Cast in Steel 2025

Designing, Modeling, Casting, and Testing of George Washington's Sword

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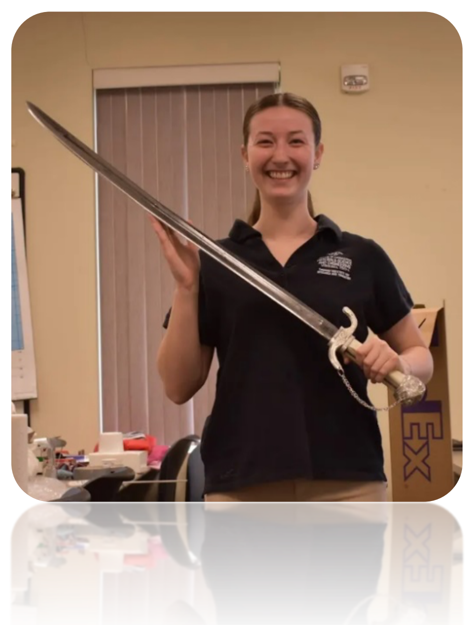

Foundry Partner: Midwest Metal Products

Abstract
For our submission, we based our design off the Silver Lion-Headed Cuttoe owned by George Washington in the late 18th century. Our goal was to produce a replica of this sword within the parameters of the competition. The team considered many designs and modeled them in MAGMAsoft and ended up casting six sword blanks, varying in thickness- 1/4", 3/8", and 1/2". Each sword was molded using chemically bonded sand and one of the 3/8" sword blanks had the addition of a riser. From this, the best quality blank had the gating cut off, then underwent a rough grinding process to obtain the correct shape and a 30 degree roughly ground profile was put onto the sword. After this, the blade was sent to Southwest Specialty Heat Treat and heat treated (austenitized at 1850ºF for 45 minutes, air cooled to <150oF, the tempered for two cycles of 4 hours at 1000°F) to produce a hard steel blade with high toughness. After this, a fuller was ground into the blade and the final profile was put on with a belt sander. The edge was then sharpened, honed with a soapstone, and polished with a leather strop.

During this process, the chemical composition of the steels cast were determined using an optical emission spectrometer to ensure our cast metal was within our desired specifications. Brinell hardness tests were conducted to determine if our heat treating process had the desired effect on the mechanical properties of the blade. The microstructure of our heat treated steel was also determined. Our final sword was very similar to the Lion-Headed Cuttoe in appearance and should perform well in testing.

Introduction
SFSA created this competition to encourage students to learn about making steel products using casting process and applying the latest technology available. SFSA has a significant focus on networking with industry representatives and building connections. Additionally, our team wanted to adhere to the spirit of this competition, as it is a cast steel competition. Our sword was cast and we did not utilize forging. The actual George Washington sword would have been forged. The competition specifies that the sword must be within 2" of the original sword length, have a single sharpened edge, weigh less than 4.4 lbs. (2 kg), and not exceed 43" in length with a blade length of less than 35".

History (al., 2016)
This design we chose was based on the Lion-Headed Cuttoe shown on the Mount Vernon website, Figure 1. This sword was purchased by George Washington in the 1770s and was potentially the first American-made cuttoe purchased by the general. As Virginia non-importation resolutions were in full swing, Washington turned towards the metal workers in the colonies to produce the sword. This makes this sword a very unique piece. While the guard, handle, and lions head pommel were made in the future United States, the blade likely was made in Europe. It served as a symbol of the new emerging country's formation.

Figure 1: George Washington's Lion Headed Cuttoe

This symbolism is advanced when you look at the time that Washington carried the sword. While fighting in the French and Indian War and his earlier days of serving in the Virginia Colonial forces, it is likely that he carried this sword, which he inherited from his grandfather, John Augustine Washington II. In the early 1770s, Washington purchased the lions-headed cuttoe which he carried with him in his latter days of serving in the Virginia Colonial forces and during the War of the Revolution, according to a notarized statement from Lanier Washington, the last family member to own the sword. Later, in 1778 or 1779, George Washington purchased the Bailey Silver and Ivory-Hilted Cuttoe. All this evidence backs up the fact that this sword was a true bridge between the colonial days of the United States and the newly emerging country that George Washington was eventually tasked to lead.

Design

When looking at the blade, there are four distinct components: the guard, the handle, the pommel, and the blade. The pommel is a silver lion's head with an ornamental border on the bottom where the pommel connects to the handle, Figure 2 (al., 2016). A silver ring, designed to hold the upper end of the knuckle chain is attached at the center of the lion’s teeth.

Figure 2: Pommel (left) and original sword’s pommel (right) (al., 2016)

Although most handles were made from ivory, bone was more readily available to the American producer. The handle was carved from animal bone even though it was not as reliable as ivory (al., 2016). We used modern G10 scales for our sword for its durability, accessibility, and shared visual similarities. The guard was designed to provide protection to the hands of the user while maintaining the weapon's lightweight and decorative appeal. It features a knuckle guard that extends from the hilt, curving toward the pommel Figure 3 (al., 2016). The curved knuckle guard ensured a secure grip during use.

Figure 3: Pommel, Handle, and Guard of Original Sword (top) and Our Sword (bottom)

The blade is 30 inches in length, which is longer than the typical cuttoe. Knowing that there are intricate details on this sword, the team decided to cast a steel blank for the sword and create the handle, pommel, and guard separately. For the steel blank, we reached out to our industry partner for a CAD model to use as a baseline. The steel blank CAD file provided had a widened tip, so it does not come to as much of a point, which was better from a casting perspective. The thickness of the blank was set at 3/8". Oven baked clay was used to make the guards and pommel. Once the clay pieces were dried, a Dremel was used to produce fine details.

Filling and Solidification Analysis

After collaborating with our industry partners, we created three CAD files: one for a tapered sword blank, one for a sword blank with a fuller, and one for a sword blank without a fuller. To maximize the likelihood of a complete fill, we opted for a vertical pour. A riser was added under the tang to eliminate porosity, as this is a high-stress area and is typically where swords break.

We used MAGMAsoft to create our gating system that consisted of a pouring basin, a downsprue, and a riser, Figure 4.

Figure 4: Gating system created in MAGMAsoft

Upon analyzing the results, we encountered issues with porosity at the bottom of the sword. To address this, we added a well to catch the first metal poured into the mold. After finalizing the gating system, we conducted a design of experiments (DOE) with the three CAD files to determine which sword design we should actually cast. The sword without the fuller showed the cleanest results in terms of porosity, Figure 5, so we proceeded with the remaining simulations using only that CAD file.

Figure 5: Porosity Percentage in the Results Perspective of MAGMAsoft

While we successfully eliminated most of the porosity, we still experienced high velocity during pouring and a potential for microporosity throughout the casting, Figure 6.

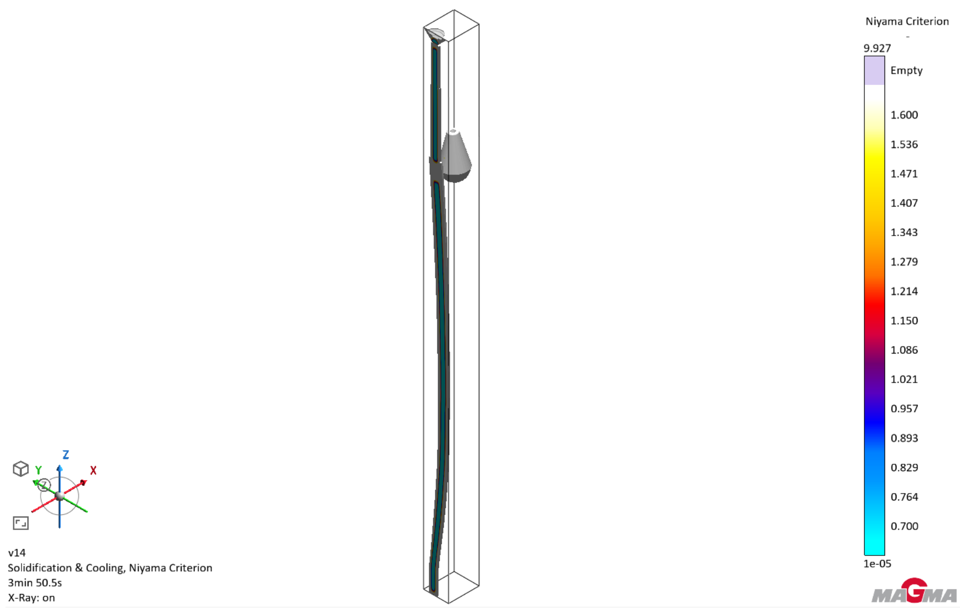

Figure 6: Niyama Criterion in the Results Perspective of MAGMAsoft

To resolve this, we consulted with a MAGMA representative, who suggested adding a chill to accelerate solidification. Using the same gating system, we ran another DOE with two different chill materials: pure copper and steel. However, we made limited progress with this approach, so we decided to experiment further by running the DOE three additional times—once without the riser, once without the well, and once without both the riser and well. The cleanest result came from the gating system without the well and riser and with the addition of a steel chill, Figure 7.

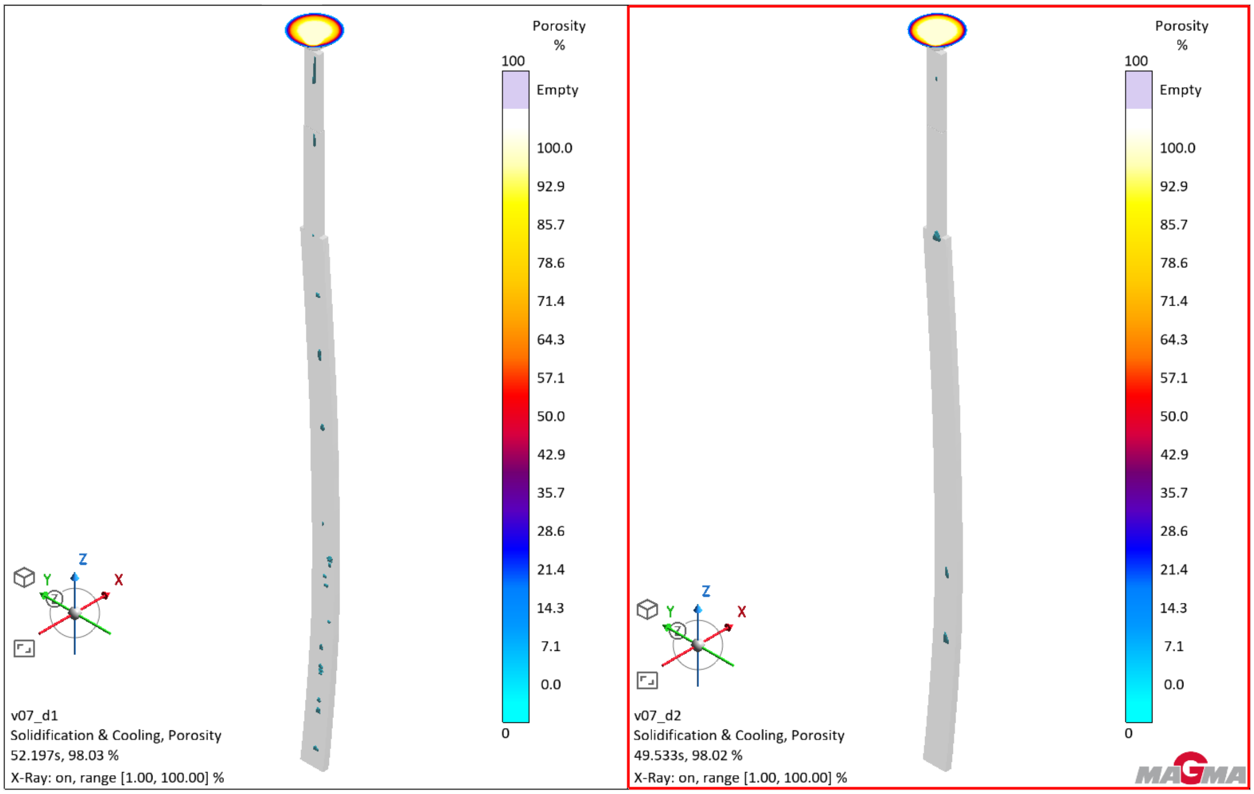

Figure 7: Porosity Percentage in the Results Perspective of MAGMAsoft with Copper Chill (left) and Steel Chill (right)

Ultimately, we concluded that replicating the mold with a chill and shaping it to fit the sword's contours would be too challenging. Ultimately, we used the gating system with a riser that showed the least amount of porosity. However, this casting was failure due to a hot tear at the riser connection. Considering this, we decided to take a different approach and cast the sword without the riser, but kept the well to ensure our cast sword blank had the cleanest metal with the least porosity.

Cast Alloy Selection

Our criteria for selecting an alloy was that it needed to have high hardenability, high hardness, and high toughness. All the members of our team are Materials Science and Engineering majors so there was a large focus on choosing the right steel for the sword. We chose H13 steel since the final microstructure would be tempered martensite plus alloy carbides, leading to high hardness and high toughness. To obtain this microstructure, the target chemistry range was 0.32 to 0.45 wt% C, 4.75 to 5.5 wt% Cr, 1.1 to 1.75 wt% Mo, 0.8 to 1.2 wt% V, 0.8 to 1.2 wt% Si, and 0.2 to 0.5 wt% Mn. Due to the high alloy content, H13 steel air hardens, which eliminates the need for quenching the steel in oil or water that may cause warping or cracking. This steel was originally proposed by our partner foundry, Midwest Metal Products, for the Cast-in-Steel Bowie knife competition. As the tests that will be performed are unknown, this was our best engineering guess – use a steel that will sacrifice a little hardness for a significant increase in toughness.

Mold Preparation and Casting Process

Two vertically parted molds were created using no-bake chemically bonded sand. First a pattern was manufactured, attached to a baseplate, and painted with a release agent (aluminized paint). This pattern included the well but did not include the riser shown in the MAGMA analysis. Multiple patterns were made at 1/4", 3/8" and 1/2" thickness. After this, a pattern box was constructed. The pattern was coated with baby powder and then sand was cascaded down into the pattern box to create one side of the mold. The second side of the mold was created using the same procedure. Finally, the two mold halves were clamped together. Once the mold was complete, it was place into the pit below our induction furnace for pouring.

The standard casting procedure used consisted of first charging the induction furnace with low carbon steel punchings. The steel punchings were then melted, the Mn and Si allowed to oxidize, and the oxide slag removed. A carbon boil was then allowed to occur to remove the majority of the carbon from the melt. When the melt reached 2850-2900ºF, the steel was killed using aluminum shot and pure Cr, FeMo, and FeV were added. When the melt returned to 2850-2900ºF, sorel was added to the melt as a source of carbon. When the melt reached 3000-3050ºF, FeMn and 75%FeSi were added. After approximately one minute, a chemistry sample was taken. Immediately after the chemistry sample was taken, the steel was poured directly from the furnace into the sword molds.

During the first heat, a 1/4" and a 1/2" thick blank were cast. Our ultimate goal was to cast our blank at 3/8", as simulated in MAGMAsoft, so this initial test was to ensure that the alloy that we poured had sufficient fluidity to fully fill these thicknesses. The actual charge materials were 65 lbs. of low carbon steel punchings, 4.3 lbs. of aluminothermic Cr, 1.9 lbs. of FeMo, 1.3 lbs. FeV, 8.144 lbs. of sorel, 0.34 lbs. electrolytic Mn, and 1.1 lbs. of 75%FeSi. The mold was poured and the castings allowed to cool for about 30 minutes before shake out. Both of these blanks turned out well with both blanks completely filling.

For the second heat, the team decided to attempt to cast the sword with the riser that showed the least porosity in the MAGMAsoft simulations. This was done by attaching a riser to a 3/8" pattern and creating a mold in a similar fashion to the first batch of molds. Another mold without a riser was also produced. The two molds were clamped together and placed in front of our induction furnace. This time 65 lbs. of low carbon steel punchings, 4.504 lbs. of aluminothermic Cr, 1.930 lbs. of FeMo, 1.46 lbs. FeV, 9.198 lbs. of sorel, 0.341 lbs. of electrolytic Mn, and 1.102 lbs. of 75%FeSi were used. This heat had a slightly higher carbon content then targeted (probably due to the presence of a small amount of residual gray iron in the furnace). While the design with a riser succeeded in simulations, there was a hot tear at the riser that rendered the sword blank unusable. At this time, we determined the pattern makers shrinkage factor for our steel and determined it to be 2.5%, in the middle of the expected range for cast steel. We concluded that high shrinkage, additional constraint caused by the riser, and longer solidification time at the riser contact caused the hot tear.

For third heat, two 1/4" blanks with no risers were cast in a similar way to the first heat and poured. This time 65 lbs. of low carbon steel punchings, 4.5 lbs. of aluminothermic Cr, 2 lbs. of FeMo, 1.465 lbs. FeV, 8.028 lbs. of sorel, 0.34 lbs. of electrolytic Mn, and 1.1 lbs. of 75%FeSi were used. These blanks filled fully, had acceptable surface finish, and had no significant defects. One of these cast sword blanks was used for our final sword.

Degating and Rough Grinding

In collaboration with our industry partner of Midwest Metal Products, the team shipped three sword blanks to be Blanchard ground to a final thickness of 3/16". The casting thicknesses were 1/4", 3/8", and 1/2". This would ensure that the sword blanks were ground flat and parallel. The Blanchard grinding setup is shown in Figure 8.

Figure 8: Blanchard Grinding Setup

Since the Blanchard grinding process took longer than expected due to problems with the shipper (UPS), our final sword was rough ground in our foundry. The sword blank was ground down to a thickness of 3/16" using a surface grinder. The rough shape of the point and tang was then formed using a cut-off wheel. The sword was ground using a vertical belt sander with a 36-grit belt to achieve the desired shape. Care was taken to create a smooth curve where the tang connected to blade in order to not create a stress riser that could lead to failure. After this, the blade bevel was ground. The final sword profile is shown in Figure 9. A 30 degree edge angle was chosen to provide a mix of durability and sharpness needed to stand up to intense testing without fracturing or rolling an edge.

Figure 9: Final Profile of the Sword

Chemical Analysis

The chemical composition of the steel cast was determine by optical emission spectroscopy. The result from this testing is shown in Table 1. For Heats 1 and 3, the alloy was in specification according to ASTM A681-08. Heat 2 was slightly high in carbon.

Table 1: Chemistry of the H13 Steel Cast (wt%)

Element	Carbon	Chromium	Molybdenum	Silicon	Vanadium	Manganese	Iron
Specification (ASTM, 2022)	0.32-0.45	4.75-5.5	1.1-1.75	0.8-1.25	0.8-1.2	0.2-0.6	bal.
Heat 1	0.39	5.08	1.40	0.96	>0.96*	0.45	bal.
Heat 2	0.50	5.20	1.36	0.91	>0.96*	0.50	bal.
Heat 3	0.41	5.11	1.46	0.88	>0.96*	0.54	bal.

* maximum calibration range value

Heat Treatment:

After the team was satisfied with the rough grinding of the sword, it was taken to Southwest Specialty Heat Treat. The rough ground blank was first pre-heated at 1550°F for 15 minutes to let it equalize. Then the temperature of the furnace was increased to 1850°F and the sword was kept there for 45 minutes followed by forced air cooling. The blank was then tempered at 1000°F for 4 hours, cooled under fans to room temperature, and then tempered again at 1000°F for another 4 hours and cooled under fans to room temperature. Austenitizing was performed in an endothermic atmosphere with a 0.4 wt% carbon potential to prevent decarburization of the steel. This specific heat treatment was performed to produce a hard steel with excellent toughness.

Metallography

A sample was cut from an extra piece of the sword blank after heat treat for optical analysis of the microstructure. The sample was mounted, ground, polished and then etched with 3% Nital to reveal the structure, Figure 10. The microstructure of the steel after heat treatment appeared to be tempered martensite plus alloy carbides. A scanning electron microscope should be used to more fully characterize this microstructure.

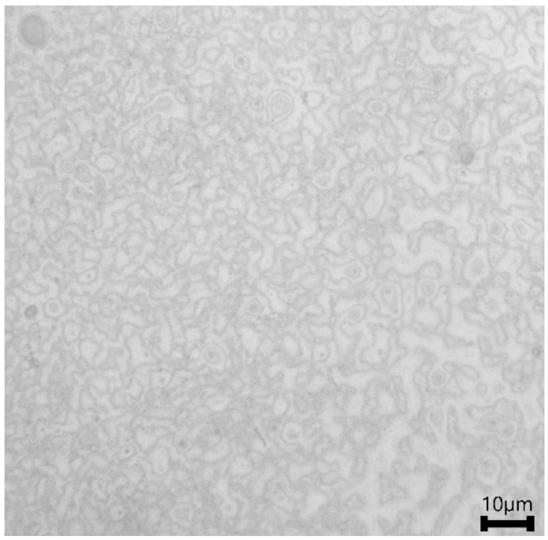

Figure 10: 500x Microstructure of Heat Treated H13 Steel.

Hardness Testing

Multiple Brinell hardness tests were conducted on the sword throughout the sword making process. During rough grinding, excess material from the tang was removed and tested. This resulted in a value of 627 BHN (60 HRC) for the as-cast steel. Southwest Specialty Heat Treat also performed a Rockwell C hardness test after the heat treatment was completed and measured a hardness value of 59 HRC. An additional Brinell hardness test was performed at our foundry after heat treatment and a hardness value of 572 BHN (56 HRC) was measured.

Final Grinding and Sharpening

After the sword was heat treated, final grinding was done to add the final bevel shape and the edge to the sword. A fuller running the length of the blade was added using a surface grinder to reduce the overall weight of the sword and make it consistent with the original. The final edge was then ground onto the sword using a vertical belt grinder. Once the edge was added, a Work Sharp Precision Adjust sharpener was used to give the final sharp edge to the sword. It was ground on increasing grits of sharpening stones going from 200 to 400 to 600 to 800 at approximately 100 passes per grit to sharpen the edge. After this, the edge was further honed using a soapstone pad and a leather strop to bring the edge to the desired sharpness range. After sharpening, the edge was tested using a PT50A Industrial edge sharpness tester. This test measures sharpness in grams of force required to sever a wire of test media. Values ranging from 300-375 grams of force were observed along the length of the blade, within the range of standard commercial knife sharpness. After all grinding steps were complete, the blade had a length of 29.5 inches and the tang was 6 inches.

Handle Construction
To create the pieces for the handle, the guard, spacers and lion head pommel were carved in hardenable clay. The clay was allowed to harden before the pieces were ground to the correct size and the details were added using a Dremel. After grinding, the clay pieces were used as patterns to create bonded sand molds of each piece of the grip construction. The parts were then poured in pewter alloy AC. The components were finished in the grit blaster to remove excess sand and sanded to ensure they would fit onto the tang. The guard and spacers were then added to the tang to prepare for adding the handle material.

The handle was made from ivory colored G10 scales. The scales were cut to length and stacked two high to create a handle that was comfortable to hold and use. Two 1/4" holes were drilled through the scales and tang using a pure carbide drill and brass pins were inserted to ensure that the handle would not come loose during testing

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The lion head pommel was also poured in pewter alloy AC. After inspection of the finished casting, a large region of shrinkage was observed on the side of the lion's head. This was due to not including a riser during the casting process. An initial solution to this problem was to melt extra material and fill the shrinkage. However, due to concerns about the overall weight of the sword, the shrinkage was filled in using JB Weld steel reinforced epoxy putty. The lion's head was then attached to the base of the tang to finish the handle construction before all the pieces were secured using System Three Blade Pro™ epoxy and allowed to set for 12 hours before finishing.

After the handle finished curing, the brass pins were sawed flush, and the G10 scales were ground using a 120-grit belt to create a rounded, ergonomic design. Care was taken to remove sharp edges while keeping the sword comfortable to use. After grinding, 60-grit sandpaper was used to score the G10 scales to increase grip in use. A music wire pin was added to the pommel to ensure that that it would remained firmly affixed to the tang during testing. Once the handle was complete, a 1/8" hole was drilled into the pommel and the guard to attach the chain between the two pieces. Figure 11 shows the completed handle after all steps were completed. The finished sword was then coated with a thin layer of silicone lubricant to preserve and protect the blade from corrosion and to remove any smudges.

Figure 11: Completed Handle Design

Acknowledgements

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