SFSA Cast in Steel 2025

George Washington's Silver Lion Headed Cuttoe

Technical Report

Iowa State University – CyCast

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1. Introduction

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 CyCast team used a variety of modern design tools and advanced manufacturing techniques to bring to life a sword from the Revolutionary War era. This project has given CyCast members a new appreciation of the versatility and complexity of the steel casting process, from the design of a pattern to the metallurgical considerations.

1.1 History of the Blade

The Silver Lion Headed Cuttoe is the sword that George Washington used at the advent of the Revolutionary War. This blade never saw the battlefield but is nonetheless an important marker in the history of America's birth. The blades wielded by Washington in years prior were imported from British craftsmen, and were a symbol of support of the imperial rule of Great Britain. In 1769, Virginia House of Burgesses passed a nonimportation resolution, blocking trade with Great Britain to stimulate economic progress in the American colonies [2]. Washington was an avid supporter of this resolution and was even instrumental in its passing, which drew him to ask craftsmen in Philadelphia to replace his British-made sword for one made locally. This new, American-born sword was the Silver Lion Headed Cuttoe.

Figure 1: The handle of Washington's Silver Lion Headed Cuttoe

Unfortunately, much of the history of this sword has been lost to time. For a simple cuttoe, it was rather large, around 35 inches compared to the 27" standard length. George Washington's larger stature (standing at about 6'2") is the most likely reason for this. It is thought to have been made by the famous silversmith and cutler, John Bailey, who was renowned for making similar swords with a lion-head pommel. The construction of the handle was bone, a contrast to the typical british ivories, but a material much more readily available in colonial America. The sword still holds some colonialist influences, with a slightly curved, European style blade and the lion head popularized by many British silversmiths [1] of the time, and continued by John Bailey.

1.2 Accuracy and Modernization

The CyCast team's reproduction of the Silver Lion Cuttoe blends the rich history of the blade with modern capabilities and production techniques. Without taking all the time and experience that a 18th century swordsmith would have put into their work, the team has created a sword that demonstrates the advancement in production and material science. Many features of the original cuttoe are intricate and hand-carved by a master swordsmith, beyond the technical abilities of the team. Modern production processes allow these features to be recreated with enhanced properties.

1.2.1 Material Considerations

Of course, the original blade is made with silver components. Keeping this in mind, the team chose another relatively soft precious metal for the pommel and crossguard in copper. This kept the idea of the sword as more of a showpiece, with beautifully detailed copper components in the same shape as initially designed. The contrast of the copper and steel provides a more striking appearance, fit for the Commander-in-Chief. Another consideration was the current concerns with ethically sourcing animal bone for the handle. To represent these changing ideals in America and show the advancements in material technology, the was decided to be 3D printed out of Thermoplastic Poly-Urethane (TPU). This material provided a lightweight, comfortable, and shock-absorbing handle in the same style as the original.

1.2.2 Updated Design for Modern Techniques

The pommel is based on images found from various sources, which provided us a basis for the design and a reference to maintain as much historical accuracy as possible. The pommel was to be machined in a way that engraving would be impossible. It was determined that the engravings would be done by hand with a dremel. The crossguard was simplified in hopes of avoiding hand engraving and in the absence of a laser engraving system powerful enough to engrave copper without issues due to its high thermal conductivity and reflectivity. Engraving the crossguard would be done with simpler designs that can be performed by a 3 axis CNC machine. The handle design was as close to historically accurate as possible, however the handle was scaled outwards to create a more lean profile that grants the user edge control without rolling. The handle would be made of TPU, a flexible and tough plastic rather than bone to provide more grip and shock-absorption.

2. The Design Process

2.1 Metallurgy

The metal chosen for the blade was done so by considering multiple factors including toughness, hardness, tensile strength, and castability. It was assumed early on that casting defects such as porosity would be present, especially with the thinness of the casting. Further swords are not typically cast, as the forging process aligns and elongates the grains of the steel, increasing strength and flexibility. Whereas the casting process produces random grain structures. These reasons led to toughness being the highest priority, as a brittle failure from the shock of hitting a target was feared.

Due to the fear of brittle failure, the priority of toughness, and the desire to demonstrate the abilities of steel alloys, plain carbon steels like AISI 1095 were not considered. The team identified 6 possible steels; AISI 4130, 4140, 4340, 5160, S7, D2. Tool steels such as S7 and D2 were an ideal choice because of their air-hardening abilities. The team did not have access to a temperature controlled furnace, and avoiding a quench would reduce the risk of bends or cracks. However the teams foundry partner Omaha Steel does not pour either of these steels. 5160 steel was an obvious choice as many swords and knives are made out of this strong spring steel. However once again Omaha Steel does not pour this steel.

This left the team with the 4100 series and 4300 series steels, these steels were offered by Omaha Steel. These steels were chosen based on the effects of their alloying elements, seen in the SFSA Casting Material Properties supplement. Chromium improves oxidation resistance, molybdenum improves hardenability and high temperature strength, and nickel improves toughness [4]. The improved hardenability from the chromium and molybdenum allow the 4000 series steels to reach a hardness of up to 58 HRC with less carbon content than a plain carbon steel. With toughness being the highest priority it was determined that the blade would be poured with 4340 steel due to the nickel content.

These steels were also compared numerically with an online database MatWeb. This tool has a large database that includes different heat treatments. Comparing hardened 4140 and 4340 steel shows that 4340 is harder, with 4140 registering a 28 HRC compared to 4340 at 39 HRC [5]. 4340 is also much stronger with an ultimate tensile strength of 1207 MPa compared to 883 MPa. These values aligned with the element decision, supporting 4340 steel [6].

2.2 Digital Design

Every component in our design, aside from connection pieces and the chain, required digital modeling. Our blade was designed in SOLIDWORKS and Fusion 360, turned into a pattern, and sent to the foundry for casting. The outline was designed based on the shape of reference images and scaled to the proper length, maintaining near-exact specifications for the curvature and size of the blade. A stress analysis as seen in Figure 2 was conducted to determine whether an angled tang, which seemed to be used in the original construction, would be stronger than a straight tang. Various angles were tested; ultimately, an angle of 1.9° was chosen to be the strongest, as shown in Figure 3. The max Von Mises stress calculated from the simulation was 2559 Mpa, and the max shear was 262 Mpa. While these values were higher than the ultimate strength of the material, the comparison was between the different tang angles with the same load.

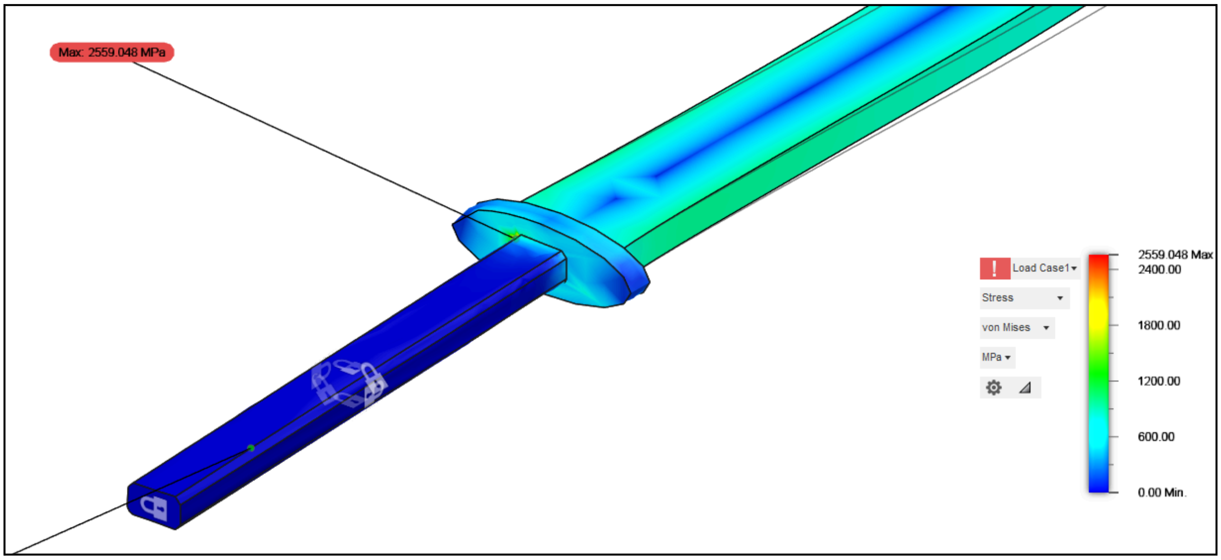

Figure 2: Stress analysis of tang. 500 lb load applied to the blade a distance of ⅔ the blade length.

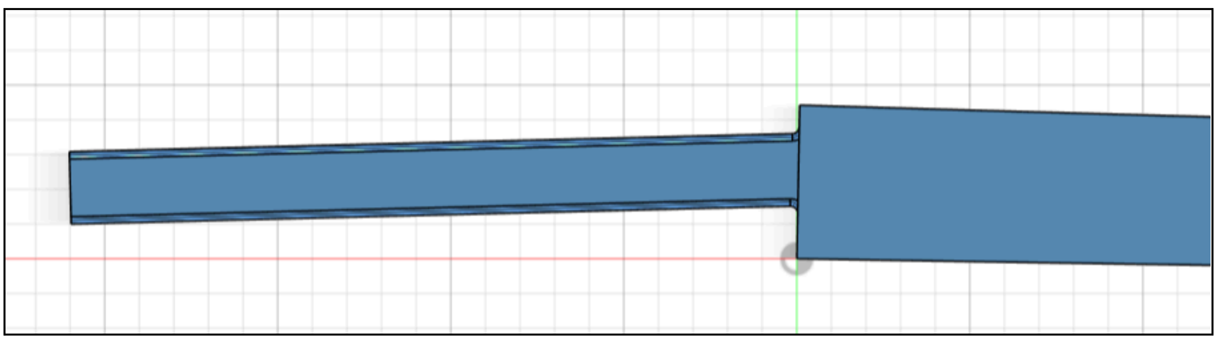

Figure 3: Fusion model of angled tang.

The pommel and crossguard were designed using a mix of SOLIDWORKS and Blender modeling software. Many potential designs were considered for the crossguard, and several iterations were created in this stage. It was determined that the pommel was to be hand engraved due to limitations on creating fine detailing with the machinery Iowa State had to work with. There was some difficulty in creating the hairs of the lion's head, and the final part file used both a shell from Blender with over 100,000 faces for the fine detailing as well as additions in SOLIDWORKS, which allowed for the pommel to be machined using CNC Rapid-Prototyping (CNC-RP) on a Haas VF-2SS. This technology allows a 3D model to be machined with automated toolpath generation. The model is fit inside round stock and 3+1 axis toolpaths are generated, with a ¼ inch tab connecting the model to the stock. This also solves the issue of fixtureing the model. The limitation to this machine is the file size, a model with too many faces will not be able to be processed. The hairs and other engravings led to too many faces on the model, thus just the underlying shape of the lion head was modeled. This model, along with the engraved version, is shown in Figure 4.

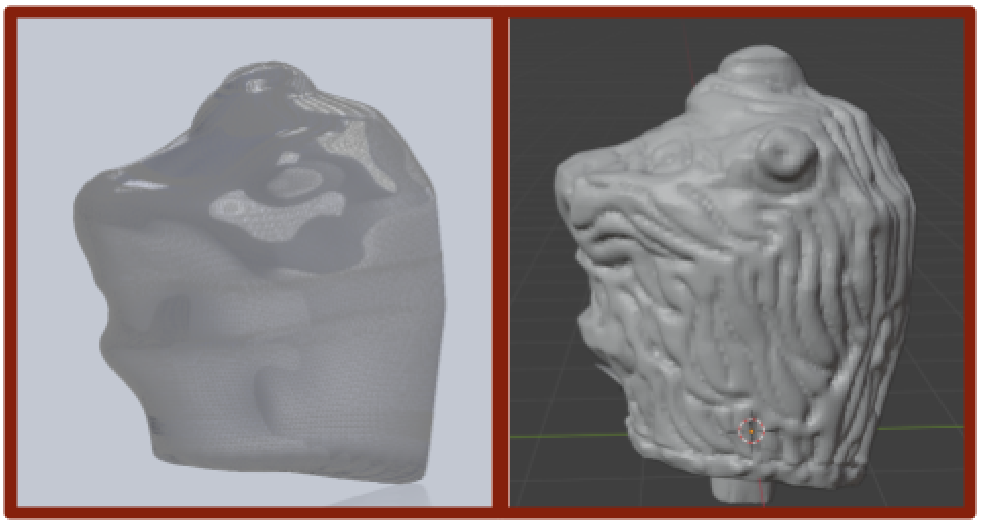

Figure 4: The pommel used (left), and the desired, engraved pommel (right)

It was desired to have some engravings on the sword that were machined, to demonstrate the precision and control of the modern manufacturing process. CNC-RP was unable to engrave the pommel, so it was decided that it would be hand-engraved. Modeling the original engravings was difficult and were not feasible with the tools available. To still have machined engravings present, the team chose to engrave the crossguard. Once the crossguard was modeled as close to the original as possible, the team decided to engrave the SFSA logo on one side. This is a nod to the organization that hosts this competition, as well as an organization dedicated to the advancement of industry, a key theme in George Washington's life. The other side would say "Victory or Death", a nod to the password used on the night Washington crossed the Delaware, possibly with the Silver Lion Headed Cuttoe. Figure 5 shows a few different iterations of the crossguard that were designed before arriving upon the final engraving.

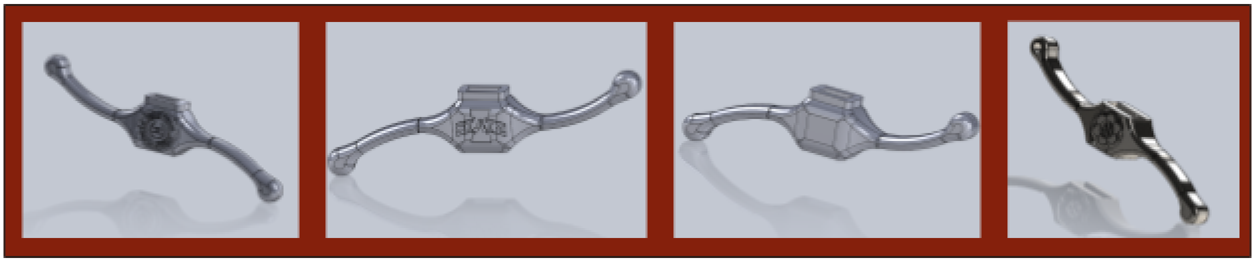

Figure 5: Various crossguard iterations

The precision required to machine the crossguard profile and engravings meant CNC-RP could not be used. CNC-RP utilizes tools with high stick out to reach the stock between the 4th axis jaws. The high stick out inherently leads to chatter, thus a machined surface with a fine surface finish is nearly impossible. The team would have to use 3 axis machining with a parallel operation and shorter tools to machine a smooth crossguard. This introduced the fixtureing problem. The crossguard will not sit flat in a vise, as there are no parallel sides. To avoid this, a window was designed around the crossguard to hold the crossguard during machining. The tabs would then be cut and sanded, minimizing the inconsistent surface finish. The crossguard with the window can be seen in Figure 6, note the engravings are not modeled as they were created during toolpath generation.

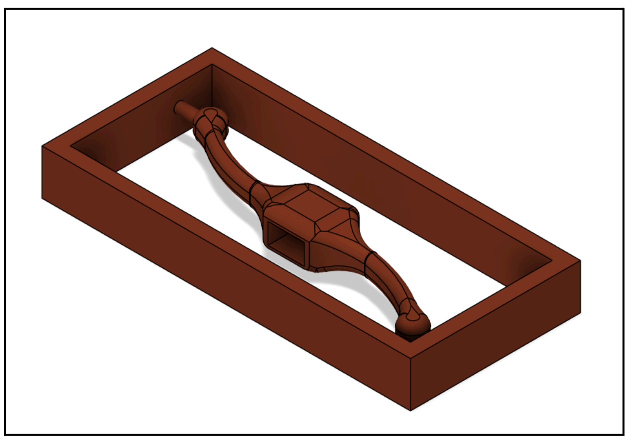

Figure 6: Crossguard with fixtureing window

The handle design was a much more iterative process, with dozens of sizes tested. 3D printing allows for rapid prototyping, a model can be turned into a physical object in a few hours for a very low cost. The design maintained the helical grooves of the original design, however it was determined that a skinnier vertical profile would be most comfortable and allow the user to have control over the edge. Prototypes were printed out of PLA (PolyLactic Acid) to increase production time and reduce cost. Once a final model was made, it was printed out of TPU. A side effect of 3D printing is the visible layer lines, to avoid this the team smoothed the handle with a heat gun. Initial tests indicated deeper grooves would prevent over-smoothing, so the handle grooves were designed with this in mind.

2.3 Pattern Design

Once the model of the blade was created, a pattern had to be made. It was known that multiple swords would be desired as the chance of porosity, hot tears, and misruns was high. To minimize complexity and size, it was decided that two swords would be cast in the same pattern. This would allow a central runner to feed both swords at the same time. A meeting with the foundry concluded with the gating ratio being 1:2:2 and the sprue being 1 inch in diameter. A runner extension was also discussed, to allow the impurities to collect. Using these parameters, a runner was designed, tapering to slow the metal. According to the SFSA Steel Castings Handbook Supplement 1 the minimum section thickness of steel casting is .25 inches [7]. Our blade was to have a thickness much less than this, so a casting blank had to be made. This blank was .25 inches thick and would serve as the template for our blade to be ground out of. The blank also allowed a draft angle of 3 degrees to be applied. To avoid alignment issues, the entire blade was placed in the cope, with the gating system in the drag. The casting blank can be seen in Figure 7.

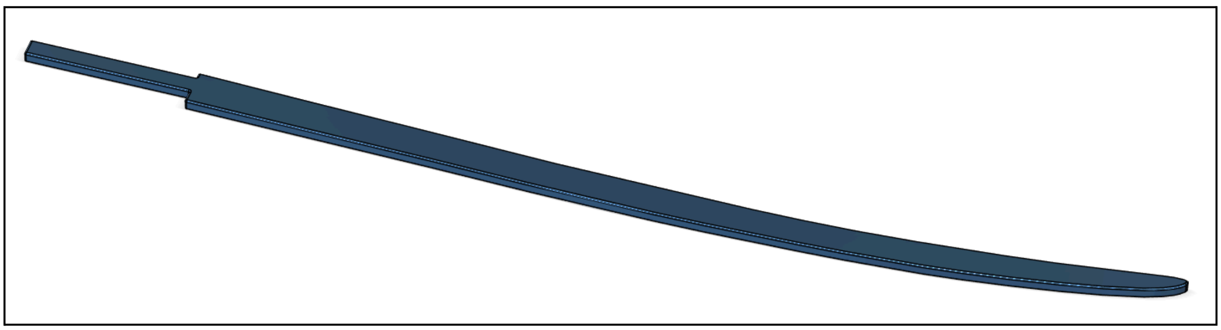

Figure 7: Casting blank with 3 degree draft

With the total length of the blank being roughly 35 inches, it was decided to have four gates along the blade to avoid the metal traveling more than 4-5 inches. It was feared that the thinnest of the blade would cause the metal to lose heat too fast. To further avoid this, the gates are arranged vertically and follow the .25 inch minimum section thickness rule. The pattern is shown below:

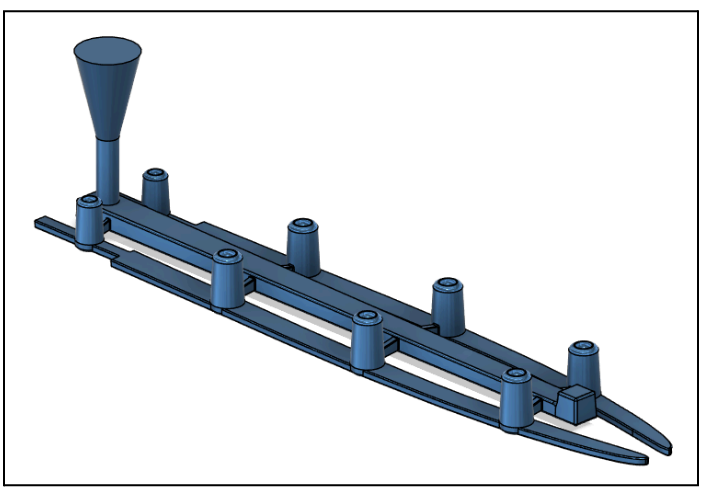

Figure 8: Model of casting pattern

To test the pattern design the team utilized the software Magmasoft. Magmasoft is a simulation software that helps visualize and optimize the casting process. It uses finite element analysis and computational fluid dynamics to model the entirety of the casting process. It models the filling, solidification, and cooling of the metal, while providing thermal and stress analysis. This software allows porosity, hot spots, and other casting concerns to be visualized before casting the part.

Initial designs had the risers either on the runner or between the gates. These designs showed porosity in the blades as seen in Figure 9. This porosity was probably caused by the metal in the gates or the blade cooling and cutting off the feed from the risers.

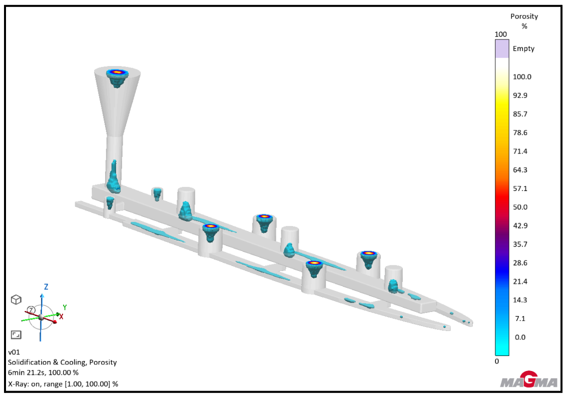

Figure 9: MAGMA porosity simulation with risers between gates. Note porosity between risers

The team altered the riser placement according to the Feeding & Risering Guidelines for Steel Casting which mentions that in thin castings feeding becomes highly dependent on the filling process. Further, if a thin section is gated through a riser, feeding distances up to twice as long have been reported. The team moved the risers to the gate locations and had the gates flow through the riser. Simulations then showed almost no porosity. Further the hotspots are seen to be contained within the risers as seen in Figure 10.

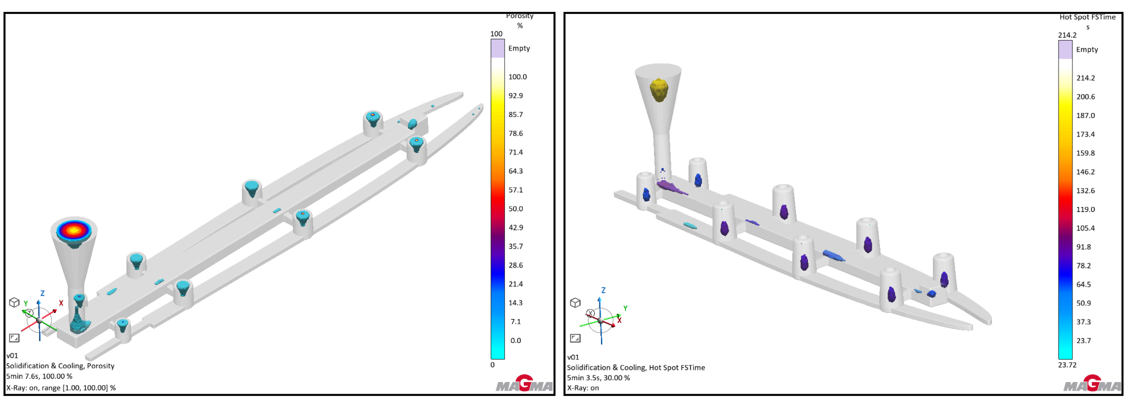

Figure 10: MAGMA simulations of pattern with gated risers. Note minimal porosity and hotspots in risers

With this good simulation, work began constructing the pattern box. The pattern itself was 3D printed out of ABS plastic. This plastic is strong and durable, allowing it to withstand the compaction and abrasion of multiple molds. Because the pattern is larger than the 3D printer, the pattern was cut into sections. These sections were then “welded” together with a soldering iron and extra filament. This resulted in a single piece with a consistent surface. Finally the layer lines were sanded away to avoid sand sticking to them. It should be noted that the pattern was printed with five walls to avoid sanding through to the infill.

To align the pattern on the cope and drag, circular tabs were added to the model. These tab locations were then carefully plotted on the board and drilled. The patterns were secured using Gorilla Glue and excess was trimmed away. Alignment cones were also added. Finally the walls were built, allowing at least 3 inches of sand around the pattern. The walls had a 5 degree draft to facilitate mold removal. The final patterns are shown in Figure 11.

Figure 11: Left - Drag box containing gating system pattern. Right - Cope and drag boxes

3. Foundry Results

Omaha Steel was able to make 10 swords by making five molds with the pattern box. Four of the 10 swords were non-conforming casts, and the foundry kept them. 6 swords were returned to the team to work with. Five of the swords were degated and had the risers removed at the foundry, expect one in which the risers and vents were kept on as shown in Figure 12.

Figure 12: Preprocessing cast swords.

All of the blades experienced hot tears at the risers, which required production welding for a uniform final product. This welding was done with a 4340 stick to ensure similar metals. The possibility of the hot tears were predicted by Magmasoft simulations, however the thinness of the blade, the size of the risers, and the actual pour rate all could contribute.

The foundry provided a chemical analysis of the heat, **provided in the appendix**. The foundry does not typically pour steels with carbon as high as .4% so the foundry ran a half heat for our team. To make our steel the foundry raised the carbon content to .46%, slightly higher than anticipated. This difference was determined to be desirable as more carbon would result in a harder blade.

Finally, it was requested upon ordering that the blades be normalized after casting. This was done to alleviate residual stresses from the casting process as well as ensure the steel is in a softened state. A lot of grinding and possible machining was going to be required, so machinability was a concern. All of the blades were normalized at the foundry.

3.1 Initial Inspection and Specifications

The blades were returned with an as-cast steel finish with various deformations. There were welds made on the hot tears, warping of the blades, and various surface defects. These were all visually inspected and evaluated to give an initial ranking of blades. The 5 blades used were labeled 1 to 5 and ranked.

The first observation done was a qualitative weld ratings. The hot tears required welding to be done which can be seen in Figure 13. All blades had to be welded. Table 1 shows the rankings of the blades out of 10. 10 was considered perfect welding, i.e. very smooth and uniform weld bead with no porosity, and 1 was considered very bad welding, i.e. not fully welded, porosity. From the rankings, blade 3 was the best and blade 4 was the worst.

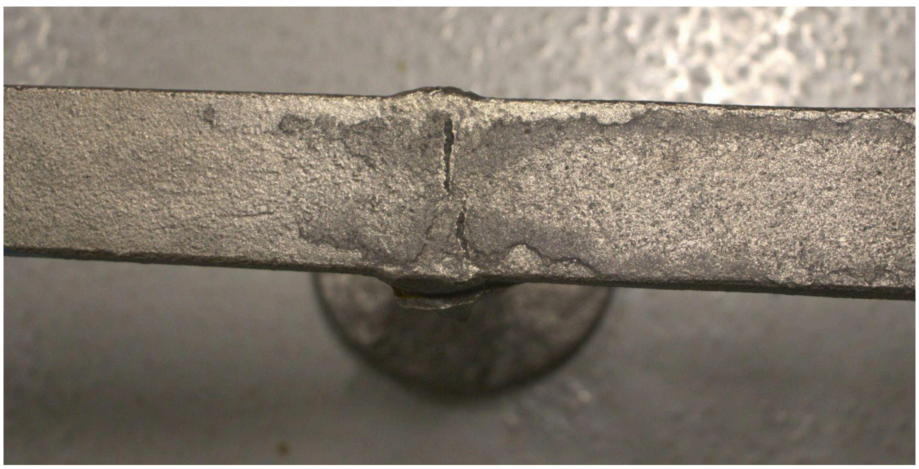

Figure 13: Un-welded hot tears

Blades	1	2	3	4	5
Weld score	6/10	5/10	7/10	3/10	5/10

Table 1: Hot Tear weld ratings

The next observation made was a quantitative warp rating, evaluating the distance from the tip to the table when the tang is flush with a table. This was necessary as all of the blades had some degree of warpage. Table 2 shows the distance in inches the distance was from the tip to table. Blade 2 had the most warping and blade 4 had the least warping.

Blades	1	2	3	4	5
Tip distance (in)	1.3	2	1.4	0.75	0.85

Table 2: Warp distance

The team conducted another qualitative test looking for other significant defects such as visible porosity and cracks. Table 3 shows the ranking of the blades on a scale from 1 to 10. 10 means that there were no defects, pores, or cracks, which none of the blades exhibited. 1 meant there were significant defects, which were present in the 4 the foundry kept. Blade 3 had the least amount of pores and cracks which was the best of all 5 blades. Blade 4 had the most defects and cracks with small chunks missing which made it the worst.

Blades	1	2	3	4	5
Defect score	5/10	3/10	7/10	2/10	6/10

Table 1 : Defect rating

The final initial test was a hardness test. The tests were done where the blade meets the tang, moving ⅛" towards the end of the tang. The test was done on the tang because the tang has to withstand the stresses of impacts, thus hardness is needed. This was also the thickest section of the blade

The data showed that Blade 1 was the hardest and blade 4 was the softest. These were initial hardness testing, and the hardness was expected to greatly increase with work hardening.

Distance from where tang meet blade (in)	Sword Number				
	1	**2**	**3**	**4**	**5**
0.125	43.7	48.2	39.5	35.1	38.9
0.25	46.1	43.5	37.4	34.5	38.2
0.375	43.9	45.7	41.2	36.8	41.7
0.5	49.9	46.2	37.8	34.6	40.3
0.625	47.6	45.5	39.8	37	42.5
0.75	48.2	49.1	37.1	33.7	39.2
0.875	50.2	50.2	41.5	38.4	43.5
1	49.6	48.9	33.2	30.9	37.7
Average	47.4	47.1625	38.4375	35.125	40.25

Table 4: Hardness Testing Data

After the initial tests and evaluation, Blade 1, 3, and 5 were the best overall blades, blades 2 and 4 were eliminated as final blades.

4. Post - Processing

4.1 Blade Processing

Due to steel casting dimensional limitations, the swords required material removal. After a discussion of possible methods, it was decided that an angle grinder with a flap wheel would be best. Additionally the blades experienced warping during the cooling and solidification process that required correction. Along the way, porosity and cracks needed to be fixed. Finally a heat treatment was required to harden the steel, followed by a final polish.

4.1.1 Grinding to Shape

From the design process, a dimensionally accurate model was made. This model was then 3D printed to the correct dimensions giving a physical model to base the grinding on. The model had 6 sections, again due to the sword being larger than the 3D printer, that could be interlocked to form a full blade and also taken apart to have smaller sections. The 3D model was laid on top of the cast swords and then traced to form the blade face. The swords were then ground down to those lines.

The next step was to grind the distal taper. A centerline was marked down the spine of the blade. The 3D model was taken apart into pieces. The spine of the 3D model section was lined up with the centerline on the spine, and the profile was traced. These steps were repeated down the entire blade until a thickness profile was made. The blade was then ground to the correct taper thickness. A base thickness of .3 inches and a tip thickness of 0.025 inches was desired for the rough grind. Further refinement would be done with finer sanding methods.

The blade edge and fuller were marked on the blade, with fuller being 0.3 inches from the spine and the edge taper being 0.5 inches from the cutting edge. The lines were averaged and smoothed by hand near the tip to account for the taper. The fuller was ground by following the line with the edge of the flap wheel. It proved difficult to maintain a consistent line as the grinder wanted to wander. The edge was ground to the line, ensuring a consistent edge profile.

As the blade was ground, porosity bubbles were revealed. The bubbles were marked on the blade, and then milled out to allow filler material to get in the cavity. These holes were filled in using TIG welding. To ensure similar metals, a vent from the casting seen in Figure 14 was cut off and used as a TIG rod. Smaller pores were simply fused shut with no filler metal. All visible indications were welded as seen in Figure X. The process of grinding the blade to shape was then repeated in order to remove the additional marks and provide a smooth blade, followed by a second round of TIG welding.

Figure 14: Blade with weld beads and finished blades.

The bulk of the grinding was done using a 60-grit sanding wheel on the angle grinder. This took a good amount of material (almost 1.75 pounds per blade) off but still allowed for excess material for finishing. Prior to heat treatment, the blades were sanded with an orbital sander using 80, 120, and 220 grit paper. This resulted in a smooth blade free of deep scratches.

4.1.2 Heat Treatment

The grinding, welding, and sanding of the blades introduced a lot of heat to the blades. The heat generated from these processes helped straighten the blades a good amount, but also induced a lot of internal stresses. It was attempted to control the amount of heat added to the blades, however processes like TIG welding, especially in random areas, are difficult to control.

The primary heat treatment was done with a hardening and then tempering process. The hardening process involved heating the blade to roughly 1525 degrees Fahrenheit. The Iowa State University Industrial Engineering department does not have a controlled furnace, thus verifying the temperature was mostly visual utilizing Figure 15, a Steel Heat Color Temperature Chart. Another test was a magnet on the end of a rod. The blades were heated until no longer magnetic, indicating a temperature near but slightly less than needed. Once the blade reached the ideal color, it was held at that temp, allowing the austenite phase to develop. The blade was then removed from the heat source and quenched in automatic transmission fluid (ATF). The quenching oil was based on availability, with ATF, motor oil, canola oil, and hydraulic oil considered. ATF was chosen as the viscosity was ideal under high heat and the thermal properties are similar to quenching oil. During the quench, multiple blades experienced warping and pings were felt possibly indicating cracking. The tempering process was done by reheating the blade up to between 850-950°F then quenching again. This was done to reduce the brittleness of the blade, increase toughness, and reduce the internal stresses. The tempering temperature was chosen based on the tempering diagram provided by Atlas Steel as seen in Figure 16 The temperature was found during this part by using an infrared thermometer on the blades.

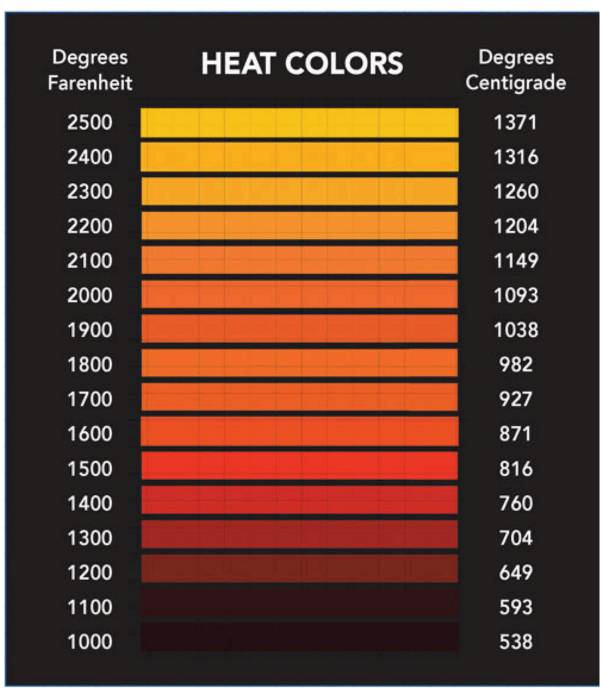

Figure 15: Steel Heat Color Temperature Chart

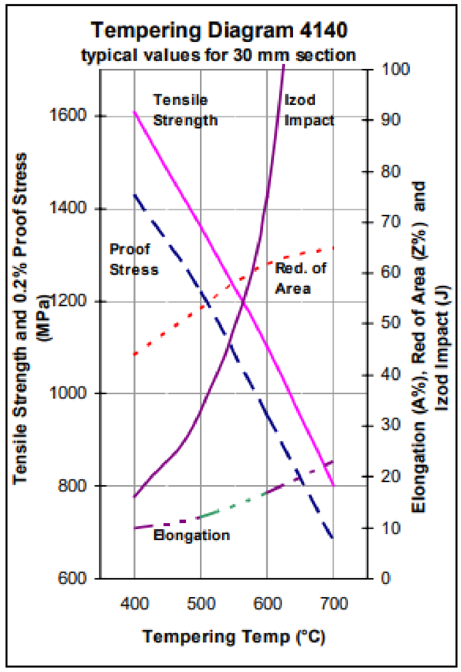

Figure 16: Tempering diagram of 4340 steel [8]

The heat source was generated by burning a combination of anthracite coal and split log wood. Anthracite coal was chosen because it can burn at very high temperatures of over 1500°F. The fire was started using wood and a leaf blower to introduce lots of oxygen to the fire, increasing heat. The coal was then added. Once the coal had ignited, it was spread out into a bed with additional logs placed atop. The leaf blower was used continuously to provide air to the fire, allowing high temperatures to be reached. A thermocouple probe was used to register the temperature. A team member inserted the probe near the center and got readings of 1400°F. Due to the heat, the probe was not able to be put into the hottest part of the fire, but it was estimated to reach over 1600°F where the sword was. A file was used to determine if the swords had hardened. The file did not skate over any of the blades.

After the heat treatment, scale formed on the sword. This required the sword to be resanded. Like previously done, 120-grit then 220-grit were used. Then 400-grit sandpaper was used by hand. This was followed by 600-grit, 800-grit, and finally, 1000-grit sandpaper. The final polish was done using a dremel with a buffing wheel attachment combined with a polishing compound.

4.2 Pommel Construction

The pommel was milled out of copper round stock using a Haas VF-2SS. After the CAD model was designed in Fusion 360, it was uploaded to Dr. Mathew Frank's CNC-RP. 3+1 axis toolpaths were automatically generated for the operation and the model is automatically fixtured in the stock. Once the pommel was machined, the features of the lion were hand engraved. A team member used a dremel with a 3/32 inch tungsten carbide engraving tool. It proved difficult to maintain a straight line, as the dremel wanted to wander a lot. Once the rough engravings were done, the whole model was sanded with an abrasive pad attachment for the dremel, creating a smooth, uniform surface. Some of the engravings needed to be re-applied for consistent depth followed by another round of sanding. A hole was drilled through the pommel to allow for a bolt to hold it to the tang. Another hole was drilled into the mouth and tapped with an M3 bolt. A wire ring was formed and silver-soldered to the bolt, creating a ring that can be screwed into the pommel. This ring would hold the chain.

To hide the bolt fixing the pommel to the tang, a copper bar was turned on a lathe to match the diameter of the hole drilled. Light sanding was done to ensure a proper fit. The rod was then cut to a proper length and rounded at the end, creating a nib at the end of the sword, much like the original design.

4.3 Cross-Guard Construction

The crossguard was machined out of a block of copper using a Haas UMC-750 5-axis milling machine. The machining process began with the CAD model being made in Fusion 360. The toolpaths for the operation were made in Fusion 360's CAM module with operations for efficiency and surface finish. The crossguard had a complex shape which required a 3 axis parallel machining strategy to be used with two setups.

The copper block was squared and secured into the UMC-750's dual-axis trunnion table in a precision, self-centering vice. A ruby-tipped probe was used to establish the work coordinate system. The machining began by roughing material and milling a basic shape of the cross-guard. Once the profile was established, finishing passes were done with a ¼ inch ball end mill with a stepover of 0.002 inches, creating a smooth and consistent surface. SFSA's logo and "Victory or Death" were etched into the crossguard during their respective setups.

Once machined, the crossguard was cut from the window with a bandsaw and the contact patches were sanded smooth. A manual vertical mill was used to cut the hole for the tang. Careful measuring followed by finishing with a file ensured a tight fit to the tang. The crossguard was finished with a buff from the dremel.

4.4 Handle Construction

As previously stated in the Material Considerations section, the handle is made of Thermoplastic Poly-Urethane (TPU) utilizing Fused Deposition Modeling (FDM). This technique is a form of 3D printing that uses a thermoplastic filament, which is then melted and extruded through a nozzle to build the handle layer by layer.

The final handle design was an iterative process. By utilizing FDM along with a cheaper filament Polylactic acid (PLA), rapid prototyping was done to find the ideal shape and size of the handle. In addition to various shapes and sizes, multiple textures were printed to balance historical accuracy, grip, and comfort. Seven handles were printed and tested, which are shown in Figure 17.

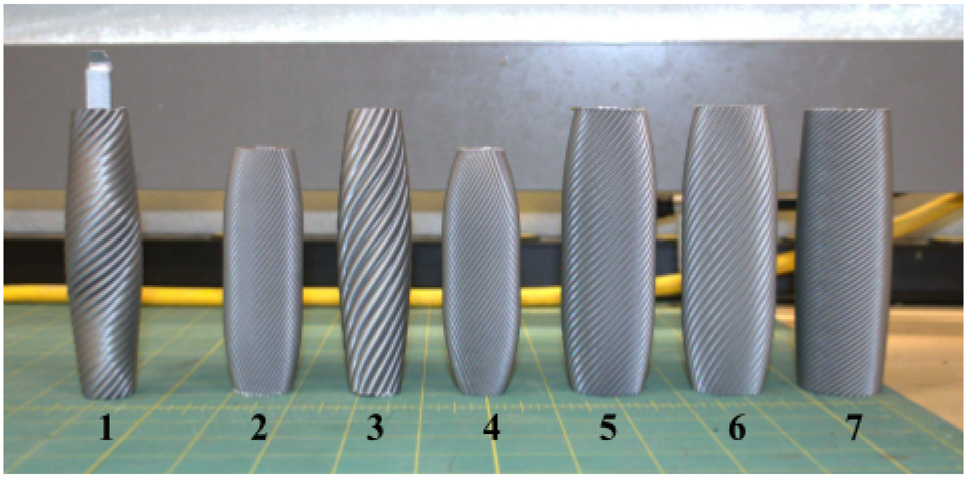

Figure 17: PLA 3D printed handles.

These prototype handles served as a guide for the final design. TPU was used to print the final design with three different infills. By changing the infill, the grip had varying cushioning when held and swung. Infills of 40%, 55% and 75% were chosen in either gyroid or cubic patterns. These infills offer uniform strength in all directions, and are dense enough to provide firmness. 55% cubic infill was chosen as the final handle. The TPU color was chosen to be white, it was desired to use a bone color to match the original, however this color was not available in TPU.

Figure 19: Final TPU 3D printed handle

5. Testing and Analysis

5.1 Ultrasonic Inspection

An immersion based ultrasonic inspection was performed on one of the blades for a form of nondestructive evaluation. Ultrasonic testing was chosen in order to get a proper skin depth and level of clarity, without requiring the power and cost associated with performing radiography. This was done to detect critical indications in our best sample, and therefore was done with a relatively large transducer diameter and low frequency. Large indications at the base of the blade would point to significant potential stress concentration points, and therefore the base of the blade most likely to become the final product was examined. Specifications of the scan are listed below:

- **Frequency:** 10 MHz
- **Transducer Diameter:** ¼ ”
- **Length Examined:** 4” - 17” (from flat end of tang)

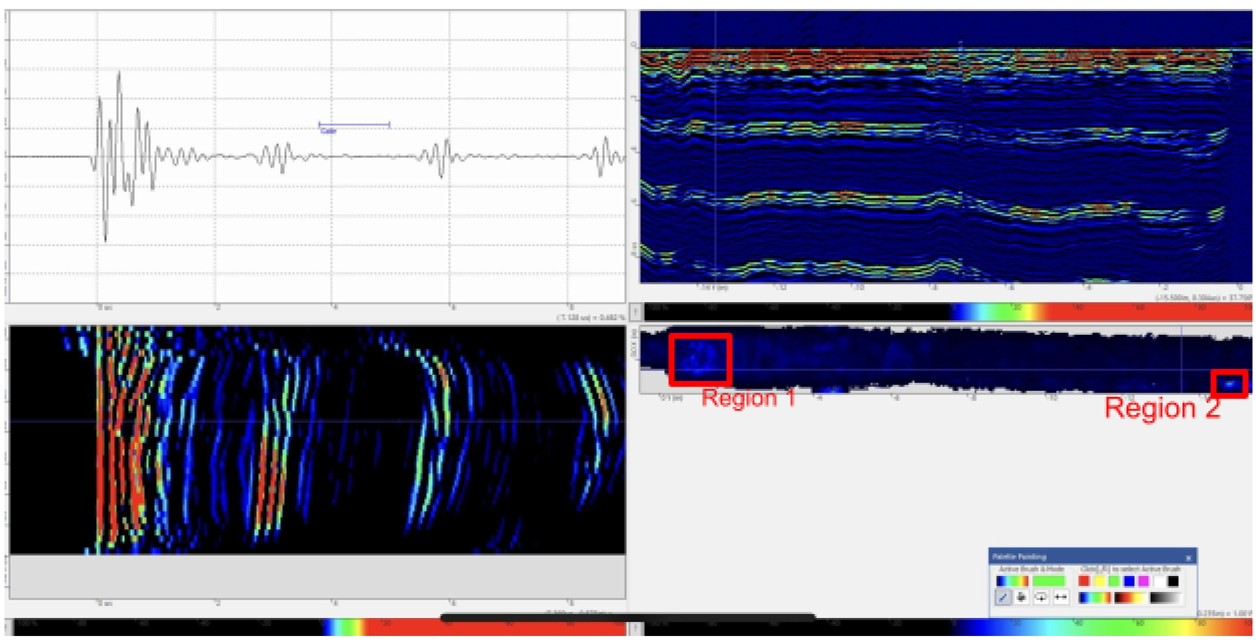

Figure 20: C-Scan, B-Scan, A-Scan plot of the base half of the blade

As shown in Figure 20, the base end of the sample tested showed no indications significant enough for the transducer and frequency selected to pick them up. It is important to note that there was significant porosity in the samples of the blades, but the one tested had some of the least towards the base, and the air pockets found were mostly too small for this specific inspection to see. At the connection between blade and tang, complicated geometry due to the Omaha Steel logo caused a region of unknown quality, marked as “Region 1” in the C-Scan. Towards the end of the scanned portion of the blade, “Region 2” in the C-Scan corresponds to a porosity bubble on the edge of the blade, and was marked to be filled. Most other non uniform coloring was due to surfaces not perfectly parallel to the transducer.

5.2 Hardness & Strength Testing

After the heat treatment process, the team decided to hardness test a single blade that would not be turned in. It was assumed that the heat treatment process was reasonably uniform across the blades, and a hardness test leaves a visible dent on the material. At this point the final blade selection was between two blades, as the others had visible cracks appear during heat treatment. A hardness test was performed and a value of 32 HRC was recorded. This was harder than the normalized steel, indicating a successful heat treatment. A blade that was deemed unfit was selected for destructive testing. The blade was struck repeatedly against a tree trunk until a shatter occurred. The shatter occurred where a hot tear had been welded.

6. Final Product

Figure 21: Final CyCast Lion Head Cuttoe

6.1 Specifications

The final blade chosen was Blade 3. This blade was chosen because of its minimal pores, surface defects and its high strength.

6.2 Error and Future Correction

Unfortunately casting can often lead to lots of error and complications, especially in such a thin part like a sword. One of the biggest errors in the casting of the sword was porosity. Porosity riddled the sword and it was difficult to fix without introducing other imperfections. The biggest issue that the sword experienced was hot tear likely due to a fast pouring rate and air vents being used as accidental risers during solidification. Future correction will be made through taking note of everything that could be introduced to the mold and how it could affect the part by discussing with the foundry ahead of time and performing more simulations to weed out the errors.

Lack of tools and resources was a struggle for the team as there is no inhouse foundry capable of producing metal and no furnaces or quenching equipment at Iowa State. So the team had to improvise heavily and fund a part of the sword in order to meet the final deadline. Time was a huge struggle for the team in that the team was only made aware of the competition a month after it was announced. This caused some miscommunications and rushed components.

Luckily, these are all things that can be easily improved through structure and diligence of everyone involved. So much knowledge and networking has been obtained throughout the past months.This has been an amazing opportunity for all the students involved and we thank SFSA for creating such an intriguing competition.

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