for 30 minutes at that temperature to normalize. The quench oil was preheated to an average temperature of 150°F, before the axe head blades and pikes were dipped into the oil for 10 seconds on each side. Only 2-3“ of the blade and pike were dipped into the oil, and the blade was done first to ensure that it was the strongest point of the axe, due to being quenched with no heat loss when in contact with the air. This was done to ensure the center mass of the head was still soft enough to absorb impacts. The axes were cooled to room temperature, before being placed back into the forge at 500° Fahrenheit for one hour to temper. The axe heads were then left out to fan cool, finishing the process. It is important to note that the shafts of the axes underwent the normalization and tempering process but were not quenched.

After the heat treatment was complete and the axe heads and shafts were cooled completely, Bay Cast welded to axe heads onto the shafts. Figure A.19.a shows an image of the forge setup that was used for the heat treatment process, while Figure A.19.b shows the axes after the heat treatment, NDT, and welding processes all took place.

Cleaning, Sharpening and polishing

Upon retrieval from Bay Cast, the axes had scale on the surface from the heat treat and quenching process; this was removed using a buffing wheel on an angle grinder. The blade sharpening of the axe was done by hand using a 400-grit diamond whetstone at approximately 22.5° on either side to an inclusive angle of 45°. This was to get the secondary bevel onto the axe head, and the tertiary bevel was also done by hand using a 1000 grit diamond whetstone at a 30° on either side. The angle was decided to be 45° to withstand heavy impact without sacrificing sharpness.

Final Weight Check

The last step before the final assembly was verification that the final weights were achieved. To do so we used a scale with a resolution of 0.001 kg and placed the welded axe assembly, the rondels, brass pins, and leather to be used for the grip on the scale. Design One weighed 0.13 kg overweight, and Design Two weighed 0.057 kg overweight. This sparked conversation amongst the team. Since Design Two was closer to the final max weight, it was decided that it would be the focus for competition. Design One would be used for comparison and testing. The three proposed solutions to decrease weight on Design Two were, first shrink both rondels, remove the bottom rondel and use a leather pummel or leather strap, or lastly, to remove the top spike completely.

The team decided to remove the bottom rondel and change the original design of the leather grip to create a cap on the bottom and a ring that would provide support, like how a rondel would function. To do this, the bottom profile was cut out as well as a single strap for support; these were all stitched using continuous loops to tie the bottom strap and bottom cap in place. With this modification the axe was now 0.057 kg underweight which would be made up in epoxy used during final assembly.

Fabrication – Shaft Assembly

Once all verifications were done and all the pieces for the shaft were individually made, the next task was to assemble them all using a 2-part epoxy, onto the cast shaft. First the ½“ portion of the cast shaft was scuffed with 80 grit sandpaper and wiped clean, then the epoxy was mixed and liberally applied. The top rondel was placed on, then the wooden handle. These components were then clamped in place and left to sit for 24 hours.

Once the epoxy had cured, the pilot holes that were drilled in the wooden handle were used to drill through the cast shaft. Once more, the 2-part epoxy was mixed, and the brass dowels were coated, then placed in location. The last step was to coat the inside of the leather grip and brass pins to slide it into place. This was then set for 24 more hours to fully cure. The completed axe, which is shown on the title page, was tested and submitted for shipment on Friday, March 27, 2026.

References

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[6] *Steel Casting Mechanical Properties David Poweleit & Raymond Monroe*, www.sfsa.org/sc3/downloads/Steel%20Casting%20Properties.pdf. Accessed 23 Mar. 2026.

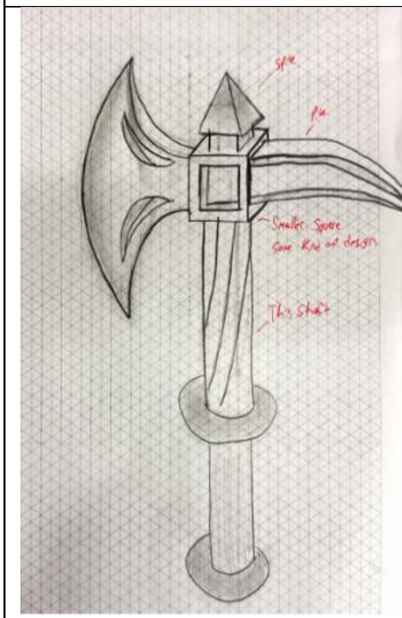
[7] ASM International. (2009). *Casting Design and Performance*. ASM International

[8] "Standard Guide for Magnetic Particle Testing." *E709*, store.astm.org/e0709-21.html. Accessed 22 Mar. 2026.

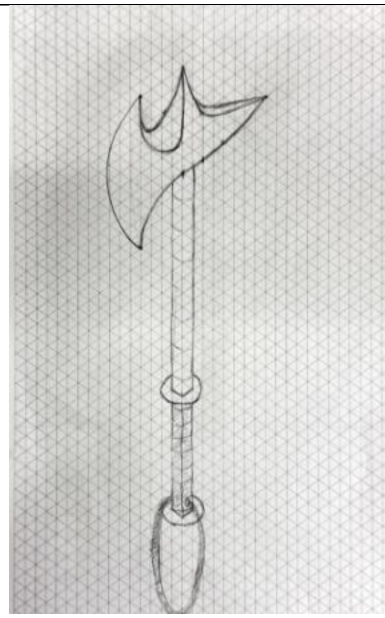
Appendix A

Figure A.1 “Horseman’s Ax of Cardinal Ippolito de’ Medici (1511–1535) ”[3]

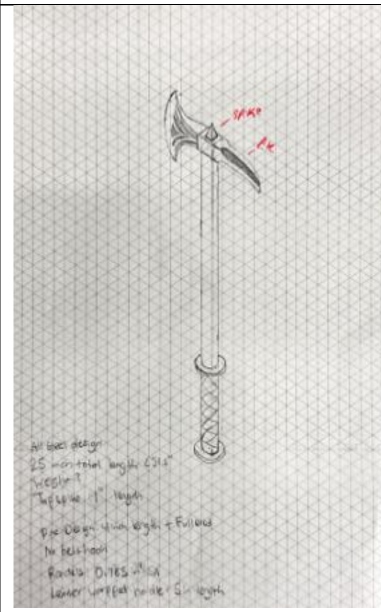
Concept 1



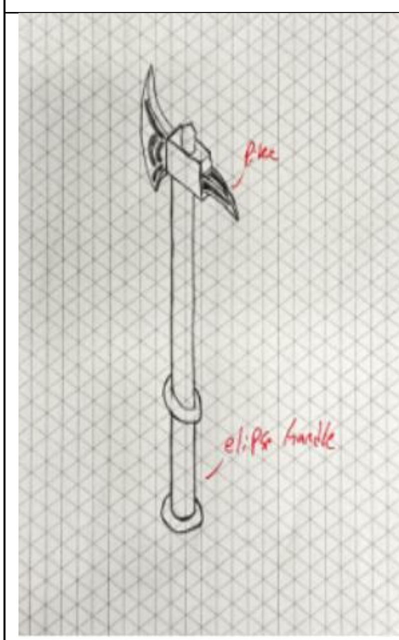
Concept 2



Concept 3



Concept 4



Concept 5

Concept 6

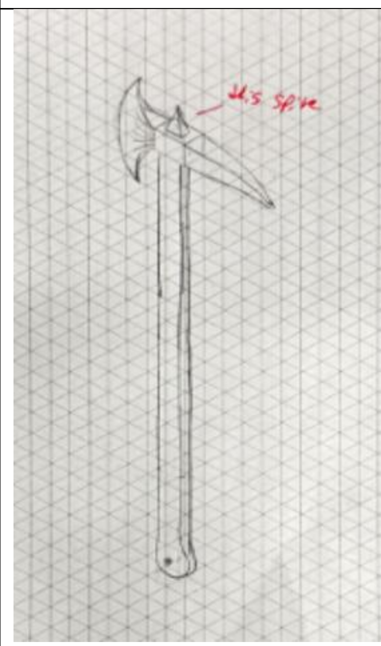


Figure A.2 Horseman's Axe Concept Sketches

Table A.1 Product Needs

Specification	Product Need
1	Axe fits competition weight requirement
2	Axe fits competition length requirement
3	Axe looks finished/complete
4	Axe is historically accurate
5	Axe is balanced in weight
6	Axe handle has good feel/ergonomic
7	Axe is created using casting processes
8	Axe can withstand impact/stress testing
9	Axe has minimal fabrication/machining
10	Axe can be finished with minimum economic concern

Table A.2 Design Specifications

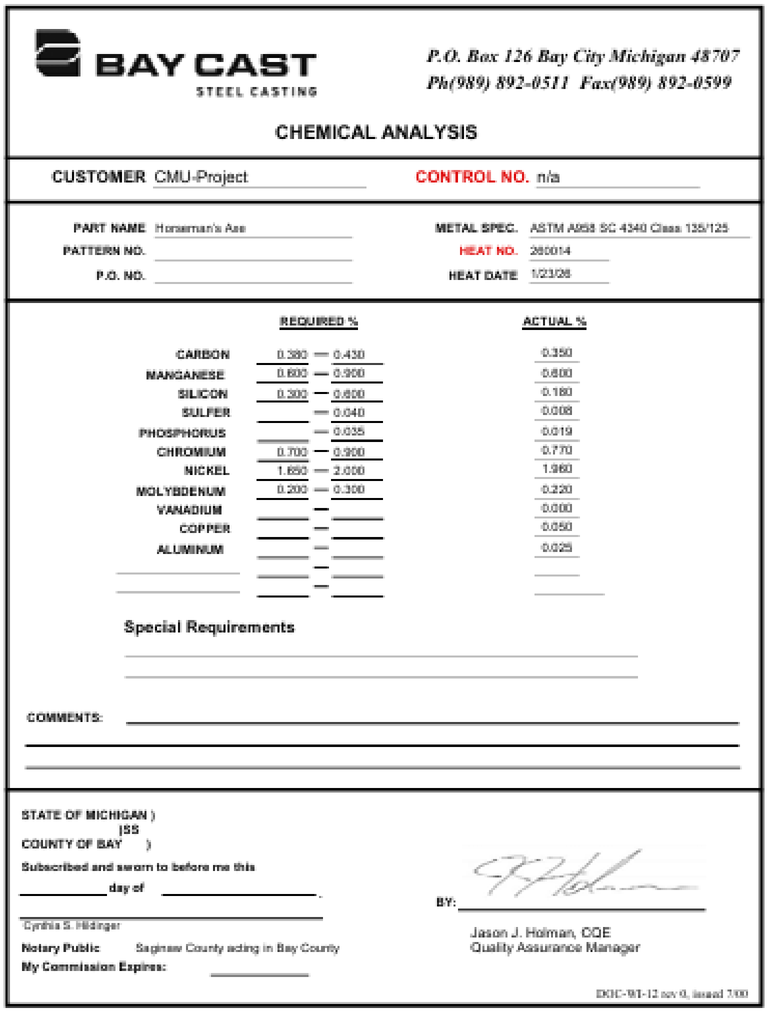
Specification	Need(s) Met	Metric	Importance	Units
1	1,5,6,9,10	Axe weighs less than 3.3 lbs	5	lbs
2	2,4,5,6,10	Axe is less than 31.5 " in length	5	"
3	7,10	Castable Design (extra material, fillets, rounded corners, etc.)	5	Yes/No
4	7,8,9,10	Minimal material removed in fabrication	4	lbs
5	3,4,5,6,7,10	Handle material	3	Material
6	8	Strong axe head	5	PSI
7	3,4,5,6	Reasonable handle size	3	"
8	3	Sword is Aesthetically Pleasing	2	Opinion
9	10	Accessible materials	3	Opinion
10	4,5,6,8	Pike Length	3	"

Table A.3 Scoring of Design Concepts

Concept		1		2		3	
Spec	**Importance**	Eval. Score	Weight Score	Eval. Score	Weight Score	Eval. Score	Weight Score
1	5	4	20	4	20	4	20
2	5	5	25	4	20	5	25
3	5	4	20	3	15	4	20
4	4	3	12	5	20	4	16
5	3	5	15	5	15	5	15
6	5	4	20	5	25	5	25
7	3	3	9	5	15	5	15
8	2	5	10	5	10	4	8
9	3	5	15	5	15	4	12
10	3	4	12	4	12	4	12
Sum			158		167		168
Concept		**4**		**5**		**6**	
Spec	**Importance**	Eval. Score	Weight Score	Eval. Score	Weight Score	Eval. Score	Weight Score
1	5	4	20	3	15	5	25
2	5	5	25	5	25	4	20
3	5	4	20	4	20	2	10
4	4	4	16	4	16	4	16
5	3	5	15	5	15	4	12
6	5	5	25	5	25	4	20
7	3	5	15	4	12	5	15
8	2	5	10	5	10	4	8
9	3	5	15	5	15	4	12
10	3	4	12	5	15	4	12
Sum			173		168		150

Table A.4 Effect of Alloying Element on Steel[6]

Element	Effect on Steel Properties
Carbon (C)	Increases strength but decreases toughness and weldability (most common and important)
Manganese (Mn)	Similar, although lesser, affect as carbon
Silicone (Si)	Similar to carbon but with a lesser effect than manganese (important for castability)
Nickel (Ni)	Improves Toughness
Chromium (Cr)	Improves Oxidation Resistance
Molybdenum (Mo)	Improves hardenability and high temperature strength
Vanadium (V)	Improves high temperature strength
Tungsten (W)	Improves high temperature strength
Aluminum (Al)	Reduces the oxygen or nitrogen in the molten steel
Titanium (Ti)	Reduces the oxygen or nitrogen in the molten steel
Zirconium	Reduces the oxygen or nitrogen in the molten steel
Oxygen	Negative effect by forming gas porosity
Nitrogen	Negative effect by forming gas porosity
Hydrogen	In high quantities, results in poor ductility
Phosphorus	Can increase strength but drastically reduces toughness and ductility
Sulfur	Reduces toughness and ductility



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CHEMICAL ANALYSIS

CUSTOMER CMU-Project **CONTROL NO.** n/a

PART NAME Horseman's Axe
PATTERN NO.
P.O. NO.
METAL SPEC. ASTM A958 SC 4340 Class 135/125
HEAT NO. 260014
HEAT DATE 1/23/26

	REQUIRED %		ACTUAL %
CARBON	0.380	0.430	0.350
MANGANESE	0.600	0.900	0.600
SILICON	0.300	0.600	0.180
SULFER		0.040	0.008
PHOSPHORUS		0.035	0.019
CHROMIUM	0.700	0.900	0.770
NICKEL	1.650	2.000	1.960
MOLYBDENUM	0.200	0.300	0.220
VANADIUM			0.000
COPPER			0.050
ALUMINUM			0.025

Special Requirements

COMMENTS:

STATE OF MICHIGAN)
)SS
COUNTY OF BAY)
Subscribed and sworn to before me this
_____ day of _____.

Cynthia S. Hildinger
Notary Public Saginaw County acting in Bay County
My Commission Expires:

BY:
Jason J. Holman, CQE
Quality Assurance Manager

DOC-93-12 rev 0, issued 7/00

Figure A.3 Material Chemical Analysis of 4340 Steel for Casting

Figure A.4 Preliminary Axe Head CAD Models

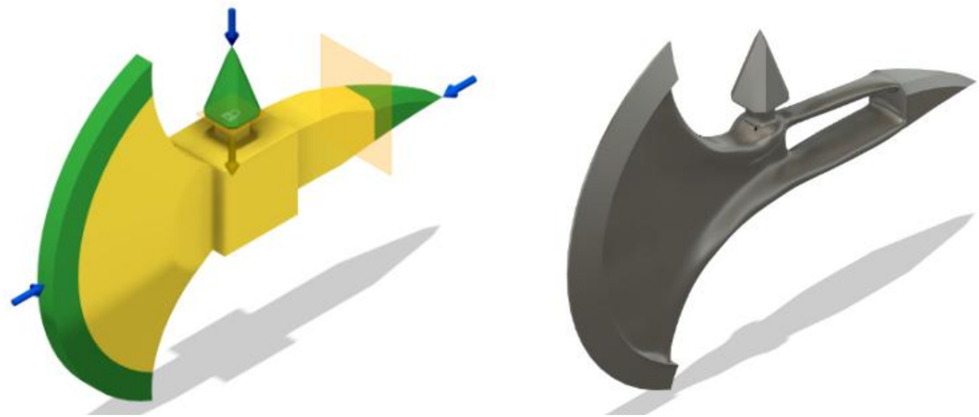


Figure A.5 (a) Topology Axe Loads (b) Topology Axe Head

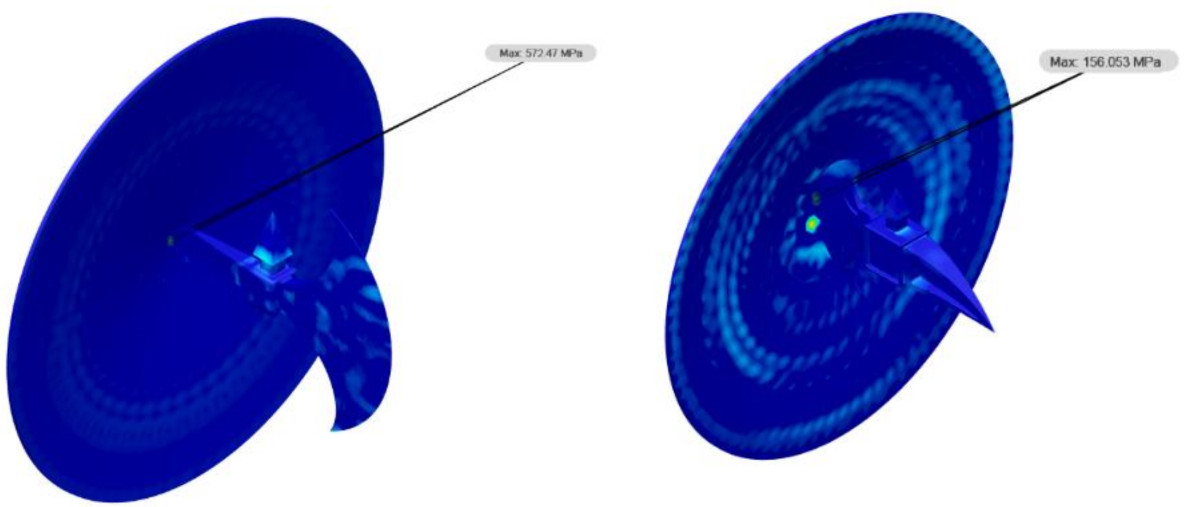


Figure A.6 Pike and Blade Non-Linear Impact Simulations

Table A.5 Non-Linear Impact Simulation Results and Comparison

	Axe 1		Axe 2	
	Blade	Pike	Blade	Pike
Max Stress (MPa)	125.25	572.47	156.05	1254.83

Table 2: Common Cast Steel Properties

ASTM A915 (Grade)	Minimum Low Strength Tensile (ksi) Yield (ksi) Elongation (%)	Minimum High Strength Tensile (ksi) Yield (ksi) Elongation (%)	Median Composition Ideal Critical Diameter (inches)
SC4340	90-60-20	210-180-4	8.0

Tensile Strength for 4340 Steel: 210 ksi = 1447.9 MPA

Maxmimum Recorded Stress: 1254.83 MPA

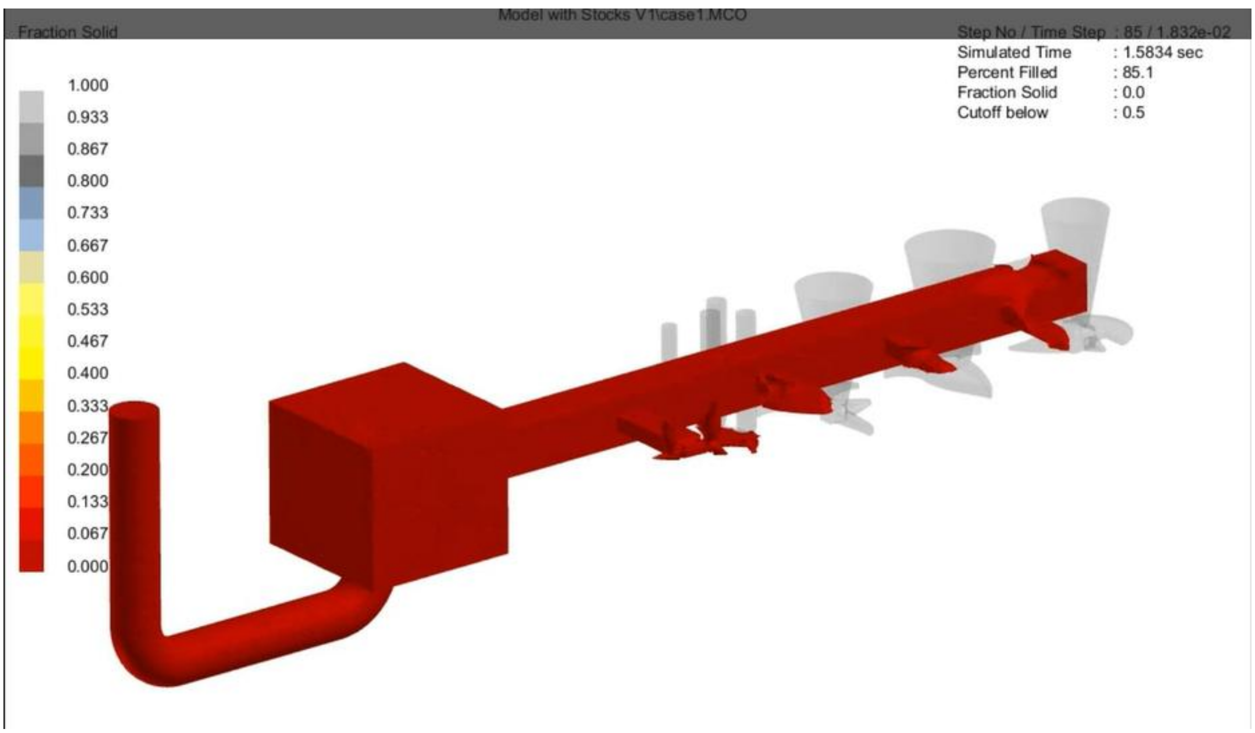


Figure A.7 QuikCAST Flow Simulation of Sand Casting

Figure A.8 Binder Jet 3D Printed Sand Molds

Figure A.9 Mold and Runner System in Sand Mold Building

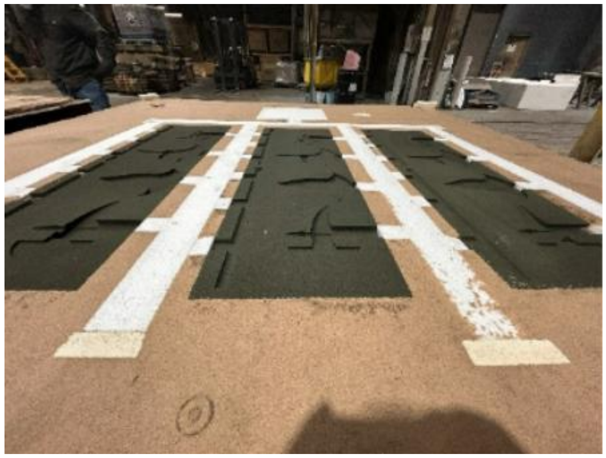


Figure A.10 Surface of Completed Drag for Sand Casting

Figure A.11 Axe Heads and Handles Pre-Machining

Figure A.12 Design One Axe Head Post Milling Processes

Figure A.13 Axes Pre-Welding and Heat Treatment

Figure A.14 Manufacturing of Rondel for Handle Assembly

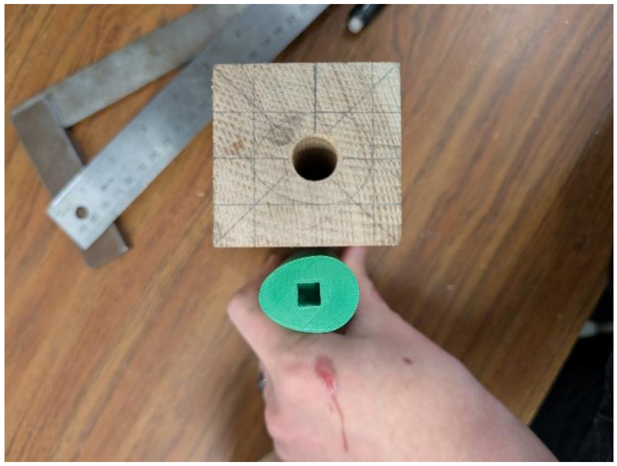
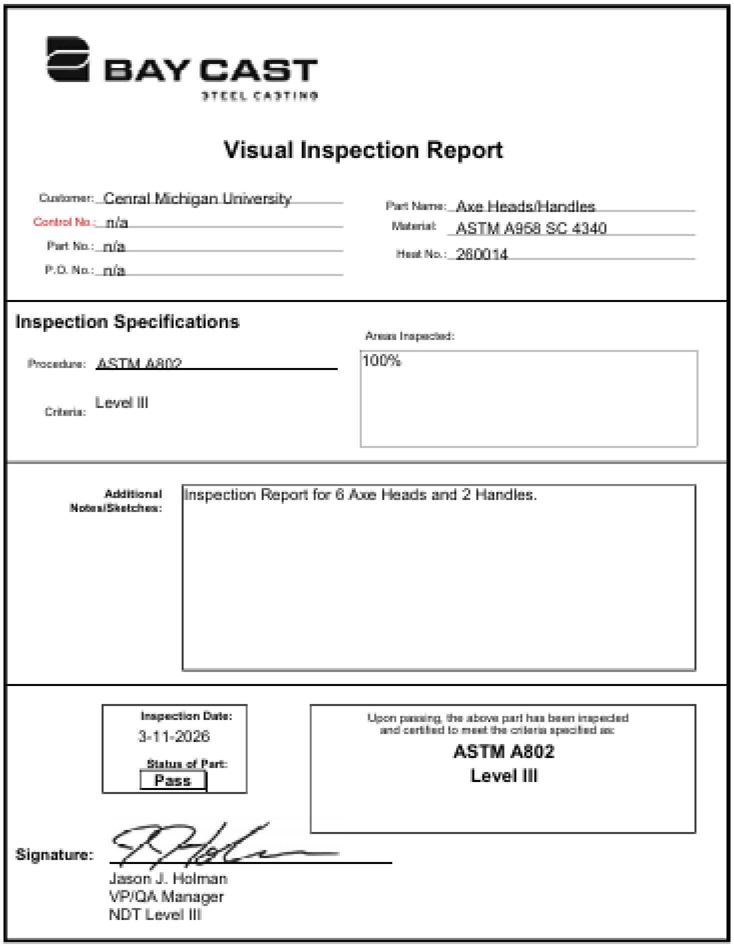


Figure A.15 Wooden Handle and Prototype Comparison

Figure A.16 Leather and Wooden Handle Addition Assembly


BAY CAST
STEEL CASTING

Visual Inspection Report

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

Inspection Specifications

Procedure: ASTM A802
Criteria: Level III
Areas Inspected: 100%

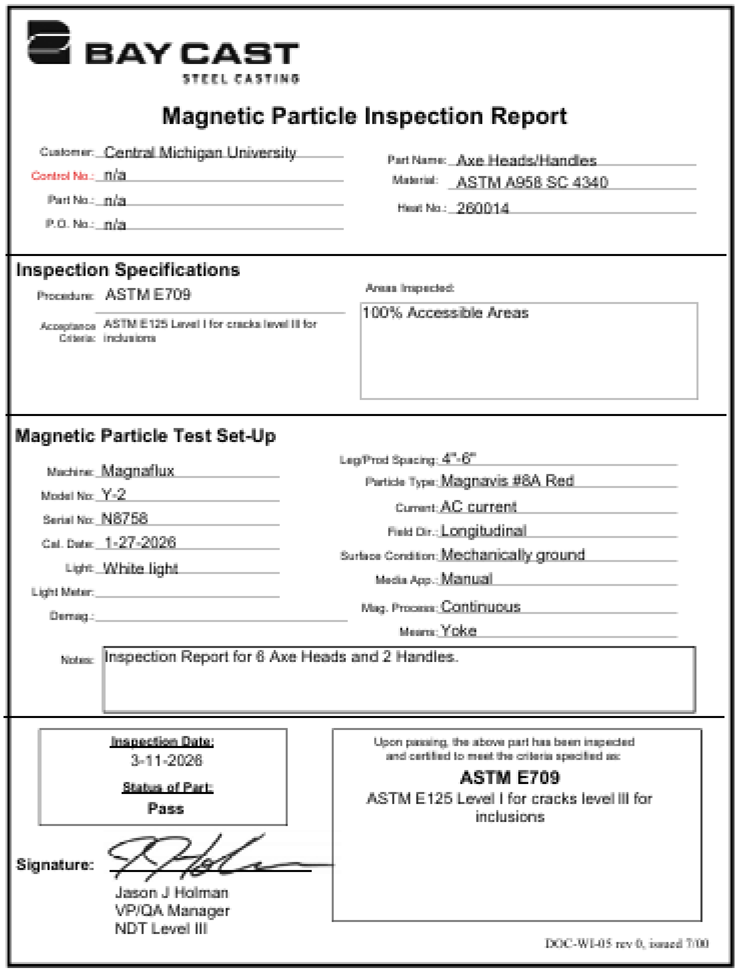
Additional Notes/Sketches: Inspection Report for 6 Axe Heads and 2 Handles.

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

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

Signature:
Jason J. Holman
VP/QA Manager
NDT Level III

Figure A.17 Visual Inspection Report from Bay Cast



BAY CAST
STEEL CASTING

Magnetic Particle Inspection Report

Customer: Central Michigan University
Control No.: n/a
Part No.: n/a
P.O. No.: n/a

Part Name: Axe Heads/Handles
Material: ASTM A958 SC 4340
Heat No.: 260014

Inspection Specifications

Procedure: ASTM E709
Acceptance Criteria: ASTM E125 Level I for cracks level III for inclusions

Areas Inspected: 100% Accessible Areas

Magnetic Particle Test Set-Up

Machine: Magnaflux
Model No: Y-2
Serial No: N8758
Cal. Date: 1-27-2026
Light: White light
Light Meter:
Demag.:

Leg/Prod Spacing: 4"-6"
Particle Type: Magnavis #8A Red
Current: AC current
Field Dir.: Longitudinal
Surface Condition: Mechanically ground
Media App.: Manual
Mag. Process: Continuous
Means: Yoke

Notes: Inspection Report for 6 Axe Heads and 2 Handles.

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

Upon passing, the above part has been inspected and certified to meet the criteria specified as:
ASTM E709
ASTM E125 Level I for cracks level III for inclusions

Signature:
Jason J Holman
VP/QA Manager
NDT Level III

DOC-WI-05 rev 0, issued 7/00

Figure A.18 Magnetic Particle Inspection Report from Bay Cast

Figure A.19 (a) Forge Used for Heat Treatment of Axes (b) Post Heat Treatment Axes