SFSA Cast In Steel 2025 – George Washington Sword Technical Report

Central Michigan University – Fired Up Casting

Team Members:

Jacob Darling, Grant Ruddy, Chistopher Herrera, Katie Warsop, Davis Heinzen

Advisor(s) Name:

Dr. Soo-yen (Samson) Lee

Foundry Partner:

Bay Cast

Table Of Contents

Abstract

Central Michigan University collaborated with Bay Cast to create a functional metal casting of George Washington's Sword. The sword consisted of multiple parts using various casting methods. The blade was sand-cast out of 4340 Steel using innovative technology in 3D-printed ed binder jetted sand molds. The guard, caps, and pommel of the sword were cast out of Pewter Britania Alloy using the investment casting technique. The grip was machined out of hardwood using a CNC mill. An assembly of the components was constructed and evaluated in the Steel Founder's Society of America (SFSA) 2025 Cast in Steel competition.

Chapter 1. Introduction

1.1 Overview

Central Michigan University (CMU) was challenged with designing and creating a functional George Washington sword for the Steel Founders' Society of America (SFSA) 2025 Cast in Steel competition. Since 2019, six unique competitions have been held, and CMU has participated in four as follows: Thor's Hammer, Celtic leaf sword, African Spear Point, and Halligan bar. The SFSA established this annual competition to encourage students to learn about making steel products using the casting process and applying the latest technology available (Cast in Steel, 2024). The CMU team, comprised of five students and a faculty advisor, partnered with Bay Cast, a prominent metal casting company in Bay City, Michigan, to assist with the casting of the sword.

1.2 Constraints

One of the key challenges faced by the team is that swords are normally forged rather than cast, so before kicking off the project, the team met with Foundry Engineer Anup Shrestha from Bay Cast, to understand constraints and how the casting process works. Key things to note are as follows:

1) Casting Scale: Bay Cast typically produces very large castings (often >4000 lbs.); this sword is Bay Cast's smallest project to date.
2) Casting Method: Bay Cast utilizes sand casting and buys 3D-Printed molds from Voxeljet, a leading additive manufacturer who specializes in binder jetting 3D printing.
3) Casting Resolution: Bay Cast features are limited to ½ of an inch.
4) Casting Count: Multiple blades will be produced to minimize risk.
5) Flow Analysis: Bay Cast will design the placement of risers and gates for the mold.

6) Heat Treatment: Bay Cast will perform heat treatment.
7) Machining: Bay Cast has a workshop, but due to scale, the machining and sharpening will have to occur at CMU's metals lab.
8) Testing: Ultrasonic testing and non-destructive testing will be conducted by Bay Cast.
9) Material Verification: Bay Cast will provide a sample of the metal alloy and perform spectroscopy analysis to verify the alloy composition.

1.3 Competition Requirements

After meeting with Bay Cast, it became apparent that the project required research prior to designing and creating the sword. Research on history, design, metallurgy, casting, heat treatment, and machining had to be conducted with the goal of meeting the SFSA competition requirements.

Table 1.1 SFSA Competition Requirements.

Number	Requirement
1	Make their version of a George Washington Sword • Your sword should weigh no more than 4.4 lbs. • Your sword should not be longer than 40 inches in overall length.
2	Document their project with a professional Technical Report of less than 30 pages supporting their decisions.
3	Produce a Project Video, not to exceed 5 minutes, that documents their project.

Chapter 2. Project Formulation

2.1 Overview

This project seeks to recreate a version of George Washington's sword using modern casting technology. This can be done through careful historical analysis, selection of steels, new technology in 3D-printed molds, design for manufacturing, analysis software, modern casting techniques, and heat treatment processes.

2.2 Historical Analysis

George Washington is one of the most well-known presidents in American history. His life has been studied and analyzed for hundreds of years. Scholars and students often learn about his accomplishments in the army and as the president. Yet, this project focuses on his swords and how the history of his swords is worth telling. Each sword carries an important part of history and has been used by George Washington in different moments of his life. These swords were by his side through the early stages of America. George Washington had 10 known swords, that vary in size and purpose. The swords were made of different materials, including wood, ivory, silver, and steel. The swords fall into a few categories, which include cuttoe, small swords, and the presentation swords. Throughout this project, the team's goal is to capture the history and authenticity of a George Washington sword while using modern steel casting techniques. (Goldstein, 2016)

2.3 Forging and Casting

Steel is typically processed through two main techniques: forging and casting. Both methods have distinct advantages, making them preferable for different applications, which presents a challenge when attempting to improve one process over the other. For example, most swords are forged instead of cast, leading to research on how to make the cast sword functional, or even superior, to a forged sword.

Forging involves shaping metal by applying compressive forces, such as hammering or pressing. This process enhances the material's strength and ductility by dislocating grain boundaries, resulting in a durable and reliable product. However, forging may lead to parts with low tolerance levels and limitations in shape complexity.

Casting is a manufacturing process used to shape molten metal into various forms. Sand casting is the most common technique, which involves a mixture of sand and a binding agent that allows it to be packed and maintain its structure; however, it results in a porous surface. Investment casting, which uses lost wax and ceramic molds, can achieve high levels of detail and complex geometries required.

To improve cast steel properties, specific alloying and heat treatment can be used to provide a similar balance between strength and ductility of forged steel. For instance, cast grades following ASTM A915 and A958 employ grades that closely resemble their wrought grades, inclusive of comparable mechanical properties. (Poweleit)

2.4 Binder Jet 3D Printed Sand Molds

A new advancement in the sand-casting process is 3D-printed sand molds. 3D printers are used to create sand molds and cores by placing thin layers of sand and binding agent repeatedly. In the situation where varied and smaller batch sizes are needed, this technique provides a cost-effective way to create these parts. Unlike traditional sand casting, multiple parts, molds, and cores can be printed in a single job box, optimizing the build volume utilization and reducing cost per part. (*Industrial 3D Printing*)

2.5 Metallurgy

Metallurgy is the science and technology of metals, encompassing the study of their physical and chemical properties, as well as their behavior during processing and use (Singh, 2020). This topic plays a vital role in many industries, from manufacturing and construction to healthcare and technology. Understanding metallurgy involves concepts such as alloy composition, heat treatment, and grain structure, all of which significantly influence a material's strength, durability, and performance.

The sword must be cast in steel, a material that is known for its hardness, strength, and impact resistance. Depending on the grade of steel, different compounds are added or mitigated to alter steel properties as shown in Table 2.1.

Table 2.1 Alloy Elements and Effect on Steel Properties (Poweleit).

Element	Effect on Steel Properties
Carbon (C)	Increases strength but decreases toughness and weldability (most common and important)
Manganese (Mn)	Similar, although lesser, effect as carbon
Silicon (Si)	Like carbon but with a lesser effect than manganese (important for castability)
Nickel (Ni)	Improves toughness
Chromium (Cr)	Improves oxidation resistance
Molybdenum (Mo)	Improves hardenability and high temperature strength
Vanadium (V)	Improves high temperature strength
Tungsten (W)	Improves high temperature strength
Aluminum (Al)	Reduces the oxygen or nitrogen in the molten steel
Titanium (Ti)	Reduces the oxygen or nitrogen in the molten steel
Zirconium (Zi)	Reduces the oxygen or nitrogen in the molten steel
Oxygen (O)	Negative effect by forming gas porosity
Nitrogen (N)	Negative effect by forming gas porosity
Hydrogen (H)	In high quantities, results in poor ductility
Phosphorus (P)	Can increase strength but drastically reduces toughness and ductility
Sulfur (S)	Reduces toughness and ductility

Upon consultation with Bay Cast, the team identified high-toughness steels, particularly the 51XX, 41XX, and the 43XX series, as potential material options. The 41XX series has a mixture of chromium and molybdenum, which improves its hardenability and improves oxidation resistance. The 43XX series has a mixture of chromium, nickel, and molybdenum. The added nickel improves toughness, which is an important quality in a sword. The 51XX series has low chromium and no nickel or molybdenum. The numbers, designated by X’s, define carbon content. Carbon is one of the biggest indicators of the hardness of steel, which allows a blade to retain a sharp edge (Allen, 1976). Carbon increases strength but decreases toughness and weldability (Poweleit). Comparisons of select steel alloys are compared with chemical compositions and mechanical compositions in Tables 2.2 and 2.3, respectively.

Table 2.2 Steel Alloys Chemical Composition (Allen, 1976).

Grade	C %	Mn %	P max %	S max %	Si %	Ni %	Cr %	Mo %
4130	0.28/0.33	0.40/0.80	0.035	0.04	0.20/0.35	---	0.80/1.10	0.15/0.25
4330	0.28/0.33	.60/0.90	0.035	0.04	0.20/0.35	1.65/2.0	0.70/0.90	0.20/0.30
4340	0.38/0.43	.60/0.90	0.035	0.04	0.20/0.35	1.65/2.0	0.70/0.90	0.20/0.30
5160	0.56/0.64	.75/1.00	0.035	0.04	0.20/0.35	---	0.70/0.90	---

Table 2.3 Steel Alloys and Mechanical Composition (AISI 4330, 2013) and (World Material).

Grade	Hardness (HRC)	Tensile Strength (MPa)	Yield Strength (MPa)
4130	17.5	560	460
4330	30	860	690
4340	17.5	745	470
5160	12.7	724	275

The selection of 43XX series was found to best suit the needs of the team, as it offers balanced hardness and medium-high toughness due to high nickel content. While the as-cast hardness is not ideal compared to forged blades, it is important that the blade not be too hard, as a high hardness could make sharpening the cast product difficult. Bay Cast will follow ASTM A915: Standard Specification for Steel Castings, Carbon, and Alloy, Chemical Requirements Similar to Standard Wrought Grades, to ensure the material grade is met.

2.6 Heat Treatment

One of the most critical processes in creating a durable and effective blade is heat treatment. Blacksmiths can manipulate the microstructure of the steel, optimizing its hardness, toughness, and flexibility by heating steel past its critical temperature and rapidly quenching, (Neely, 2000).

During heating, the molecules in the metal move, and the rapid cooling in oil or water reorders these molecules into a tight structure, resulting in a hard blade. There are many factors that need to be considered when choosing whether to quench in oil or water. Quenching in water cools the blade faster which can help with a tight grain structure, but it can also increase the possibility of the blade fracturing. Water can be very aggressive, and the blade can cool too fast causing it to shatter. Using water also adds concerns of mineral content within the water, which can cause distortion differences. Using oil, due to a lower heat transfer coefficient, is a more consistent and safer option for such a crucial step in the process. There are also many different oils to choose from, which increases versatility within the manufacturing process. Commonly used oils for quenching are engine oils, vegetable oils, quenching oils, and mineral oils. These types contain a multitude of subsequent oils that possess different quenching properties. These different properties can affect the toughness and hardness of the blade after quenching.

Higher viscosity oil results in coarser microstructure due to its slower cooling rate, which affects the steel's microstructure and contributes to improved impact toughness. Tempering temperature significantly influences microstructural characteristics. This not only relieves internal stress but also improves impact resistance while maintaining hardness. (Bhagyalaxmi)

To address brittleness, the tempering process is employed to reduce some hardness while preserving the microstructure, thus minimizing the risk of breaking or shattering. The tempering process of a blade requires it to be heated anywhere from 400 to 1200°F and then air-cooled. This process enhances the blade's strength while maintaining its sharp edge (Neely, 2000). The objective of the heat treatment process is to reduce the microstructure size, which creates more surface area of the grain boundaries. This creates more strength and increases the blades' hardness. Overall, the heat-treating processes can enhance the material properties of steel, as seen in Table 2.5.

Table 2.5 Material Properties of Quenched and Heat-Treated Steels. (Budynas, MatWeb).

Grade	Hardness (HRC)	Ultimate Tensile Strength (ksi)	Yield Strength (ksi)
4130 Q&T	39	128	116
4330/4340 Q&T	40.4	231	213
5160 Q&T	37	170	155

A big challenge working with Bay Cast was learning that Bay Cast's melts are usually greater than 3500 lbs. of metal, and the sword had to be less than 4.4 lbs. The composition of such a large melt may result in areas where the metal composition is not homogeneous or consistent when poured. It is important that the metal composition contains enough carbon to hold a sharp edge yet has enough toughness to resist shattering upon impact.

Additionally, the composition must minimize the potential of gas porosity. Another issue that can come up is in “Sandcasting, in particular, is a process that depends on gravitationally pressurized flow, which makes it difficult to feed the solidification contraction of the metal. This can be minimized by proper pressurization of the mold through geometry modifications and the mold design. (Mahomed, 2020), (Sunrise 2024)

2.7 Design for Manufacturing

To create a strong, aesthetically pleasing sword, it is necessary to consider the overall shape of the sword in the initial 3D rendering. Sharp corners and thin modeled pieces on the sword will inevitably cause weak spots in the cast and could ultimately lead to failure. There must be fillets connecting the tang to the rest of the blade, and along the top of the blade to dampen the impact from a blow.

To create a strong blade that can withstand a substantial impact, it is crucial to understand where the most stress is applied to the blade and how to avoid it before it creates a significant problem. One option for engineers to test stress and strains on products is to use Finite Element Analysis (FEA). By using FEA, the team can determine where stress is present in the blade and use that information to adjust the weight, shape, and material of the blade. This technology is crucial for creating a blade that can withstand a strength test.

Chapter 3. Project Implementation

3.1 Timeline and Responsibilities

The team is composed of five unique individuals with diverse backgrounds and experience.

- Jacob Darling [JD], a mechanical engineer and the team's lead, will manage the project, coordinating tasks such as site visits, meetings, professional communication, and ensuring that deadlines are met.
- Katie Warsop [KW], a product design engineer technologist, will research history on George Washington’s swords, design the sword to fit the competition's needs, and model the sword using CATIA, a 3D modeling software.

- Chris Herrera [CH], a product design engineer technologist, will assist with designing the sword in CATIA & Siemens NX, assist with manufacturing finishing processes, and lead the production of the project video.
- Grant Ruddy [GR], a mechanical engineer technologist, will research and implement metallurgy principles into the creation of the sword, assist with the manufacturing finishing processes, and assist with acquiring funds.
- Davis Heinzen [DH], a mechanical engineer technologist, will assist research on metallurgy, assist with manufacturing finishing processes, and assist with acquiring funds.

Each member will contribute meaningfully to the project, as seen in Table 3.1.

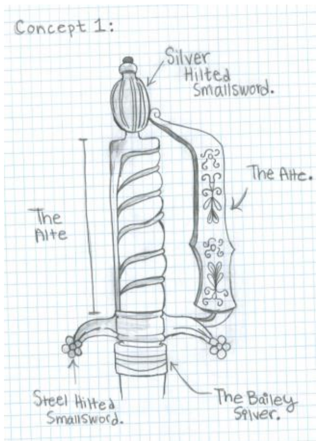
Table 3.1 Breakdown of Major Responsibilities Among Team Members.

Role	Person Responsible
Group Team Lead	JD
Standards Research and Selection	JD
Metallurgy Research	GR, DH, JD
History Research	KW
Design For Manufacturability Research	GR, DH
Concept Design and Drafting	KW, CH
Travel and Funding	DH, JD
CAD	KW, CH
FEA	CH, GR, DH
Machining Grip	KW
3D Printing	JD
Casting Handle	DH, GR
Sharpening and Polishing	JD, GR, DH
Heat Treatment	JD, GR
Video	CH

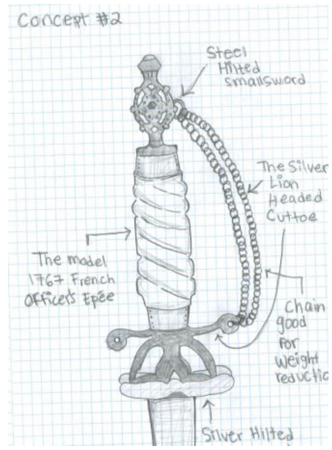
3.2 Concept Design

To effectively determine a final design, a weighted selection process was conducted. Several designs were mocked up while considering the requirements set forth by the Cast in Steel competition. The handle design concepts are pictured in Figure 3.1.

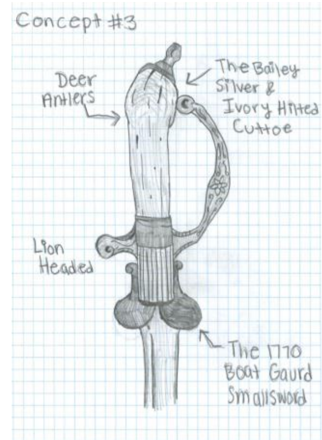
Concept 1



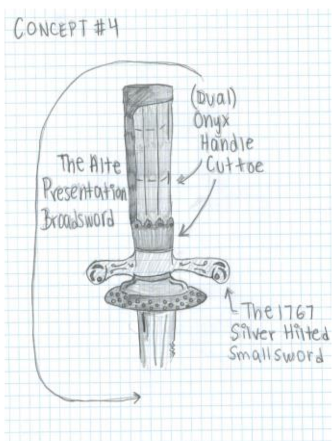
Concept 2



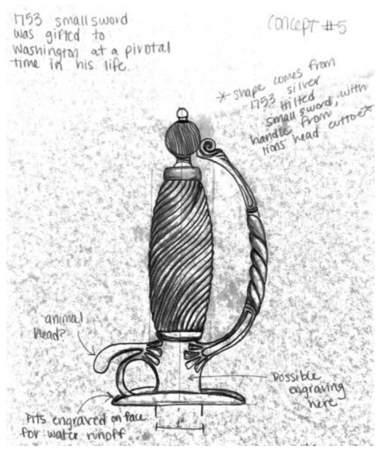
Concept 3



Concept 4

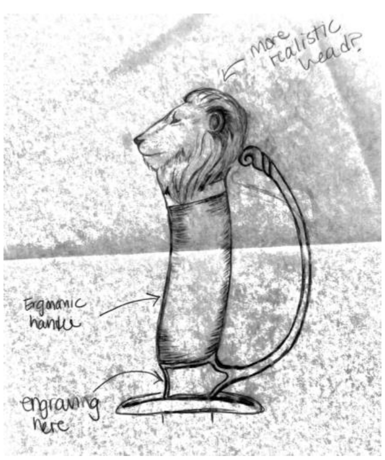


Concept 5



Concept 6

Concept 7



Concept 8

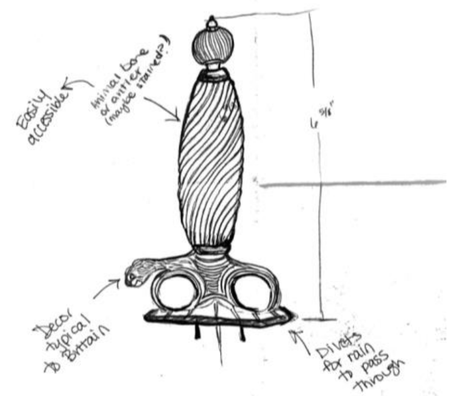


Figure 3.1 Handle Concept Sketches.

Concepts 5, 6, and 8 feature a twisted handle made from ivory or deer antler. This handle is reminiscent of the Silver Lion Headed Cuttoe that Washington is believed to have sported at the beginning of the Revolutionary War. This feature is common in several designs because the material would be easily accessible, relatively easy to machine, and reminiscent of the period in which Washington lived. The Bailey Silver & Ivory Hilted Cuttoe, from Washington's collection, also utilizes ivory in the handle. It was common for swords to be adorned with animal-shaped quillons and pommels during the late 1700's. Concept 7 utilizes a wooden handle with a realistic lion head pommel. The purpose of the realistic head is to show how today's technology can be used to sculpt more realistic designs than what was used to create Washington's original, less anatomically correct, Silver Lion-Headed Cuttoe. (Goldstein, 2016)

Figure 3.2 Washington's Silver Lion Headed Cuttoe and Concept Design 7.

Concept 5 draws inspiration from one of Washington's most adored swords, the 1753 Silver Hilted Smallsword. The overall shape of Design 5 nearly mirrors the design of Washington's beloved sword, with one les Pas d'ane (i.e. Finger holes alongside the quillon block). In the summer of 1755, Braddock led an expedition to overtake Fort Duquesne alongside an army of 1400 Anglo-American forces in efforts to halt French expansion. Braddock and his men were ambushed by an army of 900 Frenchman, Canadians, and Native Americans, resulting in the massacre of 977 of Braddock's men. General Braddock was one of the hundreds wounded in battle and would eventually succumb to his injuries, leaving Washington to be the only surviving general of the attack. Before his passing, it is believed that Braddock gifted Washington the 1753 Silver Hilted Smallsword. This battle was an extremely pivotal moment in Washington's life, kickstarting his career as a commanding general. Including details from this sword shows a strong consideration towards Washington's preferences. (Goldstein, 2016)

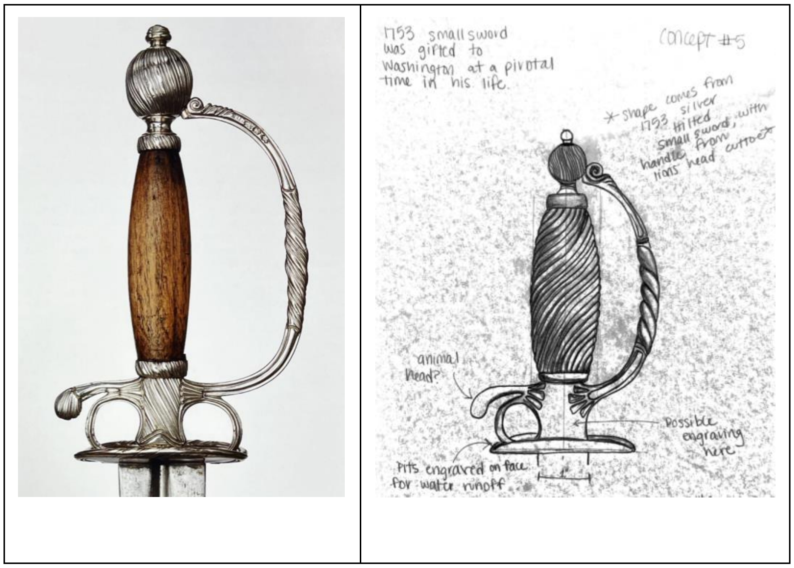


Figure 3.3 Washington's 1753 Silver Hilted Smallsword and Concept Design 5.

The original swords from this period, especially those crafted in the American colonies, were modeled after British designs. By the time of the American Revolution, lighter sabers with curved blades became popular. Washington's sword, like other examples of the era, had a longer blade and used a nut to secure the tang to the pommel instead of rivets (Peterson, 264). The following are sketch iterations of the swords Washington carried. These designs were scored. (Goldstein, 2016)

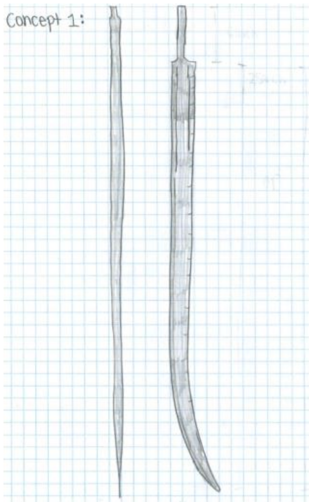
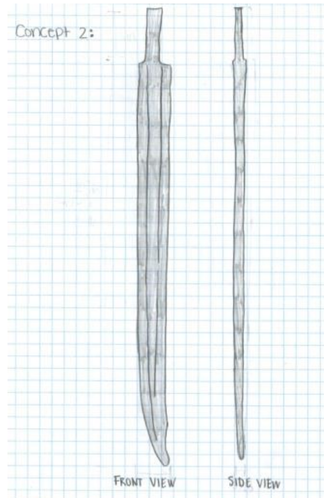
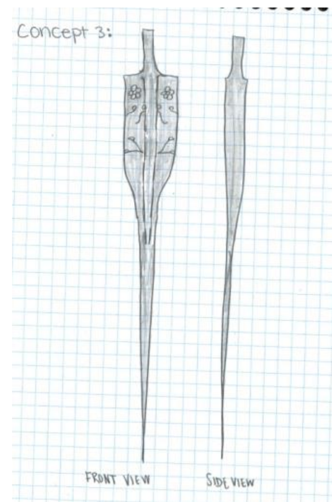
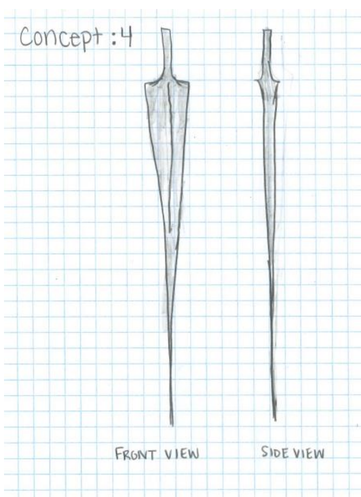
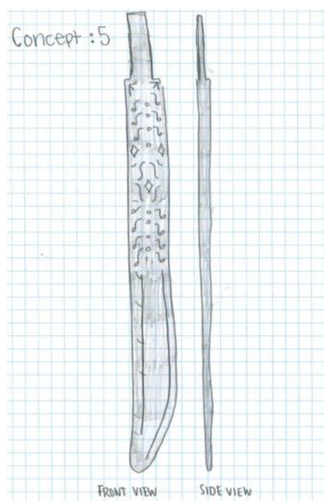
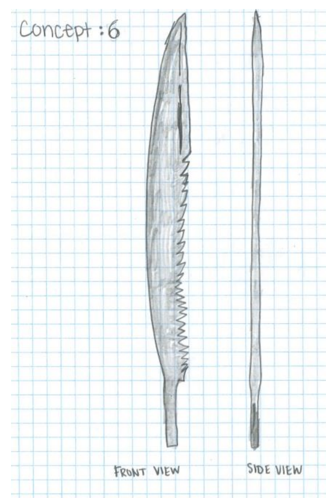
Concept 1	Concept 2	Concept 3
		
Concept 4	**Concept 5**	**Concept 6**
		

Figure 3.4 Blade Concept Sketches.

To determine which designs fit both the needs of the competition as well as the historical significance, a needs matrix was created for the handle and blade designs. The customer needs identified are shown in Table 3.2. Measurable qualities of the handle were identified based on customer needs and assigned a level of importance seen in Table 3.3.

Table 3.2 Customer Needs.

Spec	Customer Needs
1	The Sword is lightweight
2	Blade has luminous finish
3	The sword is created using a casting process
4	The sword handle is ergonomic
5	The sword is reminiscent of the time period (1700s to 1800s)
6	The sword is balanced in weight
7	The sword is unique
8	The blade is cohesive with the handle
9	The blade is strong enough to withstand a stress test
10	Fits competition requirements
11	Low cost

Table 3.3 Design Specifications.

Spec #	Needs Met	Metric	Importance	Units
1	1	The Sword is no more than 4.4lbs (including handle)	5	lbs
2	1, 4, 6	Aerodynamic	2	Drag
3	9, 10	Strong Blade	5	psi
4	3, 11	Castable Design	5	yes/no
5	2, 4, 5, 7, 8	The sword is aesthetically pleasing	3	Opinion
6	1, 4, 10	Reasonable handle size	3	Inches
7	5, 6, 10	The sword is no longer than 40 in. in overall length	5	Inches
8	1	Minimal material removed during finishing	2	Inches
9	9	Fillets at corners for durability	4	Inches
10	11	Readily accessible materials	4	Opinion

After reviewing each handle design as a team, scores were assigned. The handle design that scored the highest was Concept 6. Further, the type of blade was chosen in a similar manner that would fit the needs of the project. The blade that scored the highest was Concept 1, a Cuttoe-style blade. The combination of the design Concept 1 blade and the design Concept 6 handle must create a sword that fulfills the needs of the competition utilizing available resources at hand as seen in Figure 3.5.

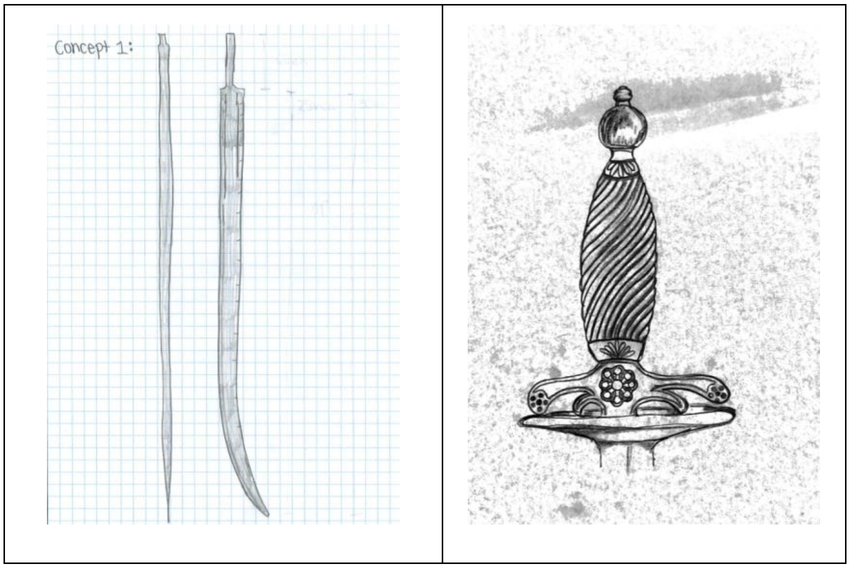


Figure 3.5 Blade Concept 1 and Handle Concept 6.

3.3 CAD

Figure 3.6 CAD Assembly.

The CAD assembly must consist of a blade, guard, handle, handle ring caps, and pommel that will be assembled into our functional inspiration of George Washington's sword. The geometry of the blade ensures that the angle of the blade's sharp edge is within the constraints of 30 to 35 degrees, which is typical for western-made blades.

3.4 Material Selection

The blade will be cast out of 4330 steel using sand casting and 3D-printed sand molds. The handle will be constructed of an assembly of components. Washington's sword handles were made of precious materials like silver and ivory; hence, pewter and antler could be substituted. The guard and pommel will be cast out of pewter using investment casting, while the grip will be made of wood or antler. Pewter does not have nearly as much strength as silver but aesthetically looks like silver, is low cost, and has a low melting point of 564°F, allowing it to be melted in the CMU metals lab.

Chapter 4. Project Execution and Engineering Analysis

4.1 Overview

The team settled on three unique blade designs, numbered 3, 6, and 7. Calculations, Finite Element Analysis (FEA), and cast flow and solidification analysis were performed prior to manufacturing the three unique blades and handle components. The manufacturing processes involved sand casting the blade, investment casting the decorative components, machining the handle, and creating an assembly. After the manufacturing processes, ultrasonic testing, heat treatment, and material verification were performed, and final specifications were analyzed.

4.2 Calculations

One of the most crucial steps in the design of a blade is to understand how it will react when forces are applied to it. The impact force of the blade striking an object will cause bending stress throughout the length of the blade. For a force of 200 lbs applied to the length of the blade, blade geometry, and a design factor of 1.75, the maximum bending stress is 187,500 psi. The yield strength of quenched and treated 4330 and 4340 steel is around 210,000 psi; therefore, the blade should sustain impact forces and resist ductile failure.

4.3 Finite Element Analysis (FEA)

Static FEA was utilized to validate edge retention. A static distributed load of 200 lbs. was applied to the blades across an area of 0.075 inches by 0.6 inches. The small area simulates striking a very small, tough object, likely to damage the blade edge. Results for 200 lbs exerted on blade 3 are shown in Figure 4.1.

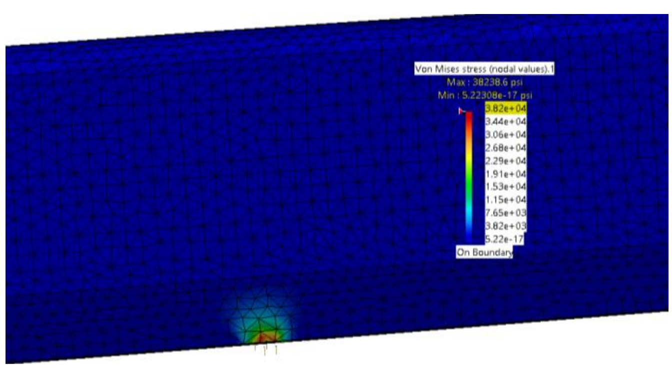


Figure 4.1 Blade 3—Von Mises Stress for Applied Force of 200 lbs.

Blade 3 presented the lowest stress value, and Blade 7 exhibited the highest stress value for each loading condition. The geometry, including the angle of the edge or overall flatness of the blade, likely influences the stress values. Across all blades, the edges hold up for an applied force of 200 lbs. Under these testing scenarios, Blade 3 is the most promising design to retain edge geometry.

Table 4.1 Blade Design and Von-Mises Stress.

Blade Design	**Maximum Von-Mises Stress for 200 lb case (psi)**
3	38,328
6	71,192
7	82,628

4.4 Cast Flow and Solidification Analysis

After sending the blade designs to Bay Cast, they were able to place risers and gates on the designs and simulate the solidification using QuikCAST Software as shown in Figure 4.4.

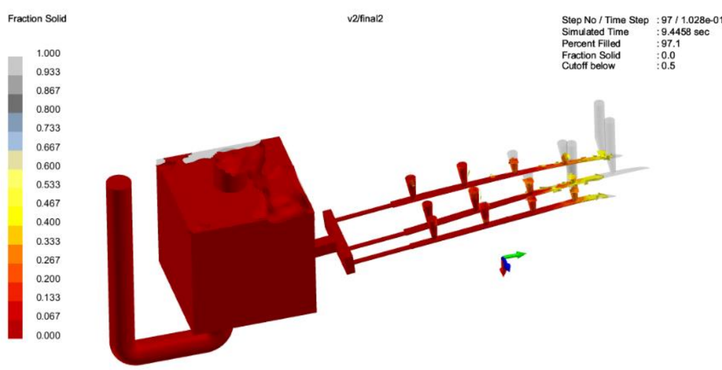


Figure 4.2 QuikCAST Solidification Model.

After Bay Cast decided on the optimal risers and gate placement, they ordered 3D-printed sand molds inclusive of a cope and drag from VoxelJet.

4.5 Manufacturing Procedures

4.5.1 Blade - Sand Casting

After Bay Cast received the 3D-printed molds, Bay Cast allowed the team to participate in the mold-making and pouring processes. The team had to first clean the 3D-printed sand molds with a vacuum and brush, ensuring that any loose sand particles were removed. After, the team sanded any sharp entrances to the mold using sandpaper and then washed the molds with a special paint. The special paint prevents metal from penetrating the mold surface and improves the surface finish of the cast product. The paint was then allowed to dry, and then holes were drilled into the mold to help aid in gas removal. Vent tubes were then secured to the holes using an adhesive as well as chill bars.

The 3D-printed molds were then ready to be packed into a larger cope and drag packed out of sand. The cope and drag were then placed together and allowed to cure overnight and then opened to be washed with the special paint on any surface that molten metal would touch. Afterwards, the cope and drag were closed and fastened with bolts and were ready for a metal pour.

Molten 4330 was poured into the gate and then allowed to cool overnight. The cast product was then removed from the mold. Upon removal, it was found that metal solidified about one third of the way through the mold. Under Bay Cast's recommendations, revisions were incorporated to improve the flow, including increasing the overall thickness of the blade from 0.25 in to 0.37 in and adjusting the composition of the metal from 4330 to 4340.

Repeating the molding process, Bay Cast then initiated another pour. Upon removal, it was found that metal solidified about one half of the way through the mold. Bay Cast then decided to incorporate a new gating design with multiple gates across the length of the sword, as seen in Figure 4.3.

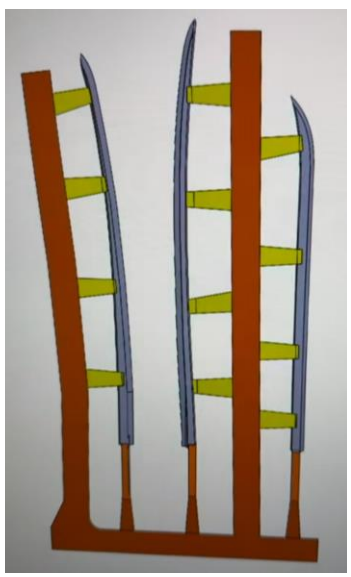


Figure 4.3 Revised Gating Design. Blades 7, 6, 3 from Left to Right.

Additionally, a new simulation was performed on the new gating design as seen in Figure 4.4.

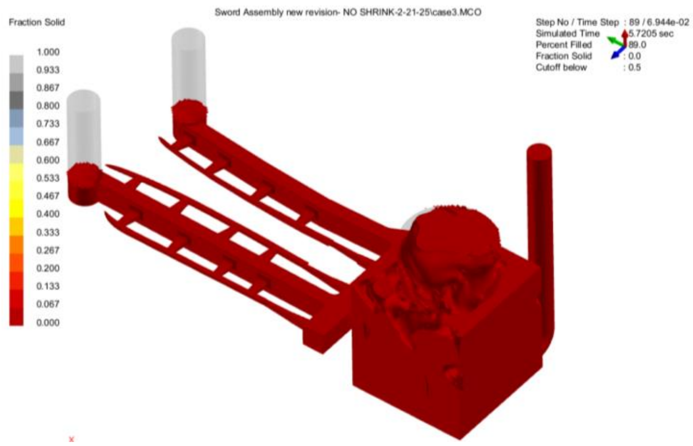


Figure 4.4 Revised QuikCAST Solidification Model.

With the new gating design, Bay Cast repeated the molding process and initiated a third pour. The new gating design proved to be a success as three complete swords were cast, as seen in Figure 4.5.

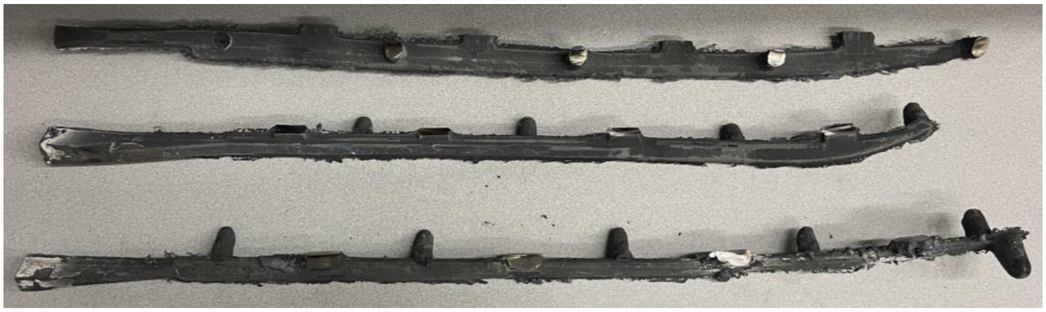


Figure 4.5 Casting Results of Pour 3. Blades 6, 3, and 7 From Top to Bottom.

Once the team received the blades, the team started inspecting them. It was found that all three of the blades were cut one to two inches too short at the tang, and that Blade 6 had a spot of porosity.

The team decided to cut chunks of 4340 from previous incomplete casts, and Tungsten Inert Gas (TIG) weld the extra material to the tang prior to grinding the entire blade to shape, shown in Figure 4.6.

Figure 4.6 Cleaned up Blades 6, 3, and 7 From Top to Bottom.

Once the swords were ground to shape, it was found that several spots of porosity were present where the risers were removed. The blades were then taken to Bay Cast, and Bay Cast performed magnetic particle testing using iron oxide powder and magnets to visualize cracks or defects. Ultrasonic testing following ASTM A609 standards for ultrasonic testing was also conducted. Questionable areas in the blades were marked accordingly and were ground and TIG welded. The next day, the blades underwent the heat treatment and quenching processes. The blades were heated to a temperature of 1550°F, above the critical temperature of 1525°F, for 45 minutes, as seen in Figure 4.7. After that the blades were immersed in soybean oil, preheated to 130°F for 30 seconds, as seen in Figure 4.8.

Figure 4.7 Heat Treatment.

Figure 4.8 Oil Quench.

The blades were then immediately clamped between two pieces of wood and left to air cool to ambient temperature. After, the blades were tempered at 500°F for 45 minutes. A hardness test was performed, and the blades exhibited a hardness of 49 Rockwell C. As seen in Figure 4.9. The hardness value was 49 Rockwell C higher than anticipated and therefore offered increased resistance to localized plastic deformation, meaning better edge retention.

Figure 4.9 Rockwell C Hardness Test Apparatus.

The composition of the steel was verified by Bay Cast following ASTM A915/A958: Chemical Requirements Similar to Standard Wrought Grades by Weight. The composition was within the expected range, with elements meeting the required values as seen in Table 4.2 and certified in Appendix A.

Table 4.2. Theoretical and Actual Composition of 4340 Steel.

Element	Required Value Per ASME A915/A958	Actual Value
Carbon (%)	0.380-0.430	0.410
Manganese (%)	0.600-0.900	0.840
Phosphorus Max (%)	0.035	0.012
Sulphur Max (%)	0.040	0.005
Silcon (%)	0.300-0.600	0.450
Nickel (%)	1.650-2.000	1.760
Chromium (%)	0.700-0.900	0.880
Molybdenum (%)	0.200-0.300	0.280

Once the team received the blades back, they were ground further and inspected. All three of the blades exhibited small warps, with Blade 6 exhibiting the least deviation from the intended shape. Efforts were then focused on Blade 6 with the intention to send the blade to competition. The blade was polished and sharpened using grinders and a whetstone.

4.5.2 Decorative Components— Investment Casting

Polymaker Polycast, an investment cast filament, was used to print 3D parts that were coated with the ceramic slurry mixture and were allowed to dry for 2 hours before being dipped again for a total of 12 dips. After a thick shell was built up, the ceramic shells were heated to 2000°F for 2 to 2.5 hours, allowing all the Polycast filament to smoke and sinter out of the ceramic shell. Once the shells were fully burned out, 1 to 1.5 lb. of pewter was melted to a temperature of 800°F and immediately poured into the ceramic shells. The cast product was allowed to solidify and cool for 1 hour, and then the ceramic shell was chipped away using a series of hammers, chisels, and pliers. Once the ceramic was removed, a Dremel rotary tool was used to polish the pewter cast.

4.5.3 Handle – CNC Mill

A CNC mill was used to cut a preprogrammed block of cedar wood to the intended handle shape. The handle is a two-part assembly with a male half and a female half. Each half can be seen in Figure 4.10.

Figure 4.10 Disassembled Sword 6.

4.5.4 Assembly and Finishing

An assembly of the sword was created using a blade, two ring caps, a guard, a handle, and a pommel fixed together with JB Weld epoxy as seen in Figures 4.11 and 4.12.

Figure 4.11 Handle Assembly of Sword 6.

Figure 4.12 Assembly of Sword 6.

4.6 Results and Specifications

The fully assembled sword feels well-balanced, making it easy to maneuver with precision and control. The wooden handle has a smooth, polished finish, providing a comfortable and secure grip, with a diameter wide enough to ensure stability without feeling awkward. The thickness of the blade looks like it can endure rigorous use without compromising its integrity. The overall construction is solid, with well-fitted components that enhance both durability and functionality. Table 4.3 displays the measurement specifications of the sword, including the blade length and weight along with the assembled length and weight, showing that the requirement standards of the competition were met.

Table 4.3 Measurements and Weight of Sword 6.

Measurement	Required	Actual
Blade Length	20-35 inches	30 inches
Blade Weight	N/A	2 lbs
Total Length	25-43 inches	37.75 inches
Total Weight	<4.4 lbs	3.2 lbs

Chapter 5. Conclusion

5.1 Lessons Learned

The team created a beautiful assembly of Washington's Sword, using sand casting and investment casting. However, several lessons were learned. The team ran into many setbacks and unfortunate failures, but with that, gained a lot of experience and knowledge. In the creation of the sword, the team, along with their industrial partner Bay Cast, had to create three unique mold designs due to two failures. The first two designs were a single gate mold, which exhibited flow issues, leaving the cast blade incomplete. To account for this issue, Bay Cast came up with a multi-gate option allowing for more optimal flow throughout the entire mold. Also, in adjustment to a lack of flow, the team switched to 4340, which is less viscous than the initial choice of 4330. The simulation proved that the two initial mold designs should have worked, however, the cause of failure was unknown until further investigation was done to uncover that the pour rate was slower than simulated.

The team also discovered many other lessons throughout the in-house investment casting process. Some of these lessons involved the number of dips into the ceramic slurry the parts needed, the drying time of the slurry on the part, the burnout time and temperature to achieve a clean and ash-free mold, and the cleanup and polishing of pewter. The biggest takeaway from the investment casting process was the switch to the Polymaker Polycast, a 3D-print filament that sinters when heated to 2000°F—perfect for a ceramic mold. The team's initial plan was to pour wax into a silicone mold and then remove the piece to then dip it into the ceramic slurry. It was quickly realized that this was not a suitable option due to the weakness of the wax piece and the pour surface finish that was achieved in the wax. The 3D printed filament allowed for a detailed surface finish. It also allowed for a unique and intricate part design while controlling the precise placement of risers.

The team also faced challenges in the process of creating the wooden handle. Prior to CNC milling any of the wooden prototypes, the team created an aluminum handle to test the fit and size of the handle before using wood for the final product. The aluminum handle was machined with minimal issues, leading the team to believe that there would be little difficulty when machining the wooden counterpart. However, this was not the case. The first attempt of machining the wooden handle wielded an oblong, ovular handle instead of the circular handle that the team was able to achieve previously, leaving the team stumped. After reviewing the numerical control code to identify the issue, the team found that the stock size of the wood in the initial program was slimmer than the wood being used, causing each half of the handle to be machined too short. The team updated the code several times and, through trial and error, were able to achieve the correct handle width. A second problem arose when machining the center channel of the handle. Opposed to the aluminum handle, the wooden handle's channel was off center for nearly every iteration the team created. It was discovered that, during the machining process, the handle needed to be probed several times to identify the correct location of the center channel, making the process considerably more time-consuming. After multiple attempts, the group was successful in creating two halves of a wood handle, which would then be assembled with JB Weld.

5.2 Evaluation of Project Success

Overall, the project was a success due to the teams' desire to make the best possible sword. To maximize efficiency, tasks were delegated based on each member's strengths and expertise, ensuring that everyone took on a role they felt confident executing. The team developed a well-structured timeline that was both realistic and flexible, allowing extra time to address any potential errors.

As talked about in section 5.1, the team faced adversity with the first two blade pours, which required us to reassess our approach and make necessary adjustments. At a crucial part of the decorative component's creation, both furnaces in the metal lab at CMU broke down due to them being outdated and not being used for some time. The School of Engineering and Technology at CMU acknowledged our challenge and provided us with a brand-new furnace within two weeks, allowing us to stay on track and complete the handle components before the due date. This support was invaluable to the project's success, but it also underscores the ongoing need for continued investment in updated tooling and equipment. Such funding is essential not only for the completion of student projects but also for fostering innovation and providing students with the resources necessary to address complex engineering challenges in the future.

5.3 Sponsor Feedback and Acknowledgements

Bay Cast demonstrated exceptional support, perseverance, and teamwork throughout the entire project. Known for handling large castings, typically weighing 3,500 lbs or more, this project marked their smallest casting to date at about 4lbs per blade. Despite the challenges, including three trials before achieving success, Bay Cast remained committed to the process.

The team would like to give special thanks to Anup Shrestha, the foundry engineer, for his meticulous attention to chemistry, mold design, and overall process. Additionally, the team appreciates Nathan Ryder, a nondestructive technician, for his assistance with ultrasonic and magnetic particle testing, heat treatment, and quenching.

Additionally, several individuals played key roles in the project’s success. Nolan Mango, a skilled student, TIG welded the blades and shared his expertise to aid in the CNC milling of the handle. Aaron Wenzlick, the engineering building technician, was instrumental in acquiring tools and materials throughout the project and brought great enthusiasm to the team. We would like to thank Dr. Ben Ritter for encouraging the Cast in Steel competition to qualify as a senior design project as well as his presence in the CMU metals lab. We are grateful for Dr. Samson Lee, our project advisor, for his unwavering support, patience, and encouragement throughout the project, allowing for individual creativity and exploration. The team appreciates the School of Engineering and Technology and College of Science and Engineering for their funding and support of the competition. Finally, we are thankful for the Steel Founders Society of America (SFSA), for offering a unique competition that advances education of the steel casting practices through collaboration and innovation.

5.4 Areas for Future Research

For future iterations of this project, several key areas should be researched further. During the project, many of the blades were found to have porosity spots. To address this, further investigation into degassing techniques, improved simulation models, and optimized riser and gate placements would help mitigate porosity.

Additionally, conducting more research into dynamic Finite Element Analysis (FEA) would assist in refining the production of models, improving weight distribution, and identifying testing scenarios to produce the most optimal geometry and design choices. Lastly, considering design for manufacturing, specifically ease of sharpening, would be beneficial.

References

1. AISI 4330 alloy steel (UNS J24045). AZoM. (2013, July 13). https://www.azom.com/article.aspx?ArticleID=6670#:~:text=AISI%204330%20alloy%20steel%20is%20heated%20to%20829%C2%B0C,then%20quenched%20to%20gain%20strength
2. AISI. American Iron and Steel Institute. (2020, December 7). https://www.steel.org/about-aisi/
3. Allen, D. K. (1976). Metallurgy Theory and Practice. American technical Society.
4. *Alloy AC Casting*. RotoMetals. (n.d.). https://www.rotometals.com/alloy-ac-casting-pewter-ingot-92-tin-7-75-sb-0-25-cu-britannia-563f-650f/
5. Bhagyalaxmi, Hegde, A., Sharma, S., & Jayashree, P. (2023). Analysis of tempering\temperature and vegetable oil quenchant viscosity effect on mechanical properties of 42CrMo4 steel. Cogent Engineering, 10(1). https://doi.org/10.1080/23311916.2023.2216052
6. Budynas, R. G., & Nisbett, J. K. (2014). *Shigley's mechanical engineering design* (10th ed.). McGraw-Hill.
7. Campbell, J. (2011). *Complete casting handbook: metal casting processes, metallurgy, techniques and design* (1st ed.). Elsevier.
8. *Cast in Steel*. (2024). Sfsa.org. https://www.sfsa.org/subject-areas/castinsteel/
9. Goldstein, E., Mowbray, S. C., Hendelson, B., & Cadou, C. B. (2016). *The swords of George Washington*. Mowbray Publishing.
10. *Industrial 3D Printing & 3D printer manufacturer*. Voxeljet. (2024, October 23). https://www.voxeljet.com/
11. Mahomed, N. (2020). *(PDF) shrinkage porosity in steel sand castings: Formation, classification and Inspection*. Research Gate. https://www.researchgate.net/publication/347495293_Shrinkage_Porosity_in_Steel_Sand_Castings_Formation_Classification_and_Inspection
12. MatWeb, LLC. (n.d.). AISI 4140 Steel, Annealed. Retrieved from https://www.matweb.com/search/datasheet.aspx?matguid=1b9e2d5f05104d158f97f7221b734e82&ckck=1
13. MatWeb, LLC. (n.d.). AISI 4340 Steel, Normalized. Retrieved from https://www.matweb.com/search/DataSheet.aspx?MatGUID=ce0a7097f18b45bba87d315f492c8b97
14. Neely, J., & Bertone, T. J. (2000). *Practical metallurgy and materials of Industry*. Prentice Hall. Peterson, H. L. (1956). *Arms and armor in Colonial America: 1526-1783*. Bramhall House.
15. *Pla vs. ABS: Which filament should you use?* Dassault Systèmes. (2023, July 5). https://www.3ds.com/make/solutions/blog/pla-vs-abs
16. Poweleit, D., & Monroe, R. (n.d.). *Steel casting mechanical properties*. Steel Founders' Society of America.
17. Singh, R. (2020). *Applied Welding Engineering: Processes, codes, and standards*. Butterworth-Heinemann.
18. Sunrise. (2024, March 21). Understanding and preventing shrinkage porosity in die casting. Sunrise Metal - Aluminum Die Casting Expert. https://www.sunrise-metal.com/shrinkage-porosity
19. World Material. (n.d.-a). https://www.theworldmaterial.com/

Appendix A. Certifications

BAY CAST
STEEL CASTING

Material Certification Report

CUSTOMER CMU _ SFSA Project **CONTROL NO.** n/a

PART NAME Sword
PATTERN NO. n/a
P.O. NO. n/a

METAL SPEC. ASTM A958 SC 4340 Class 135/125
HEAT NO. 250058
HEAT DATE 3/4/25

	ACTUAL
CARBON	0.410
MANGANESE	0.840
SILICON	0.450
SULFER	0.005
PHOSPHORUS	0.012
CHROMIUM	0.880
NICKEL	1.760
MOLYBDENUM	0.280
VANADIUM	0.000
COPPER	0.070
ALUMINUM	0.025

COMMENTS:

BY:
Jason J. Holman, CQE
Quality Assurance Manager

DOC-WI-12 rev 0, issued 7/00