SFSA Cast In Steel 2026 – Horseman's Axe

Technical Report

University of Wisconsin- Madison – Mad Badger Metalcasters

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Abstract

This report presents the design, simulation, manufacturing, and heat treatment of a functional and aesthetically inspired horseman’s axe developed for the Steel Founders' Society of America Cast in Steel Competition. 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 axe was engineered to balance lightweight construction, durability under repeated impact, and effective mass distribution for one-handed use on horseback. A custom CAD model was created with a focus on structural integrity, including an optimized eye geometry for secure handle attachment and smooth transitions to minimize stress concentrations.

4140 alloy steel was selected due to its favorable combination of hardness, toughness, and fatigue resistance. Casting performance was evaluated and refined using MagmaSoft simulations, which guided the optimization of gating design, filling behavior, and solidification to reduce turbulence, porosity, and hot spots. The final design achieved controlled flow characteristics and effective directional solidification.

Investment casting patterns were produced using Polycast PLA, followed by ceramic shell formation and metal pouring at approximately 2900°F. Post-processing included gate removal, grinding, and surface finishing prior to heat treatment. A controlled heat treatment process consisting of normalization, austenitizing, oil quenching, and double tempering produced a martensitic microstructure with a hardness of 46.1 HRC, ensuring a balance of strength and toughness.

The white ash handle was carved to be comfortable to hold with the pig leather wrapped handle and the Australian timber oil to give it a nice color. Electroetching with salt water and vinyl cutouts created the final blade etch design.

The final product through non-destructive testing demonstrates successful integration of historical design principles with modern casting and materials engineering practices, resulting in a durable, functional axe with minimized defects and optimized performance.

Historical Research

The horseman’s axe in its history is designed for wielding with one hand while on horseback for battle. Impact weapons were sought after for combat as armor improved over time, and the axe utilized both a blade and pick edge: the blade being used for swinging overhead and the pick used for penetrating armor. Some in history are also crafted in a primarily aesthetic manner to be given to figures of authority [1], but our axe will be aiming for both aesthetics and function. For the best mechanical properties in terms of repeated usage, comfortability, and overall functionality, the axe assembly had to be lightweight, tough for repeated impact for both the blade and pick ends, and model a proper weight & moment of inertia distribution to fully utilize the moment arm for swinging.

CAD Modeling

The first part of the axe head that was designed was the eye, since above all else, the axe head must maintain a strong connection to the wooden handle. In order to accomplish this, the hole for the eye was rectangular in shape in order to prevent the head from rotating on the handle. The hole also extended all the way through the head and was given an hourglass-shaped profile, which would allow the handle to be firmly wedged in place.

Next, the profiles of the blade and the rear spike were designed. Inspiration was taken from historical examples, but ultimately the design was an original creation that was proportional in size to the existing eye. Smooth transitions were made to ensure strength and avoid any undue stress concentrations.

The design was also scaled to a proper portion for both size requirements for our 3D printers and estimated weight via material assignment in CAD to ensure we are within the mass constraints. The final dimensions were measured at 6.96 inches tall, 8.31 inches long, and 1 inch wide at the handle housing. The estimated weight was 1.28 lbs using Solidwork's mass properties feature.

Finally, all edges and corners were filleted to avoid making sharp interior corners in the investment mold, which may have acted as stress concentrations and cracked the mold.

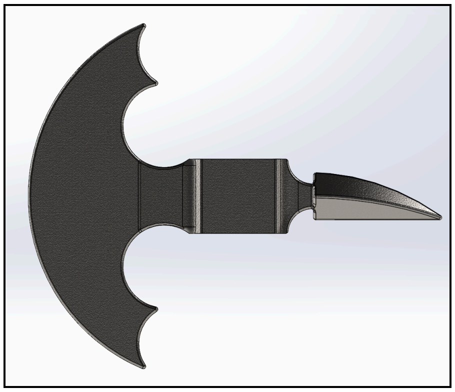

Figure 1. Final CAD Model of axe head

Alloy Selection

4140 steel was selected for the axe head due to its strong combination of hardness, toughness, and durability, which are essential properties for a striking and cutting tool. An axe must withstand repeated high-energy impacts while maintaining a sharp edge, and 4140 steel provides the material characteristics needed to meet these demands.

One key advantage of 4140 steel is its moderate carbon content of approximately 0.40%. This level of carbon provides sufficient hardness potential for a cutting edge while still maintaining good toughness. As a result, the steel can absorb significant impact energy without fracturing or chipping, which is important for tools that experience frequent shock loading.

The presence of alloying elements such as chromium and molybdenum further improves the steel's mechanical performance. These elements strengthen the iron structure and allow 4140 to reach higher strength than plain carbon steels with similar carbon content. After proper heat treatment, the steel achieves high tensile strength, helping prevent bending, warping, or permanent deformation during repeated use.

Another important property of 4140 steel is its excellent hardenability. Compared with plain carbon steels, 4140 can achieve both full hardness with a slower cooling rate more easily and a higher hardness deeper towards the center of the material due to its alloying elements of Chromium and Molybdenum delaying phase transformations during cooling. This allows thicker sections, such as an axe head, to develop a more uniform hardness throughout the material rather than only at the surface by maintaining its martensite formation.

During material selection, other options were also evaluated, including high-carbon tool steel grades and alternative martensitic alloys such as 4150 steel and AR450 steel. Tool steels offered excellent hardness and wear resistance, but their increased brittleness made them more susceptible to chipping under repeated impact. Similarly, 4150 steel, with its higher carbon content, could achieve greater hardness but at the expense of reduced toughness, increasing the likelihood of cracking under shock loading. AR450 steel, while highly resistant to abrasion, is primarily designed for wear applications and does not provide the same balance of impact resistance and toughness required for a striking tool.

Finally, 4140 steel offers good wear, impact, and fatigue resistance. Carbides formed during heat treatment improve resistance to abrasive wear and edge dulling, helping the blade stay sharp longer. The combination of strength and toughness also allows the material to withstand thousands of repeated strikes without cracking, making it well suited for durable tools like axes.

Casting Process, Simulations & Gating Design

For our casting process, we selected investment casting for our axe. The process produces near-net shape parts at high accuracy, provides a smooth surface finish, and can help reduce post-processing. It is also well-suited for our axe's challenge with thin geometry, curves and transitions with more controlled metal flow for fewer defects.

For our simulations we utilized MagmaSoft for theoretical results from our gating sizes and design, along with optimizing the filling and feeding process for a robust axe. For the filling results, we wanted to minimize the turbulence and waterfalling for our axe to ensure a consistent flow pattern into our mold. Picking a proper melt temperature was also crucial to maintain above liquidus temperature so that the full mold could fill. For feeding, we wanted to have minimal hot spots in our part, and for any that would occur to be as far away from critical stress areas as possible. We also wanted to ensure that the sprue and gates stayed hot enough to feed the mold so the feeding would not be cut off. For solidification, we also wanted to have gate locations in ideal spots on the axe where it would impact hard-to-reach spots for feeding the most and aid in directional solidification for the axe blade and pick. On top of optimizing the pouring and solidification process, we also wanted to minimize post-processing.

With these criterias, objectives, and constraints, the initial gating designs for the axe are shown in Figure 2. The bottom gate was located at the neck of the axe blade for directional solidification and assistance with feeding to the thin blade section. The top gate was chosen to feed the pick end and draw shrinkage away from the neck of the pick, where stresses are expected to be significant. The initial runs from Figure 2(Left) showed risk for hot spots in the blade and porosity in solidification due to lack of feeding. Figure 2(Right) was designed to counteract this flaw with larger gates and a third gate directly attached to the blade. Although this showed a stronger feeding for minimizing hot spots and porosity, there was concern for warping and improper solidification with two large hot spots splitting the blade's solidification direction. The pick also had porosity at its surface.

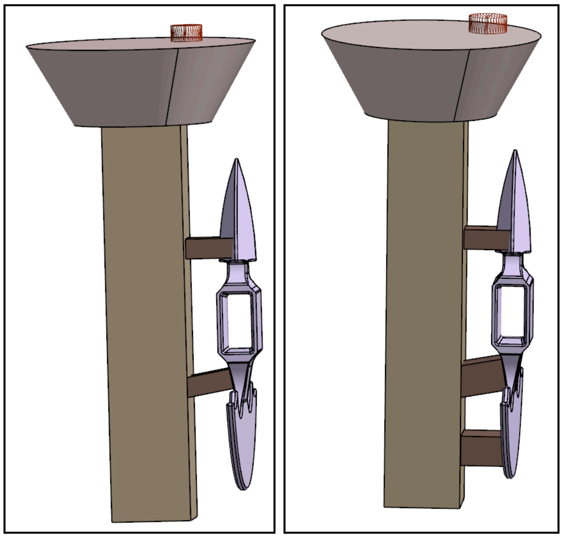

Figure 2. Initial iterations of gating design for axe. Left: Iteration with smaller gate sizes. Right: Iteration with larger gate sizes with a 3rd gate attached to the blade.

The final gating design for the axe is shown in Figure 3. The gate sizes were maximized on the mated faces for feeding and were not increased further to lessen the post-processing work needed for aesthetics and functionality. Figures 4-7 highlight key takeaways from our simulation results for filling and feeding, such as the sprue and gate temperature for feeding, minimizing turbulence, hot spots, and porosity.

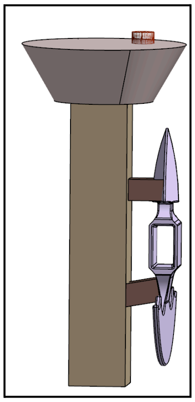

Figure 3. Final iteration of the gating design.

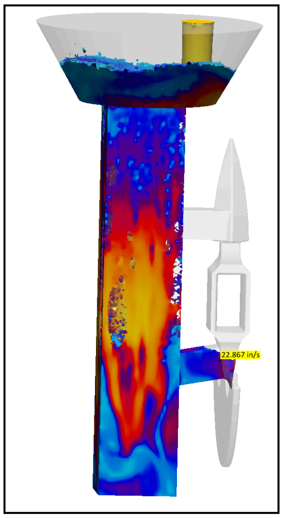

Figure 4. Velocity results for entry of gate. Our highest velocity was 22.867 [in/s], which is near our optimal goal of 20 [in/s] for minimizing turbulence.

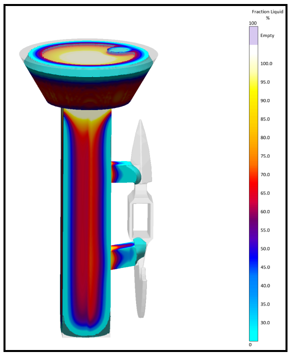

Figure 5. Fraction liquid results near full solidification of the part. When observing the animation, no isolated hot spots within the part occurred, and the sprue & gates maintained temperature to prevent any cutoffs at the gate.

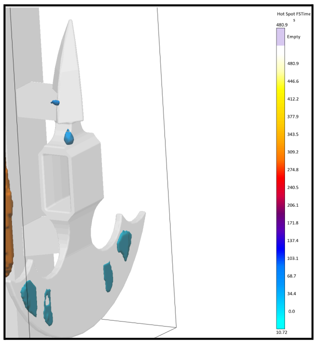

Figure 6. Hot Spot FSTime results. This software characteristic shows thermally isolated regions that remain liquid longer in comparison to the surrounding regions. The simulation shows some potential shrinkage areas within the blade ends and at the gate-to-pick connection.

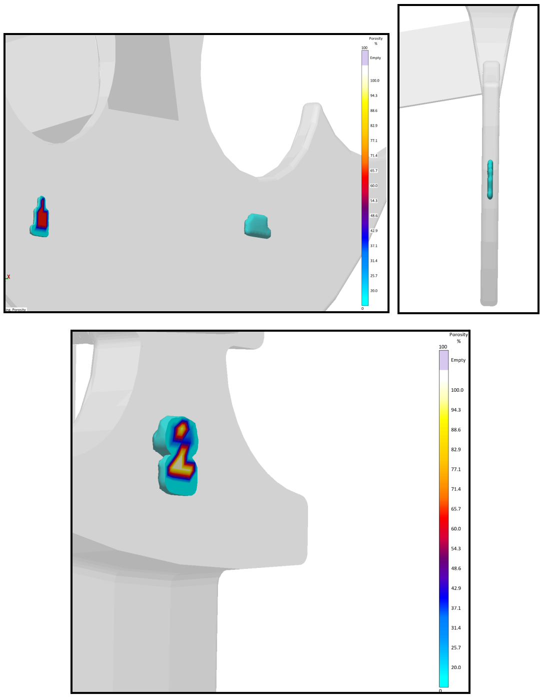

Figure 7. Porosity Results. The left shows a section view showing porosity gradient from 20-100%. Left: section view of porosity in blade. Right: Thickness of porosity width-wide for the blade. Bottom: Section view of porosity in the neck of the pick. Although almost guaranteed to exist, the areas are small and not located at a critical stress area nor at the surface, as displayed.

The pouring temperature was selected at 2950℉ which is roughly 370 degrees higher than its liquidus temperature[6], and the shell temperature was selected to be 1700℉ for a preheat temperature. The pouring time was also set for 4.5 seconds. Our results for our final iteration show an acceptable degree and location of porosity and filling characteristics.

3D Printing

Once our axe and gates were designed, the part was 3D printed using Polycast PLA on an H2D Bambu Lab printer. Polycast is a natural PLA filament designed specifically for investment casting; it provides excellent printability and surface finish, along with a clean burnout that typically leaves an ash residue of <0.003% by weight. To achieve a smooth finish, we used a 0.08mm "Extra Fine" preset and normal supports with a 45° threshold angle. Our team postprocessed these prints with isopropyl alcohol smoothing and manual sanding.

Gating & Sprue Assembly

We set up our gating system with Metaltek at their facility. After coming prepared with all of our 3D printed axe heads, we used sealing wax to fill in any gaps in the prints for a better surface finish as seen in Figure 8.

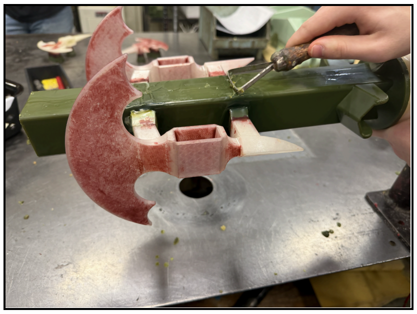

Figure 8. Sealing wax on axe heads

Before connecting our printed axe heads to the tree, we ensured there would be enough room for Metaltek to cut the metal axes off with no damage. The safest precaution to do this was to extend our gates with more wax. We melted the end of wax cubes and attached them to our previous gates with an adhesive material. These wax pieces were cut to fit our gates with as little overlap as possible, so no metal would get caught while pouring. After preparing the axes, we attached them to the sprue by melting and bonding wax with adhesive and heat. We added cone-shaped wax vents and a side wax tube to allow air and gases to escape, preventing porosity during metal pouring.

Figure 9: picture of axe heads on table

Shell Building

After our tree was built, Metaltek dipped the assembly repeatedly in a liquid ceramic zircon-silica slurry. A pre-heat of the shell for the mold at 1800℉ is fired to burn off any wax remnants and sinter the ceramic.

Figure 10. Ceramic coating for tree assembly

Pouring

The metal was poured at 2900℉ into the pre-heated shells. From the two pours, there was a roughly timed average of ~3.25 seconds for pouring times.

Finishing

After receiving the axes from Metaltek, we inspected them for surface defects. We removed the gates using a hacksaw, then used a 60-grit belt sander to eliminate excess material. Further smoothing was done with 60- and 120-grit sanding on a belt sander and Dremel. Because the axe was underweight, we worked carefully to avoid removing too much material. We added a bevel to improve cutting, sharpening, and penetration before heat treatment, and finished with 120-grit sanding to reduce more difficult post-treatment work.

Figure 11. Photos of the axe head. Left: As-Cast with the sprues removed. Right: Axe after post-processing.

Heat Treatment

Heat treatment was conducted in-house using parameters from the ASM Handbook for low-alloy steels. The process included normalizing at 1600℉ for 1 hour (air cooled) to improve microstructural uniformity, followed by austenitizing at 1570℉ for 1 hour. The part was then oil quenched to form martensite while minimizing distortion and cracking. Finally, it was tempered twice at 400℉ for 3 hours each to reduce internal stresses and improve toughness. These parameters theoretically resulted in a target hardness of ~50–55 HRC, balancing strength and toughness for the axe.

Figure 12. Post-Heat treatment axes

To verify our heat treatment process, we had also treated excess gate material that was hack sawed off before to give us a sample part to check our microstructure. It was important for us to use the same batch of 4140 steel instead of a random part of the same alloy, as the same batch will contain roughly the same tolerances for alloy content. Upon grinding and polishing the sample part, we were able to analyze under a microscope and confirm that our part reached the microstructure we were aiming for, as shown in Figure 13.

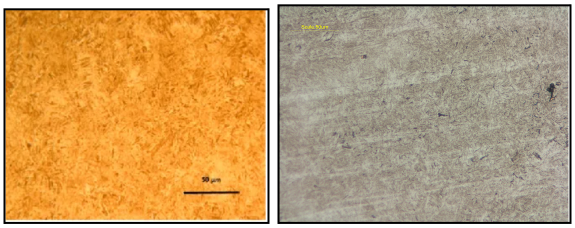

Figure 13. Photos of 4140 steel microstructure with a 50 micrometer scale. Left: Online photo of martensite microstructure for 4140 steel[5]. Right: Scanned photo of heat treatment sample's microstructure.

We also tested the HRC of our part using a Buehler Macromet 2 hardness tester. With our sample part, we tested a 46.1 HRC value, which is lower than our expected value of 50-55 HRC. One theory is that our process didn't involve a carb restore, thus exposing the surface to oxygen and creating a softer outer layer the machine tests on.

Handle

Wood was selected as the handle material, as opposed to steel, in order to reduce weight and absorb shock for the comfort of the user. Specifically, white ash was chosen since it is a strong, durable wood that is suitable for tool handles and is commonly used to make wooden baseball bats.

First, a rough piece of wood was split out of the heartwood of a white ash log. This was done to ensure that the piece of wood that would become the handle had no knots, defects, or grain runout, thus resulting in the strongest piece of wood possible. After hewing and planing the wood so that it was straight and square, the end of the handle was tapered so it slid snugly into the eye of the axe head, and the rest of the handle was shaped so it had an oval cross section for comfortable wielding and easy control. Finally, two perpendicular slits were cut in the end so the handle could be wedged securely onto the head.

Once the wood handle was prepared, we finished it off with Australian timber oil for an aesthetic stain and protection. We also wrapped pig leather around the handle for aesthetic and grip and fastened it with brass pins.

Figure 14. Picture of wood handle

Polishing

We proceeded with removing oxide buildup caused by the heat treatment from the axe's surface with wire brushes followed by 120-1200 grit sandpaper. More breaks were taken for the post-heat treated part during the sanding and polishing process to prevent overheating of the part that would disrupt our heat treatment. The blade end's bevel was sharpened by the belt sander and finished off with a wet stone.

Assembly

Once the axe was fully polished and the handle was prepared, we moved forward with assembly. The axe head was ensured to be level on the handle before the handle was driven in. Wedges with wood glue applied were inserted into the handle slits and forced into the wood, causing it to expand outward. The wedges were then sawed and sanded off for a finer finish at the handle top.

Electro Etching

The team opted to electroetch our blade as an appeal to a tarnished, more historic appearance. A design was created for the electroetching and vinyl cut. This vinyl was then carefully transferred and applied to the surface of the axe blade smoothly to negate air bubbles. The electroetching was done by attaching alligator clips to a 9V battery, where the positive end was clamped to the blade and the negative end was clamped to a cotton swab. The swab was then dipped in salt water solution (in a water to salt ratio of 4:1) and applied to the face of the axe, rubbing slowly. Swabs were changed as necessary and the saltwater was continuously applied as evenly as possible across the entire area spanned by the design. The vinyl decal was then carefully removed from the axe using tweezers, and the surface of the axe was rubbed with denatured alcohol to avoid corrosion and rusting. This process was then repeated on the other face of the axe blade.

Figure 15. Picture of Etch design on axe

Non-Destructive Testing

It was time to put our axe to the test. Our team gathered fruits, cans, and bottles to test the sharpness of both the axe and pick. We also tested the toughness of our axe with an impact test on a wood palette to great success.

Figure 16. Action shot of Mathias cutting open a soda can.

Results

The total length of our axe was 27.875 inches, and our weight was 2.06 lbs even. The cumulative materials used were white ash for the handle, pig leather for the straps, brass for the handle pins and 4140 steel for the axe head. These parameters are successfully within the competition constraints of 31.5 inches and 3.3 lbs.

Sources

[1]"Horseman's Ax of Cardinal Ippolito de' Medici (1511–1535)." *Italian - The Metropolitan Museum of Art*, 2021, https://www.metmuseum.org/art/collection/search/26548

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[3] "Heat Treating of Irons and Steels"ASM Handbook Volume 4D, *Jon L. Dossett; George E. Totten*, 2014

[4] "Aisi 4140 alloy steel (UNS G41400)," AZoM, https://www.azom.com/article.aspx?ArticleID=6769 (accessed Mar. 27, 2026).

[5] L. Carvajal and A. Artigas, "monitoring heat treatments in steels by a non destructive ultrasonic method," Monitoring Heat Treatments in Steels by a Non Destructive Ultrasonic Method, https://www.researchgate.net/publication/319258695_Monitoring_Heat_Treatments_in_Steels_by_a_Non_Destructive_Ultrasonic_Method (accessed Mar. 27, 2026).