SFSA Cast In Steel 2025 – George Washington's Sword Technical Report

California State Polytechnic University, Pomona – Vernon Vanguard

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1. Executive Summary

The Steel Founders' Society of America (SFSA) has facilitated this competition to teach aspiring students about the casting industry. From the initial design phase to casting the part, the students will have to work together to manufacture their workpiece with the aid of an industry partner. SFSA's 2025 Cast In Steel competition challenges students to design and manufacture a blade worthy of George Washington's hands, either a replica from his collection or sword consistent with what he wielded.

During his tenure as a lieutenant colonel during the French and Indian war and Commander-in-Chief of the Continental Army during the Revolutionary War, Washington owned many swords. Some were used by him directly in battle, some were gifts from allies, but all have seen the United States of America become a part of history. Most of Washington's collection consisted of cuttoes, a one-handed blade used for slashing, and this is the type of blade he used during the wars. Due to the sword being one-handed, it needs to be relatively light because it is very easy for the user to hurt themself with a sword that is too heavy. Said injuries are damaging muscles and joints, or losing control of the swing and hitting oneself. A light, easy to swing sword is what Washington would have taken to the battlefield.

There were many iterations of the blade printed with FDM 3D printers, and being able to physically wield each of them allowed us to more effectively identify aspects that needed to be altered. The grip was the main focus, with it being presented to many colleagues to get their opinion. When the team was satisfied with the final iteration, it was printed in PolyCast™, a brand of filament designed to burn without producing ash. Perfect for Aerotec Alloys, Vernon Vanguard's wonderful industry partner that specializes in investment casting, since the clean burn wouldn't affect the casting quality. After that, it was shipped off to be heat treated and returned to the team to sharpen, a process the team outsourced to a local knife sharpener.

The sword weighs 2.4 pounds and was about 36 inches long, cast with two different alloys. The grip and guard are cast in aluminum bronze, and the blade itself was cast in H-11 tool steel. The team aimed to design a sword that would win the practical portion of the competition, with the aesthetics representing aspects of each member and Washington. On the grip, each team member chose a flower/fruit to represent themselves, whether it be their culture, personality, or aesthetic, each of the team members left their own touch on the grip. Aerotec also has their logo featured on the grip as an extra touch for their contribution. The guard is a bald eagle, an American symbol that dates back over 250 years, and is the current national bird. Emblazoned on both wings is the American flag, on the left featuring the original flag flown after winning the revolutionary war and on the right is the modern version. On either side of the blade two quotes are featured, one representing the team and one directly from Washington himself. The quote was attempting something and learning from it-even if it ends in failure. Washington preached about being learned, educated to make the right decisions in life but also to be kind when going about it.

2. Introduction

2.1 Objective and Constraints

At a fundamental level a blade needs to be a sharp piece of metal that can cut things. However, there are a multitude of factors that need to be considered. The sword needs to be lightweight to be properly wielded with one hand, short enough to be safely swung, balanced correctly to not injure the wielder,be sharp enough to cut through obstacles, durable enough to not shatter on impact, hold an edge after use, be aesthetically pleasing, and adhere to the guidelines set by SFSA for the competition. These constraints stack up fast when considering how much overlap they have and considering the cost to develop and implement them, both in time and cost.

The SFSA guidelines listed a blade that weighed less than 2 kg (4.4 lbs) and 1.09 m (43 in). The length limit is about 10 inches greater than the average length of one handed swords produced during the time. Any longer than 43 in, and the blade could be considered a two-handed weapon. The weight is a safety concern, since wielding a one handed sword that is too heavy can easily sprain the wrist with the twisting motions. Aside from competition requirements, there are basic performance requirements as well. Holding an edge is an easy goal, this leads to a workhorse of a sword that stays sharp swing after swing. This ensures that the blade can perform well for the whole competition, not just the first test. To hold an edge well, the blade needs to have strong hardness. This leads to the next point: durability. The sword needs to straddle the line between having high hardness and high ductility. If the blade is too hard it becomes brittle and will shatter upon use, if it's too soft, it'll bend and not cut anything. Having the best of both worlds means a sturdy blade that will hold an edge and survive multiple rough swings without shattering.

2.2 Summary of the Design Process

A Gantt chart was utilized to consolidate the project tasks and milestones into feasible deadlines *(See Figures 2.2.1 - 2.2.6)*. The project timeline was divided into six phases to maintain a well-organized list of tasks delegated to each team member. Phase 1: Proposal was the team formation, project timeline development, and proposal submission to SFSA to register Team Vernon Vanguard's intent to participate in the SFSA Cast in Steel 2025 Competition. Phase 2: Industry Partner were the initial meetings with the team's industry partner, Aerotec Alloys, Inc., coordinating a foundry facility tour, and contacting Subject Matter Experts whose specialties are relevant to the competition's objective. During Phase 3: Design, the team conducted historical research about George Washington's swords and literature research about steel alloy materials and heat treatment options. The team divided into Structural Design and Aesthetic Design subteams to draft ideas then develop multiple CAD iterations of the sword. After the sword design and gating system were finalized and approved by Aerotec Alloys, the manufacturing subteam 3D printed a total of eight sword patterns. Phase 5: Video Production occurred simultaneously with Phase 4 to capture footage for the required team video. Phase 6: Final Deliverable is the final stage of the project timeline. The team transported the sword patterns to Aerotec Alloys for the investment casting process.

Team Vernon Vanguard held weekly meetings developing the sword's functional and aesthetic design. They poured over Washington's collection to see what blades he favored, and decided that a slightly longer cuttoe would be his preferable weapon. After the blade type was chosen, the aesthetic design was next. Ideas were thrown around, some were Billy Bronco (CPP's mascot) themed, while others played into a more traditional look, but they were both scrapped. Instead, the team used a bald eagle as the guard, with flowers and Aerotec's logo extruded on the grip for a personal touch. After modeling this in SolidWorks, multiple iterations were 3D printed using FDM printers to gauge how practical each design was. When all the kinks were ironed out, the team printed the final iteration with Polycast™, an ashless FDM filament used for investment casting. The investment casting process was completed at Aerotec Alloys and sword sharpening was done at Johnny's Art of Sharp.

Phase 1: Proposal					
Team Formation (AMS + Advisor)	Aprille	100%	9/4/24	9/5/24	1
Team Gantt Chart Submission to Advisor and Industrial Partner	Aprille	100%	9/16/24	9/23/24	7
Submit Preliminary Proposal to SFSA	TEAM	100%	9/16/24	12/2/24	77
Submit Competition Registration on SFSA CiS Website	Aprille	100%	9/16/24	10/4/24	18
Major Milestone: Phase 1 Complete	**TEAM**	**100%**	**9/4/24**	**12/2/24**	**89**

Figure 2.2.1: Phase 1

Phase 2: Industry Partner					
Introduction to Foundry by Advisor	Aprille	100%	9/16/24	9/17/24	1
Competition Information & File Sharing	TEAM	100%	9/4/24	9/5/24	1
Initial Meeting with Industrial Partner	TEAM	100%	9/17/24	9/25/24	8
Coordinate Foundry Facility Tour	Aprille	100%	9/25/24	10/4/24	9
Find Subject Matter Experts	Aprille	100%	9/4/24	9/27/24	23
Introduction to Subject Matter Experts	TEAM	100%	9/17/24	10/4/24	17
Major Milestone: Phase 2 Complete	**TEAM**	**100%**	**9/16/24**	**10/4/24**	**18**

Figure 2.2.2: Phase 2

Phase 3: Design					
Literature Review on Design, Casting Process, and Materials	TEAM	100%	9/23/24	10/18/24	25
Research Casting Process	TEAM	100%	9/30/24	10/6/24	6
Research Alloy Materials	TEAM	100%	9/23/24	10/28/24	35
Research Heat Treatment Options	Aprille	100%	9/30/24	10/28/24	28
Conduct FMEA Analysis on Top 5 Materials	Aprille	100%	10/14/24	10/27/24	13
Conduct Materials Testing: Tensile, Hardness, Impact.	Aprille	100%	10/14/24	11/3/24	20
Conduct Heat Treatment Testing	Aprille	100%	10/14/24	11/3/24	20
Proposed initial draft designs	Design Team	100%	9/30/24	10/13/24	13
Design Iteration # 1	Design Team	100%	10/7/24	10/20/24	13
Design Iteration # 2	Design Team	100%	10/21/24	11/3/24	13
Design Iteration # 3	Design Team	100%	11/4/24	11/17/24	13
Gating System (3 alternatives) and Simulation	Ethan	100%	11/18/24	12/1/24	13
Major Milestone: Phase 3 Complete	**Manufacturing Team**	**100%**	**9/23/24**	**12/1/24**	**69**

Figure 2.2.3: Phase 3

Phase 4: Pattern Production					
List of supplies needed to Advisor	Aprille	100%	10/13/24	10/20/24	7
Production Method Testing (Parameters and Procedures)	Victor, Aprille, Daniel	100%	10/21/24	10/27/24	6
Pattern Production Initial	Victor, Aprille, Daniel	100%	10/28/24	12/31/24	64
Pattern Production Revisions	Victor, Aprille, Daniel	100%	11/4/24	11/17/24	13
Pattern Production Final	Victor, Aprille, Daniel	100%	11/18/24	12/6/24	18
Pattern Production Extras	Victor, Aprille, Daniel	100%	11/18/24	12/6/24	18
Deliver 3D-printed patterns to Javier (Aerotec Alloys, Inc.)	Aprille	100%	11/18/24	12/6/24	18
Major Milestone: Phase 4 Complete	**3D Printing Team**	**100%**	**10/13/24**	**12/6/24**	**54**

Figure 2.2.4: Phase 4

Phase 5: Video Production					
Video filming: School	Chris	100%	10/7/24	12/31/25	450
Storyboard	Chris	100%	10/7/24	1/29/25	114
Photos	Chris, Aprille, Victor	100%	10/7/24	1/29/25	114
Video filming: Foundry	Chris, Aprille	100%	10/9/24	2/28/25	142
Film Editing	Chris	100%	12/16/24	2/28/25	74
Major Milestone: Phase 5 Complete	**Video Production Team**	**80%**	**10/7/24**	**2/28/25**	**144**

Figure 2.2.5: Phase 5

Phase 6: Final Deliverable					
Design Final Heat Treatment Plan	Aerotec Alloys, Inc.	100%	1/5/25	1/31/25	26
Casting Production	Aerotec Alloys, Inc.	100%	1/5/25	2/28/25	54
Post-processing (machining, heat treatment, etc.)	Aerotec Alloys, Inc.	100%	1/5/25	2/28/25	54
Product Testing on-campus/foundry	TEAM	100%	1/20/25	1/31/25	11
Shipment of Final Product to SFSA CiS	Aerotec Alloys, Inc.	100%	3/1/25	3/21/25	20
Review Final Report and Video	TEAM	100%	3/3/25	3/9/25	6
Final Report and Video Submission to SFSA	Aprille, Chris	100%	3/10/25	3/21/25	11
Major Milestone: Phase 6 Complete	**TEAM**	**100%**	**1/5/25**	**3/21/25**	**75**

Figure 2.2.6: Phase 6

2.3 Literature Review

During the late 1700s, infantrymen from both the American and British armies carried similar types of weapons to battle, due to them sharing the same weapon culture and preferences. There were many types of blades used during the wars, with broadswords, cutlasses, smallswords, cuttoes, sabres, hangers, and more. However, many were light, one handed blades that could be used to inflict deep slashes or thrusts into the opponent. Washington’s collection had variety, but was mainly of smallswords and cuttoes.

Cuttoe originated from the French word couteau, meaning a large knife. In practice the cuttoe is a hunting knife that hunters would usually bring as their side arm as well as a tool to help them take hunted games apart. The sword features a thin, slender single edge blade with sharp tip. The edge helped skinned the games while the tip helped finish the prey off after they were severely wounded. The use of cuttoe back then was very similar to a machete today, as a tool. Although originally a must for sustaining a family, hunting eventually became a sport for the rich as one of their entertainment, as a gentleman's sport. The cuttoe evolved with the change in the nature of hunting as well, it is no longer just a tool for cutting, skinning prey or as last line of defence, it became a status symbol for those that can afford to play the sport.

Due to the nature of the time period, the wealthy are usually the one educated and were often put in the positions of officers or commanders during the revolutionary war. The resources were also short for the revolutionary army leading to many soldiers and officers bringing their own belongings to the front, cuttoes became sidearms for many officers.

A cuttoe (or most one handed swords) are made of three components, the blade, the guard, and the grip. The blade is around 24 inches, but varies due to the wielder's height. It is a single edge blade with a slight curve to increase the length of the slash, but not as pronounced as a sabre. The blades were relatively thin as well, with it being a single handed weapon. There was always a guard attached to a cuttoe, and while there are many variations, most were simple rounded guards with a piece of metal running over the grip, protecting the hands. Only one sword in Washington's collection did not have a rounded guard, the Bailey Silver and Ivory Hilted cuttoe, which had crossguard instead (a piece of metal perpendicular to the blade). The grip is self explanatory, but is usually a slight barrel shape to conform comfortably to any hand. It was usually made with metal or wood, with additives such as ivory, leather, or chord for a better grip/aesthetic.

The was a very close quarters weapon, with minimal range due to its small size. However, these design choices allow it to deliver devastated slashes to opponents. The blade is light and short, allowing for controlled swings that can precisely target weak points, such as the neck and joints. Deep slashes can be made with minimal effort if done correctly, this is accomplished thanks to the curve of the blade, which allows for longer contact with the edge while cutting deep despite the weight of the sword.

Due to the cuttoe being a one handed sword, there are very specific design constraints it must adhere to so that it can be wielded safely. First is the weight, which must be kept at a minimum, with the average cuttoe from this time period around 1-1.5 lbs. Besides tiring out the wielder from swinging a heavy piece of metal, the excessive stress placed on the wrist can easily damage it. The twisting motion from slashing and thrusting, combined with the weight, is a recipe for joint pain. Next is the size and center of gravity, which go hand in hand for safe wielding. If the weapon is too long, then the center of gravity is higher in the blade than it should be (it should be just above the guard). When someone swings, the momentum will carry forward far too much, leading the wielder to be thrown forward with it. This can lead to them cutting their legs, or cause a fatal mistake in battle. Proper size, weight, and center of gravity are key to producing a functional blade.

3. Design

3.1 Sword Design

3.1.1 Grip

The team employed the “5 W's” in engineering to help get a clear understanding on what and how to make a successful sword. The design cycle started with the team choosing and voting on what exactly they wanted to make for General Washington. After they had confirmed what to make and had done research on the weapon, it was time to employ the W’s.

First was to focus on what exactly to make. The conclusion was an iconic, easily recognizable and desirable weapon that will also succeed in all possible performance tests. According to research, Washington didn’t like to carry the broad sword. The suspected reason was that the sword, being mainly an ornamental sword, is probably too heavy and poorly balanced. Thus the customer’s need has been determined, in the case of Washington, would be a light weight sword with good balance so that the comfort of the user could be maximized.

As a sidearm and possible weapon of war, the sword would accompany Washington wherever he goes. Besides being in the scabbard, the part where the user would interact with the most is the grip of the sword. Due to this, significant efforts were put into its design. The grip should not slip from the user's hands as well as being comfortable to hold. The grip has gone through a total of 30 different iterations from a basic copy of the grip from one of Washington’s cuttoes to a multi-part composite in the latest metal grip design.

Throughout all the changes the main focus is human engineering and ergonomic design. The team researched average male hand sizes and compared those to Washington’s height to estimate his hand size. It is found that his hand breath should be between 60th to 80th percentile of the modern U.S. male population. In the end, the 75th percentile hand breath size was chosen and the grip length was 3.65 inches. The grip length for the design is defined as the “gripable length between handguard to the edge of the pommel”.

Due to the similarity of the forces a hand will experience during a slashing motion between a hammer and a sword, as in both situations the grip is counteracting the torque caused when a tool head or a blade edge sustains impact, research was focus on the ergonomics design on the grip of a hammer. The results of the research suggests that an ideal grip should have a cross section very similar to an ellipse where the ratio between major and minor diameter should be as close to 1.25 to 1 as possible.

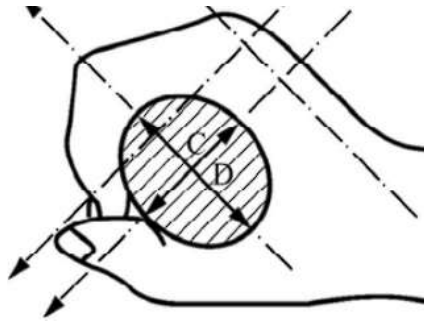


Figure 3.1.1: C is the minor diameter and D is the major diameter.

The resulting design is variable length between 1.2 to 1.3 inch for the major diameter and uniform length of 0.815 inch for the minor diameter (thickness of the grip). The resulting ratio between the two is about 1.47 to 1, it is close to the ideal ratio but the thickness has to be reduced in consideration to the weight and overall balance of the sword. The cross section is not an ellipse either as some space was needed for the aesthetic design, the solution found was to model the grip a lot larger to fit the ideal ratio and made two cuts on both sides to meet the needed thickness and provide a flat surface for better grip and aesthetic design. The decision to add flat surfaces to the sides of the grip was made after multiple testing and feedback from people with various hand sizes around the campus. Each iteration of the grip was printed with a 3D printer with very high precision so that the testing results and data will be relevant to the design.

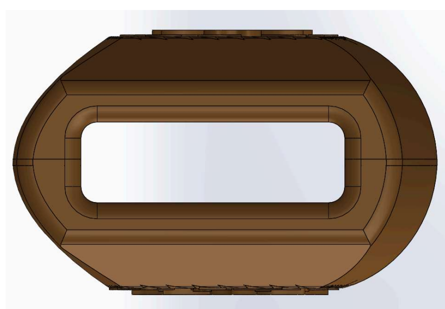


Figure 3.1.2: Top view of the grip displaying the flat sides to prevent rotation during a slashing motion.

Although the majority of cuttoe found from the era usually have extremely thin grip when compared to their blades, the larger grip was chosen for the comfort of the user. The other major benefit of having a larger grip is the wider tang for the sword. The tang is a crucial part of the sword as its design is extremely important for a sword's usability and success. Typically the wider the tang the more robust the connection between the blade and the grip is. Considering casted metal are typically weaker to their forged counterpart, a cautionary approach was taken and the tang was designed to be thicker and wider to combat potential weakness. In traditional construction, holes would be drilled on the tang so that a pin can be used to secure the grip. This simplifies the tang design but introduces potential stress points around the drilled hole, as the wrong size and position could result in the sword breaking after hitting hard objects. In the final design such weakness does not exist as the need for pins was replaced by shaping the tangs with two bevels with matching bevels on the casted grip. This creates an extremely strong connection between the grip and the tang. See Figure 1 for reference. The grip will be made of two halves to simplify the construction of the sword and reduce the casting difficulties for the industry sponsor. The grip will be casted in aluminum bronze.

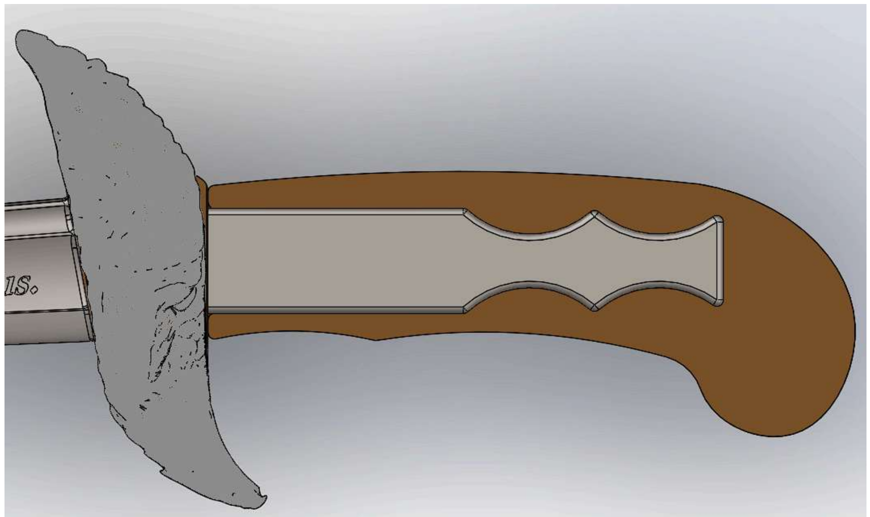


Figure 3.1.3: Tang

Similarly to the grip, the “pommel”, in this case the end portion of the grip, also went through numerous iterations and design changes. The main purpose for the pommel in the design is to provide additional grip security when held, providing counter weight for better balance and more areas to express the team’s creativity.

During the research it was discovered that Washington’s main fighting style was highly likely to be fencing, as it was the main sword fighting training regular British officers of the time would have gone through, as well as being considered to be a more “gentleman” way to fight. The team decided to take that into consideration when designing the pommel. Research showed that when holding a rapier, the fencer’s hand would ideally be holding the sword similar to a modern pistol, whereas the wrist would rest in as close to the default position as possible to ensure comfortability and reduce injury.

Taking all of the above into consideration, the final grip included a clear 90 degree elbow bend similar to the elbow joint for PVC pipes. The design allows the user to hold the sword similar to how a modern fencing athlete would with their rapier, in the pistol grip position. The other purpose the design served is the stopper for the user's hand when holding the sword. Due to the grip material being aluminum bronze and more slippery when compared to ivory or wood, it is likely that the sword might slip off the user’s hand. With the pommel in the back, as long as the user is trying to grip onto the sword it would be very difficult for the slipping to happen. To reduce the possibility of slipping even more, extrusion designs were added to the grip for added security. The grid also included a bevel between the index and middle finger, which can further prevent the user’s hand from moving once they grip onto the sword. The final result was a grip that allowed the user to comfortably use it as both a slashing and fencing weapon.

3.1.2 Handguard:

The Handguard started out as a very simple “S” shape design similar to Washington’s Bailey Silver and Ivory-Hilted cuttoe. The decision came from the fact that most of his cuttoe all had relatively simple designs. After some considerations and design changes it was decided that the guard design was to be an eagle instead. This design decision came from the attempts to combine all team member’s ideas into the sword. The ideas were: “to have a hollow/windowed design on the sword”, “Washington crossing the river reference”, “eagle design that represents the USA” and “a sword that can connect the past to the present just as Washington did winning the revolutionary war, ending and starting an era”.

The final design of the handguard is of an eagle that was landing. The view from the pommel with the edge facing down, the handguard has a shape similar to a “U”. The side profile is similar to an “S” shape. The view from the tip of the sword with the edge facing up the handguard has a similar shape to an “A”. Beside the eagle’s main body are two wings swept back with the area between the sword and the wings hollowed out as per desired design specification from a team member as well as weight reduction purpose. The eagle’s head is facing down as if it is looking for prey, this design acts as protection for if an enemy’s sword strikes the head it will slide off creating a window of opportunity to strike back. The swept back wings create a visual effect where it seems as if the eagle is rapidly descending. The raised wing tips also served as protection as when an enemy sword strikes that area it will be guided toward the sword’s spine, away from the user’s hand, which can potentially assist the user during combat situations. The bottom of the eagle’s head is sanded smooth, making sure when the user’s hand comes into contact with the area it will be a comfortable experience and letting the user know exactly where their hand is.

Holding the sword with the edge facing away from the user, there are two flags behind the wings of the eagle, US flag of 1776 with 13 stars on the left and modern US flag with 50 stars. The left side of the eagle symbolises the past and the right, present. The gap in the middle was supposed to represent the river that Washington crossed during the war, but due to the inability to create such detail it was left blank. This fulfilled one of the design needs from a member as well as creating a unique handguard that would help us stand out from the competition.

The center of the handguard is a rectangle hole that would simplify the assembly process, the tang’s shape in this area is created specifically to maximize the width of the tang and keep the handguard from detaching from the sword. The complex and precise shape is something that casting will have a clear advantage over forging as it would be extremely difficult to create such a shape. It is a good showcase of the strength of modern casting capabilities and precision as the guard, grip and the tang are casted separately. Figure 3.1.4 showcased the cross section of the handguard.The shape was designed to prevent the handguard from sliding upward during a swing.

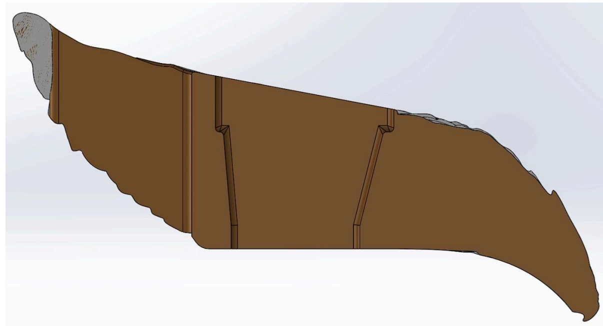


Figure 3.1.4: The complex shape is clearly shown in the middle part of the handguard.

3.1.3 Blade Design

The blade design is the most important part of the project since the part the final tests will mostly be done on. Excluding the mass produced swords, the cuttoe at the time are usually tailor made to fit their user and differ from person to person. It is similar to buying a tailored suit today, where the blacksmiths had to make sure the user could carry the sword without too much trouble.

Solidworks was used to estimate and replicate Washington's Bailey Silver and Ivory-Hilted cuttoe, which is a cuttoe with 30 inch blade and about 6 inch hilt for a total of 36 inches. The design is a modified version with similar side profile and width to the blade, where the thickness and blade geometry was designed based on research after comparing various swords from 1700s to 1800s. These included sabre, cuttoe, naval cutlass, cavalry sabre and officer's sabre of different origin. Due to the length of the sword, the thickness of the sword at the base is a lot thicker than near the tip to ensure structural integrity. The blade employed two fullers across about ⅔ length of the blade. These are very important in weight reduction and balanced while maintaining good toughness of the sword. The fullers were usually done by grinding the excess material off the sword for the desired balance, but in this case it was possible to cast with the fullers already hollowed out, reducing the need for additional post-processing to complete the sword.

The blade edge is carefully designed to be thin, yet have enough materials to back up the razor sharp edge while reducing as much weight as possible. The entire blade can be divided into 6 major portions, one of them being the tang and was discussed in the grip section. The rest of the 5 portions consist of 5 major edge geometry differences whereas the middle of them are those geometry but gradually changing from one to another.

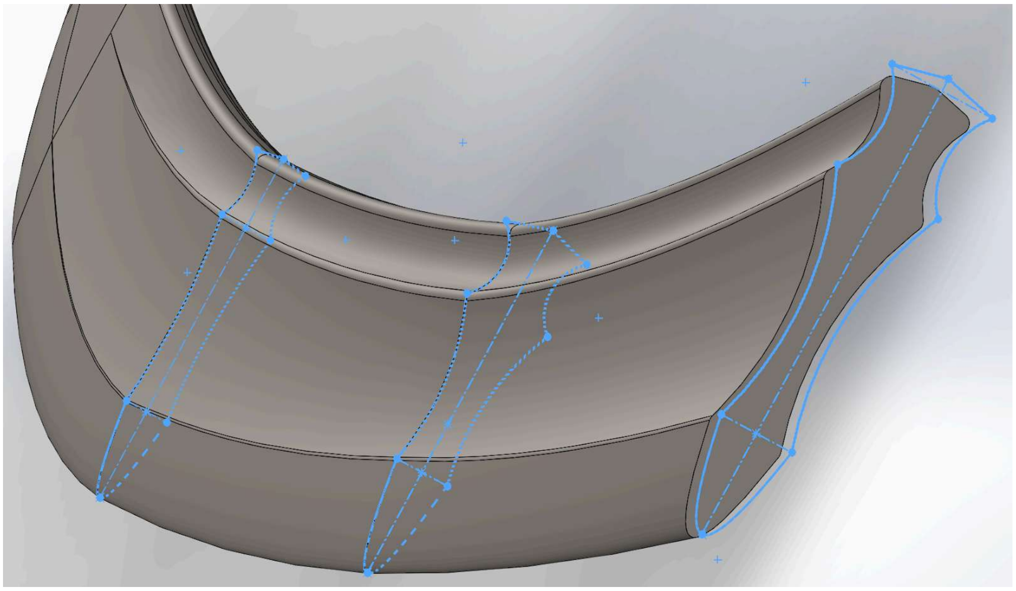


Figure 3.1.5: Example of the cross-section of the blade at different blade lengths.

Figure 3.1.6: The side profile of the blade and tang, the estimated length of the edge is 30 inches.

The rounded edge in the program and casted part provided some materials that could be removed to achieve the desired sharpness. The additional roundness to the edge made it easier in the shell making process for Aerotec, as too sharp of an edge can cause the shell to break during metal pouring. The overall length of the blade was also longer than needed for the same purpose, so that during testing if the tip gets damaged there would still be enough material to work with.

For the aesthetic design of the blade part it was decided to include some extruded text, something that is next to impossible for a traditional forging process with a hammer. The text is extruded along the fuller with uniform height to the fuller from their respective position on the sword. To continue the design theme of the sword, the left side of the sword represents the past, thus the quote there came from general Washington himself. The right side of the sword had a more modern quote, both were chosen via voting within the team.

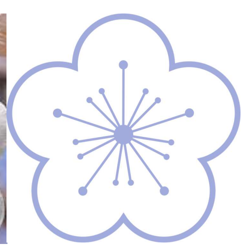
Figure 3.1.7: Left side quote along with the unique tang design.

Figure 3.1.8: Right side quote.

3.1.2 Symbols and meaning:

The team wanted to include as much of themselves and Washington in the design of the sword. In order to do so, flowers of significant cultural importance were chosen by each member with the exception of the foundry sponsor as their symbol design is not a flower. There are a total of 6 symbols on the grip, where 5 were flowers that represent each member and are special to them in some way. The connection between all of the symbols is the rose vine that would represent Washington himself, also as the national flower of the United States. From research it appeared that roses are very important to Washington. Just as Washington helped uniting the colonies and people back then, he became the connection once more for the team and the sponsor, therefore being significantly symbolic.

Aerotec Alloys:
The symbol and logo of the industrial partner, Aerotec Alloys, Inc. They played a significant role throughout the project. Aerotec provided invaluable feedback and guidance all throughout as well as allowing us to create multiple prototype designs.

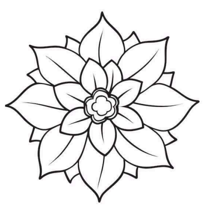


Chinese Plum Blossom (*Prunus Mei*):
The Chinese Plum Blossom that represents Team Vernon Vanguard's Design Lead, Victor Wang. The Chinese Plum blossom is the national flower of the Republic of China (ROC). The plum blossom can withstand cold temperature, symbolises faithful, resolute and holy. As the representation of the country, its meaning is something that all should strive for.


Forget-Me-Nots (*Myosotis Sylvatica*):
The forget-me-nots are the national flower of Armenia. This represents Team Vernon Vanguard's Research Specialist, Daniel Hovakimian. They represent the eternal memory of the fallen souls of the Armenian Genocide by memorializing the past, present, and future of the tragedy. This representation is significant because it is an integral piece of his culture, something that he will carry with him for the rest of his life and never forget.


Sampaguita (*Jasminum Sambac "Maid of Orleans"*):
The Sampaguita is the national flower of the Philippines. This represents Team Vernon Vanguard's Team Leader, Aprille Joie Le Baquin. This jasmine cultivar symbolizes purity, humility, and strength of the Filipino culture. It is deeply rooted in royal traditions and legends of eternal love and fidelity beyond death. Its name is believed to be derived from the phrase "sumpa kita," which means "I promise you."


Black Eyed Susan (*Rudbeckia Hirta*):
The Black-Eyed Susan, native to North America, thrives in meadows, gardens, and roadsides. This represents Team Vernon Vanguard's Video Production Lead, Christopher Ramirez. This flower symbolizes resilience, encouragement, and justice due to its hardy nature and widespread growth. It is also associated with motivation, positivity, and strength through adversity.

Marigold (*Tagetes*):
The Marigold is a flower native to Central and Southern Mexico. This represents Team Vernon Vanguard's Test Specialist, Ethan Beltran De Anda. It represents passion and strength, due to its connection to the sun. The Marigold is also used in the Mexican holiday, the Day of the Dead, to honor loved ones that have passed.

3.2 Design Selection

The final selection of the sword came down to several parts of the sword and choosing between their versions. The grip design was a combination of 3 separate designs with the final version being the highlight of all three. The final grip has the version 9.0 shape, 9.1's spiral and 9.2's vine/root design with added symbols to represent each team member.

The final version of the handguard was a modification of the version 7.0 design after the team made the decision to switch from a much simpler guard to the eagle handguard. The handguard went through several iterations and structural changes, but the design language was largely intact.

The final version of the blade was chosen between 4 different versions. Version 7.0 was the heaviest design with no fuller was about 1.2 pounds. Version 7.1 had a single fuller in the middle of the sword and was about 1.12 pounds. Version 7.2 had the same fuller design as 7.1 with another smaller fuller added and was 1.06 pounds. Version 7.3 was the lightest design, with two fullers similar to version 7.2 but deeper, thus removing more material and was 0.96 pounds. After a voting session with all team members and the industry sponsor, the chosen version 7.2 entered further development. Version 8.0 series were experimentations on how to implement the quote. Version 9.1 and 9.2 had engraving vs extrusion for the quote, the team voted for the extrusion as it is something very difficult to do with any other method beside casting. Version 9.2 is then modified into the final version with cut out fitting for the tang.

3.3 Final Design

The sword's final design was the 30th iteration of the grip, 2nd iteration of the handguard and the 10th iteration of the blade. The final grip iteration was created shortly after the decision to change the material was made. Although the grip was made relatively quickly, all the ideas and findings from previous iterations were implemented into the final design. The overall design was comfortable and allowed the user to wield the cuttoe in two different configurations, slashing and thrusting. The final weight for the grip is about 0.9 pounds for both halves.

The handguard was made by manipulating and heavily modifying an open source model of an eagle landing. The end result is the eagle with its wings swept backwards with major focus on the detail of the model. The back of the wings have 2 different US flags on each side forming a “V” shape, the area between the wings and eagle’s body was left open to create a unique window design while reducing the overall weight of the handguard. The final design weighs in at 0.4 pounds.

The blade was chosen between version 7.0, 7.1, 7.2 and 7.3. Version 7.0 of the blade was the most robust version of them all with each version being a slightly lighter version of the previous ones, with the 7.3 being the lightest version weighing in at 0.96 pounds. Along with the aesthetic design update and slight optimizations the final version, version 10.0, weighed 1.1 pound in simulation.

When assembled the final weight of the overall sword should be about 2.4 pounds plus minus 0.1 pounds. The design is about half to ¾ of a pound heavier than the historical examples of the sword, but should still be very usable when considering the center of mass placement being about 2 inches above the handguard, making it an ideal center of mass position for the cuttoe.

3.3.1 Simulations:

The simulation function that SolidWorks provided is a tremendously helpful tool that allowed the team to estimate stress points and possible points of failure. When a force greater than the yield strength is applied to a material, the material exits a stage known as the elastic stage, where the material will experience permanent deformation. In short, if a force greater than the yielding force is applied the sword will be bent and will not bounce back to its original state. For all simulation situations a scale to the right is provided, the color of the part corresponds to the color on the scale. The force in pounds (lbf) is equivalent to the weight of such force, so if a 2 pound brick is left on a table, then the table is experiencing 2 pounds of force excluding all other forces acting on it.

Situation 1 (Figure 3.3.1):

Force of 500N(112.4 lb) on the tip portion of the sword, and this is about the maximum amount of force the sword can take before permanent changes happen.

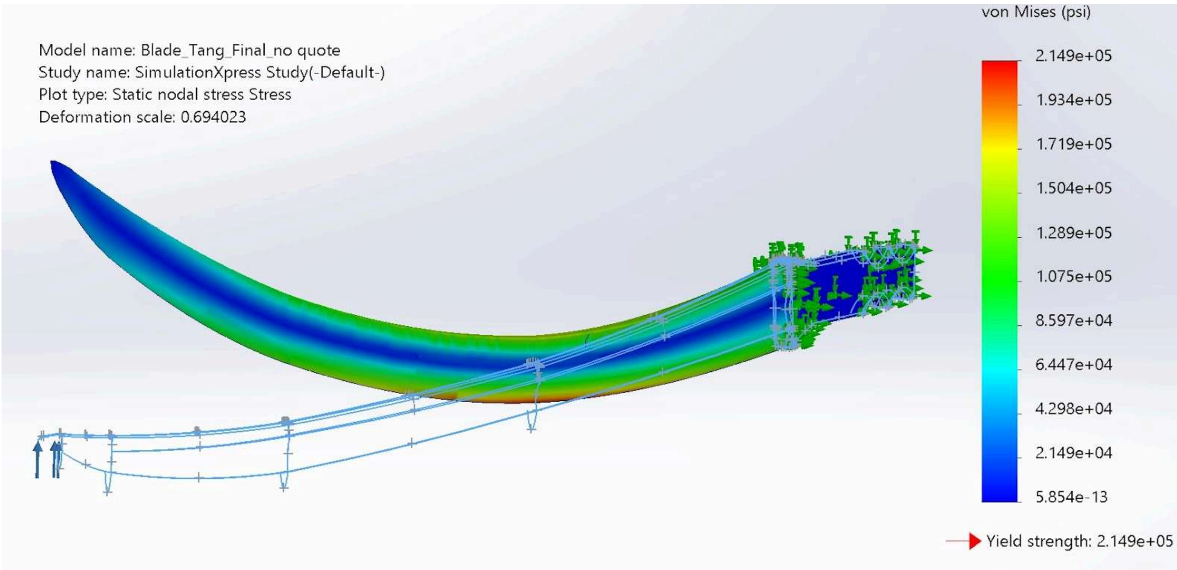


Figure 3.3.1 Situation 1

Situation 2 (Figure 3.3.2):

A force of 667N (149.9 lbf) is applied near the tip of the sword, simulating a slashing motion. According to the simulation result, the middle of the sword where the color is red will be bent permanently. In this case the maximum force the sword can sustain is 550N (123.6 lbf).

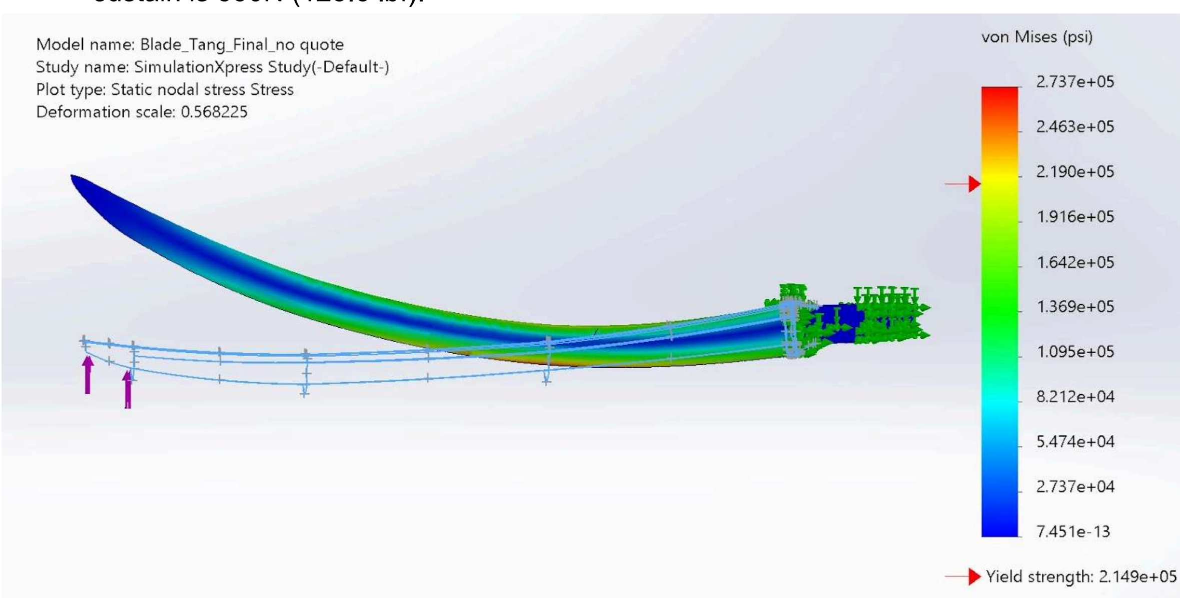


Figure 3.3.2 Situation 2

Situation 3 (Figure 3.3.3):

A force of 667N (149.9 lbf) is applied near the ⅓ portion of the sword near the tip, simulating a slashing motion. According to the simulation result, the middle of the sword where the color is red will be bent permanently. In this case the maximum of the force the sword can take is 625N (140.5 lbf).

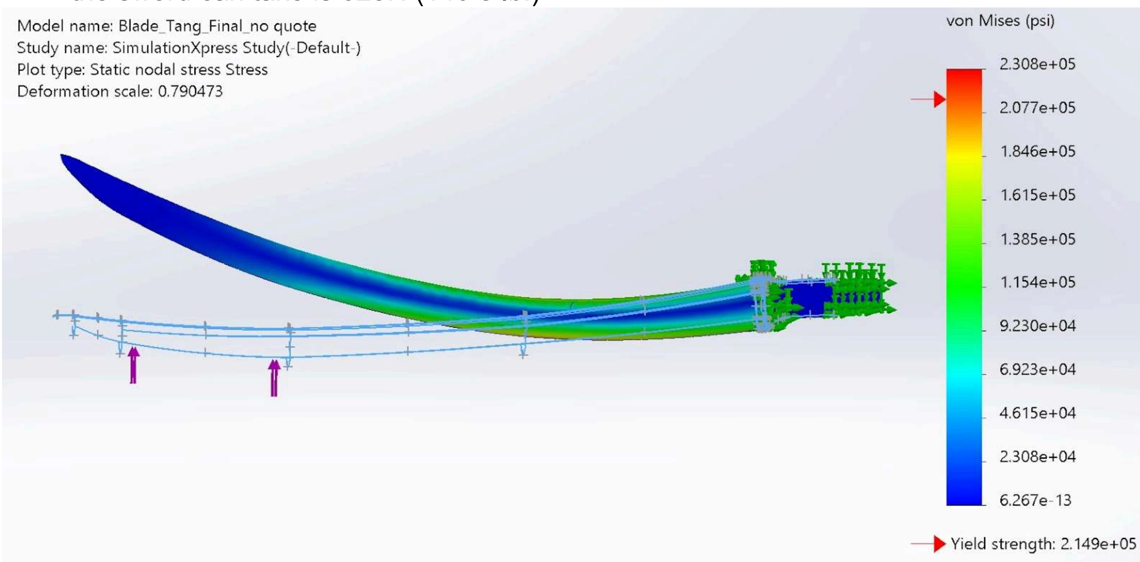


Figure 3.3.3 Situation 3

Situation 4 (Figure 3.3.4):

A force of 667N (149.9lbf) is applied at the middle portion of the sword, simulating a slashing motion. In this case the maximum of the force the sword can take is 1000N (224.8 lbf).

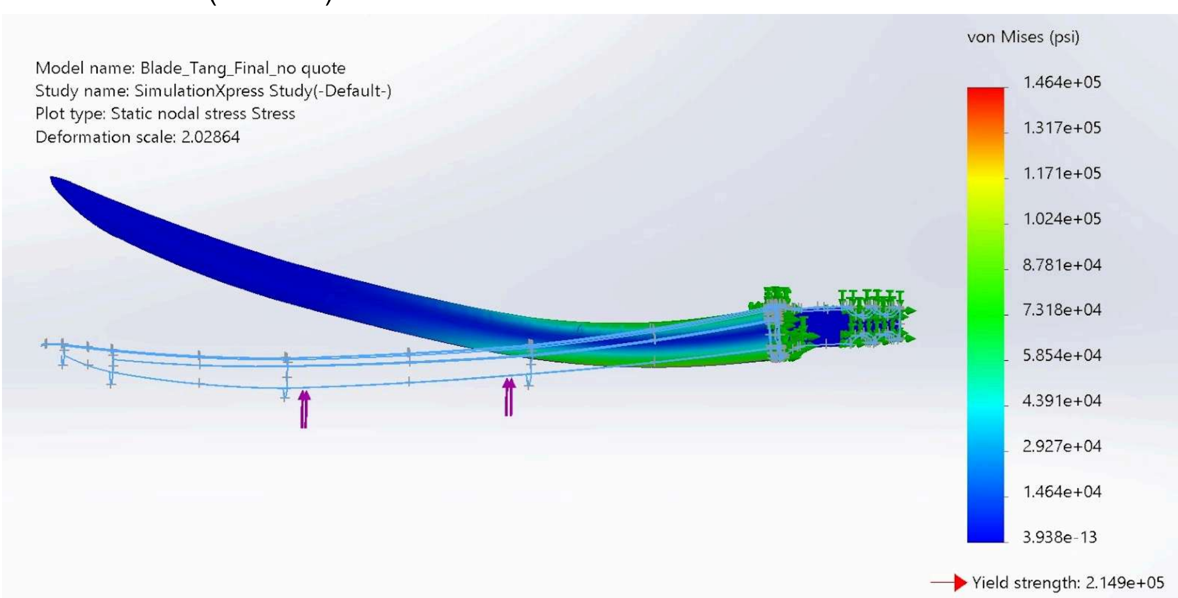


Figure 3.3.4 Situation 4

Situation 5 (Figure 3.3.5):

A force of 667N (149.9lbf) is applied at the middle portion of the sword, simulating a slashing motion. In this case the maximum of the force the sword can take is 2850N (640.7 lbf).

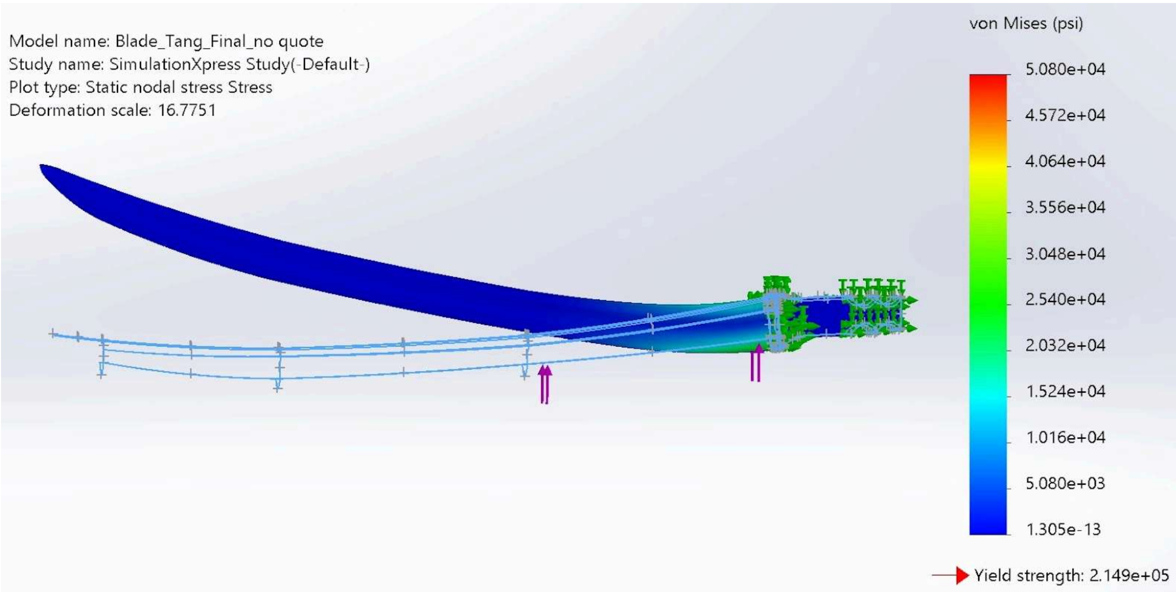


Figure 3.3.5 Situation 5

Situation 6 (Figure 3.3.6):

A force of 10000 (2248.1 lbf) is applied at the tip of the sword simulating a thrusting motion. According to the simulation the sword would've returned back to it's normal state once the force is removed from the situation.

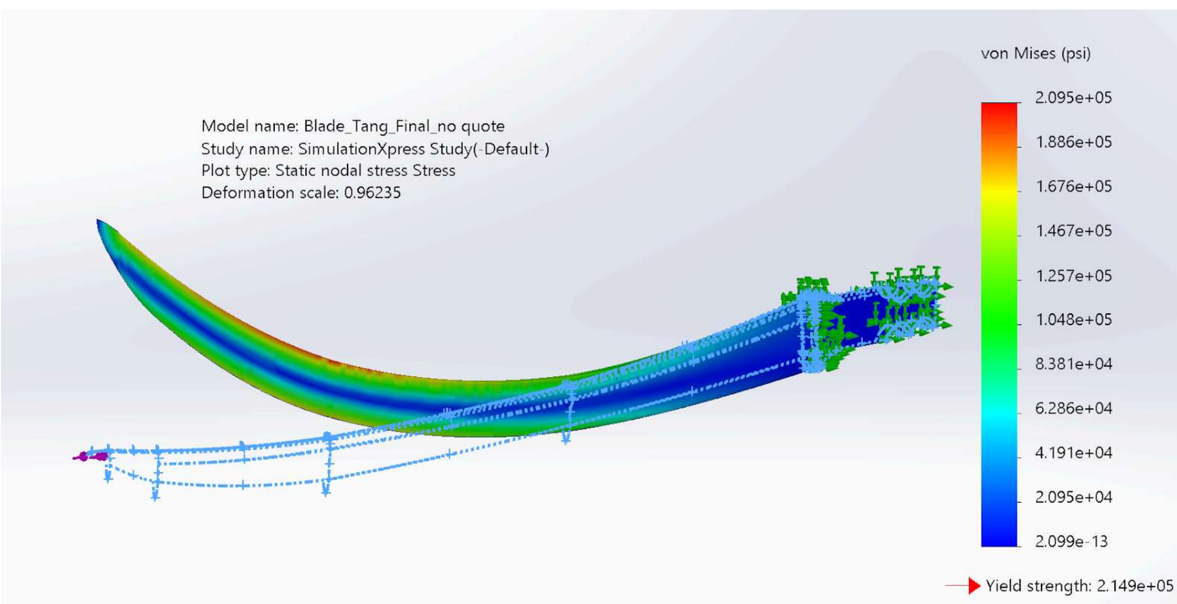
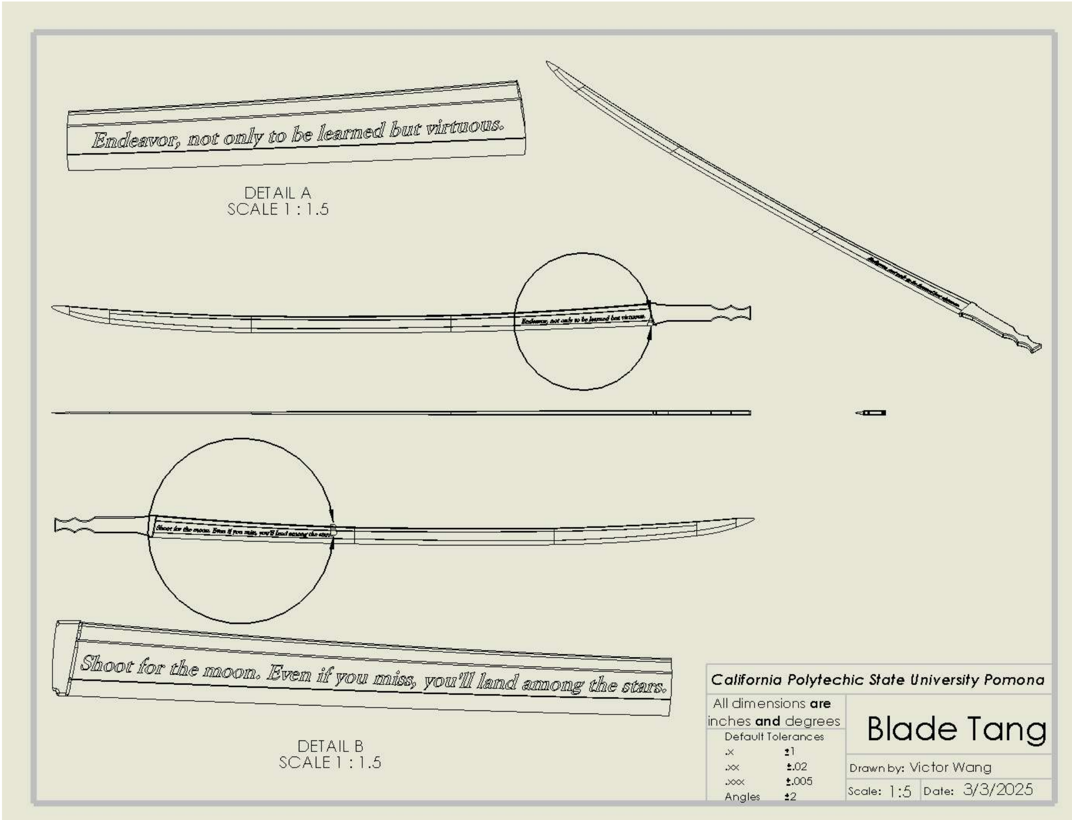
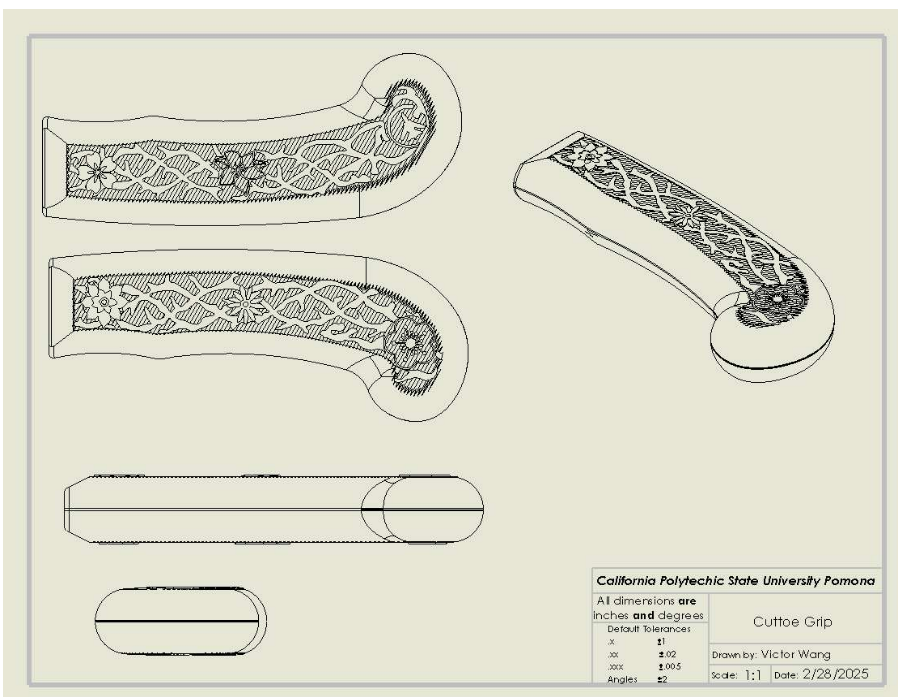


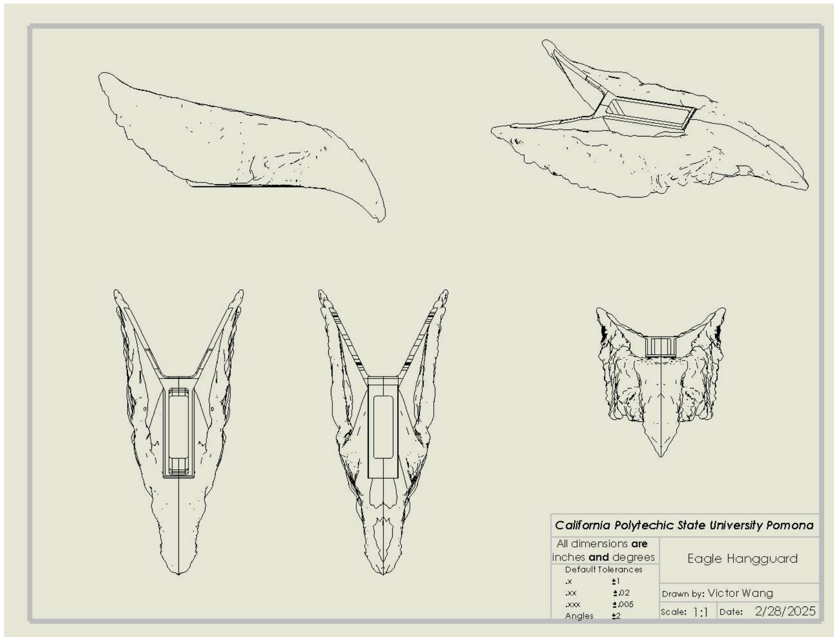
Figure 3.3.6 Situation 6



Drawing 3.3.1. Drawing of blade-tang part of the sword.



Drawing 3.3.2. Technical drawing of the grip.



Drawing 3.3.3. Technical drawing of the handguard

4. Manufacturability

4.1 Alloy Selection

Team Vernon Vanguard conducted extensive literature research and discussed the key features in selecting an optimal steel alloy for the sword. The list of potential alloys was reduced to the top three tool steel materials: A2, H11, and H13 specialty alloys.

A2 alloy is a high-carbon tool steel that is used for versatile applications, such as tooling, automotive, and aerospace. It goes through a cold-working, air-hardening process, and its chemical composition provides the highest hardness range and corrosion resistance out of the top three alloys. However, A2 alloy is brittle and least suitable for impact resistance features of a sword, which can be a challenge for metal casting and machining. Its lowest toughness range and highest hardness range does not meet the team's desired specifications.

H11 alloy is a hot work tool steel used in tooling and aerospace applications. It is known for its exceptional resistance to high-impact and thermal fatigue. This alloy undergoes annealing, air hardening, and tempering process. The lower hardness range allows slight ease in machining and metal casting compared to the A2 and H13 alloys. The high chromium and low vanadium levels of H11's chemical composition contribute to its ability to achieve higher toughness, hardenability, and high-temperature resistance. However, H11's microstructure is sensitive to heat treatment conditions, which can reduce its mechanical performance if it is not tempered correctly. To achieve a balance of hardness, toughness, and ductility, H11 alloy's optimal heat treatment process is oil quenching and double tempering at 1020 °F.

H13 alloy is another hot work tool steel used in tooling and mold-making applications. It has a similar carbon content to H11 alloy but higher chromium, molybdenum and vanadium content. This alloy has a well-balanced toughness, wear resistance, and high-temperature resistance. However, H13 can be very challenging to machine and requires additional surface treatments to improve corrosion resistance. It also has a limited welding capability.

A materials trade study and failure analysis were conducted to determine which of the three top alloys best suit the specification of the team's sword (See Figure 4.1.1). This resulted in the H11 steel alloy to be the optimal material. Although this specialty alloy is an unconventional choice to fabricate a sword, its properties makes it well-suited for the competition.

FMEA Analysis of Top 3 Steel Alloy Materials		Ranking	Reasoning
		1	Unacceptable
		2	Less preferred
# 1:	H11	3	Indifferent
# 2:	H13	4	Preferred
# 3:	A2	5	Most Preferred

Criteria	Castability	Elongation	Yield Strength	Hardness (45 - 55) HRC	Corrosion Resistant	Results
# 1:	5	3	5	5	4	**1500**
# 2:	4	4	4	4	4	**1024**
# 3:	3	4	4	4	5	**960**

Fig 4.1.1 FMEA Analysis of H11, H13, and A2 steel alloys

4.2 Manufacturing Processes

The manufacturing process for this sword is rather simple. First, the sword was designed in SolidWorks. After casting the simulation, the gating system was confirmed and finalized. Then the patterns were 3D printed using Polycast™ and sent to Aerotec Alloys for the investment casting process. Aerotec coated the print in stucco powder, then ceramic slurry to create a plaster shell; these two steps were performed several times to create the shell. Afterwards, the shell was baked in a furnace to harden the plaster and remove the 3D printed pattern, then molten metal was poured immediately in the hot mold. When it cooled the plaster was broken away, the gating system cut off, the blade was heat treated, and finally sharpened.

4.3 Prototyping

Additive manufacturing was implemented to prototype the sword patterns using three FDM printers. The grip went through a total of 30 iterations. A grip takes approximately 1 hour per pattern. Troubleshooting and printing iterations of the grip usually takes about 2 days to be fully realized and an improvement plan could be made. Several full scale swords were also printed so the team can not only visualize the design on paper and software, but in reality as well. Needless to say, without the printers, the design process would have met with more resistance.

Thanks to Aerotec Alloy's support, the team was able to design and cast a ½ scale sword for testing purposes. The ½ scale sword is based on an earlier iteration of the sword, version 4.0 blade combined with 4.0 handguard and 4.1 grip. The resulting ½ scale prototypes were then hardened, sharpened and used in various testings for the purpose of helping the team understand the material. The result of the tests greatly helped the team in designing and understanding the limitations of the material and designs.

4.4 Production Processing

Production processing involved three members of the team, 3D printing patterns *(See Fig 4.4.1)* of the blade, the handguard, and two halves of the handle. Each member handled the mass printing of different sections. After considering the limits of investment casting, the printed patterns that could be assembled efficiently.

Fig 4.4.1 3D Printed Parts

With the blade being a long and thin piece, it was found best to cast the part vertically *(See Fig 4.4.2)*. This decision was made to prevent any major warping. This orientation also allows the metal to fill and cool evenly. Gates were placed along the spine of the blade. The gates on the handguard were placed on the flats of the model to ensure cohesion with the gate pads. Regarding the grip, the model was cut in half for both assembly purposes and to make gating easier.

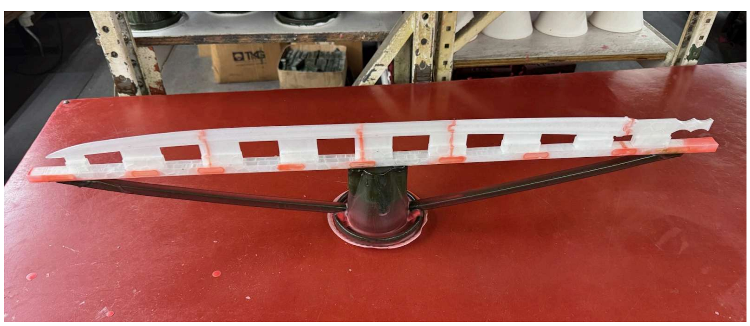


Fig 4.4.2 Gated Sword With Wax

The parts were then dipped in a ceramic slurry and fully coated *(See Fig 4.4.3)*. Once fully dried, this process will repeat for 4 coats. After that process is complete, the metal is poured in the cast at a temperature of 2610°F. The temperature was determined using the

Solidcast *(See Fig 4.4.4)* program. After the pour is finished and the blade is cooled, the blade goes through the knockout process. Once cleaned up, the blade gets sent to heat treatment.

Fig 4.4.3 Coated Sword

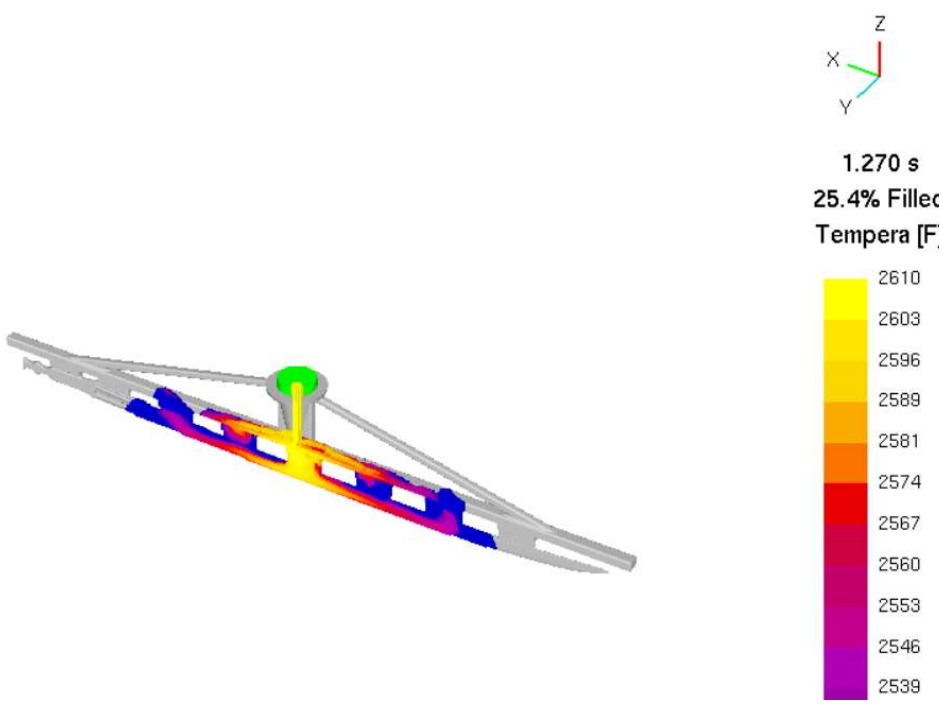


Fig 4.4.4 Solidcast Simulation

Heat treatment *(Table 4.4.1)* was conducted by Varco Heat Treating Company in Garden Grove, CA.

In total there were two cycles done with the full scale sword. The first cycle *(Table 4.4.1)* went through a full annealing process at 1600°F for 2 hours and 46 minutes, then cooled at 200°F per hour to 1000°F. After the full anneal the pieces were inspected and tested to record hardness. The second cycle *(Table 4.4.2)* followed a process of hardening at 1850°F for 2 hours and 29 minutes with a forced gas quench. Following the hardening was the tempering process at 1050°F for 4 hours and left to air cool. The tempering process was repeated 3 times and inspected for hardness.

Quantity	**Part Name/ Part Description**	
4	CAL-POLY SWORD FULL SCALE SWORD Heat Treating Specification: AMS-H-6875C	
Customer Requirements		
Hardness (HRC)	Min. -	Max. 30
Results		
Hardness (HRC)	Min. 72.5	Max. 72.5
Process Steps		
Step 1:	Process: Full Anneal	1600°F for 2 hours & 46 minutes, furnace cool 200°F per hour to 1000°F, gas fan cool
Step 2:	Process: Inspect	Test and record hardness.

Table 4.4.1: First Cycle Heat Treatment Process

Quantity	Part Name/ Part Description	
4	CAL-POLY SWORD FULL SCALE SWORD (C/S 0.250”)	
Customer Requirements		
Hardness (HRC)	Min. 50	Max. 55
Results		
Hardness (HRC)	Min. 50	Max. 51
Process Steps		
Step 1:	Process: Harden	1850°F for 2 hours & 29 minutes, forced gas quench
Step 2:	Process: Temper	1050°F for 4 hours, air cool
Step 3:	Process: Temper	1050°F for 4 hours, air cool
Step 4:	Process: Temper	1050°F for 4 hours & 1 minute, air cool
Step 5:	Process: Inspect	Test and record hardness. 100% test required

Table 4.4.2: Second Cycle Heat Treatment Process

5. Quality and Performance

5.1 Chemical Composition

Understanding the chemical composition of steel alloys is crucial to selecting the optimal material for the sword. The table in Figure 5.1.1 displays the chemical makeup of the H11 steel alloy. It has a moderate carbon level which is well-balanced between hardness and toughness. The increased levels of chromium contribute to its ability to withstand wear and tear and improved corrosion resistance. The formation of carbide particles will hinder the dislocation movement of H11’s primary structure, increasing its strength. There is a significant level of Molybdenum which enhances the alloy’s hardenability and resistance to thermal fatigue in high-temperature settings.

Steel Alloy	Requirement	C	Mn	Si	Cr	Mo	V	Ni	Cu	P	S
H11	Min. %	0.33	0.20	0.80	4.75	1.10	0.30	-	-	-	-
	Max. %	0.43	0.60	1.25	5.50	1.60	0.60	0.30	0.25	0.03	0.03

Fig 5.1.1 Chemical Composition of H11 Steel Alloy. Table referenced from ASTM A681-08.

5.2 Inspection and Testing

The ½ -scale sword was inspected and sharpened once by the industry partner and performance testings were conducted at Aerotec Alloys under supervision of the Director of Engineering. The tests included a slashing test against pool noodle, and a structural test against 3D printed parts, 2” x 2” wood, aluminum bar, sheet metal for metal shelving. Upon analyzing the test results and observing the structure of the sword, it was determined to withstand high impact tests. However, the sharpness against pool noodle did not perform well. The sword blade was observed to bounce back and did not execute a clean cut into the noodle. The blade maintained its edge against different types of metal and no major damage was seen. The observed damage was slight edge and tip deformation. The spine of the sword was bent slightly to the right along the ⅔ of the length from the grip.

A second round of performance testing was conducted after being sharpened with a belt grinder and a 1000-grit wet stone. A slicing test was performed using a pool noodle and plastic water bottles hanging from a tree branch. A 2” x 4” wooden block and ¾ inch anchor bolt used for concrete foundation were used for the slashing test. Another wooden block was used to strike the sword into a larger wooden beam, resulting in splitting of the large wooden beam. The sword was observed to have spine deformation from striking it but no damage on the blade. Some edge deformation was observed upon impact of the anchor bolt. However, the sword had no other observable chipping or other noticeable damage.

The ½ scale sword was sharpened again for a third round of performance testing. A red cabbage, iceberg lettuce, and watermelon were used to observe the quality of the sword’s slicing ability. All food items had a clean cut and the team members noted little to no resistance of the sword. During the slashing test against baking pans, the blade edges had observable rolling effect after the test.

6. Final Product

6.1 Basic Requirements and Uniqueness

The SFSA Cast In Steel competition tasked each team to cast a sword that George Washington would have used during his military career. Each team was responsible for designing the blade and reaching out to an industry partner to cast the blade. Afterwards, the team will write a technical report detailing the process to get to this point, and film a team video that shows off their weapon.

The blade should be cast in a steel alloy, given the name of the competition. The sword must not weigh more than 2 kg (4.4 lbs) nor should it exceed 1.09 m (43 in) in overall length. If the team chooses to cast a replica sword, the blade must either be a single edged replica that matches the tolerance of the original sword within 2 inches. If not, then the team will have to design an original sword that would be appropriate in style and function to George Washington's needs. The technical report must not exceed thirty pages, and the project video must highlight the sword, the design process, and whatever else the team feels contributed to its creation. A weighted score will be used to judge each sword: design and process (25%), George Washington sword authenticity (15%), casting (25%), video (10%), and performance (25%).

With the basic performance requirements addressed, unique aspects can be brought up. The sword needed that *something*, the detail that draws the eye and holds it. The chosen aesthetic designs radiate this with each team member's personal vision made material with the advancements made in investment casting. Every detail stitches together the theme of tying together the past and present.The eye is first drawn to the guard, the majestic bald eagle. An iconic symbol of America that dates back over two centuries fits perfectly for a weapon that is going to be wielded by one of the first true Americans to exist. Behind the wings of the national bird are two flags, both American. On the left is the flag from the revolution, 13 stars in a circle representing the 13 colonies. On the right is the modern flag, 50 stars and all. This ties back into the aesthetic vision, to gaze on one side of history one must reflect on the other. By utilizing investment casting there will be an unmatched attention to detail, down to each individual star so that no state or colony is left behind.

The guard catches the eye first, but the grip is where the attention is captivated. This is where the culmination of the team's culture and ideals truly comes to fruition. With investment casting details down to a fingerprint are possible to cast, and the team capitalized on this to bring their individuality to reality. Cast onto each side is a flower representing each team member, Aerotec Alloy's logo, and vines connecting it all together. Realistically, the grip is where the team had the biggest opportunity to express themselves, and they did not disappoint. The thin details here are the product of ancient culture and modern craft coming together to bring out who each member is into a real, tangible thing that can be held. Culture does not define a person, but represents a large part of them, from their looks, religion, food, clothes, it all boils down to where they came from. Each member utilized these parts of themselves to find a floral aspect that represented who they were not only culturally but for their individuality. Looking at the choices made, each member chose wonderfully, and Aerotec Alloys did a perfect job to capture every detail that was modeled.

Lastly is the blade itself, which has a special feature made possible with investment casting: quotes. Carving into a blade cuts out material, damaging it and creating stress points that can shatter the blade. With investment casting, the team was able to have full length sentences cast into the blade, and have each letter be perfectly legible. The team chose an original quote from themselves and one from George Washington himself. For the team, they chose: "Shoot for the moon, even if you miss, you'll land amongst the stars." They chose this quote because it describes their situation perfectly. This is a national competition with very serious competitors, there is no guarantee that they will win, but that doesn't matter. The team was able to go beyond the textbook knowledge from their courses and into the industry-the real world. Even if they don't win the competition they will have something even greater: experience. For Washington, his quote was: "Endeavor not only to be learned, but virtuous." This line embodies everything Washington stood for and how he wants others to behave in the country he is fighting to create. An educated person can make the correct choices not only for themselves, but for others around them. But what good is it without kindness? By making the correct choices backed by knowledge and compassion, the most good can be attained as a result.

7. Improvements

After reviewing the overall design and manufacturing processes of the sword, Team Vernon Vanguard highlighted improvements that can be implemented to the future of the project. One improvement discussed was focusing more attention to the aesthetic details of the symbol designs of the sword's grip. Drafting additional iterations will provide various ideas that display the level of cohesion to unify the designs smoothly.

Another improvement is a river design that was originally planned to be placed on the rear side of the handguard. Due to time constraints, the team opted to omit the river design. With improved time management skills, the design subteam can draft multiple iterations of the river designs to determine its proper placement on the sword.

There was a noticeable split in 6 out of 8 blade patterns that were observed in several ceramic shell molds and metal castings. In future projects, the team must verify that the 3D printed patterns are completely sealed prior to the wax gating and ceramic shell coating processes. During the blade sharpening of the final sword, the blade edge was observed to curl on the opposite side of the sharpened edge. The team was not aware until experiencing this circumstance. In future projects that involve a sharpened edge, the team must research the material's ability to be sharpened.

8. Conclusion

Team Vernon Vanguard consists solely of students progressing through their undergraduate degree who are using it as a learning experience first and foremost. This competition allowed every member to turn their book academics into practical knowledge, to see how products are manufactured in their entirety. The team rose to the occasion every step of the way to prove they have what it takes to make it in the industry. They designed the sword, modeled it in CAD, successfully partnered with a foundry to cast it, heat treated it, sharpened it, and sent it to Atlanta for the competition as a successful cast. They did it all with help from each other and contacts they networked while participating in the competition. This task was far from easy, but that didn't matter to them no, what mattered was the experience, the knowledge, that was the goal. It doesn't matter who wins the competition or not, but who stands there. Team Vernon Vanguard is there because they proved they have the drive to conquer whatever roadblock dares stand before them.

9. Acknowledgements

We would like to express our gratitude to Dr. Victor Okhuysen for his unconditional support, which ensured the successful completion of our project. We are deeply grateful to our industry partner, Javier and the Aerotec Alloys team for their expert guidance throughout the design and manufacturing processes of our team project. We also appreciate their generosity in allowing us to use their facilities to manufacture our sword. We extend our thanks to our Subject Matter Experts, Dariush “Dar” Izadi and Alvarado “AJ” Mendoza from Precision Castparts Corporation, for sharing their engineering expertise which has helped us build a comprehensive understanding of the steel alloy materials, heat treatment processes, and materials testing process. We would also like to thank David Seo from Precision Castparts Corporation for his guidance in data analysis. Special thanks to Dr. Placensia for his valuable feedback on the grip design, which was instrumental in implementing human ergonomics and unique design elements. We appreciate Matthew Parker for hosting a blade sharpening workshop and teaching us proper sharpening techniques. We thank Wesley Tarr, a highly talented graphics and prop designer, for his valuable feedback that contributed to the cohesive design of our sword. We would like to express our warm thanks to Johnny Sousa from Johnny’s Art of Sharp for his blade sharpening services and enthusiastic support for our team.

We are eternally grateful for the time everyone has taken out of their busy schedules to mentor us in our project for the SFSA Cast in Steel 2025 Competition in Atlanta, Georgia. This experience has provided us with invaluable educational and industrial insight, significantly contributing to preparing our future professional engineering careers.

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