Cream City Cavaliers – Horseman’s Axe

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Abstract

Historically, steel weaponry used in combat by infantry and cavalry was manufactured using a forging process. SFSA’s Cast in Steel competition challenges students to reimagine the making of these tools using a casting process instead.

The Cavaliers employed an investment casting technique, utilizing intricate resin printing to make a component with a hollow center. This avoided the complexity of making cores for sand casting, while also preserving a fine surface finish to reduce post-processing and machining. An S5 tool steel was selected, as it is known for superior shock absorption while maintaining formidable hardness. The high silicon content of S5 steel increased the fluidity of the melt, allowing for thin cross-sections to be cast with confidence. Samples were heat treated under various tempering parameters and tested for hardness to pinpoint ideal blade material properties. The blade must be hard enough to hold an edge when used against softer steels without chipping or cracking. While there were issues with casting defects in the final parts, the Cream City Cavaliers were able to tweak their design to deliver a well-balanced, functional axe.

1. Introduction

A redesign of the Horsman’s Axe to be made as a casting required careful consideration. The properties that result from the traditional method of forging an axe are not easily replicated in a casting. In a forged component, forming minimum cross-sections is trivial, as a part can be worked into a desired shape, whereas traditional castings are bound to a thickness dictated by the fluidity of the melt.

When an ingot is worked, a few other controllable variables are introduced. As cast, an ingot will inherently have some amount of internal porosity, in the form of shrinkage or gas precipitating out of solution as the metal transitions to the solid phase. Forging works to densify the ingot, welding closed a percentage of the porosity inherent to a casting. The as-cast ingot will also commonly form anisotropic grains upon solidification. When work is applied to the ingot along a particular orientation, the grains will stretch in a coordinated dimension, creating an anisotropic grain that may have benefits in resisting forces in a resulting dimension. Also, this work done in deforming a material through forging creates a density of dislocations within the grains of the material, increasing both hardness and yield strength, as described by the Hall-Petch equation. All the above-mentioned mechanisms are useful in the creation of a strong, durable cutting edge, ideal for a Horseman’s Axe.

If we take forging off the table, what controls are left to influence the properties of a casting that may increase its usefulness in this application? Modern casting practices and techniques allow for greater control over the development of as-cast properties. To address the issues with thin cross-sections in cast products, smart selections in alloying elements and proper heat control can go a long way in changing the fluidity of a melt. Fighting back the specter of detrimental internal porosity can be assisted with finite element analysis software and smart mold design. Smart mold design can also play a role in the encouragement of directional solidification, which can be used wisely to introduce strengthening anisotropy in the part. Finally, smart use of alloying elements, cooling rate and heat treatment to control the size of precipitates can work as a tool to control hardness and yield strength without the use of forging.

The challenges the Cream City Cavaliers faced in this endeavor did not end at a change to standard manufacturing technique. The other limiting factors outlined by SFSA in the guidelines for this challenge necessitated tough decisions. The weight and length restrictions played a major role in the team's design and material choices. Additionally, this being UW-Milwaukee's inaugural participation in SFSA's Cast in Steel competition, working with a first-time faculty advisor meant that the UWM teams participating needed to break new ground in the process of manufacturing an axe, and the Cavaliers pushed the buck of on-campus manufacturing to the limit.

2. Methods

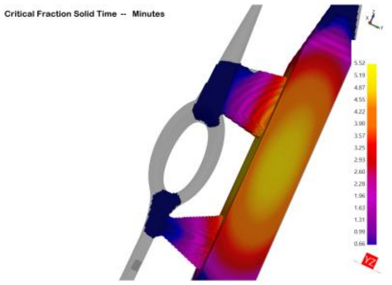
The Cream City Cavaliers' Horseman's Axe is the outcome of months of research and development. A weapon whose creation stems from the synthesis of experience and knowledge of the individuals that comprise the team.

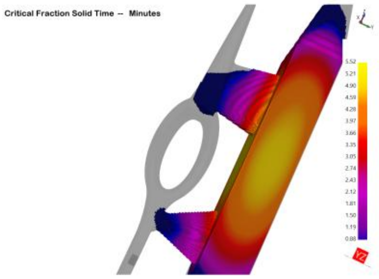
AXE DESIGN & PATTERN MAKING

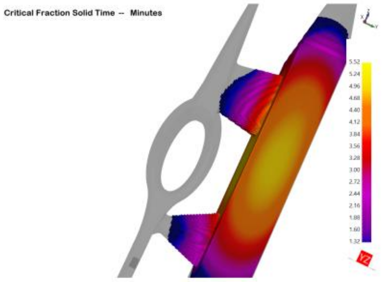
Performance and reliability: These traits were the main design criteria for the Horseman's Axe. To ensure the longevity and soundness of the axe, we began by simplifying the design, removing details that introduce risk in the manufacturing process. By electing for an eye-hafted axe head, the team was confident that a design could be made that would be sturdy and compact while having acceptable resistance to torsional forces likely experienced in mounted combat, as well as the relative historical accuracy, considering western European weaponry dated to the Early Medieval times. This choice led to the removal of the top spike as an intrinsic component to the casting, as the team felt that too complex a geometry may result in more internal defects, like shrinkage porosity or cracking at areas of extreme angles or cross-sectional change.

The decision was made to cast the axe head consisting of a long blade with a slight beard on top and bottom for control. The cutting edge was placed sufficiently far from the haft to maximize the lever arm, amplifying the torque at the blades edge, and a curved rhombohedral, spiked peen counterbalancing the blade for stability, control maneuvers, and armor penetration.

An A-frame sprue angled two axe heads at 10 degrees from parallel to encourage laminar flow of melt into the mold. Runners connected the sprue to the axe directly above and below the eye, feeding the thickest parts of the axe head. Solidification modeling was done using SolidCast. This was used to verify the directional solidification of the part, starting in the blade and peen and progressing into the runners. An ideal casting leaves no liquid area unfed, as this can lead to serious shrinkage porosity. Making sure that the sprue and runners are the last to solidify gave the team confidence that this design was feasible.







For pattern making, the team used Bambu Labs PLA plastic for initial prototyping and Formlabs Clear Cast Resin for the final pattern. Clear Cast Resin was chosen for the final pattern over the PLA due to the better aligned approach with the requirements of investment casting. The Clear Cast Resin is a resin developed by Formlabs specifically for casting. The Clear Cast Resin also provided significantly higher dimensional accuracy and surface finish. With the PLA prototypes, layer lines in the parts were visible, and surface roughness was evident, which would then show up in the final casting. The Clear Cast Resin is specifically formulated to create small and smooth layers and to burn out cleanly, which helps to produce minimal ash and residue during final firing. The transparency of the Clear Cast Resin also helped us to visually inspect internal features and verify pattern integrity prior to investment casting. Below are two figures of the setup for the prototype and final patterns. Overall, the use of Clear Cast Resin resulted in more precise patterns, reduced post-processing, and improved mold quality.

MATERIAL SELECTION

Material selection is a very important process when making tooling of any kind. In the case of an axe, the material is ideally able to resist high-energy impacts. Precise cutlery, like a kitchen knife or scalpel, should use harder material to prioritize edge retention. An axe, however, must be much tougher so that it doesn't chip or crack (experience brittle failure). This toughness often comes at the expense of edge retention.

The most important alloying element to the hardness of the steel is carbon. The Cavaliers decided to use a medium carbon steel (high end of medium carbon or low end of high carbon) because of its inherent balance between toughness and edge retention, but the specific grade chosen required more consideration.

The Cavaliers decided to pursue the S-series tool steels. This AISI classified series is called the S-series because it is shock resistant and tough, which is ideal for the application of an axe. The options within this series include S1, S2, S5, S6, and S7.

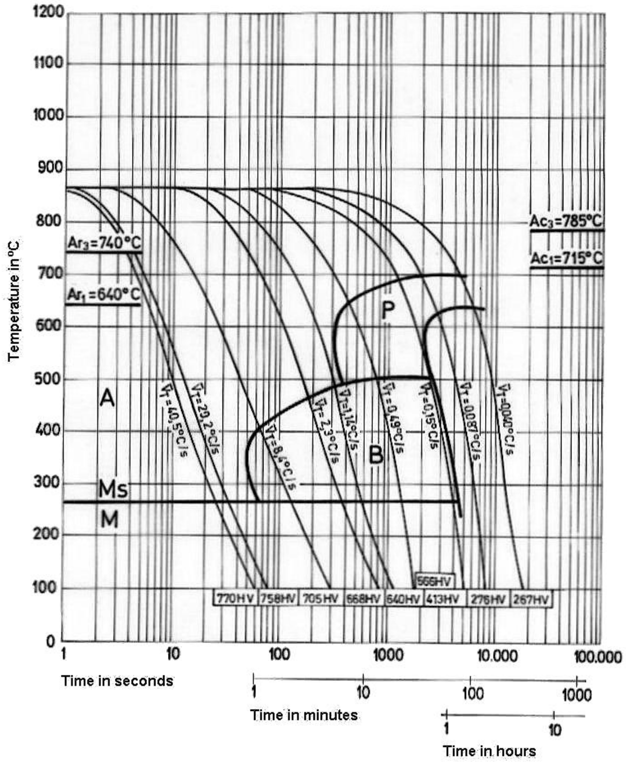
Among the S series, the Cavaliers chose S5 because of its alloying elements. It has the ideal level of carbon at around 0.60% and its high silicon content improves toughness and improves fluidity during casting, which is extremely important to reduce porosity and casting defects. Other alloying elements like molybdenum and manganese improve hardenability, wear resistance, and toughness.

MOLD MAKING & CASTING

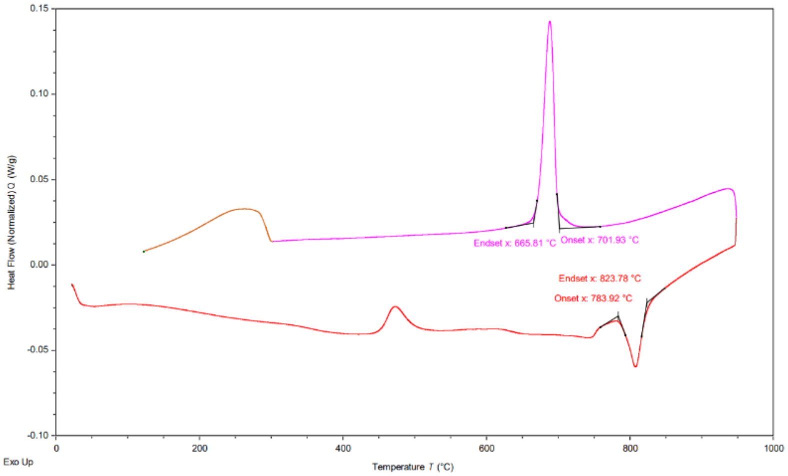
With consultation from Ransom & Randolph, a manufacturer of refractory slurries, SuspendaSlurry FS was selected for shell material. After the patterns were constructed, they were dipped into the slurry, and a layer of silica sand was applied. After full sand coverage, the molds were hung to dry in front of a box fan. This process was repeated until eight layers were applied. Four molds were made in total.

HEAT TREATMENT

Heat treatment is perhaps the most important part of making a cutting tool. The Cavaliers knew that proper heat treatment was the difference between a strong tool and a failed part. The team decided to use a martensitic heat treatment because of its potential for excellent hardness and strength. S5 is an oil-hardening steel, but the Cavaliers wanted to confirm a cooling rate for successful martensitic formation. The figure below shows different cooling rates required for different transformations. The cooling rate required for martensitic formation (40.5°C/s in the case of S5) is consistent with an oil quench (approximately 50-100°C/s), so an aggressive water quench could be avoided.



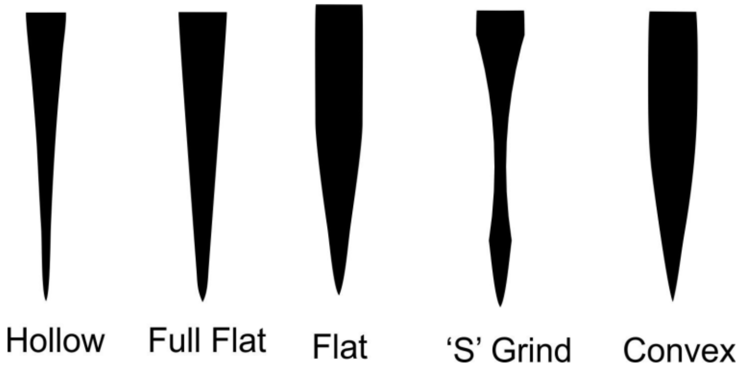
Next, the Cavaliers had to come up with a plan for heat treatment. The first step in this process is deciding on a quench temperature. If the temperature chosen is too low, austenite won't be formed and a martensitic formation would not occur. If the temperature chosen is too high, weakening grain growth can occur and the rate of decarburization can increase. The Cavaliers ran Differential Scanning Calorimetry (DSC) data to pinpoint the temperature at which austenite is formed for S5 steel. The figure below shows this data.



The DSC data confirms the critical temperature at about 820°C. The Cavaliers decided to quench from 850°C to give a slight buffer zone to ensure the critical temperature was reached without going too high. After the quench, the steel must be tempered (held at an elevated temperature for an extended period) to relieve internal stresses and improve toughness. The tempering temperature has a great impact on the final part. Tempering greatly increases toughness, but it reduces hardness. This is where the balance between toughness and hardness really comes into play. If the steel is tempered too cool, it will remain brittle and could crack or chip. If the steel is tempered too hot, the hardness will be greatly decreased, and the tool will not be able to hold an edge and resist deformation. If done at the right temperature, the tool will have a sufficient balance of hardness, edge retention, and toughness.

GRINDING AND FINISHING

Grinding and finishing is another extremely important aspect of cutting tools. The Cavaliers had prior knowledge of edge geometry from other projects, so they knew just how important it was to grind and finish their axe correctly. Below are some common edge geometries for different applications.



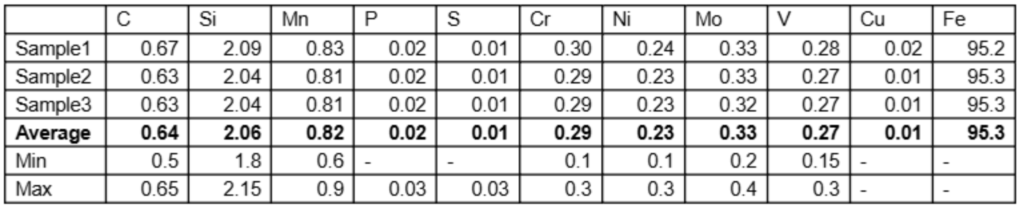
While these differences may not necessarily seem drastic, the team's research indicated that edge geometry plays a critical role in the performance of a cutting tool. A hollow or S grind, for example, would be used for kitchen cutlery, where precision and surgical sharpness is required, and durability is not as important. The convex grind was selected for the axe. This geometry keeps more material behind the edge, leading to higher edge stability and strength, but sacrifices sharpness due to its higher edge angle.

For an axe, convex geometry is most common because it is very impact resistant and durable. Because of the nature of most axe uses (wood splitting for example), sharpness is seen as secondary to impact energy, so sharpness is often sacrificed. The team also considered the idea that a Horseman's Axe is seen as a weapon rather than a tool, so sharpness may be more important. Unable to make a concrete decision from just this information, the Cavaliers decided they needed to test different edge geometry with their steel later in the process.

3. Results

The steel selection process was a collaborative process among all UW-Milwaukee teams, as all teams had the same industry sponsor in MetalTek, and consensus was needed to coordinate the pour for all UW-Milwaukee-designed components.

The Cream City Cavaliers set a goal of accomplishing as many manufacturing steps in the creation of the axe as possible. Burn-out and sintering were attempted on campus in a high temperature furnace, but without proper ventilation, the process was determined to be unsafe. The test was aborted before completion, and the mold failed. It was not understood at this time if the failure was caused by rapid quenching as the furnace door was opened, or expansion of the PLA and resin patterns upon heating. The three remaining green molds were sent to MetalTek in Watertown, Wisconsin, to be burned out, sintered, and prepared for casting. There, MetalTek experienced the same problem with mold cracking. They elected to add two more layers of fused silica as an extra reinforcement. This proved to be an effective solution with both molds surviving to cast. The castings were made onsite at MetalTek. The maximum temperature reached was 1,654°C when the furnace was tapped into a ladle and the melt was poured into the mold preheated to 800°C. Finally, the axes were cut from the sprues using an oxyacetylene torch, and the gating was removed via abrasives.



	C	Si	Mn	P	S	Cr	Ni	Mo	V	Cu	Fe
Sample1	0.67	2.09	0.83	0.02	0.01	0.30	0.24	0.33	0.28	0.02	95.2
Sample2	0.63	2.04	0.81	0.02	0.01	0.29	0.23	0.33	0.27	0.01	95.3
Sample3	0.63	2.04	0.81	0.02	0.01	0.29	0.23	0.32	0.27	0.01	95.3
Average	**0.64**	**2.06**	**0.82**	**0.02**	**0.01**	**0.29**	**0.23**	**0.33**	**0.27**	**0.01**	**95.3**
Min	0.5	1.8	0.6	-	-	0.1	0.1	0.2	0.15	-	-
Max	0.65	2.15	0.9	0.03	0.03	0.3	0.3	0.4	0.3	-	-

The chemistry tests by MetalTek were consistent with the planned chemistry of S5, meaning the Cavaliers could continue with their original plan for heat treatment. Their ideal result was a final HRC of around 58-60 with stable enough edge geometry to prevent chipping despite having a relatively hard edge. After quenching into oil from 850°C, the team found an as-quenched hardness of approximately 60 HRC. After two hours of tempering at 204°C (400°F), the hardness decreased to approximately 58 HRC, meaning there was a small change in hardness and an increase in toughness. These values were exactly what the Cavaliers wanted to see out of our heat-treated samples.

To test the effect of edge geometry on the stability of the blade, two samples were prepared from the gating system. One was ground to a straight taper, and the other was ground to a convex taper. When tested against a steel nail, the sample ground to a convex taper sustained less damage than the sample with the straight taper. This result confirmed that a convex edge would better withstand the forces expected in the application of a Horseman's Axe.

After grinding and finishing, the axe was hafted to an ash handle using a wedge. Ash provides high elasticity and shock absorption while also keeping historical accuracy to medeival Europe. The handle was given a fawn's foot to prevent slippage from the hand, and was made with an oval cross-section to index the axe, keeping the cutting edge in plane with the swinging of the axe.

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