SFSA Cast In Steel 2026 – The horseman's axe Technical Report

Universidad Autónoma de Nuevo León – ***Melting Bears UANL***

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Acknowledgements

To the Academic and Industrial Community:

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Thank you all for your invaluable contribution to the excellence of this project.

Content

1. EXECUTIVE SUMMARY

The present report documents the comprehensive process of design, simulation, and manufacturing of a horseman’s axe, developed by the "Melting Bears" team from the Universidad Autónoma de Nuevo León for the SFSA Cast in Steel 2026 competition. This project arose as a technical and creative response to the challenge of reinterpreting a historical 15th-century weapon, integrating modern engineering methodologies with advanced metallurgical design principles. The design was grounded in the historical context of the European "Military Revolution" (1490–1500), a period during which the effectiveness of plate armor demanded the development of impact weapons capable of concentrating great force in small areas. The selected concept, a "crow’s beak" type axe, was parametrically modeled in SolidWorks to optimize mass distribution and ensure a balance that would favor energy transfer upon impact. As a critical validation phase, the SOLIDCAST tool was used to simulate metal filling and solidification, allowing the team to identify and mitigate possible defects such as porosities or hot spots before the actual casting. For manufacturing, AISI 4140 low-alloy steel was chosen for its high hardenability and excellent balance between toughness and impact resistance. The production process began with 3D printing the model and gating system in PLA, followed by green sand molding with refractory coatings to ensure optimal surface finish. After casting at 1600 °C, the piece underwent a rigorous heat treatment that included solutionizing at 850 °C, followed by water quenching and a final tempering at 550 °C for four hours. This thermal cycle was specifically designed to reduce internal stresses and adjust the material’s hardness, ensuring the axe could withstand severe dynamic loads without brittle failure. The final result is a component that harmonizes historical authenticity with the precision of contemporary engineering, demonstrating the viability of modern casting processes in the creation of high-performance tools.

2. INTRODUCTION

The Steel Founders' Society of America (SFSA) established the Cast in Steel competition to promote the development of engineering skills through the design and manufacture of steel components using casting processes, while integrating modern technologies and advanced analytical tools.

In the 2026 edition, the challenge focuses on the design and production of a horseman's axe, requiring teams to either replicate a historically accurate model or develop a reinterpretation grounded in 15th-century design principles. This framework not only encourages the application of technical competencies, such as computer-aided design (CAD), simulation, and casting process development, but also demands a rigorous understanding of historical functionality and constraints. Consequently, the competition fosters the integration of engineering analysis with historical authenticity, promoting solutions that balance performance, manufacturability, and realism.

To establish the design criteria for this project, it is essential to consider the historical context in which the horseman’s axe emerged. By the late fifteenth century, European warfare was undergoing profound transformation. Between 1490 and 1500, the rise of professional armies and the increasing dominance of pike and early firearm formations led to the gradual decline of feudal chivalry, which had defined military power for centuries. Warfare evolved into a more structured and technical discipline, driven by innovation, organization, and continuous adaptation.

Between 1490 and 1500, the landscape of European warfare underwent a profound transformation characterized by the decline of feudal chivalry and the ascendancy of professional armies structured around the innovative use of pike formations and early firearms. This period marks a critical phase in the so-called “Military Revolution,” during which the adoption of gunpowder weapons catalyzed changes in military organization, tactics, and the socio-political framework of warfare.

The traditional military paradigm, dominated for centuries by heavily armored knights and feudal levies embodying the ethos of chivalry, increasingly gave way to more technical and regimented forms of combat. Firearms such as the arquebus and muskets, although initially limited in accuracy and rate of fire, were rapidly integrated into infantry units. This introduction of firearms was paralleled by the development of dense pike formations, which served both defensive and offensive roles in countering enemy cavalry and maintaining battlefield cohesion. The combination of pikemen and arquebusiers, often used in coordinated volleys, dramatically reduced the battlefield effectiveness and prestige of mounted knights, who had previously constituted the core of feudal military power.

These evolving tactical formations demanded disciplined, trained soldiers capable of operating within complex battle orders rather than the loosely assembled feudal levies led by noble cavalry. The necessity of managing firearms and the associated logistics—ammunition supply, training, and coordinated firing—further incentivized centralization and the emergence of standing armies under princely or royal authority. Larger, professional forces replaced the smaller, more fragmented contingents that characterized earlier medieval warfare, aligning military success with bureaucratic efficiency and technical innovation rather than individual valor or chivalric ideals.

This transition was not isolated but part of a broader European military revolution identified by historians such as Geoffrey Parker, who emphasized that the penetration of firearms and artillery led to the rise of centralized states capable of sustaining larger armies and conducting protracted sieges. The growing reliance on gunpowder weapons diminished the battlefield dominance of the chivalric knight and the feudal military system, subordinating the aristocratic warrior's role to the rationalized, state-controlled machinery of war.

Moreover, the tactical innovations during 1490–1500 illustrate the continuous adaptation and experimentation that defined early modern warfare. Infantry units equipped with pikes and firearms became the linchpins of battle, enabling armies to impose firepower and discipline against traditionally dominant cavalry. This development laid the groundwork for modern military doctrines where technological proficiency, organizational skill, and centralized command increasingly dictated the outcomes of conflicts.

In sum, the decade between 1490 and 1500 encapsulates the transformation of warfare from a chivalric, valor-driven activity into a structured, technical discipline characterized by professional infantry armed with pikes and early firearms. The decline of feudal chivalry corresponded with this shift, as military power became inseparable from innovation, organization, and the capacity for continuous adaptation under the auspices of emerging centralized states—a change that irrevocably altered the nature of European military and political power. This synthesis aligns with the scholarly understanding of the period's military evolution as integral to the broader "gunpowder revolution" that reshaped early modern Europe (Ágoston, 2014; Chase, 2003).

This transition is exemplified by the events of September 12, 1494, when Charles VIII of France met Ludovico Sforza in Asti prior to the French invasion of Italy, marking the beginning of the Italian Wars. These conflicts illustrate the intersection between medieval and Renaissance warfare, in which traditional knightly combat coexisted with emerging military systems and technologies.

Within this evolving environment, the horseman's axe represents a critical adaptation in weapon design. During the first half of the 15th century, prior to the widespread adoption of firearms, this weapon served both symbolic and functional purposes. Its reduced handle length and balanced geometry enabled effective one-handed use on horseback, while its concentrated mass and cutting edge allowed for high-impact strikes capable of damaging armor and destabilizing opponents. In some configurations, the inclusion of a rear spike or hammer element further enhanced its versatility in close combat.

From a performance standpoint, the horseman's axis addressed the limitations of swords against plate armor, particularly in close-range or constrained engagements where lances were ineffective. Its adoption by mounted combatants reflects a broader engineering response to changing battlefield conditions, emphasizing adaptability and functional efficiency.

However, as Renaissance tactics matured, the effectiveness of cavalry-based weapons diminished. The proliferation of dense pike formations and the advancement of early firearms significantly reduced the operational role of heavy cavalries. Consequently, by the late fifteenth and early sixteenth centuries, the horseman's axe transitioned from a primary combat weapon to a historical artifact, marking the end of its practical relevance.

Despite this decline, the horseman axis retains significant technical and aesthetic value. Its design reflects careful consideration of the weight distribution, geometry, and functionality, as well as a high level of craftsmanship. Among the knightly weapons, it stands alongside the mace and war hammer as a key example of a specialized close-combat tool.

From an engineering perspective, this project leverages the horseman's axe as a platform to integrate historical design principles with modern manufacturing methodologies. The selected design was developed as a cast steel component, incorporating CAD modeling, process simulation, and controlled casting techniques. This approach enables a performance-driven reinterpretation of a historical weapon, bridging the gap between traditional craftsmanship and contemporary engineering practice.

3. GERMAN AXE

3.1 DESIGN CONCEPT

The development of the crow's beak cavalry axe design began with the creation of a two-dimensional sketch, which served as the basic geometric reference for defining the general proportions of the system. This approach made it possible to systematically establish the relationship between the critical elements of the design, including the blade, the impact beak, and the interface with the handle, prioritizing both mechanical functionality and historical coherence.

From this initial outline, the three-dimensional model was generated in SolidWorks, incorporating the previously determined dimensions and transitioning to a solid geometry. During this stage, the design was refined based on structural performance and manufacturability criteria, ensuring proper mass distribution and a balance that would enhance impact efficiency, particularly in the area of the beak, a key element in penetrating rigid surfaces.

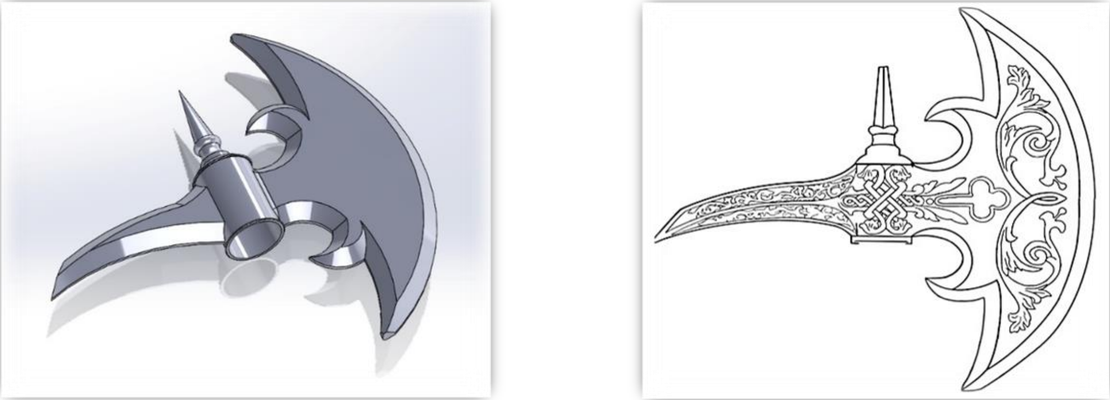


Figure 1. 3D CAD model of the horseman's axe developed in SolidWorks.

3.2 RAPID PROTOTYPE IN PAPER

As part of the early design validation, a full-scale physical paper prototype was developed with the aim of quickly and inexpensively evaluating the general geometry of the axe and its spatial interaction. This approach made it possible to transfer the conceptual model into a tangible environment, facilitating the verification of proportions, preliminary ergonomics, and the relationship between functional elements, particularly between the blade and the striking pick. The prototype served as a qualitative analysis tool to identify possible geometric interferences, imbalances, or inconsistencies that were not evident in the two-dimensional stage. Additionally, it allowed for agile iterative adjustments before consolidating the three-dimensional model, reducing the risk of complex modifications in later stages of the design.

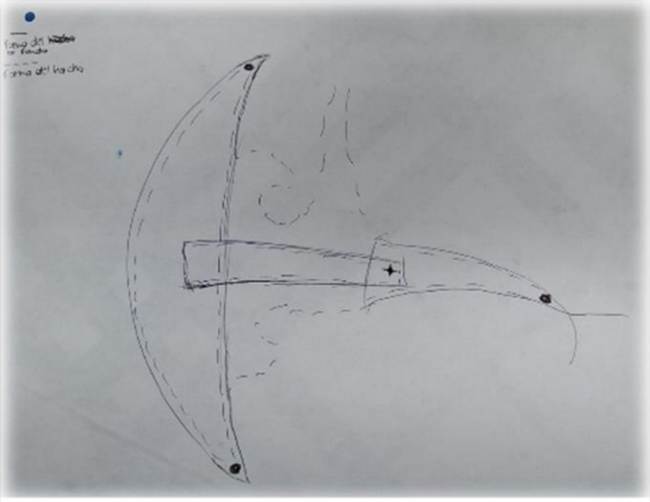


Figure 2. Prototype

3.3 CAD MOLDEL

The three-dimensional model of the cavalry axe was developed in SolidWorks as a direct evolution of the previously validated conceptual design. This stage aimed to consolidate a solid, parametric geometry that would allow the integration of mechanical performance criteria, dimensional precision, and manufacturing feasibility within a single design environment. During modeling, the critical geometric features were defined in greater detail, such as the blade profile, the length and angle of the crow's beak, as well as the configuration of the assembly cavity for the handle. Special attention was given to achieving an appropriate mass distribution to optimize the system’s balance, favoring energy transfer in the impact zone without compromising stability during use.

Additionally, the model was adjusted to account for the specific requirements of the casting process, including the incorporation of draft angles, smooth transitions between sections, and the reduction of stress concentrations. These decisions not only improved the structural integrity of the part, but also minimized the likelihood of process-related defects, such as porosity or solidification failures.

4. METALLURICAL CONSIDERATIONS

4.1 ALLOY

The selection of material for the crowbill-type axe was based on the functional requirements of the component, prioritizing an appropriate combination of hardness, toughness, and impact resistance. Since the geometry of the beak is designed to concentrate stresses in a small area during contact, the material needed to withstand high dynamic loads without exhibiting brittle failures. In this context, a medium-carbon steel was chosen, as it offers a favorable balance between mechanical strength and heat-treatability. This type of alloy allows for adequate levels of surface hardening while maintaining a core with sufficient toughness to absorb energy during impact, which is critical to prevent crack propagation in areas of high stress concentration.AISI 4140 steel is widely used in the manufacture of mechanical components subjected to severe service conditions, such as shafts, gears, crankshafts, engine cylinders, connecting rods, rotors, turbine shafts, rear axles, as well as nuts and bolts exposed to torsional and impact stresses. It is a chromium-molybdenum alloy steel that typically has the following chemical composition ranges: 0.38–0.43% carbon (C), 0.15–0.30% silicon (Si), 0.75–1.00% manganese (Mn), with a maximum phosphorus (P) content of 0.035% and sulfur (S) content of 0.040%, in addition to 0.80–1.10% chromium (Cr) and 0.15–0.25%

molybdenum (Mo).This material is characterized by its high hardenability, which allows for homogeneous mechanical properties even in relatively thick sections, as well as its good dimensional stability during heat treatments. It also exhibits suitable performance under fatigue and torsion stresses, making it suitable for dynamic applications. It can be surface hardened through direct quenching or induction hardening, reaching hardness levels above 54 HRC without compromising core toughness.

4.2 CASTABILITY IN SOLID CAST

SOLIDCAST is a tool that allows you to evaluate and analyze the behavior of the system based on the selected parameters and configurations. Through these simulations, it is possible to determine the optimal conditions for the model's performance. To identify the best results, simulations were carried out focusing on different aspects such as distribution, performance, and potential critical points.

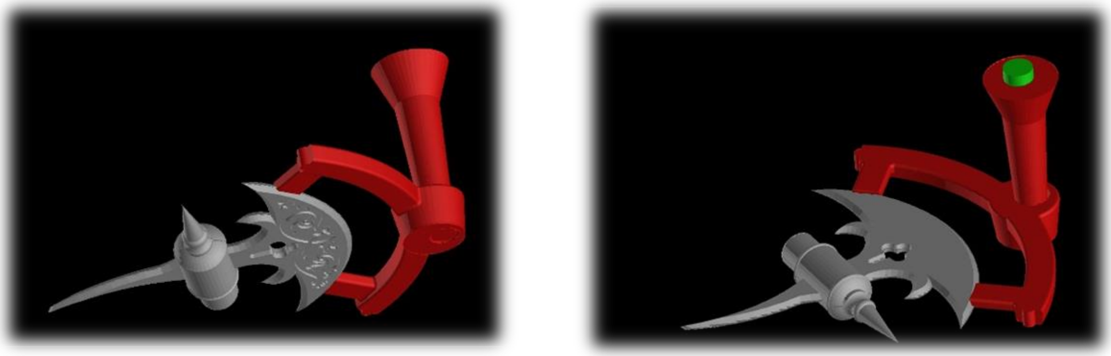
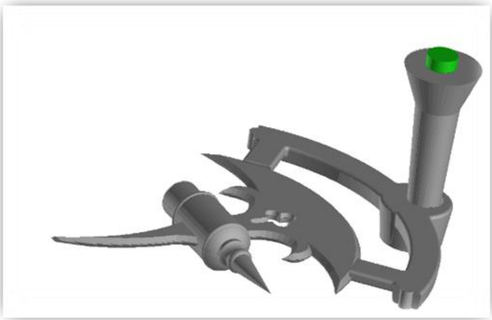


Figure 3. Casting system design in SolidCast showing gating and feeding configuration.



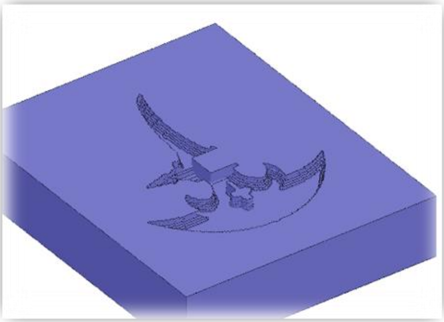
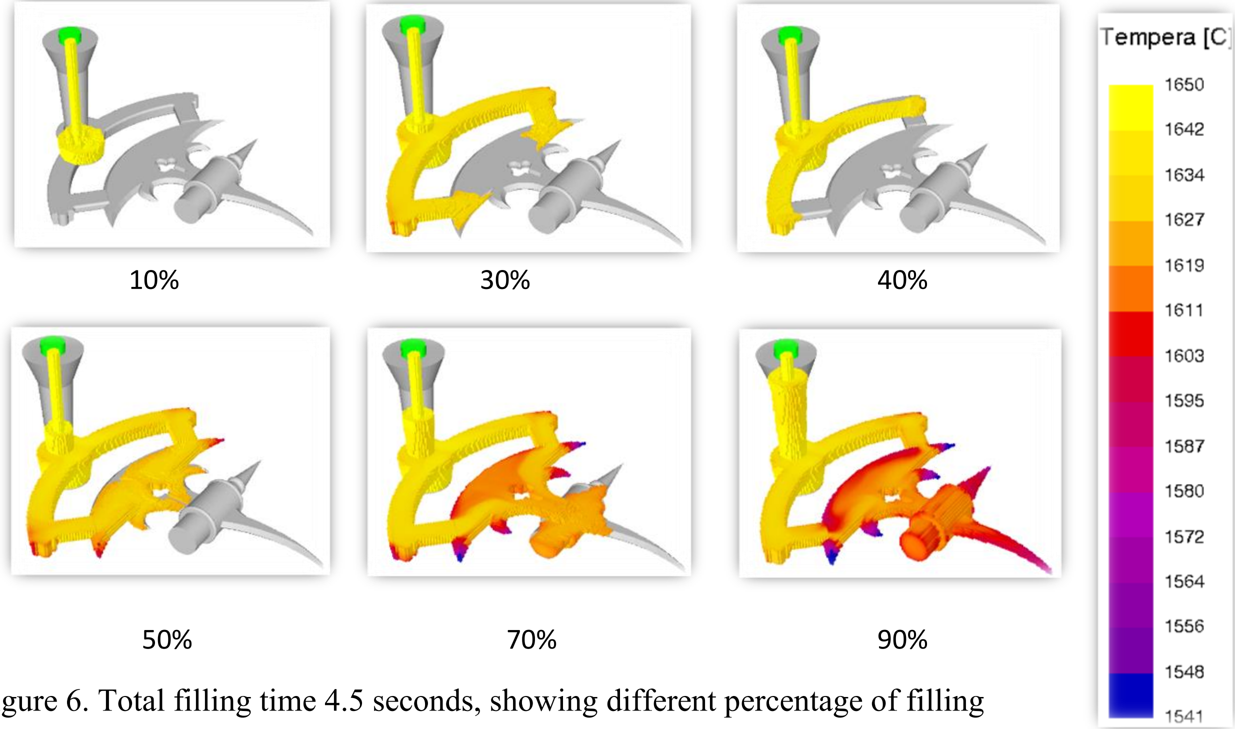


Figure 4. Assembly of the axe with gating system prepared for casting simulation in SolidCast.

Figure 5. Mold cavity generation for the axe geometry in SolidCast.

Steel 4140, cast in silica sand, in 3,500,000 nodes, cast at 1600 C and pour during 4.5 seconds



10%

30%

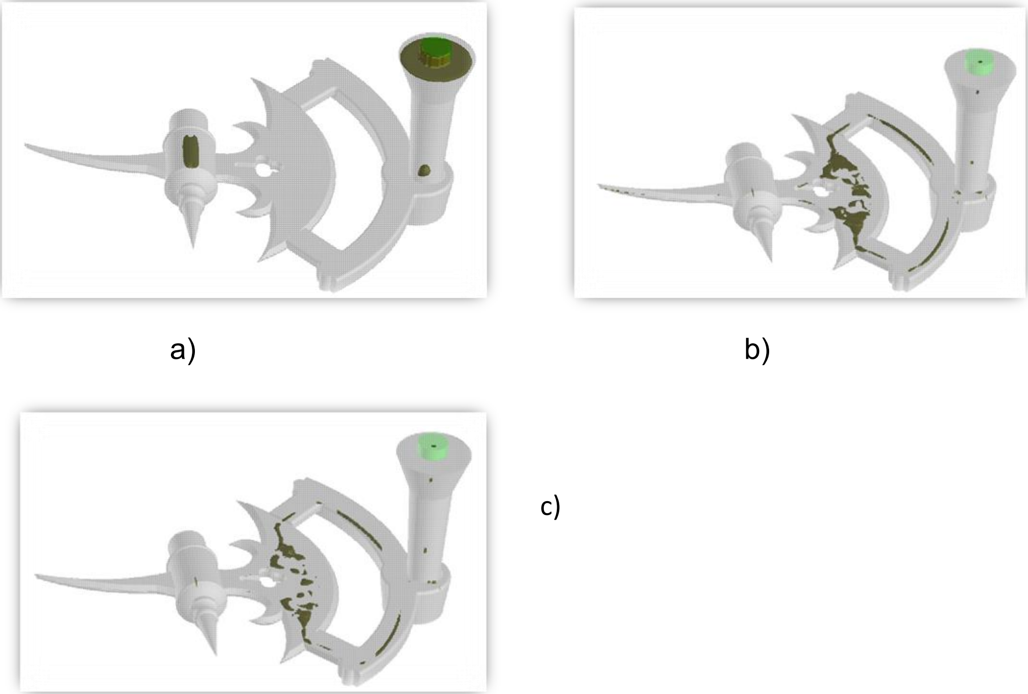
40%

50%

70%

90%

Figure 6. Total filling time 4.5 seconds, showing different percentage of filling



a)

b)

c)

Figure 7. Casting results: a) porosity on the top which was reduced with the help of a raiser, and b) hot spots and c) Niyama criterion

4.3 HEAT TREATMENT

For AISI 4140 steel, the application of quenching and tempering heat treatments is planned in order to increase its hardness, mechanical strength, and wear resistance without compromising its toughness. These treatments are essential to optimize the performance of the material under service conditions involving dynamic loads and impact stresses. The quenching process consists of an initial austenitizing stage, during which the material is heated to a temperature range of approximately 820 to 850 °C, ensuring the complete transformation of the microstructure to austenite. Subsequently, rapid cooling is performed, commonly in oil or salt baths, in order to obtain a martensitic microstructure, characterized by its high hardness.

After quenching, tempering is carried out, which involves controlled heating to a temperature below the austenitizing temperature, followed by appropriate cooling. This process reduces the internal stresses generated during quenching, improves the toughness of the material, and adjusts the hardness to the levels required for the specific application. For AISI 4140 steel, it is not recommended to achieve hardness values above 56 HRC, since this could compromise its impact resistance and favor the appearance of brittle failures. The combination of both heat treatments allows for a microstructure of The behavior of AISI 4140 steel during heat treatment can be analyzed by means of time-temperature-transformation (TTT) diagrams. As shown in Figure 8, rapid cooling following austenitizing prevents the formation of phases such as pearlite or bainite, favoring the attainment of a martensitic microstructure responsible for the increase in the material's hardness.

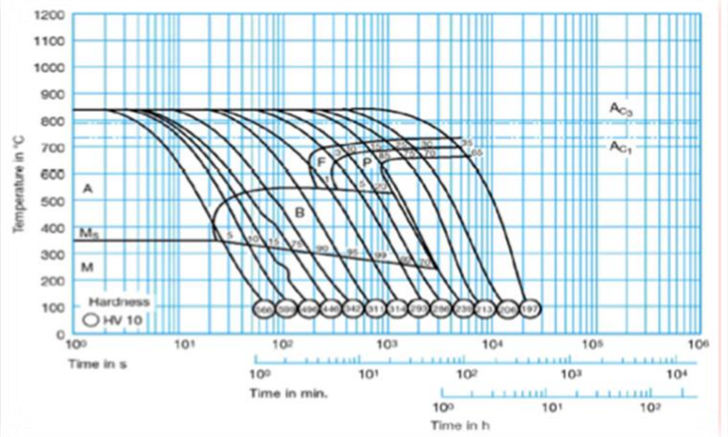


Figure 8. TTT diagram of AISI 4140 steel

Note. Taken from Technical data sheet for SAE 4140 steel, by Europer S., 2022.

5. PROCESS

5.1 PRINTG THE MODEL

The axe model was designed in SolidWorks, taking into account the dimensions, tolerances, and shrinkage inherent to the casting process for AISI 4140 steel. In the first stage, the geometry of the component was developed and a suitable gating system was integrated, which was validated through simulations in SolidCast to ensure proper filling and minimize solidification defects. Subsequently, the model was fabricated using additive manufacturing with 3D printing in PLA material, chosen for its ease of processing, low cost, and adequate dimensional accuracy. The printing time was approximately 30 minutes, resulting in two pieces corresponding to each half of the model.

Once the printing was completed, the fabrication of the molding boxes began by cutting pieces of wood to form two open frames. In each frame, one half of the model was secured using adhesives and screws to ensure proper fastening and prevent any gaps or misalignments. Finally, after drying, adjustment elements were added to allow correct joining and alignment of the boxes during the molding process.

Figure 9. Additively manufactured model (PLA) of the axe used as a pattern for the casting process.

5.2 BUILDING THE TOOL FOR MOULDING

To create the molding model, once it was printed using additive manufacturing, the silhouette of the figure was drawn and holes were made to attach the model to the wooden base, as shown in section a). A series of pegs were designed for the model, which were inserted into the previously made holes.

Figure 10. a) Cutting holes in Wood

Subsequently, a two-resin epoxy mixture was prepared, which served as an adhesive to attach the model to the board, as shown in sections b), c), d), and e). Two identical models were made.

Figure 11. b) Resin mixture

Figure 12. c) Application of resin

Figure 13. d) Axe installation

Figure 14. e) installation of the feed system

Figure 15. Rear view model

Figure 16. Front view model

5.3 MAKING MOULD BOX

For the construction of the molding box, cuts were first made in a sheet of wood to shape the box, obtaining eight strips corresponding to the sides. These pieces were joined using brackets, which were fastened with screws, as shown in images a), b), and c).

Figure 17. a) Cutting the wood

Figure 18. b) Making structure holes

Figure 19. c) Screwing the box

Once secured, the boards were attached to each frame, with the template previously adhered to them. It was properly fixed and a safety clasp was placed at the junction of both boxes to ensure they were firmly held together and aligned.

Figure 20. a) Finished model cop

Figure 20. b) Finished model drag

5.4 MOULD AND CORE MAKING CASTING

During the molding process and the creation of the sand mold, the previously made molds were used, as shown in the images in sections a), b), and c).

Figure 21. a) Application the molding coating

Figure 22. b) green sand was added to the mold

Figure 23. c) The mold was open

Figure 24. d) Application of refractory coating on the sand

Figure 25. e) Curing was carried out.

Figure 26. f) Finished mold.

5.5 FLETTING AND FINISHING

After casting, the piece was machined to remove the gating system from the model, and then the edges were rough-finished and polished.

Figure 27. a) Finished

Figure 28. b) Team work

Figure 29. c) Deburring

Figure 30. d) Polished axe

Regarding its heat treatment, the material requires precise temperature control to prevent brittleness. Forging is typically carried out between 1100°C and 1200°C, while quenching should preferably be done in oil after uniform heating to approximately 850°C to minimize the risk of distortion or cracking. The subsequent tempering, performed between 400°C and

650°C, is critical to adjust the balance between hardness and toughness according to the design requirements. Although its machinability is good in the annealed state (approximately 65% compared to 1212 steel), its weldability is considered limited; due to its high hardenability, it is prone to cold cracking, so preheating to 250°C to 300°C and subsequent stress relieving are strictly necessary. With all this in mind, for our axe, after it was cast, we proceeded to subject it to the first treatment, which consisted of solutionizing; here we heated our axe to a temperature of 850°C for 3 hours and then proceeded with water quenching for cooling. Finally, we carried out tempering to reduce stress in our material, heating it to 550°C for 4 hours, and finished with air cooling.

5.7 POLISHING AND SHARPENING

Once the casting was obtained, the excess material from the gating system was removed through an initial grinding process. Subsequently, the overall surface was treated progressive sanding using grit sizes 50, 80, 120, 150, 230, 280, and 320, with the objective of homogenizing the surface and eliminating irregularities resulting from the casting process.

Once the piece was conditioned, sectional preparation was carried out through a controlled sanding and polishing process. The blade was progressively treated using grit sizes 400, 600, 800, 900, and 1000 to achieve a uniform and suitable surface finish.

On the other hand, the beak underwent an initial grinding process using grit sizes 50, 80, 100, 150, and 230, allowing the removal of more pronounced irregularities and the definition of its functional geometry. Finally, both sections were subjected to fine polishing using a polishing tool, with the aim of improving surface quality and achieving an optimal finish.

Figure 31. Axe head during polishing and sharpening stages, showing surface refinement and final edge definition.

5.8 NOT DESTRUCTIVE TESTING

To evaluate the internal integrity of the casting, a non-destructive test based on the Archimedes principle was performed in order to estimate internal porosity through density measurements. The procedure consisted of measuring the mass of the specimen in air and subsequently in a liquid medium, allowing the calculation of its experimental density. The measured density was 7.34 g/cm³ for the AISI 4140 steel, which is lower than the theoretical density of 7.85 g/cm³. This difference indicates the presence of internal porosity, primarily associated with solidification phenomena such as volumetric shrinkage and gas entrapment. Based on these values, the porosity percentage was calculated using the density relationship, resulting in an approximate porosity of 6.5%. Although this level of porosity is typical for sand casting processes, it suggests that improvements in the feeding system and solidification control could further enhance the internal quality of the component.

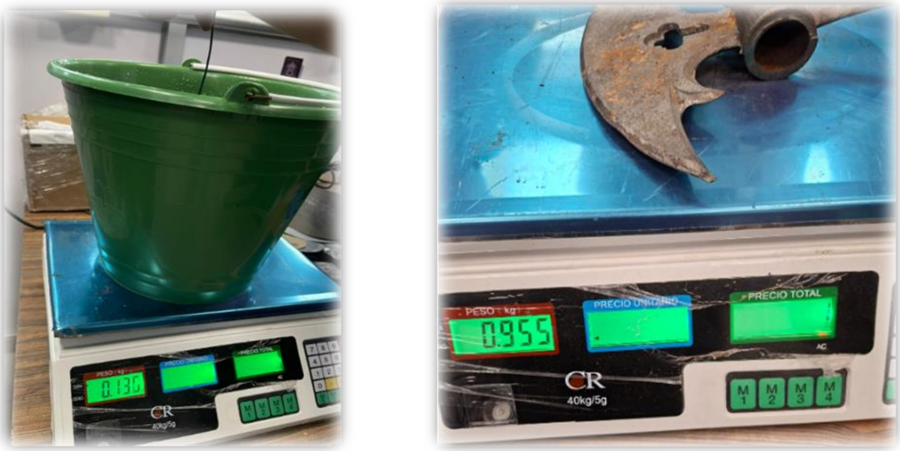


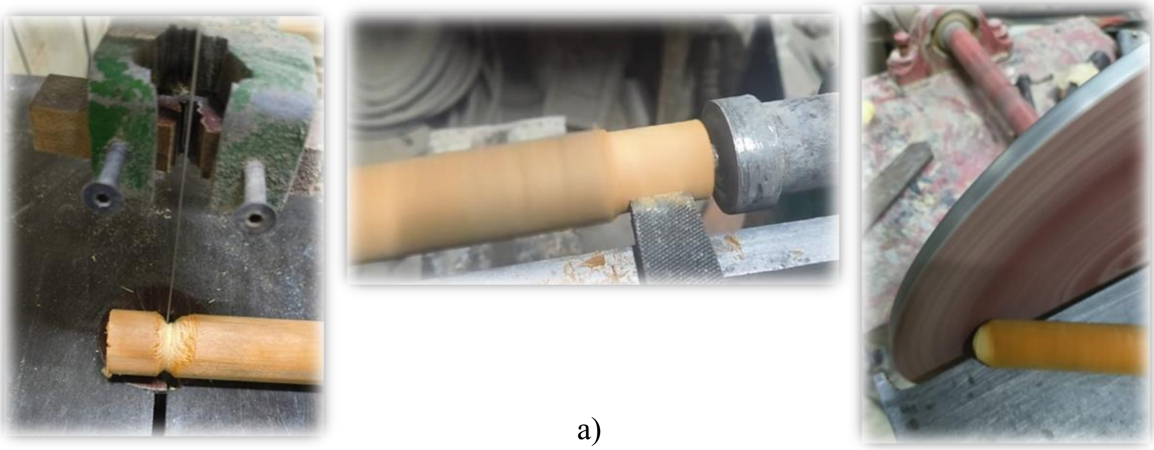
Figure 32. Experimental setup for Archimedes-based density measurement used to determine internal porosity in the AISI 4140 casting.

5.9 MAKING HANDLE AND ASSEMBLY

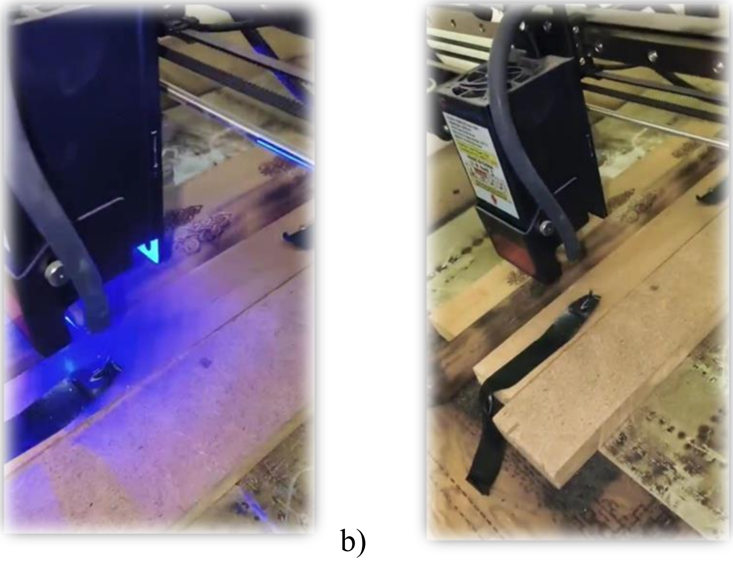
For the joint between the axe head and the handle, a combined system of mechanical fastening and structural bonding was implemented to ensure the integrity of the assembly under dynamic loading conditions. Initially, two transverse holes were drilled through both components, allowing the insertion of bolts as anchoring elements, which act by resisting shear stresses and preventing relative displacement during impact.

Subsequently, an epoxy resin was applied at the contact interface to enhance adhesion between the surfaces and promote a more uniform stress distribution. In addition to reinforcing the joint, this material helps reduce gaps and contributes to the stabilization of the system under repeated loading conditions.

Additionally, the wooden handle was finished with a laser engraving process, incorporating decorative patterns inspired by historical designs. This process not only enhances the aesthetic value of the component but also contributes to the identity and craftsmanship of the final assembly.



a)



b)

c)

d)

Figure 33. Sequence of handle fabrication and final assembly, showing machining, surface finishing, laser engraving, and mechanical integration with the axe head.

Figure 34. Final assembled axe.

6. CONCLUSIONS

The present project, developed by the "Melting Bears" team from the Universidad Autónoma de Nuevo León, documents the design and manufacture of a knight's axe inspired by the armament transition of the 15th century. The main goal was to integrate contemporary engineering methodologies with industrial foundry processes. To ensure structural integrity and mechanical performance under impact conditions, low-alloy AISI 4140 steel was selected. The design was validated through parametric modeling in CAD and solidification simulations in SOLIDCAST, which allowed optimization of the gating and riser system to ensure a part free from internal defects. Manufacturing was carried out in collaboration with Fundiciones Lerma, using casting at 1600 °C through the sand molding process with 3D-printed PLA patterns. After obtaining the piece, a critical heat treatment cycle was applied: a solution treatment at 850 °C for 3 hours with water quenching, followed by tempering at 550 °C for 4 hours with air cooling. This process transformed the microstructure to achieve an optimal combination of hardness and toughness.

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