SFSA Cast In Steel 2025 - George Washington Sword Technical Report

Penn State Behrend – Behrend Bladesmiths

Team Members:

Nicole Croushore, Jacob Gajewski, Brody Mangel, and Ellen Shade

Advisor Name:

Dr. Paul C. Lynch

Foundry Partner:

Ashland Foundry and Machine Works, LLC

Executive Summary

The Bailey Silver and Ivory Hilted Cuttoe sword was forged by John Bailey near Fishkill, New York. George Washington chose to carry this sword when he was Commander in Chief of the Continental Army [1]. There are also several paintings where Washington is depicted carrying this sword, therefore it has been labeled as being his battle sword [2]. The cast sword created by Penn State Behrend is an accurate and authentic replica of the Bailey sword because of its length and the design choices made. First, the blade of the original sword is 30 inches in length [3]. The final cast blade had a final length of 29.9375 inches. In addition, the cast sword has a handle spiraling with green and silver to accurately represent the green-stained ivory and silver tape on the handle of the Bailey sword [4]. The cross guard on the cast sword has the same shape as the sword at Mount Vernon. Finally, the overall shape of the Bailey sword blade is replicated by the cast sword. This was ensured early in the design process by overlaying a photo of the Bailey sword in a 3D modeling software, then creating the shape of the blade based on the photo. The curvature of the blade is an integral part of the sword design, so it was essential to have it correctly replicated.

The design process began with choosing which sword to replicate, then 3D modeling the sword. 3D models were made for the cast blade, final blade, guard, handle, and an assembly of the final components. Simultaneously, material selection for the blade, handle, and guard was done. Once 3D models were created, finite element analysis (FEA) and additive manufacturing of sword prototypes took place. Casting type selection began and ultimately sand casting was selected due to its prevalence in Pennsylvania. Pattern iterations were created and put through a casting simulation. Three of the mold design iterations were selected to be produced and cast due to the fluid flow and solidification modeling results of the casting configurations. The molds were created and refined for 3D binder jet printing, then printed at Matthews Additive Technologies in Pittsburgh, PA. Once the molds were printed, they were sent to Ashland Foundry and Machine Works, LLC in Ashland, PA to be cast. After casting, the blade and tang went through a hot isostatic pressing (HIP) cycle, then were machined to the final size and shape. Additionally, a heat treatment process was selected and heat treatment of the blade and keel blocks was performed before material testing. Material testing and machining of the guard and handle were completed next. Finally, polishing and painting was done. The final sword was assembled and shipped.

The final cast sword meets all SFSA Cast in Steel requirements. The blade and tang were sand cast with 17-4PH steel, the guard was machined from steel, and the handle was machined from aluminum. The final length of the assembled sword was 37.75 inches, the final weight was 2.3 pounds, which were both compliant with the contest requirements. The final blade was also a length of 29.9375 inches which is compliant with the contest requirements.

Background/Introduction

Each year, the Steel Founders' Society of America (SFSA) hosts a Cast in Steel competition which challenges university students to cast and produce a product that is typically made by forging by using casting techniques. SFSA has created this competition to encourage students to learn about making steel products using the casting process and applying the latest technology available. This year, for the Cast in Steel 2025 competition, SFSA is challenging students to cast and produce one out of six of George Washington's swords, which are shown in Figure 1. The competition involves documenting the process with a video and a written report no longer than 30 pages, and producing a final, cast product. The cast sword for this competition must be historically accurate, aesthetic, and functional.

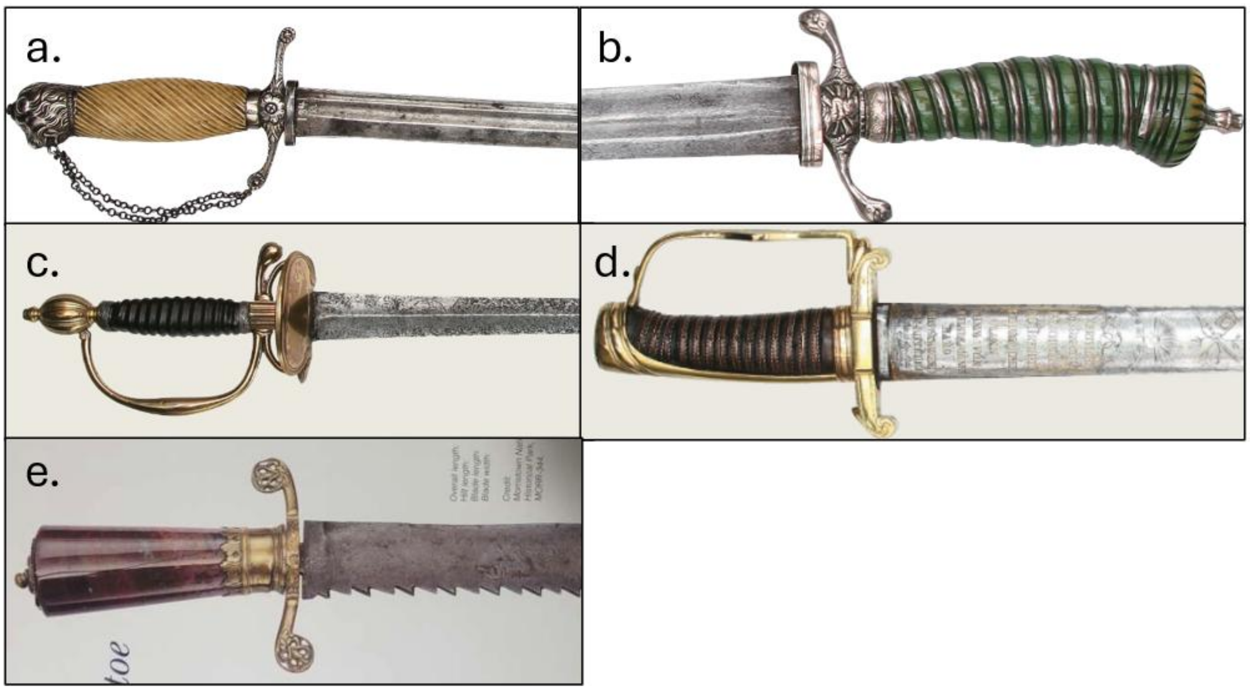

Figure 1. George Washington's Swords: a) The Silver Lion-Headed Cuttoe b) The Bailey Silver & Ivory-Hilted Cuttoe c) The Model 1767 French Officer's Epée d) The Alte Presentation Broadsword e) The 17th Century Onyx Handled Cuttoe [1]

The sword George Washington was carrying depended on the day and the task at hand. He had swords for parades, ceremonies, and war. Washington's swords were worn on his left hip regardless of the purpose. These swords were forged using techniques and processes available during the 18th century [4]. The sword that stands out the most is the Bailey Silver and Ivory-Hilted Cuttoe sword due to its historical importance. It is shown in Figure 1, and it is the sword labeled (b). The sword was forged by John Bailey in Fishkill, New York during the Revolutionary War. It was used by Washington as his battle sword while serving as commander of the Continental Army [4]. This would be an ideal sword to focus on as it would be challenging to cast, and it would be an enticing sword to add extra components to represent Penn State Behrend. The following steps were performed throughout the project; initial product design and design optimization, material selection, FEA, 3D printing, casting design, casting process selection, mold design, solidification simulations, final mold design, additive manufacturing of the final mold design, casting, HIP processing, heat treatment, material testing, and component finishing to final specifications.

Process Model

The process model of the entire project (including senior design course deliverables) is shown in Figure 2. It outlines the steps of the project, starting with the initial product design all the way to the final deliverables: the final George Washington sword, final technical report, and video of the project.

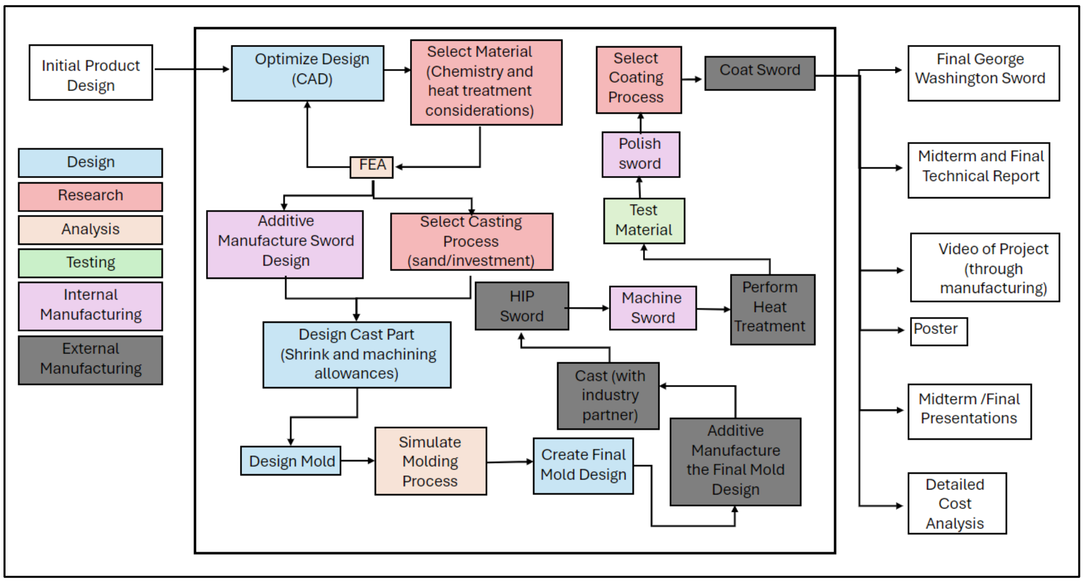

Figure 2. Process Model of the Manufacturing Process of the Sword

Research & Analysis

The first step in the project was to determine which sword to design and manufacture. Once the sword type was determined, research had to be done to decide between either sand or investment casting to make the sword. In addition, it needed to be determined how many parts the sword was going to be cast as, or if it would be cast as one part. Once the casting methods were determined, research and fluid flow/solidification simulations were performed to determine the alloy that would meet the needs of all the specifications, as well as the requirements for the competition. After the alloy was selected and the casting configuration design was complete, the mold was designed. After completing the mold design, impact testing was performed using ANSYS to analyze the forces that the sword was able to withstand, to determine what post-processing would need to be performed.

Sword Types

The SFSA website listed swords teams could choose from to replicate for the competition. These swords are shown in Figure 1. A decision matrix was used to determine which sword was going to be replicated, which is shown in Table 1. The decision matrix ranked each sword on manufacturability, aesthetics, durability, historical impact, customizability, and the materials that were used to manufacture it. Each category was weighted on a scale of 1-5, with 5 being the most important and 1 being the least important.

Table 1. Sword Decision Matrix

Category	Manufacturability	Aesthetics	Durability	Historical Impact	Customizability	Materials	
Weight	5	3	3	5	4	2	Score
Silver Lion-Headed Cuttoe	4	4	4	4	4	3	86
Bailey Silver & Ivory-Hilted Cuttoe	4	3	4	5	4	3	88
Model 1767 French Officer's Epee	2	5	1	2	5	4	66
Alte Presentation Broad Sword	4	4	4	3	4	4	83

Using this decision matrix, the Bailey Silver and Ivory-Hilted Cuttoe sword scored the highest, so it was selected as the sword to be replicated for the competition.

Initial CAD Modeling

The first model of the sword was created by doing an overlay of an image of the original sword, as shown in Figure 3. Rough measurements of the sword were found online, but these dimensions only gave the overall length and width of the sword. This caused some potential issues in the overall scaling of the sword and the more specific dimensions [4]. Areas such as the thickness of the blade at the base and the thickness at the tip were different, but neither of these dimensions were given.

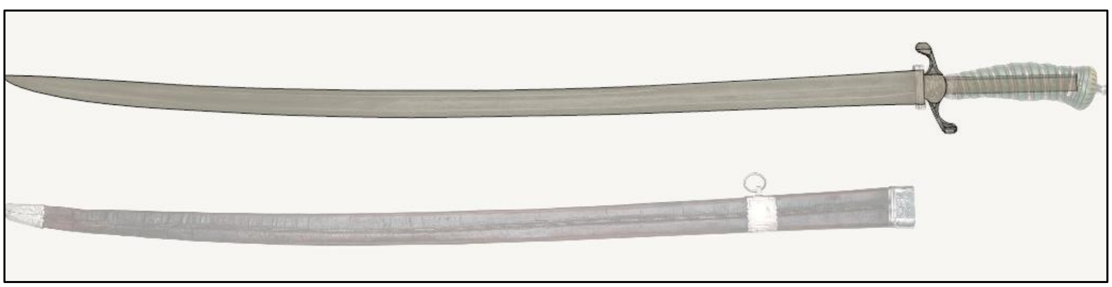

Figure 3. Sword Overlay in CAD

To model the grip of the handle, the software Nomad Sculpt was used due to its organic shape. The model in Nomad Sculpt is shown in Figure 4. This design started as a ball of clay in Nomad and was made into the desired shape, texture, and colors by slowly shaping the clay into the desired characteristics. Without any specific dimensions on the handle such as length or diameter, multiple iterations of the handle were created and then 3D printed to verify proper shape and proportions.

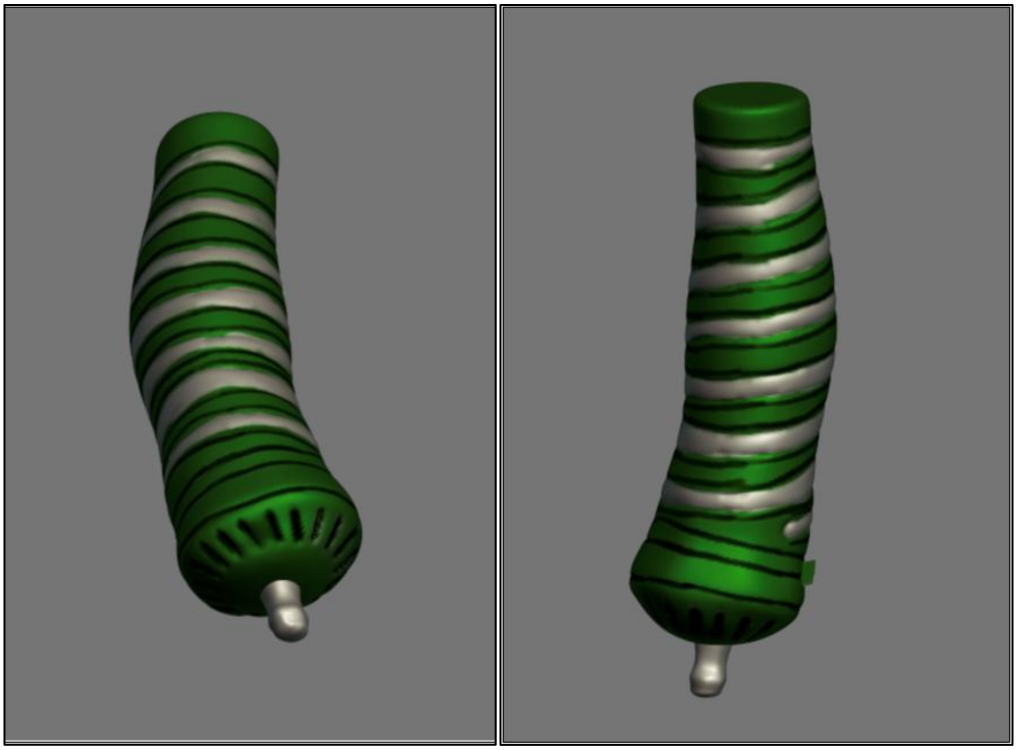

Figure 4. CAD Model of Handle

Casting Method

After determining that Washington's famous Bailey Silver and Ivory-Hilted Cuttoe sword was to be replicated, the method of casting was determined. SFSA requires the sword be made using sandcasting or investment casting [3]. A decision matrix was created to rank the two processes and is shown in Table 2. Sand casting received a higher overall score than investment casting, so sand casting was selected as the method to be used.

Table 2. Casting Process Decision Matrix

Method	Cost (W:3)	Time (W:4)	Surface Finish (W:2)	Casting Defects (W:5)	Post-Processing (W:2)	Tolerances (W:1)	Location (W:3)	Size Limit (W:3)	Total
Sand	4	4	2	2	2	2	4	4	72
Investment	2	2	4	3	4	4	2	3	64

Once sand casting was selected for the casting method, it was decided the blade would be cast by itself. This was decided due to the difficulty of getting a complete pour of a long, thin object, such as the blade. The blade would be cast in its own mold to produce a quality casting. The guard and the grip of the handle were each to be machined from bar stock because of time constraints. In addition, this allowed the freedom for each part to be a different material if desired. This would give more control over where the center of gravity is on the sword, as the location of this is important for a sword.

Alloy Research

A material decision matrix was used to decide which material the blade and tang would be cast out of. To begin, a focus was placed on the 4000 family of steels because of past success rates using that family of materials and the known balance of strength/ hardness and ductility/ toughness possible with this family of steels. AF-9628 steel and 1095 steel were also included as highlighted in orange in Table 3 below. The AF-9628 steel was recommended by the sponsor, Dr. Lynch, because of its unique set of strength/hardness properties to match with its impact toughness and ductility along with its castability. The 1095 steel was also included because it was a common material used for sword making because of its high hardness and edge retention [5]. Additionally, ASTM A747 steel with a cast alloy designation of CB7CU1, and a wrought alloy designation of 17-4PH was chosen to be analyzed due to the recommendation from Ashland Foundry and Machine Works, LLC. This material is highlighted in green in Table 3 below because it had the highest total score in the decision matrix.

Table 3. Material Selection Matrix

Options	Yield Strength (Weight:5)	Toughness (Weight:5)	Corrosion Resistant (Weight:2)	Ease of Machining (Weight:3)	Hardness (Weight:4)	Density (Weight:3)	Cost (Weight:2)	Availability (Weight:2)	Total
AF-9628	5	5	2	1	5	4	3	3	**101**
1095 Steel	1	3	1	4	3	2	5	3	**68**
4140 Steel	3	4	3	4	4	3	4	3	**92**
4320 Steel	3	3	4	5	2	3	4	3	**84**
4340 Steel	4	4	3	4	4	4	4	3	**100**
4330 Steel	5	3	3	2	5	4	3	4	**98**
ASTM A747	4	5	5	3	4	4	3	5	**108**

The rankings for each material in each criterion were determined mostly using the Granta software. The only material which was not represented in Granta was the AF-9628 steel. A plot was made for almost every property and criterion. The first plot created was for yield strength. The yield strength is an integral part of the decision matrix because it is important that the sword is durable and has high edge retention. The resulting plot is shown below in Figure 5. More plots were made similar to Figure 5 for each available criterion in Granta.

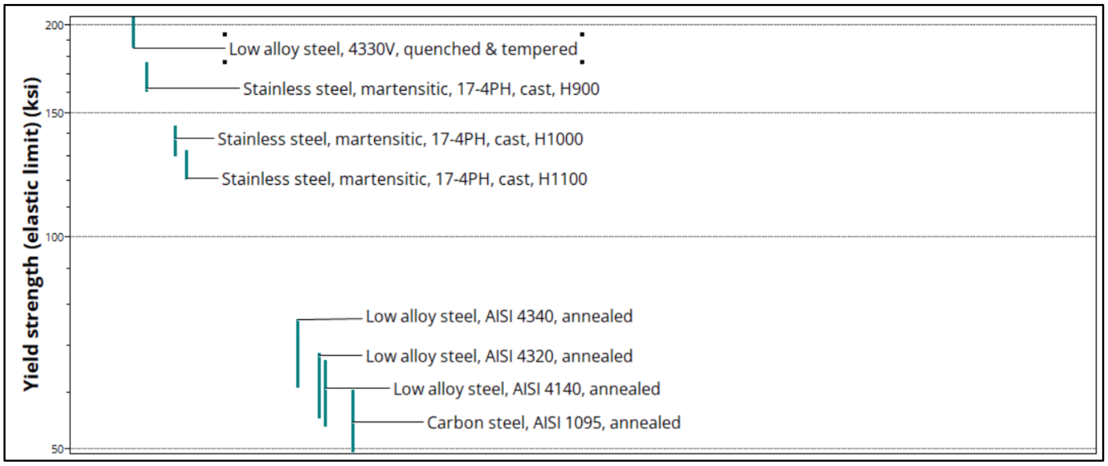

Figure 5. Yield Strengths of the Steels

Material Selection for Handle & Guard

Since the handle and guard of the sword were to be machined from wrought material, the location of where the center of gravity (CG) would be placed on the sword was analyzed. The materials considered for both the handle and guard were aluminum, bronze, and steel. After talking to a sword enthusiast at Penn State Behrend, it was determined the desirable CG of a sword was approximately five inches measured from where the blade meets the tang to the tip of the sword. He had experience with sword martial arts and swordsmanship. He provided various versions of swords, and it was determined the CG would be around five inches from the guard. The various combinations of materials are shown in Table 4.

Table 4. Material Selection for Guard and Handle

Guard & Handle Material CG From Guard (in)			
	Handle – Bronze	Handle – Aluminum	Handle – Steel
Guard – Bronze	0.680	5.058	1.092
Guard – Aluminum	0.706	5.251	1.125
Guard – Steel	0.691	5.192	1.096

As highlighted above in Table 4, it was decided to machine the guard out of steel and the handle out of aluminum. The CG for the steel guard and aluminum handle was not the closest to five inches. However, steel was much more accessible than bronze, and the center of gravity between a bronze guard and a steel guard only had a difference of 0.134 inches. The illustration of the center of gravity using an aluminum handle, steel guard, and steel blade in Autodesk Inventor is shown below in Figure 6.

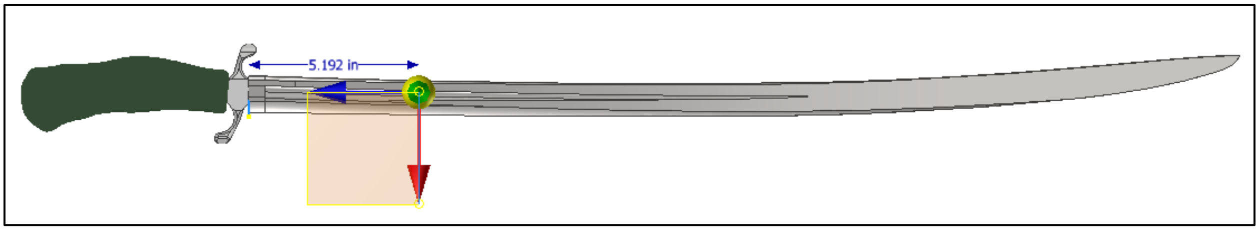

Figure 6. Center of Gravity with Steel Guard and Aluminum Handle

Pattern Design & SolidCast Simulations

After selecting sand casting as the casting method, patterns of the blade were created to design the sand molds. The pattern of the blade is shown in Figure 7. This pattern was modified from the final design of the sword by adding additional material to make the blade thickness 3/8" at the end closer to the guard and taper down to 1/4" at the top of the blade. This was to ensure the final sword could stay within the desired tolerances, as it is expected that the casting will be slightly smaller than the pattern due to solid-to-solid shrinkage. In addition, this ensures there is enough material for machining to be performed. Sharp corners were rounded to aid in preventing crack initiation sites for potential cracking during solidification and post process heat treating.

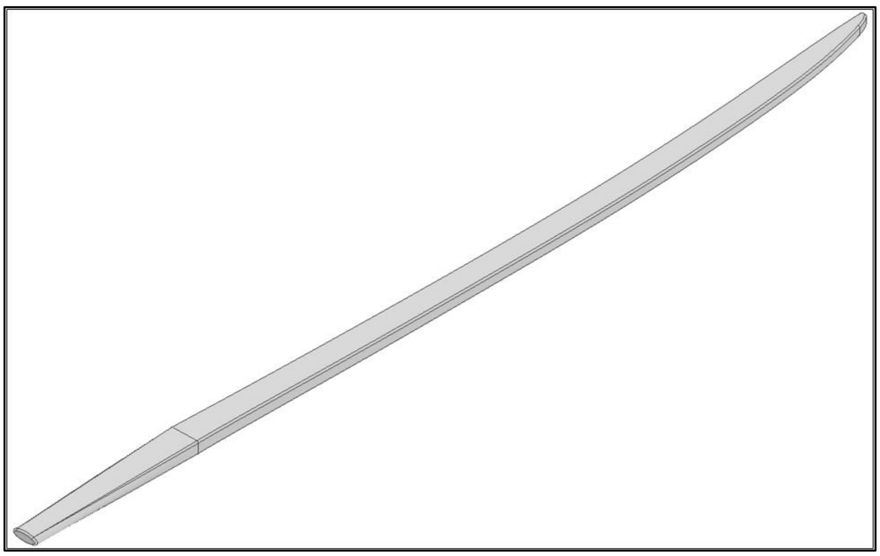

Figure 7. Pattern of Blade

To test this design, a simulation was carried out in SolidCast to visualize how the sword would cool if it was molten metal. This showed where the pattern would cool last, which helped determine where the risers should be placed. Figure 8 shows the results of the simulation, in which the yellow and orange areas show where the casting would cool last.

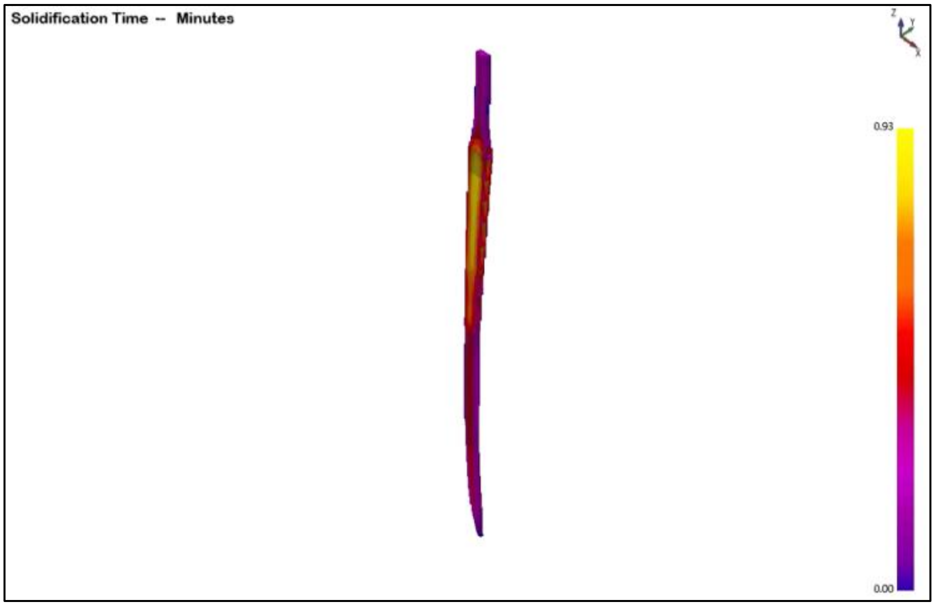

Figure 8. Solidification Time of the Pattern

Once the initial simulation was run in SolidCast, the design of the gating and runner system began. It was decided the three mold pattern designs that had the least shrinkage would each be used to create three different molds. Three mold designs were to be manufactured to ensure only one pour was needed. The first pattern with a gating and runner system had one sword per mold and is shown in Figure 9.

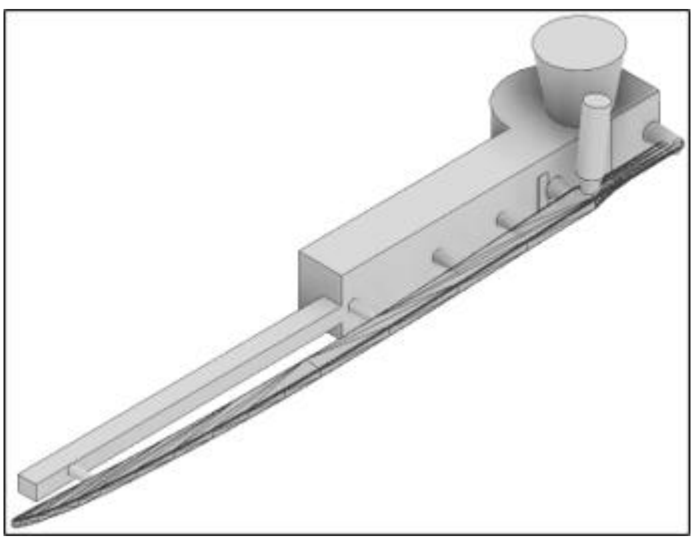

Figure 9. First Design of Gating and Runner System

From this initial design, this design was mirrored to add an additional sword to the pattern, the gates were resized, and more gates were added. These adjustments were made to account for results in SolidCast and FlowCast. Figure 10 shows a close-up image of the runner and gating system with two sword patterns. The first mold was created out of this design, before continuing with modifying the design.

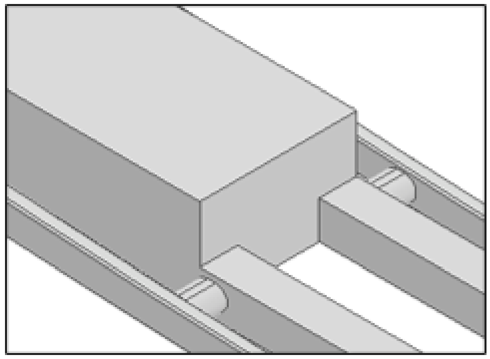

Figure 10. Mold 1 Sword Pattern & Runner and Gating System

For the second mold, which is shown in Figure 11, the large runners decreased in size, the smaller runners increased in size, and all the corners were rounded. The size of the runners was adjusted due to looking at the density plots in the SolidCast simulations, and the simulation showing shrinkage occurring.

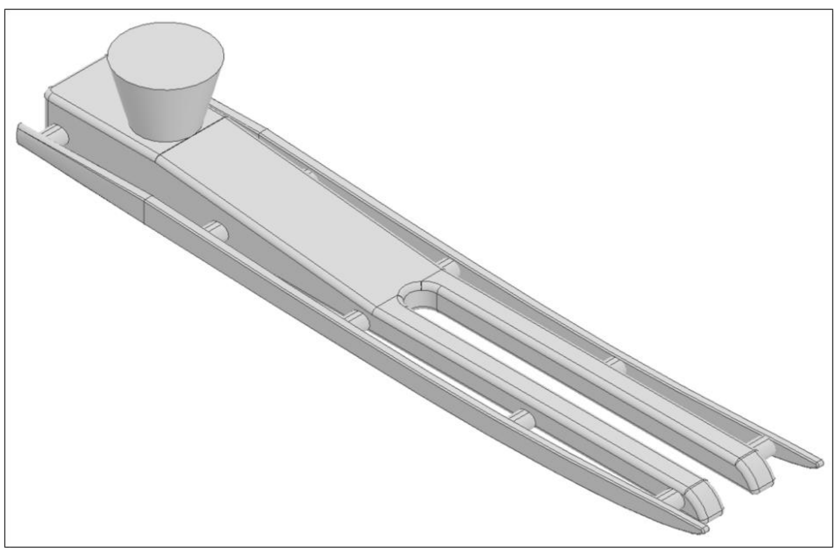

Figure 11. Mold 2 Sword Pattern & Runner and Gating System

For the third mold, shown in Figure 12, the gates were shortened, their radius increased, and the size of the pouring basin was increased.

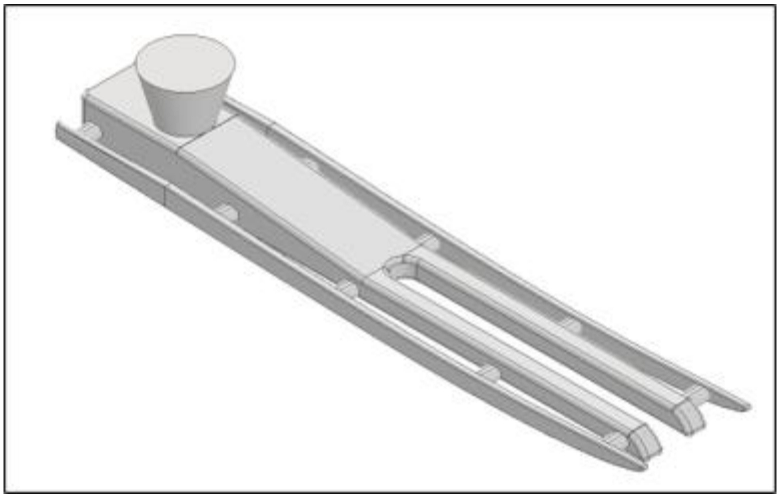

Figure 12. Mold 3 Sword Pattern & Runner and Gating System

Each of these three designs were selected based on analyzing the SolidCast and FlowCast simulation results. Figure 13 shows the density plot for mold design 2. This density plot shows that most of the shrinkage is in the runner system, which is desired so the sword itself will not have shrinkage. This process was performed on each pattern and gating design until the majority of the shrinkage was occurring in the gates and runners.

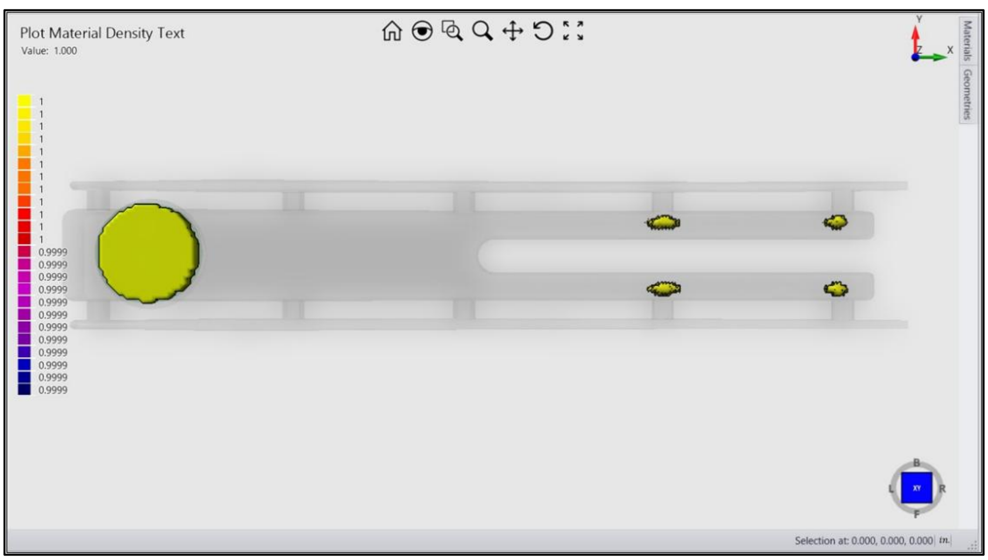

Figure 13. Iso-Plot of Material Density of Mold 2

Figure 14 shows the final design of the pattern with vents added at each of the highest points of the sword to allow air to escape from the mold. This was repeated for each pattern.

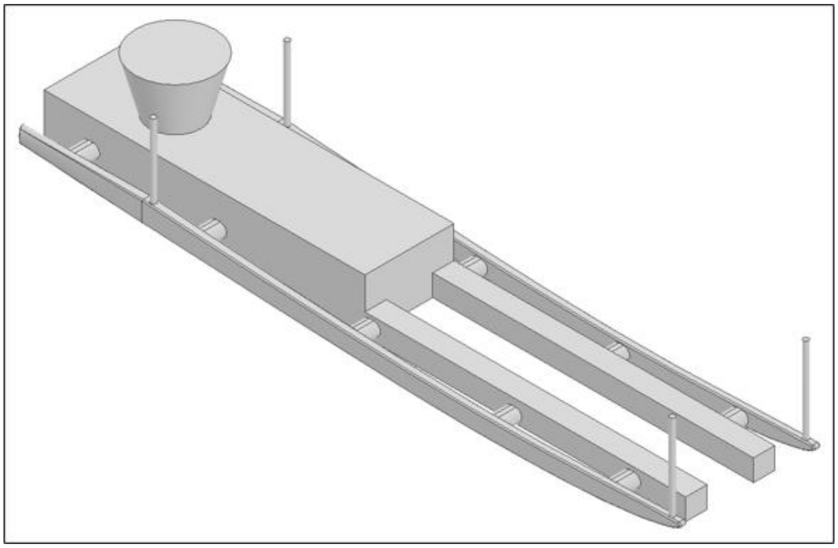

Figure 14. Mold 1 Pattern with Vents

ANSYS Impact Analysis

The sword was analyzed in an impact using Explicit Dynamics, in ANSYS. Explicit Dynamics can be used for high-speed impact where deformation is expected [6]. The sword was analyzed at a swing speed of 48 mph impacting a piece of 12” long ¾ Aluminum Conduit. Impacting an aluminum pipe is expected for the competition as one of the tests and was deemed to be an appropriate material and geometry to use for impact analysis. The conduit was fixed at both ends. Because of the high-speed impact and large strain rates, a non-linear material model must be used [7]. Using Granta EDU, the material properties for 17-4PH H900 were compared to the material properties for the Steel 4340 explicit material model in ANSYS Material Database. Comparing the two material models, it was deemed appropriate to use the Steel 4340 Explicit model for the sword [8]. The failure strain was added as a Maximum Equivalent Plastic Strain. An impact time of 0.001 seconds was used [9]. The highest vonMises stress in the blade was 51.39 ksi, shown in Figure 15. This is well below the yield stress of the 17-4PH H900 yield strength, of 180 ksi. This means that the sword does not experience any plastic deformation upon impact.

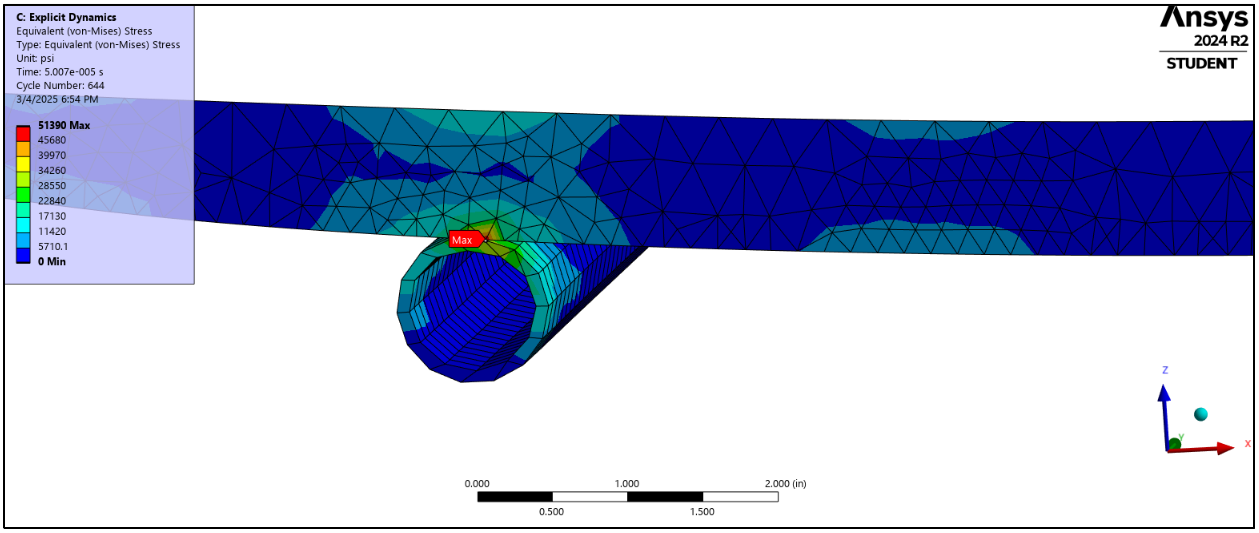

Figure 15. VonMises Stress

Manufacturing

Before the manufacturing processes for each component of the sword were performed, prototypes for each component, as well as the overall sword were created. The first prototype created was of the machined geometry of the blade, guard and tang. This prototype was created using a 3D printer and is shown in Figure 16.

Figure 16. 3D Printed Prototype of the machined blade, tang, and guard.

After creating this initial prototype, several changes were made to the design of the sword to ensure that it was a replica of the original. One of the first changes was to create a tapered thickness along the length of the blade. The initial thickness was constant from the guard all the way to the tip. By analyzing similar swords from this era and similar use, this taper was required to create a more balanced sword. Another change that was implemented was a smoother transition between the tang and the blade. The original abrupt transition would create a stress concentration in that location and could cause the sword to snap here during use. After the prototyping and revision process was complete with each piece of the sword assembly, the manufacturing of each component was performed. The blade was sand cast at Ashland Foundry and Machine Works, LLC. Both the guard and the handle were machined in the machine shop at Penn State Behrend.

Blade

Mold Design

Three mold designs were created from the three patterns that were selected from the SolidCast simulations. The thickness of the mold was a minimum of two inches from the runner system. This was done to ensure that the mold would retain its strength in transportation, as well as when the pouring of the metal occurred. Working with Matthews Additive Technologies, based in Pittsburgh, PA, the following design decisions were implemented. A parting line followed through the central axis of the gates. This was done to aid in alignment of the cope and drag assembly, along with helping to eliminate the possibility of flash during the pour. The molds had a chamfer applied to one of the corners, to aid in alignment. Vents were also added to the molds near the ends of the molds. Rebar holes were added, with a diameter of 0.550 inches, so the molds could be lifted by two people. The holes were to be placed at least 1 inch from the metal cavity, as well as 2 inches from the top of the cope. The rebar holes were tangent to the bottom edge of the drag to ensure the drag would be strong enough. Figure 17 and Figure 18 show the cope and drag for Mold 1, respectively.

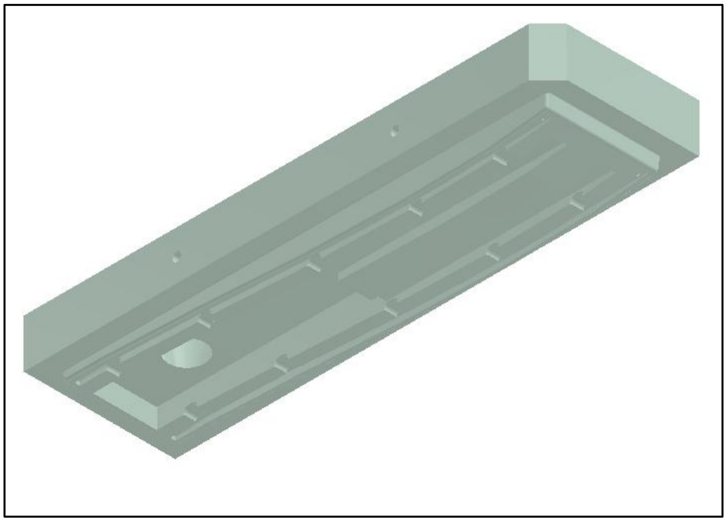

Figure 17. Mold 1 Cope

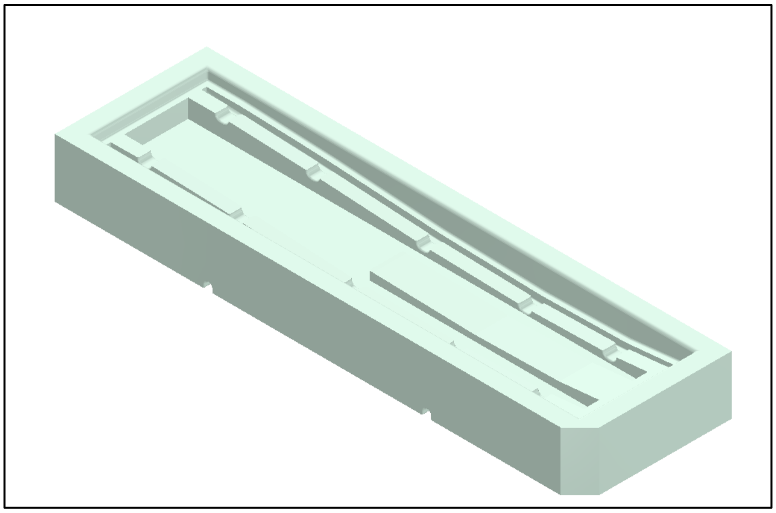

Figure 18. Mold 1 Drag

To aid with the assembly of the molds, multiple clearances and draft angles were used. For the parting line extrusion of the cope and the drag, a 5-degree draft angle was used. The draft angle would allow for an easier alignment of the cope and the drag, as well as ensuring sand would not be scraped off the walls as the cope and drag were assembled. Corners and edges were rounded to prevent scraping during assembly. Additional clearances are shown in Figure 19. These applied clearances allowed for the mating faces of the metal cavity to be perfectly meshed against each other, as shown in Figure 19. Once the mold designs were approved, 3 molds were created at Matthews Additive Technologies using an Ex-One S-Max printer utilizing silica sand and a CHP binder system.

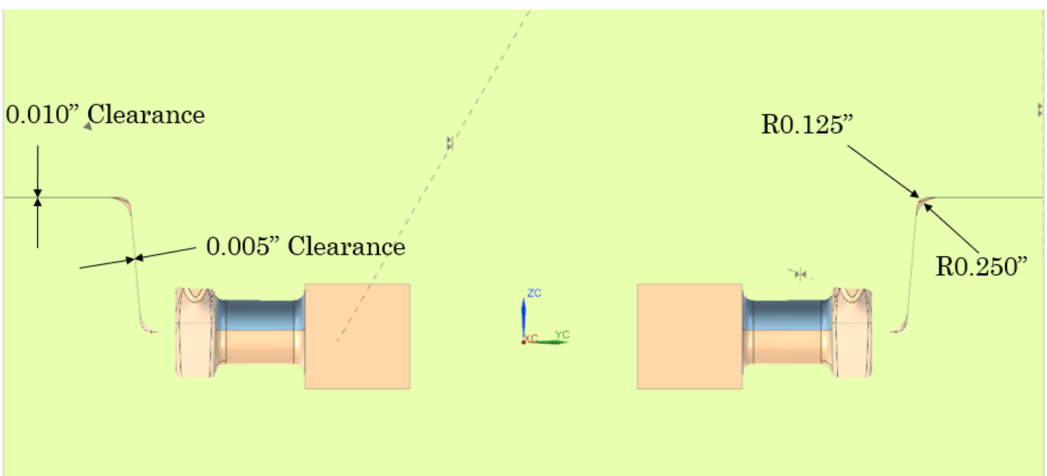

Figure 19. Cross-sectional Cut of Mold 1

Pour at Ashland Foundry

Once the molds were created, several foundries were contacted to discuss the possibility of the pour. Ashland Foundry and Machine Works, LLC, based in Asland, PA ended up fitting the pour into their production schedule. The molds were shipped directly to Ashland Foundry and Machine Works, LLC. Upon arrival, one of the molds had a crack in the drag. The crack is shown in Figure 20. The drag cracked while in transit and was glued at the foundry.

Figure 20. Close Up of the Cracked Drag

Two molds were placed into a flask, with three total flasks being required. The molds were packed into the flask with additional foundry sand. This was done to prevent blowout of the molds. The molds did not have a pouring basin located in the bottom of the drag below the pouring basin, as shown in Figure 18. Concerns over erosion in the bottom of the mold, as well as re-oxidation in the turbulent flow of the steel arose. A stepped pouring basin was added to the external surface of the mold. The steel would be poured into the stepped pouring basin. This would aid in reducing turbulent flow into the mold, lowering the amount of re-oxidation in the steel. The molds with the stepped pouring basin and the foundry sand packing two of them to a flask can be seen in Figure 21.

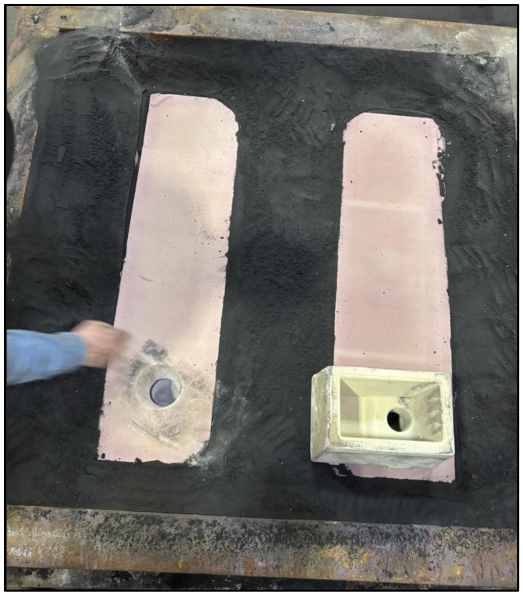

Figure 21. Molds with Stepped Pouring Basin in Flask

Prior to the pour, the chemical composition of the 17-4PH was checked while in the furnace to ensure the correct composition was being poured. Once the chemical composition was verified and the metal was to a temperature of 3,000°F, it was poured into a 500-pound ladle. The ladle, as shown in Figure 22, was designed to pour the molten metal in a manner to prevent slag from being poured into the mold. After the molds were full, the stepped pouring basin was knocked off each mold. This prevented any metal from filling in the stepped pouring basin, and effectively locking the mold shut if the metal was allowed to cool in them. The moved pouring basins can be seen in Figure 23 and the overflow of metal on top of the molds can be seen.

Figure 22. 17-4 PH Being Poured from the Furnace to the Ladle

Figure 23. Moved Stepped Pouring Basin After Pour

As the metal was cooling, the molds were broken to remove the swords. The metal was allowed to solidify, and then the flasks were repeatedly dropped to release the castings. Some of the molds started to break apart while they were still in the foundry sand, and this can be seen in Figure 24. When the castings were removed from the molds, it was determined that each of the six molds filled completely. This can be seen in Figure 25. It is to be noted that many of the swords had a crack along the central gate in the blade of the sword, where the larger runner came to an end.

Figure 24. Mold Removal Process

Figure 25. As Cast Runner System

After the blades were removed from the gating system, there were five castings out of the twelve possible blades that were deemed acceptable for finishing. These castings are shown in Figure 26 and they were the straightest blades of the castings, along with minimal surface defects such as cracks. Part of the gating system was left on the blades, since they were cut from the runner system using a plasma torch at Ashland Foundry and Machine Works, LLC. During the pour, six keel blocks were poured with 17-4PH. These were poured for material testing purposes later in the process and the cut keel legs had overall dimensions of 6 inches x 1 inch x 1 inch.

Figure 26. Five Best Castings

Guard

The guard was made of steel due to the CG study that was conducted earlier in the project. The model was created using CAD, based on the image of the guard [4]. Once the guard model was finalized, a hole was added to slide onto the tang. The model was sent over to the Penn State Behrend machine shop to be cut on a CNC mill. To customize the guard, a design of the Penn State shield logo was laser engraved onto the face of the guard by K and A Tool and Die Engraving in Erie, PA. The design is shown below in Figure 27.

Figure 27. Guard Design [10]

Handle

The handle was machined out of aluminum stock. It was made using a 7075 series aluminum alloy. A prototype of the grip for the handle, as shown in Figure 28, was created using a 3D printer.

Figure 28. 3D Printed Prototype of Handle

Post-Processing

Once the castings were cut off and the sand was cleaned from the castings, they were first sent for hot isostatic pressing (HIP) to both homogenize the castings and remove any possible microporosity. After HIP, each of the components were machined as discussed above. Following machining, a heat treatment process was performed on the swords to achieve the desired material properties. After heat treatment, polishing was performed.

Hot-Isostatic Pressing (HIP)

The five best swords and the six keel blocks were sent for HIP at Pressure Technology, Inc. (PTI) in Concord, Ohio. The cycle was run at 2,165°F, at a pressure of 15,000 psi for 4 hours. During the HIP process, the pressure vessel was filled with Argon gas to create an inert environment. The HIP process did lead to the opening of some cracks that were open to the surface of the blade. The cracks opened at the location of the central gate. The cracks of three of the swords that were sent for hipping are shown in Figure 29. The sword located at the bottom of the image in Figure 29 had the smallest of the cracks, and the crack appeared to be only along the surface of the casting therefore was used going forward.

Figure 29. Cracks in the Blades After HIP

Heat Treatment

To begin, a solution treatment and the H900 aging process were performed on the keel blocks to develop the necessary mechanical properties. This was performed on the keel blocks to be able to test the material properties before performing this treatment and aging cycle on the sword itself. The solution treatment was performed first by heating the keel blocks to between 1875 and 1920°F and holding at this temperature for 1.5 hours [11]. The keel blocks were wrapped with foil to reduce surface oxidation/ scaling, and a thermocouple was embedded within the keel blocks to monitor their temperature during heat treatment. Once the keel blocks reached a temperature of 1,850°F, the timer was started. When the keel blocks were removed from the furnace, they were quenched in a 20% polymer quench, Figure 30.

Figure 30. Polymer Quench of Keel Blocks

Following the solution treatment, the H900 aging process was performed, in which the blocks were held at 900°F for one hour and then removed from the furnace and were air cooled. The keel blocks wrapped in foil are shown in Figure 31, as well as a thermocouple that was used to monitor the temperature of the blocks throughout the process.

Figure 31. H900 Aging Process of Keel Blocks

Material Testing

Hardness, impact, and tensile testing were performed on the HIP keel blocks, which are shown in Figure 32.

Figure 32. HIP Keel Blocks

The material testing was completed by Westmoreland Mechanical Testing and Research (WMT&R) in Latrobe, PA. WMT&R machined the tensile and Charpy samples and completed the impact, tensile, and hardness testing.

Rockwell C hardness testing was performed on the keel blocks and was completed at Penn State Behrend. The anticipated hardness values for the material were between 40-47 HRC after HIP and the H900 heat treat cycle was completed [11]. A H925 heat treatment condition was used for heat treating the final blade because H900 resulted in low toughness readings from the keel blocks. These measurements resulted in an average hardness value of 25.5 HRC. Five more readings were taken after the keel blocks were heat treated and resulted in an average harness value of 40.9. Hardness testing was also performed on the finished blade after HIP, machining, and heat treating. The sword was put through the same HIP cycle as the keel blocks, however heat treatment on the blade was done using the H925 condition to improve toughness. The expected value for hardness of the 17-4PH steel under the H925 condition was 40 HRC [12]. The hardness of the blade was tested three times in different locations near the tang to not be visible after the sword is assembled. The resulting average hardness value was 36.77 HRC which is slightly lower than the anticipated value.

The expected ultimate tensile strength value for a 17-4PH steel material heat treated at the H900 condition is 190 ksi [11]. WMT&R tensile tested three different round tensile samples following the ASTM E8-24 standard and sent the results back. It is evident that the UTS value exceeded the anticipated value as shown below in Table 5. The yield strength and percent elongation values were also provided by WMT&R. The anticipated yield strength value for the 17-4PH material under the H900 heat treat condition was minimum of 145 ksi and the anticipated percent elongation was a maximum of 5% [13]. The average yield strength and percent elongation values are shown below in Table 5, and exceeded their respective anticipated values. As requested, WMT&R machined and tested four Charpy samples and followed ASTM E23-18 standard during testing. Their results from testing are shown below in Table 5. After the results of the impact testing, the desired heat treatment cycle was changed to be H925.

Table 5. Average Material Testing Values from WMT&R

Yield Strength (ksi)	UTS (ksi)	% Elongation (%)	Impact (ft*lbs)
173.27	196.07	14.00	2.75

Final Sword

Below in Figure 33 is an image of the final sword after all machining, polishing, and final assembly was created.

Figure 33. Final George Washington Sword

The sword is an accurate and authentic George Washinton sword. The length of the completed cast George Washington Sword came in at 37.75 inches. Additionally, the handle of the Bailey sword at Mount Vernon has a spiraling green-stained ivory and silver handle. The cast sword also has a spiraling green and silver handle with the same black detailing as seen on the actual handle. The shape of the guard on the cast sword is the same shape as the guard on the actual Bailey sword as well. Finally, the blade of the sword has the same curvature as the actual sword as seen above in Figure 3. Because of the aforementioned sword details, the Penn State Behrend Cast sword is an accurate and authentic replica of the Bailey Silver and Ivory Hilted Cuttoe sword. The finished sword also meets all requirements of the Cast in Steel competition. The final length of the sword is 37.75 inches, which meets the SFSA requirement of not exceeding 36±2 inches in length. The finished blade is 29.9375 inches long, which is also compliant with the SFSA requirement. Additionally, the weight of the finished, assembled sword is 2.3 pounds, which also does not exceed the SFSA requirement (4.4 pounds in weight). Sand casting was used to cast the sword out of 17-4PH steel. The guard was machined out of steel, and the handle was machined from aluminum.

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