SFSA Cast In Steel 2026 – Horseman Axe
Technical Report
University of Northern Iowa – Z.A.M.M

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Abstract

This project focuses on the design and manufacturing of a horseman's axe using 17-4 PH stainless steel through the investment casting process for the Cast in Steel competition. The goal was to produce a functional axe and study how the manufacturing process and heat treatment affect the mechanical properties.

The investment casting process was carried out at Wisconsin Precision Casting. A total of eight axe heads were poured, along with handle components and tensile test samples. During production, several problems were found, such as incomplete filling, porosity in the sprues, and shrinkage defects. Because of these issues, some tensile samples were not usable, so tensile bars had to be machined from the sprues.

After casting, the material was heat treated using a solution treatment followed by an aging process to improve its properties. A metallography analysis was also performed to compare the microstructure in three conditions: as-cast, after solution treatment, and after aging.

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1.Introduction

1.1Historical Background

The rider's axe, as it is known, is a weapon that appeared at the end of the 15th century. It was an alternative for knights because they wanted a weapon that could hit hard and penetrate deeply. Axes are characterized by having a short blade and a hammer shape, with a pointed part on the back. This type of weapon is not very heavy compared to tools, and it is short in length. However, these features help increase the kinetic energy when swinging it. Since the weight is concentrated, the impact is stronger and the vibration is reduced when it hits. (Ellis, 2005)

This type of axe also goes back to the Roman legionaries, but they used a standard spike with a short edge on a head of 48 cm and a handle of 76 cm. Later, in the 5th century, a different type appeared with the Frankish army. In this case, it had a narrow wedge-shaped head, usually with a flat curve, as shown in the photo used on the Cast in Steel competition page. It was called the francisca, an S-shaped axe, with a high spike and the rear part shaped like an S. The Franks used this weapon both for combat and for throwing. Each man carried a shield, a sword, and an axe. The short handles had the main purpose of breaking enemy shields. (McPeak, 2011)

1.2. Design justification

The design process for the horseman's axe started with research into historical axes and polearm designs. Three main options were considered: the bearded axe (commonly called a half-moon axe), the halberd (a German-style horseman's axe), and a billhook-style polearm, which influenced our final umbrella-style concept. Each design had different strengths, both in appearance and in how practical it would be to cast and assemble.

The bearded axe had a simpler shape, but it did not show the same level of design detail the team wanted for this project. The halberd had strong historical value, but its geometry would have been more difficult to cast because of its sharper transitions and more complex features. After comparing the three concepts, the team selected the umbrella-style design because it gave a good balance of historical influence, manufacturability, and overall appearance.

One of the biggest challenges during the design phase was getting the proportions right. It was important that the axe head, spike, and handle all looked balanced and fit together in a way that matched the intended style. To help with this, the team used 3D-printed prototypes throughout the design process. These prints made it possible to physically hold the design, check the size, study the proportions, and see where changes were needed. This was especially helpful for adjusting the profile of the blade and making sure the overall shape looked correct before moving forward with the final design. Using 3D prints saved time and gave the team a much better understanding of the design than looking at the CAD model alone.

Another major part of the design was the connection between the axe head, handle, and top spike. This area needed to be strong, practical, and simple enough to assemble. The team spent a large amount of time working through how to connect these parts while still keeping the top spike as part of the final design. In the end, a tapered wooden handle was selected so it could be pressed into the axe head securely. A slot was then added at the top of the handle so the spike could slide into place, and two pins were used to hold the parts together. This gave the team a strong and reliable connection between the axe head, top spike, and handle.

The bottom of the handle was also given special attention. After listening to Ben Abbot and Dave Baker discuss axe and sword design, the team recognized the importance of having a positive stop at the bottom of the handle. Based on that expert input, a steel grip feature was added to the base of the handle. This helps the user maintain a more consistent hand position and improves control during use. Including this feature strengthened the overall design by making the axe feel more secure and intentional in the user's hand.

Overall, the final design reflects a balance between historical inspiration, practical manufacturing, and usability. By comparing several historical concepts, using 3D-printed models to refine proportions, and applying expert feedback to improve the grip and handling, the team developed a design that is both functional and well suited for the Cast in Steel competition.

Figure 1. a), b), c) Design preselected. d), e) final model.

2. Methods and Materials

2.1. Material Selection

The selected material was 17-4 PH stainless steel, which is a type of steel with a high chromium content. Its structure can be martensitic, austenitic, or ferritic, depending on its processing and the properties that are needed. In this case, it is a copper precipitation-hardened steel. This type of steel is known for its high toughness, strength, and corrosion resistance. (AZoM, 2012)

We must remember that for our axes, the desired properties are: high impact strength, good penetration, mechanical resistance, toughness, hardness at the edge or tip, moderate weight, good balance, strong handle, versatility, and a compact size.

In our case, we learned that it is often preferable to use carbon steels such as 4140 or 1045, although this also depends on applying the correct heat treatments. However, for our project, we determined that the most important property is high toughness for impact resistance, together with corrosion resistance so the axe can perform well in humid or extreme environments. At the same time, we should not ignore the copper precipitation process, which helps strengthen and harden our alloy.

2.2. Simulation

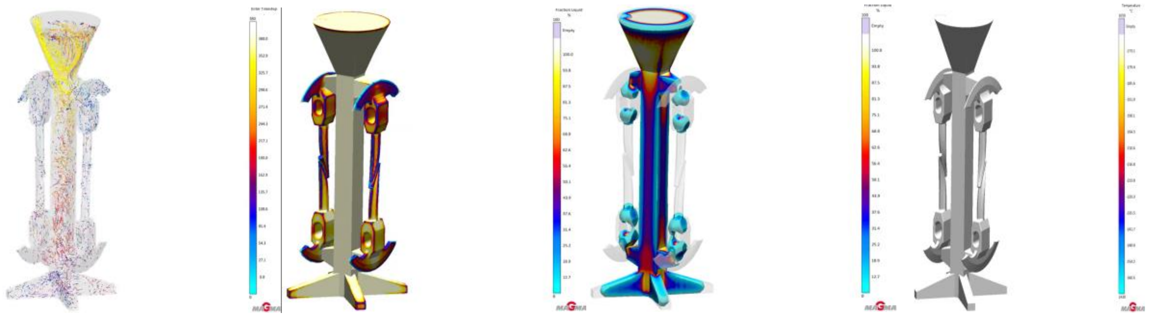

Figure 2. Simulation Process

2.3. Process

2.3.1. Pattern or Mold preparation

The mold was made at Tech Works using the investment casting process. This process begins by making the part in wax with the exact shape of the final geometry. After that, the wax parts are joined together to form the trees. Then, the assembly is coated with ceramic material: first it is dipped into a ceramic slurry, and then it is covered with fine sand or refractory material. This coating process is repeated several times until a ceramic shell is formed. In our case, we made the shell thicker to avoid fractures during the process. It is left to dry, in this case inside the furnace. Later, the mold is heated so the wax melts and leaves the mold, creating the empty space with the shape of the part. For this reason, this method is also known as the lost wax process.

Figure 3. Mold process

2.3.2 Casting Process

We went to Wisconsin Precision Casting, where they placed molds in the preheating furnace. After that, they poured the molds one by one to avoid losing temperature during the process. Since they were already running a 17-4 PH heat, this made the process easier for us. The process consisted of pouring the metal into each mold and then placing a vacuum hood to remove as much oxygen as possible. Wisconsin Precision Casting covered the mold with a barrel and let it cool inside. This same procedure was repeated for all the other trees.

Figure 4. Solidification and pouring process.

2.3.3. Removal of gates and risers

In this process, first, we used a hammer to break the shell and expose the metal. After that, the castings were placed in high-pressure water booths to clean them, leaving our parts as clean as possible. Later, they were taken to the metals laboratory, where the team cut the gates and risers with the help of the machines, especially using the bandsaw.

Figure 5. Cleaning process

2.3.4. Grinding and surface finishing

In the metals laboratory, the team performed the grinding on each part of the axe, including the handle and the tensile bar, which also had to be separated from the sprue. However, several defects were found in that area, so we still expect that we may be able to get at least one good piece. The axe heads were also machined there, together with the back spikes of the axe and the spikes located on the top part. In addition, polishing tools were used to give more shine to our pieces, since stainless steel can provide a very good surface finish.

Figure 6. Grinding and surface finishing process.

2.3.5. Heat treatment (Solution and Aging)

The heat treatment integrates work hardening and thermal processing into a single process. This is followed by a solution heat treatment or austenitizing, and subsequently by an aging treatment to promote copper precipitation. Additionally, more specialized treatments can be applied to achieve specific microstructures, control the volume fraction of precipitates, and optimize mechanical properties.

Alloying elements interfere with and influence the outcomes of heat treatments, as they directly affect the microstructure and the volume fraction of precipitates. The yield strength and tensile strength are largely attributed to copper precipitation; however, other precipitates such as NbC may also form, while elements like molybdenum and chromium induce the formation of M_2C or M_6C type precipitates. Niobium promotes grain refinement, contributing to both overall strength and impact toughness.

A key characteristic of these steels is their low carbon content, which reduces the carbon equivalent and improves weldability. Additionally, the low carbon concentration decreases hardenability and suppresses the formation of martensite during heat treatments; consequently, these steels typically exhibit ferritic microstructures.

Numerous microstructural constituents have been reported, including equiaxed ferrite with pearlitic colonies, polygonal ferrite, acicular ferrite, granular ferrite, Widmanstätten ferrite, bainitic ferrite, and martensitic ferrite. Steels under ASTM specifications exhibit yield strengths (YS) lower than 689 MPa (100 ksi); however, quenched and precipitation-strengthened versions have reached strengths up to 1190 MPa (170 ksi). In the overaged condition, no significant negative effect on impact toughness is observed.

Copper has a maximum solid solubility in ferrite of approximately 2.2 wt.% in α-Fe at 850 °C (1560 °F). This low solubility, combined with a relatively steep solvus curve, allows the nucleation of a large number of copper precipitates in the ferritic matrix. During aging, the number of precipitates can increase by up to approximately 50%, as the solution treatment effectively "resets" the microstructure. The solubility limit decreases significantly at temperatures around 700 °C (1290 °F).

Finally, nickel increases the solubility of copper in α-Fe, delaying the formation of copper-rich layers beneath the surface. (Kolli, R.P. Seidman, D.N., 2014). The process consisted of following the recommendation provided in the book (Unterweiser, P. M.Boyer, H. E.Kubbs, J. J., 1982).

The material was solution heat treated between 1875 to 1925 °F (1025 to 1050 °C) for 1 hour, followed by air cooling. Subsequently, it was aged at 900 °F (480 °C) for 1 hour and then air cooled. During packing, a carbon riser was used to prevent decarburization.

Solution Process

Figure 7 . Solution Process

Aging Process

Figure 8.Aging Process

3. Discussion

According to the observed microstructures, in the first one, corresponding to Figure 9(a), the sample shows an as-cast condition, where the grains appear deformed by the shear movement of iron atoms into a supersaturated interstitial solid solution of iron and carbon. This behavior is characteristic of a martensitic structure. For that reason, some needle-like features were formed instead of having only round grains. This indicates a distortion of the crystal lattice, which gives strength and hardness to the casting by preventing dislocation movement. This shear distortion also represents the orientation relationship between the parent phase, which is austenite with an FCC structure, and the product phase, which is martensite, as well as the surface relief around the martensite crystal. Inside the deformed grains, lath martensite can be observed as pointed island-like features, while the parent phase, represented by the white background, would be the retained austenite (International, 2004).

After the solution treatment, it is known that its main purpose is to dissolve the copper precipitates in the alloy. In this case, because the material is a 17-4 PH alloy, there are coherent and incoherent copper precipitates that grew without a defined order. This treatment also helps show how the martensitic grains become more needle-like and cross over the lath martensite islands, all within the parent phase of retained austenite. This suggests that a more homogeneous microstructure was obtained, and also a softer material that could be worked more easily during the grinding process. This agrees with the hardness results, since in the as-cast condition the hardness value was 29 Rockwell C. In that condition, the team had more difficulty during grinding because it took more time and consumed more supplies. In contrast, after the solution treatment, the grinding process was easier.

Finally, in the aged condition, the final microstructure can be observed. In this condition, the grains show a needle-like morphology, but there is also a greater amount of lath martensite throughout the microstructure. At the same time, the amount of retained austenite decreased, which is related to the final increase in hardness, reaching a value of 39 Rockwell C.

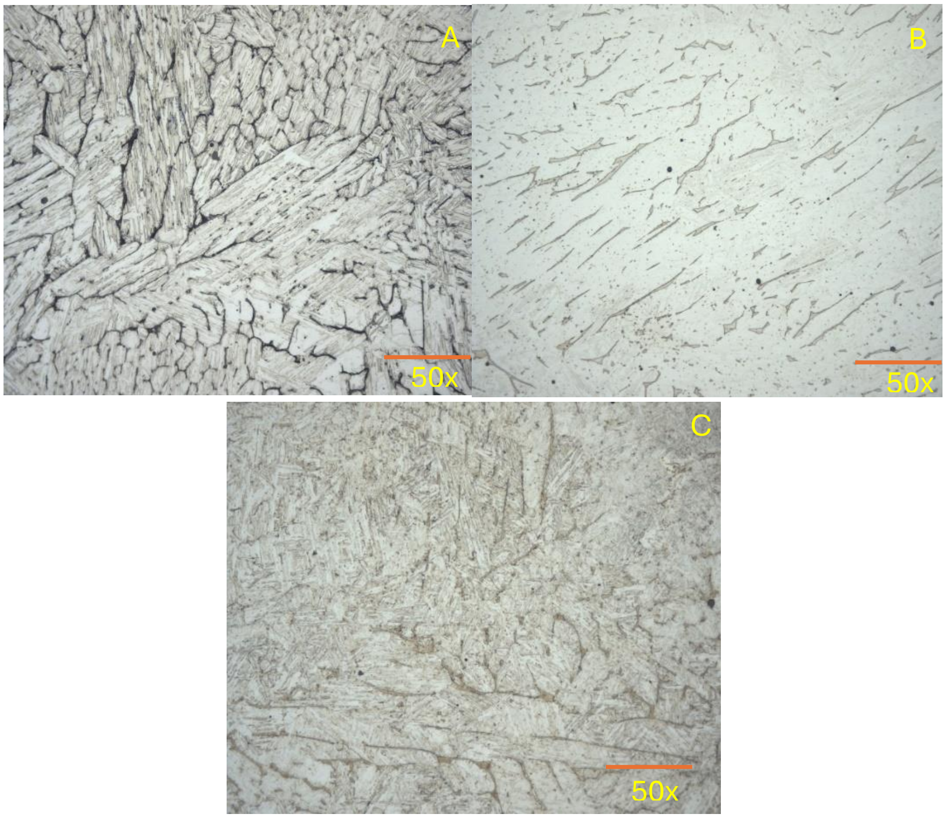

Figure 9. Optical micrographs of the sample in the as-cast, solution-treated, and aged conditions at 50x magnification. A) The as-cast sample was etched with Fry's reagent for 40 s. B) The solution-treated sample was etched with Vilella's reagent for 1 min 20 s.

4.Conclusion

In this project, a horseman's axe was successfully designed and produced using 17-4 PH stainless steel through the investment casting process. The final product met the main goal of being both functional and structurally sound.

During casting, several defects such as porosity, shrinkage, and incomplete filling were observed. These issues affected the quality of some tensile samples and showed that process control, especially gating and feeding design, is critical for this type of geometry.

Heat treatment had a clear effect on the material. After solution treatment, the material became easier to machine, while aging increased the hardness from about 29 HRC to 39 HRC. The microstructure also changed accordingly, with more martensitic features and less retained austenite after aging, which explains the increase in hardness.

Overall, this project showed how casting quality and heat treatment directly affect final properties. While 17-4 PH is a good material choice for this application, better control of the casting process would improve consistency and test results.

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