SFSA Cast in Steel 2025 - George Washington's Sword Technical Report

University of Dayton - Sword Team 6

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Executive Summary

The process began with the team doing historical research on George Washington swords. Taking note of common design decisions and also the uses Washington had for his swords. Washington occasionally used his swords on the battlefield but for the most part, he wore them on his hip for show and more as a symbol than a tool. Even with that in mind, the swords were still expertly crafted and effective when needed. The team created a cuttoe style sword, a common style amongst Washington's collections, which was required for the SFSA Cast in Steel competition. For the pommel, the team decided on using an eagle head design inspired by Washington's "Silver Lion Headed Cuttoe" which had a lion head. This change was driven by the team's desire to put a unique and personal spin on the sword and was one of the first decisions made. The eagle being a symbol of America made for an easily recognizable choice that relates to Washington's essential role in the founding of America. As for the handle, the Silver Lion Headed Cuttoe was again used as inspiration for the team's design but with another personal twist. A wooden handle was decided on, mimicking the appearance of the lion headed sword (which used animal bone), but cherry wood was used instead as a subtle reference to the cherry tree myth associated with George Washington. The handle was stained with the goal of bringing out the red in the cherry wood. Grooves were also etched into the handle, much like many of Washington's swords, with silver wire wrapped around the handle. The guard features a similar S-shaped guard which was designed mimicking the Silver Lion sword. Putting these pieces together along with the cuttoe style blade that the team crafted, the final result is a sword accurate to a lightweight cuttoe that George Washington would have worn and wielded.

The team's design process began with research not only of George Washington swords but also basic bladesmithing. The shape and lengths of Washington's swords were analyzed using solidworks to get general ideas for dimensioning of the team's blade. This provided a sense of reasonable dimensions which guided the design. Cross sections of the blade with various thicknesses and width were created and 3D printed to get a better look at the physical sizing rather than on a screen. This revealed just how small our initial blade design was which was promptly corrected. Once the team got an idea for cross section dimensions, those cross sections were extruded with a curve added to achieve the cuttoe style. The team continued with the 3D printing process to take advantage of the Skuld's AMEC casting process. This involved four different sections, due to the height restriction of the 3D printer, that were "glued" together using a 3D printing pen. Machined foam was also tested for initial casting. After receiving a blade in cast iron as a test, the team realized the current design was too thin to be casted either from foam or 3D print. After some design changes and more attempts at casting, it was determined that casting the blade was not an option considering the time that was remaining. The team eventually decided to order billets of 4140 steel and machine the blade on a manual mill instead. Three different blades were manufactured each with different thicknesses. After putting each blade through heat treatment to achieve a target hardness of 48 and 52 HRC, the thinnest of the three blades was deemed the best option after testing.

The final product is made of 4140 steel, is 34in. in long (28in. blade), and weighs 1.55lbs.

TABLE OF CONTENTS:

Executive Summary 1
1. INTRODUCTION 3
2. RESEARCH: 3
2.1 Historical Blade Design 3
2.2 Manufacturing Techniques 4
2.3 Materials 4
3. DESIGN: 5
3.1 Mechanical Design 5
3.2 Material Selection 6
4. BLADE MANUFACTURING: 7
4.1 Casting the Blade 7
4.1.1 CAD / 3D Printing 7
4.1.2 Brackets / Welding 8
4.1.3 Casting (Failures) 8
4.2 Machining the Blade 11
4.2.1 Planing the Billets 11
4.2.2 Band Saw Blade Shape 11
4.2.3 Belt Sand Bevel Edges 12
4.2.4 Mill Fuller 12
4.2.5 Pre-Heat Treat Sanding 13
4.2.6 Heat Treat 13
4.2.7 Post-Heat Treat Sanding 15
4.2.8 Blade Sharpening 15
5. HANDLE CREATION 16
5.1 Design Inspiration 16
5.2 Process Testing 16
5.3 Final Design 17
6. GUARD + POMMEL CREATION 18
6.1 Guard + Pommel Design 18
6.2 Guard Casting 18
6.3 Guard Machining 19
7. FINAL ASSEMBLY 21
7.1 Preparing for Assembly 21
7.1.1 Handle Burning 21
7.1.2 Clamping 21
7.1.3 Epoxy 21
7.2 Assembly 21
7.2.1 Tang Peening 21
7.2.2 Epoxy Filling 22
8. TESTING 22
8.1 Strength Testing 22
8.2 Sharpness Testing 23
9. FINAL SWORD MODELS 24
10. SOURCES 25

1. INTRODUCTION

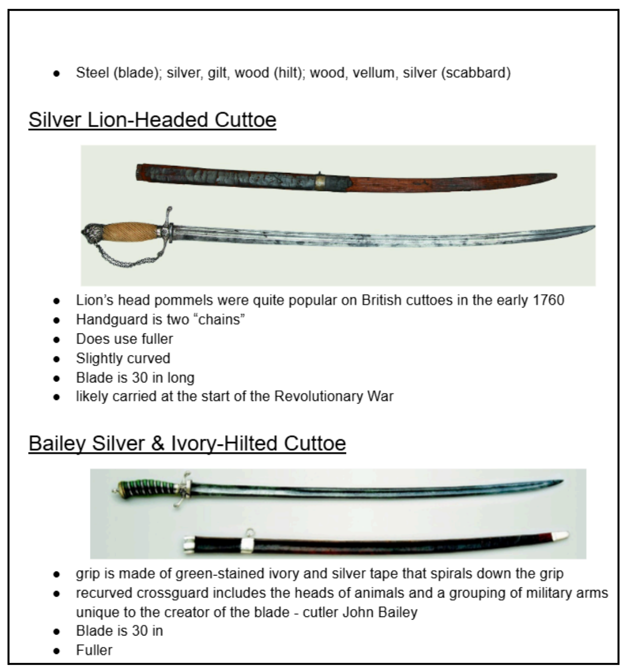
Our team was partnered with Skuld LLC for a senior capstone project for the University of Dayton beginning in August of 2024. Our primary objective for our capstone project was participation in the Cast in Steel 2025 competition. SFSA has created this competition to encourage students to learn about making steel products using the casting process and applying the latest technology available. Since no members of our team have had prior experience with bladesmithing, a significant portion of this upfront commitment was spent learning about the process of blade making, both through online research and talking with bladesmiths. From there, we were able to design a proper blade and make it with Skuld in the university's metal shop in the Makerspace.

2. RESEARCH:

Research conducted for this project can be broken down into three categories:. historical blade design, modern manufacturing techniques, and materials. The reason for this was so that the team could be well versed on the aspects of not only Washington's swords and preferences, but also to get a better understanding of how to make one of the blades today and what steels would make for a good blade.

2.1 Historical Blade Design

Before making any decisions on how the sword should look, it is important to start with a strong foundation on what details were important on historical swords owned by George Washingtion. Mount Vernon documents some of his most important swords on their website. It was from here the team created a document detailing all design decisions from each sword in this collection (shown in part in Figure 1). From this list of design decisions, common aspects amongst the swords could be picked out and provide insight on George Washington's preferences and what details mattered to him. This also gave ideas for what different directions the design of the sword could go into and what should be considered. From this information, it was decided to use a decorative wire wrap in the handle, and also create a similar s-curved guard and pommel. By doing this, we were able to make a design that would fit right in with the swords that Washington would typically carry, borrowing elements from many of his own swords, making it a historically accurate (yet unique) design. More detail on the design specifics can be found in the handle and guard/pommel design sections later.



- Steel (blade); silver, gilt, wood (hilt); wood, vellum, silver (scabbard)

Silver Lion-Headed Cuttoe

- Lion's head pommels were quite popular on British cuttoes in the early 1760
- Handguard is two "chains"
- Does use fuller
- Slightly curved
- Blade is 30 in long
- likely carried at the start of the Revolutionary War

Bailey Silver & Ivory-Hilted Cuttoe

- grip is made of green-stained ivory and silver tape that spirals down the grip
- recurved crossguard includes the heads of animals and a grouping of military arms unique to the creator of the blade - cutler John Bailey
- Blade is 30 in
- Fuller

Figure 1: Sword comparison document

2.2 Manufacturing Techniques

Skuld specializes in a form of lost casting called additive manufacturing evaporative casting (AMEC). This form of lost casting uses a 3D printed part created with natural PLA (no coloring or additives) filament on an FDM printer. The process involves coating the part in a thin ceramic coating to hold shape. During casting, the hollow natural PLA part evaporates and doesn't leave contaminants, resulting in a cast of the same geometry. To remove the vaporized PLA, this entire process occurs in a sealed system, where the PLA gases are vacuumed out through the porous ceramic coating. Additionally, Skuld is well experienced with lost foam casting (LFC) so a discussion was warranted before choosing which process to move forward with. That discussion showed the team that using AMEC could allow for tighter tolerancing and the ability to cast more complex shapes when compared to LFC. An in-person trip was taken to Skuld to look at physical samples. This helped the team get a better idea of the quality that AMEC can produce as well as its limitations. The difficulty is with getting a successful 3D-printed part with no infill, making large or flat surfaces more challenging than LFC. The cast also has a limitation on how thin the part can be for the molten metal to fill the mold completely. Ultimately since UD's cnc mill was under maintenance, AMEC was pursued for casting the blade, guard, and pommel.

Figure 2: Skuld Casting capabilities

2.3 Materials

The team began doing initial research on quality steel alloys for sword blades - specifically through a few different reputable sources, including classmate Luke Terry (Forged in Fire competitor and owner of Cave Troll Forge Co.) and blacksmith Alec Steele (runs website, sales, and YouTube channel with guidance for blacksmithing at home). Luke Terry's direct recommendation was a simple carbon steel - to choose somewhere around 0.6 - 0.75% carbon. The reasoning here was to effectively balance a good "spring" within the blade (typically associated with lower carbon) while having effective strength and rigidity within the blade (typically associated with a higher carbon steel) (Terry, Interview). Additional research, specifically Alec Steele's page on material selection, lists a number of potential steel alloys - 15n20, 4140, 4340, and a few others. Most importantly to our team, however, he also recommended both 1045 and 1080. With each alloy, Alec gives a brief description of what applications would be best for such - such as 1045 would be good for a hammer (more malleable, easier to work with and can suffer damage / deformation without compromising the functionality of the hammer). The other alloys, Alec cites, are better for use for tooling, drifts, etc… components that typically will need less flexibility or alloys that are harder to work with for heat treating. Here is where Alec's initial recommendation is 1080 - a simple, forgiving alloy that is good for beginners (referring to blacksmithing here) while still providing high performance levels. (Steele)

Regarding our industry partner, Skuld LLC, and their recent developments in Lost Foam / AMEC casting, there are a limited number of alloys that have already been successfully cast using either of these processes (for example, titanium and magnesium react very poorly and have caused explosions during testing). Skuld has expressed openness to testing new / different alloys apart from their current selection, however, given logistical challenges (ie, timeline to actually produce the sword and Skuld recently moving their operations so their furnaces are just recently back up and running), there simply would be little time to run tests on any new alloys. Should the tests fail, the team would lose a significant amount of time, potentially jeopardizing the project given the shortened time to pivot and find a new material for the blade. Different alloys and their potential success can be seen in Figure 3:

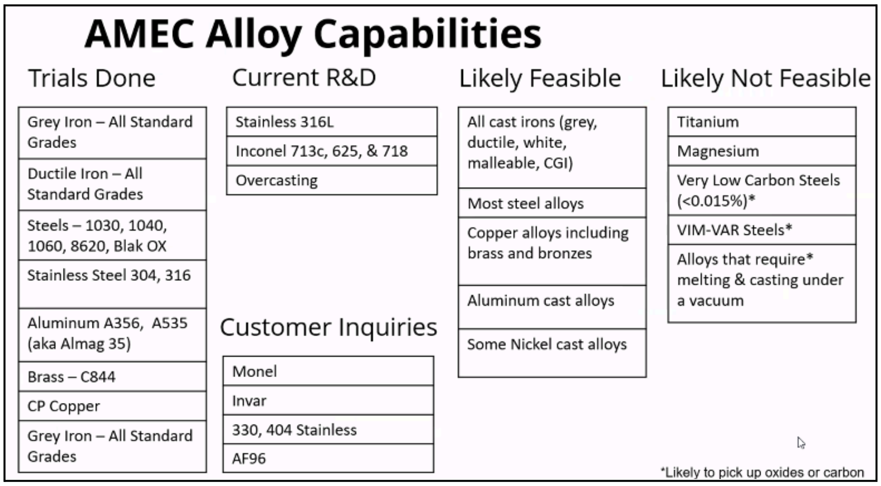


Figure 3: Skuld AMEC material capabilities chart

3. DESIGN:

The initial goal was to completely cast the sword, both blade and handguard. This was attempted by using Skuld's AMEC (additive manufacturing) process. Which was accomplished by 3D printing one-layer thick shells of the blade profile in the Makerspace lab at UD. Also attempted were machined foam profiles by Skuld to see which would have better casting quality.

3.1 Mechanical Design

To help create a balanced sword, we took typical dimensions of all of George Washington's swords to be used as constraints, and optimized the dimensions to minimize the moment of inertia while having the center of gravity approximately 2.5" up the blade from the end of the guard. These dimensions, with some potential modifications to be made to improve the casting process, are giving us a cuttoe design with a total length (end to end) of about 33".

Given the sword needs to function in a variety of tests and withstand impact testing while holding its shape, the sword cannot simply rely on material properties - it also needs to be mechanically designed to withstand slashing, bending, and stabbing. Given the slight bend of the cuttoe, most stabbing motions would also produce a bending in the blade - which means most of the functionality needs to focus on minimizing the bending of the blade (or, at the very least, minimizing the maximum stresses on the blade during impact). For this, the cross sectional area was designed with the intention of spreading the mass out towards the edges of the blade so as to add more mechanical strength against the stresses associated with bending (similar to the design of an I-beam, locating most of the mass away from the neutral axis of bending and thus increasing the total load the beam can handle while minimizing the weight of the structure).

To clarify this, the team spent time researching virtually what traditional sword cross-sectional areas were and how that shape could change the functionality of the blade. The team chose a flattened diamond profile to maximize the potential bending strength while maintaining adequate strength for thrusting and edge retainment. (SBG Forum) Given the contest requirement and historical aspect of the sword, one side is rounded to create a smooth back-edge while still retaining mass towards the edges of the blade. The other edge is profiled to be the cutting edge, with a blade angle of between 20 and 30 degrees (as recommended by a classmate Luke Terry, a Mechanical Engineering Technology major, blacksmith at home, and featured on Forged in Fire). To reduce weight, mass around the neutral axis was taken out by adding a fuller to each side of the blade (also adding accuracy to the original cuttoe design).

To maximize the stress that can be handled by the blade while operating within these parameters, the team developed a second MatLab based code structured to maximize the length of the flat (ie, the width of the fuller) in order to prioritize mass located closer to the edges. It also serves to distribute the mass of the cross-section to set the neutral axis of the blade closer to the cutting edge (not the back-edge) as research done by our team demonstrated better performing blades tend to have a center of mass (ie, location of the neutral axis) that lies closer to the cutting edge. Based on the research from the forum, our team decided on the blade shape shown in figure 4. Then, the dimensioning of this was optimized by our MatLab code which is used for our current blade design. After discussion with our industry partner Skuld, given the length of the blade compared to the thickness, Skuld expressed concerns for only pouring from one end and expecting the steel to fill in the whole blade shape. Given these concerns, the team has discussed simplifying the back of the blade to a flat, rectangular edge, which would allow inlets to be mounted directly along the length of the blade spine and easily be removed, while retaining the shape of the back end of the blade. Then, the back end can be ground out to a circular shape and rounded to create a fine finish for a back-end of the blade.

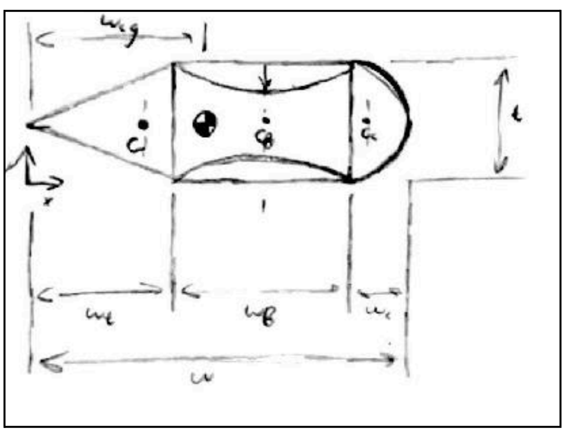


Figure 4: Blade cross section sketch

3.2 Material Selection

Given the limitations on material selection based on our method of casting mixed with the high reviews and recommendations for simple carbon steels from different reputable sources, our team met with Dr. Robert Lowe (Associate Professor at the University of Dayton, engineering materials professional) to discuss the material selection. As he recommended given the constraints, timeline, and high performance of low-carbon materials for swords, our team selected 1060 as our alloy. (Lowe, Interview) While 1060 doesn't necessarily match the recommendations of Alec Steele, it is the closest material Skuld is known to cast to his recommendations and a variety of other sources also recommend 1060 (Sword Buyers Guide and Strongblade). 1060 steel is also a simple carbon steel that has been used widely in swords, and has more than enough strength to endure impact while maintaining a good edge (assuming a proper heat treat). The team had full confidence in 1060's success in casting a blade that would be effective.

However, given Skuld's recent move to Piqua and the timeline shift of casting in January, Skuld had a number of other clients they were simultaneously dealing with. As they explained to the team, because of the low rate of casts they could do, fitting a 1060 cast in would be difficult - however, another alloy could work well - 4140. They also informed the team they would be casting 4340, and that the team could choose. After evaluating the high risk of cracking that 4340 had (and recognizing the team would need to vacuum heat treat the blades to reduce risk of cracking) the team chose 4140. However, Skuld had recent developments which meant they would only be casting 4340. As a result, the team was forced to choose 4340 as the alloy for the blades.

4. BLADE MANUFACTURING:

4.1 Casting the Blade

4.1.1 CAD / 3D Printing

CAD models of the blade were created using Solidworks, exported as .STL files, and sliced on Bambu Studio. In order for the 3D printed parts to be used in AMEC, the part must have a 1 layer thickness and no infill. The minimum amount of top/bottom layers needed for a successful print was found through trial and error. This was done to minimize the amount of filament the cast would need to vaporize and increase chances at a successful cast. As mentioned before, natural PLA is necessary to not leave any contaminates after it is vaporized. All prints were done on a Bambulab X1 Carbon at the University of Dayton Makerspace.

The printers available were not large enough to print the blade in one section, so it was split into four different segments. These segments were all printed with 1 layer wall thickness and zero infill, printed vertically off the bed. Shown in Figure 5 is the beginning of one batch of printed blade sections.

Figure 5: Initial 3D print of blade sections

4.1.2 Brackets / Welding

After blades were printed in four sections, they needed to be aligned and "welded" together. The alignment was done by printing brackets for each section of the blade, which supported both pieces to be attached and were designed to clamp securely into a vice. The clamps were designed as essentially a negative of the sword design, allowing for a tight clamp without deforming the single layer thick blade walls. Six Sets of clamps were designed, two sets for each of the three cuts along the blade. Figure 6 shows the final weld being completed on a printed sword.

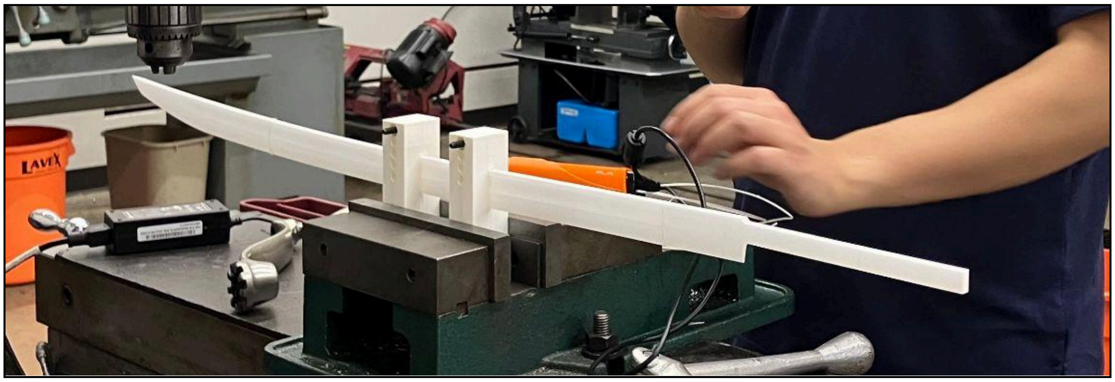


Figure 6: Welding of blade sections

After sections were aligned, a 3d printing pen (which extrudes PLA filament) was used to seal the seam between blade sections.

4.1.3 Casting (Failures)

The first attempt at casting blades came in late January - which occurred around the initial design pivot to the Mk. 3 design. The team had 3d printed and welded a Mk. 2 model at this point and had delivered this to Skuld for the first test. Talking with the partner company, they had a limited number of flask sizes, all of which could only fit one sword to be cast horizontally per pour. The team wanted to investigate if a blade could cast vertically, which could increase the number of parts per cast. To test the feasibility of this, the team asked Skuld to cast the Mk. 2 blade vertically with a ductile iron cast. The cast came out as a single solid piece but failed given sand had burnt onto the surface and that not enough material was holding the mold in place (so an overcast occurred). This can be seen in Figure 7, a picture of the tip of the blade:

Figure 7: Initial casting result

The team determined this as a relative success given the failures were not determined to be as a result of the vertical casting itself. This would mean Skuld could cast more blades per cast in future attempts, casting many additional blades vertically in the same pour.

4.1.4 The Second Cast

The second cast occurred in early February and featured 3 vertical blades and a horizontal blade in the original mold. All blades in this cast were using foam blades machined by Skuld. The cast itself was 4340 steel and the Mk. 2 blade. The result of the cast was poor - it is reported that immediately after pouring a loud boom was heard - which was associated with wet ceramic on another part in the same pour. This shockwave deformed the horizontal cast which later caused cracking in the horizontal blade. The vertical blades had issues with high porosity and large gas bubbles struggling to escape, casting incomplete blades. The high porosity is thought to be a result of the steam explosion, while the incomplete cast has been determined to be a result of how thin the part was (meaning more difficult to cast). The cast results can be seen below:

Figure 8: Second cast failure in gating

Figure 9: Second cast failure (all three)

4.1.5 The Third Cast

The third cast followed suit, featuring 3 PLA blades used for the mold of a 4340 cast. This occurred in mid-February. At the time of casting the cause of the large gas bubbles was unknown (given too many variables last cast could have caused them). As a result, the group moved forward with casting the same blade but eliminating the wet plaster as a potential root cause. This cast resulted in similar issues as the last: large gas bubbles were failing to escape quickly enough from the molten metal, which is associated with the cast cooling too fast to complete itself. Regarding the design, this meant the blades themselves were too thin to successfully cast.

Figure 10: Third casting fails

4.1.6 The Fourth Cast

After the third cast, the team investigated a number of other details that could affect the cast such as flow rate in (confirming gating was successfully secured against the mold). The team also quickly moved to change the design and decreased the fuller depth to increase the likelihood of a successful cast. The team was producing the updated 3D printed model but unfortunately the time frame to get these prepped for cast was too short for this. As a result, the Mk. 3 model was used for this rather than the Mk. 4 (increased fuller thickness) as an attempt to get a successful blade cast. This cast also occurred in mid February and was 4340 steel. Six Mk. 3 blades (Similar to Mk. 2, but about ½ in less wide) were included in this cast. As a result of the use of old thin blades, the casts were unsuccessful and once again had numerous large, unescaped gas bubbles. The gating also overcast on one of the two sets of blades. This cast can be seen to the right.

Figure 11: Fourth casting fails

4.2 Machining the Blade

4.2.1 Planing the Billets

When meeting with the partner company to review the fourth cast and the failed parts, the team's partner company recognized the difficulty in casting such a long and thin part and realized that the time and effort to produce such a part would be outside of the potential time frame. Skuld's recommendation, given the team's lack of experience and tooling available to forge, was to machine / grind the blade to shape. To assist in speeding up the time frame, Skuld ordered a 0.5" x 1.5" x 36" billet of 4140. The decision to switch to 4140 rather than 4340 was simple: the vendor Skuld (and as a result, the team) orders from, Alro Steel, only carried bar stock of 4140, not 4340. All of their 4340 stock was round.

The first billet was ordered on Wednesday February 19th, but given the number of potential risks that could potentially occur during the manufacturing process, the team figured it would be best to order more billets and make multiple blades - so should one fail along the way, the project is not compromised.

Figure 12: Planing the billet

As a result, the team ordered 3 more billets of 4140 Friday afternoon (the 21st) measuring 0.375" x 2.5" x 36". The reason for the oversize was to allow for a large arc along the length of the blade and for different blade thicknesses to be produced. This also allowed for the blade to be machined down to just above thickness, then ground down to produce a finer surface finish (and to reduce potential crack initiation locations).

The first step in creating the blade was machining these billets to thickness. The thickness of each blade changes between variations and is recorded in the Final Sword Models Section. The thickness was achieved by mounting each billet onto the bed of a manual mill using step clamps and using a 2.5" fly cutter with carbide tips to plane each billet. Running at 300 rpm, each pass took 0.015" off until the final thickness was achieved. This process can be seen in Figure 12.

4.2.2 Band Saw Blade Shape

A drawing of our CAD model of the Mk. 3 was printed out to full scale. This was then cut out of the print, and the profile was taped onto the billet of steel. The profile was then traced out with a paint pen, the printed drawing removed, and this outline was used as a guide when bandsawing the blade's side profile out of the billet. This gave us a constant thickness side profile of the blade.

4.2.3 Belt Sand Bevel Edges

To create the bevel edges, the belt sander was used. For thicker blades, some of this work was done first on the bench grinder, to get the edge of the blade down to a general triangular shape, and the belt sander was used to get a single, clean plane. The belt sander was also used to clean up the surface of the billet, removing all machine marks outside of the fuller and rounding off the spine of the blade.

4.2.4 Mill Fuller

When developing the fuller, the team needed to choose amongst the available tools to plunge into the side of the billet and cut. Out of the tooling available, the only viable options were to grind the shape out by hand, or to use a manual mill to carve the fuller out. After discussion with the team's Senior Design professors, the team decided to use the manual mill to mill out the fuller shapes. This decision was made based on the greater dimensional accuracy of the manual mill, the faster material removal rate of the manual mill, and the reduced risk of mistakes causing significant damage to the part.

Figure 13: Milling the fuller

The choice of the mill brought up a different issue: given the blade design curves along the length of the blade, the fuller does the same. To cut the fuller, the length of the blade would be clamped against the bed of the mill using step clamps and one side would be cut at a time. Given the manual mill was used, this would mean needed to find the correct feed rate for both the x and y axes. Given the blade design was a constant radius, this would mean either manually controlling the x and y along an arc (even if the x is fed at a constant rate, the y would not be constant), or slowly adjusting along a pre-drawn arc, which, when tested, produced significant ledges that would later need to be sanded down. This is pictured in the upper right corner.

Given the team's lack of experience with a manual mill, the team decided to break the arc of the fuller up into 4 segments of straight cuts - which would mean between each segment, the line of cut could be aligned with the x-axis of the bed of the mill (meaning the y-axis would be locked, making the fuller very easy to produce a clean cut). This is pictured on the right, as 4 segments are drawn in sharpie along the length of the blade. In total, the team had 4 individual cuts for a fuller per side of blade, meaning 8 cuts per blade.

Figure 14: Blade profile

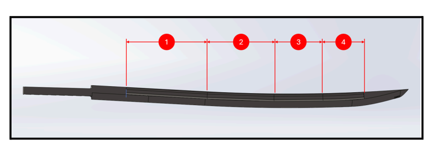


Figure 15: Different fuller sections

To produce the cut, a ¼" carbide end mill centered on each line of cut. Operating at 1400 rpm and taking cuts with a depth of 0.01" per pass, passes were made until the fuller was at max depth (as specified in blade models). Then, after zeroing the Digital ReadOut (DRO), the tooling was changed to a ½" HSS ball end mill running at 700 rpm. The centerline of this tool was then aligned at +/- 0.125" on the DRO (so the centerline was aligned with the walls of the previous cut), plunged to the depth of the fuller, and ran along the walls of the fuller. This created the desired fuller shape, rounded edges with a flat bottom. This can be seen (during the cut) on the right. After the walls were milled, the blade would be released from the bed of the mill and shifted to the next segment. This means that per side of a blade, 4 segments were milled, with 8 tool changeouts (2 per segment). Each segment was first milled with the ¼” end mill, then followed up with the ½ ball end mill. If the team had done all 4 segments with the ¼” end mill, then followed up with the ½” ball end mill (so 2 changeouts), each segment would have needed to be realigned and zeroed (making chances of misalignment and therefore a poorly made blade with deeper machine marks much higher).

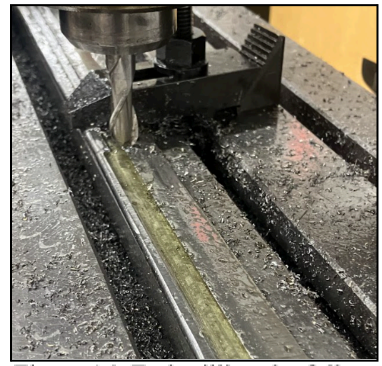


Figure 16: End milling the fuller

Initially, conventional milling was used with the ball end mill to prevent chatter (and as a matter of habit). This was producing rough machine marks in the fuller that would later take significantly longer to hand sand out. The team switched to climb milling instead, realizing it would produce shallower and fewer surface marks given the application. This later meant less hand sanding would be needed to achieve the desired surface finish.

4.2.5 Pre-Heat Treat Sanding

The blades were sanded by hand to remove all machine marks from inside the fuller, as well as aligning all sanding grains along the length of the blade, rather than across the width. The goal was to clean up the grain as much as possible before the blades were heat treated, after which sanding would become more difficult. All of this sanding was done by hand, and took about 15-20 hours per blade, most of which was spent sanding out machine marks from within the fuller. Tools such as an angle grinder or dremel were tested for this purpose, but did not work within the narrow width of the fuller. The dremel was, however, used with a grinding disc to round out the ends of the fuller on both sides before hand sanding.

4.2.6 Heat Treat

To standardize the grain structure and increase the toughness of the blade, the team needed to heat treat the blades (the team excluded the guard and pommel given they are not load bearing). Based on recommendation from the team’s partner company Skuld, the team first reached out to Cincinnati Heat Treat. When discussing the project with Cincinnati Heat Treat, the team had decided to use 4340 for casting the blade (the team was in the process of casting the blade at this point). Based on discussions with Skuld regarding the performance and behaviors of 4340, the team wanted to vacuum heat treat the blades to reduce the possibility of cracking. Unfortunately, Cincinnati Heat Treat did not have these capabilities, so the team pivoted to working with another recommendation from Skuld - Rockford Heat Treat.

As casting progressed and time became more of a constricting, the team recognized that shipping times to Rockford, Illinois would cause significant delays.

Based on this, the team went to a recommendation from Cincinnati Heat Treat - Winston Heat Treating in Dayton, Ohio. Unfortunately, this would mean no vacuum heat treating. Fortunately, Winston used climate controlled furnaces (meaning the carbon % in the atmosphere is nearly the same as the steel to prevent the steel absorbing any additional carbon). This came to a significant advantage after the team switched to 4140 as the blade material given their location is 10 minutes from Campus for the team.

When discussing the work with Winston, the team requested the final hardness be between 48 and 52 HRC. The team also requested the blades be straightened. The three blades machined by the team (Mk. 5, 6, and 7) were all submitted and subject to the following heat treatment processes:

Quenching:

The blades were heated in a controlled atmosphere at 0.4% (+/- 0.05%) at 1550 F for an hour and a half. The blades were quenched in oil (heated to 160 F) and left in the oil for 15 minutes.

Tempering:

The blades were then tempered for 2 hours at 350 F.After the initial temper, the blades were mounted into a straightening fixture, as pictured. While in the fixture, the blades were tempered at 550 F for 3 hours. They were then removed. The blades were then tempered at 350 F for another 3 hours.

Figure 17: Winston furnace

Figure 18: Blades entering heat treat
Figure 19: Treated blades

Figure 20: Blade straightening

The final heat treated parts were initially dropped off Monday, 3/3/2025 around 1 P.M., and picked up Friday the 7th around 2:30 p.m. The treated blades had a duller, darker grey surface finish and could bend significantly easier when put under load than before heat treating.

4.2.7 Post-Heat Treat Sanding

After heat treatment, hand sanding was done to bring all surfaces of the blade up to 1000 grit. All sanding at this stage was done along the length of the blade, to prevent J-scratches or other visual imperfections. WD-40 was used at higher grits to aid sanding.

4.2.8 Blade Sharpening

Regarding the design of the secondary edge, the team's research indicated an angle of roughly 30 degrees (between bevel faces) would be good for the blade. However, using even the thinnest of blades the team machined, this would require the secondary bevel to be ¼" in length and change the aesthetic / strength of the blade (see picture on right).

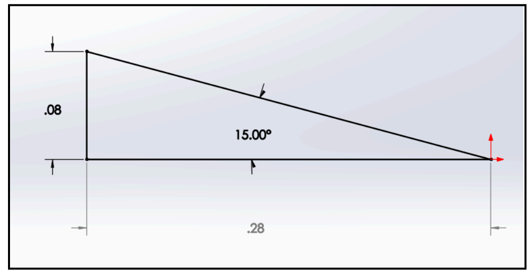


Figure 21: Secondary Edge Angle

Discussing this issue with Luke Terry, his input was that this design for a sword didn't necessarily mean the edge would be "razor sharp" as many would imagine. The team figured that, given the context that a sword like this could be used in a military context, rather than having the razor sharp edge and risk a dulled edge, it would be safer to beef the angle up slightly closer to 30-35 degrees (per side, so 60-70 total) and secure the aesthetic of the blade rather than allow the blade to be slightly sharper. This would also allow the whetstones to be angled further from the bevel (and prevent them from scratching the bevel). The team used a 200 grit diamond stone and WD40 to carve the initial shape of the secondary edge, then jumped to 300 grit to finish the secondary edge. While higher grits were available, given the time constraints the team had, they figured two things - firstly, less time improving the surface finish of the secondary edge meant more time finishing the rest of the surface of the blade (which was desired), and secondly, that a duller secondary edge would look nicer as it would stand out. After the 300 grit diamond stone surface was finished, the team used an old leather belt's back side to strop the blade (to remove any burrs and provide a final level of sharpening). The final product can be seen on the right, as the secondary edge edge just can barely be seen glimmering at the bottom right of the image in the sun.


Figure 22: Secondary Edge in Sun

Due to our 4140 material selection, a relatively ductile steel, a less aggressive secondary edge is also highly beneficial to edge retention. With steels that are lower carbon percentages, impact strength may be higher, however aggressive sharp edges are likely to roll.

5. HANDLE CREATION

5.1 Design Inspiration

After analysing various George Washington Cuttoes and consulting with a fellow UD student and Forged in Fire competitor, Luke Terry, inspiration for the handle evolved over time and the team found a design that was able to satisfy the style of George Washington sword handles as well as being designed to be comfortable to wield and have the ability to orient the blade just by holding the handle. The team also took inspiration from the Washington cherry tree myth and decided early on to make the handle out of cherry wood. The pommel and wood handle inspiration comes from the appearance of the Silver Lion Headed Cuttoe (left, although that handle was made of bone) and the silver wire wrap comes from the Bailey Silver & Ivory Hilted Cuttoe (right).

Figure 23: Silver Headed Lion Cuttoe

Figure 24: Bailey Silver and Ivory Cuttoe

5.2 Process Testing

Different handle making processes were tested to land on a design that balanced the wield-ability of the blade as well as being aesthetically appealing. Various shapes, lengths and indexes were tested as well as different staining methods to make the cherry wood pop and compliment the rest of the sword. Oven cleaner was tested due to it containing Lye which is supposed to bring out the red in the cherry wood. Red wood stain was also tested and had a nice vibrant red color and the design still had the use of cherry wood, which connects back to the cherry tree myth even though the red color is from the stain. The team found that the oven cleaner alone did not make the cherry wood pop as much as initially thought. While it looked great immediately after staining, a few minutes of oxidation turned the color from red to brown. The team then found out that Linseed oil can be applied and give a better color. After applying the oil on the oven cleaner layer, a deep red color was prominent. Beeswax was also tested after the oil layer dried and gave a nice glossy look, bringing out the red tints even more and providing a weatherproof clear coat, something that would be essential for a functional sword of the time.

Figure 25: Washing Staining Samples

Figure 26: Staining Samples

5.3 Final Design

The team landed on a comfortable design with the ability to index the blade just by wielding it. The handle fits comfortably in the palm of your hand and is optimal for swinging and slashing the blade. The handle was sprayed with oven cleaner then rinsed off and set to dry. After it dried, grooves were cut into the handle using a dremel then hand filed to size. Grooves were cut after staining because it was found that if staining is done after grooving, the lye builds up within the grooves and creates localized dark spots within the wood. Linseed Oil followed by wax was applied to create a deep red color and add some shine to the handle. Anodized aluminum wire was then wrapped around the grooves to create a sleek, appealing, and durable design. The spacing of the wire wrap was designed to be most comfortable for a right handed grip, matching George Washington's right handedness, with the grooves being spaced between finger placement along the cutting edge side of the handle.

Figure 27: Completed Handle

6. GUARD + POMMEL CREATION

6.1 Guard + Pommel Design

The appearance of the pommel was based on the Silver Headed Lion cuttoe, selecting an eagle head as an American symbol. The eagle became a national symbol in June 1782, selected by the second continental congress, and by the end of the century had become representative of the American spirit. The S-shaped guard was a common feature on most of Washington's most famous cuttoes, including the silver headed lion cuttoe and the bailey silver and ivory cuttoe. Though more detail was originally planned to be cast into this part, the details were removed due to an extremely tight schedule by the time the guards were ready to be cast. This tight schedule was a result of our original intent to cast the blades, which took most of our team's attention until eventually pivoting to machining. Left with only one week allotted to cast guards before assembly, we needed to guarantee a successful cast. The guard and pommel were to be cast from AISI 4340 steel to closely match the appearance of the blade (AISI 4140).

Initially, CAD work on the guard and pommel was attempted in Solidworks. After some trial, however, it was found that producing the more artistic, non-geometric parts required was difficult, even using tools such as lofts, sweeps, etc. Instead, the team learned and used blender to design the guard and pommel. This served two advantages. The first being that some models, such as eagle heads, were already available for use. An eagle head model was downloaded and edited (feathers were sculpted further to be smoothed out for casting, and the base was modified), and the guard was made from scratch. Blender's second advantage in this scenario is that one can manually build the mesh, allowing for easier creation of smoother curves and cleaner transitions between parts. Though it took some time to learn, the resulting model was much smoother than its SolidWorks counterpart.

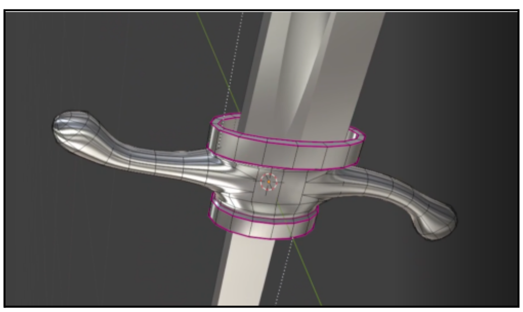


Figure 28: Blender Guard Model

Figure 29: Modified Blender Eagle Model

6.2 Guard Casting

Six guards and six pommels were cast using AMEC technology. Of these casts, three eagle heads and two guards came out looking as designed, with some small imperfections that were cleaned up post-cast. Though more trial and error would have resulted in much cleaner results, particularly on the guards, our timeline at this stage did not permit additional testing.


Figure 30: Final Guard and Pommel Cast (Guard partially ground)


Figure 31: Cast Guards

6.3 Guard Machining


Figure 32: Eagle Planing

When the guard and pommel casts were received, sand and gating were still attached to the surface of all parts and required clearing. To quickly remove all of the sand on the surface (not including burnt on), a wire wheel mounted on a bench grinder was used. This revealed a course, varying surface. For the pommel (eagle head), this was desired given the team wanted to add feathering detail to the eagle head.

To efficiently remove the gating from the cast eagle heads, the eagle head was mounted sideways in the mill and a ½" carbide end mill (at 1200 rpm) was used to remove material. Running in passes of 0.01" per pass, the y-axis was advanced until the bottom of the eagle head was flat. This process is imaged on the right. To prepare the eagle head for mounting on the tang, a 3/16" hole needed to be drilled. Initially, a 0.25" HSS center drill (at 1400 rpm) was used (successfully). Next, a 3/16" HSS drill was used (1200 rpm), which made little to no progress. The drill failed to remove any material (with oil and slow feed). After the attempt, the drill was dulled and the team needed a tougher drill. Deciding to downsize (keeping in mind the size of hole would reflect the amount of material needed to peen the tang), the team used a size 20 cobalt drill (at 1400 rpm). With oil and slow feed, this very quickly ate through the material. Even with frequent plunging / removal, oil, and chip removal, as the drill approached the bottom of the head, the drill snapped leaving the tip in the eagle head. Later discussing with another engineer working in the metal shop, the issue was simply found to be chip buildup / heat generation (lack of oil). This process is pictured on the left. To another tool failure, the team went and purchased a 3/16" carbide tipped multi purpose tool. Running at 1200 rpm, this too quickly chewed through another eagle head with little to no issue. This drill successfully cut through an eagle head. The eagle head received some additional grinding to clean up extra high spots from the cast, and a file was run across some points of the


Figure 33: Pommel Drilling

surface to create differences in surface textures. Once the grinding was complete, the bottom ring around the base of the eagle was run against the belt sander to create a shine for a base.

The guard was processed differently. The guard was first cleaned with a wire brush and light dremeling to remove all of the excess sand / material from the cast. The team then proceeded to drill a series of holes through the guard to create room for the tang. The same 3/16" carbide tipped drill was used and performed well during the first cut until, once again, near the bottom of the cut. The operation sheared the tip off and decimated the tip of the drill. As a result, the team decided to find alternative ways to assist in drilling and prevent further failures. The team blow-torched the eagle head and guard in an attempt to increase the machinability of these parts until the parts were a dull red (see picture on the right). After annealing the guard and eagle head, another attempt at drilling the guard was made with a 3/16" carbide drill borrowed from the school BAJA team. Running at 1200 rpm, this drill chewed through the guard with little to no effort. Slow plunges and frequent chip-clearing breaks were taken to protect the tooling. After side by side holes were drilled, the guard was removed and tested on the tang - to which the team decided another hole needed to be cleared. When aligning the final cut, the centerline of the drill was offset from the edge of the current hole (into material to prevent the drill from walking and snapping). Unfortunately, after drilling less than a millimeter, without any visible sign of walking, the carbide drill snapped. Given the short time frame, the team used a size 22 cobalt drill that was available Running at 1400 rpm, the drill was shifted further from the carbide crater to ensure the drill wouldn't fail. The result of this cut left slight high spots that were later cleared using files and rip saws. This process was used until the guard fit snugly onto the tang.

Figure 34: Pommel Annealing

The original guard cast left large gaps in the cast of the rim around the blade, so the team attempted to flatten this to clean up the look. The first attempt was made using the mill, trying to mill down a flat face and remove all nicks in the ring. Using a ½" inch carbide end mill running at 1500 rpm, the top face mill down 0.01" per pass until the part shifted in the vice, at which point one of the flutes caught a deep hold of one of the nicks on the part and snapped the end mill, demonstrating the brittleness of carbide. Because of how difficult the part is to mount in a vice, the team used the belt sander to get the cut down to a flat surface to prevent more machining errors. The guard was finished by dremelling the remainder to the desired shape with a grinding bit, and hand sanded up to 320 grit sandpaper.

Figure 35: Drilled Guard

7. FINAL ASSEMBLY

After the post processing machining on the guard and pommel were completed, the blade was machined and sanded, and the handle was created, the team could commence with the assembly of the sword.

7.1 Preparing for Assembly

7.1.1 Handle Burning

A pre-hole was drilled into the handle before the staining process. The purpose for this was to use the pre-hole to help aid in the process of burning the handle onto the tang to have as perfect a fit as possible as opposed to drilling the perfect hole. The sword was clamped in a way to not damage the blade but also have the ability to apply pressure while fitting the handle. Since the cherry wood is a soft wood, it did not take much heat to do the burn fit, and after testing it prior, the team was able to successfully heat up the tang to an adequate temperature and slide the handle on creating a nice fit before assembly.

Figure 36: Handle Burning

7.1.2 Clamping

One issue the team had to overcome was clamping the sword in a fashion that would allow for sliding on the guard, handle and finally the pommel and then go on with peening the tang. A similar clamping method was used that was also used for burning the handle to the tang.

7.1.3 Epoxy

Epoxy was used to help keep everything in place once the peening was done. The epoxy was mixed and spread across the tang and also into the handle. The assembly and peening would occur while the epoxy was drying. The primary use of the epoxy was not to bind the wood to the tang (which was done by peening the tang), but rather to fill in voids within the wooden handle that may have resulted from mistakes when drilling/burning the handle hole.

7.2 Assembly

7.2.1 Tang Peening

After the epoxy was applied, it was time to assemble everything. The handle was slid on and then adjusted to line up with the guard, the pommel was then slid on and aligned with the handle. A quarter of an inch of the tang was left sticking out of the pommel and then heated up until it began to turn red and soften it up for peening. A ball-peen hammer was used to get a mushroom shape at the tip of the tang. Once

Figure 37: Tang Peening

it started to look like a dome was forming, a larger, flatter 2lb hammer was used to flatten it out. This process was continued until the tang was up against the pommel and there was no movement up and down the tang of the guard, handle and pommel assembly.

7.2.2 Epoxy Filling

After the tang was peened and the prior epoxy was left to cure, we noticed that we had not completely filled the void within the handle with epoxy, resulting in a loose fitting handle, even though the guard and tang were securely attached through peening. Knowing that this problem severely degrades the functionality of the blade (for safety reasons), two attempts were made to fix this error.

Figure 38: First Epoxy Pour

The first attempt involved attempting to pour epoxy into the small gap created between the eagle head pommel and the wooden handle. The hope was that the epoxy would fill the handle void through this gap, however the gap was very small and did not leave much room for epoxy to flow into the handle. This attempt was unsuccessful.

Though not ideal, our second attempt involved drilling a ¼ inch hole in the handle on one side. Epoxy was funneled into this void, filling the inside void of the handle. A wood plug was sanded, stained, oiled, and waxed to closely match the finish of the rest of the handle, and hammered into the empty hole to seal the handle while epoxy was setting.

Figure 39: ¼ in Hole For Epoxy Pour 2

We realize that epoxy is not ideal for supporting the stresses required in a functional blade. The intention is that the peened tang will prevent all parts from sliding along the length of the blade, while the epoxy will simply fill voids within the handle to prevent it from rotating slightly around the tang. Ideally, even if the adhesion of the epoxy to the tang breaks, the handle will still be secure. If time had permitted, another handle would have been made and burned in replacement to prevent the need for any epoxy.

8. TESTING

The team ran two separate tests to both determine which blade design would be sent for competing, as well as checking the full functionality of the blades.

8.1 Strength Testing

The team tested the strength and durability of the blades to ensure they would handle testing. To do so, the team used what would be considered the mechanically weakest sword (the

Mk. 7 model) and struck the dull edge against numerous objects. This was performed prior to sharpening the blade.

Should the weakest blade withstand the blunt force of striking numerous objects with little to no damage, the thinnest blade model would be acceptable for testing. Should the weakest blade suffer some noticeable and partially irreparable damage, the next thickest blade would be chosen. Finally, should the weakest blade suffer significant damage and be completely irreparable, only the thickest blade (Mk. 5) should be used.

To test a variety of different strength tests, the team struck three different materials with the dull sword: wood, for a softer material, aluminum, for a tougher material (while still allowing the steel to be tougher), and a coconut, because we wanted to. The results can be found in Figure 40 below:

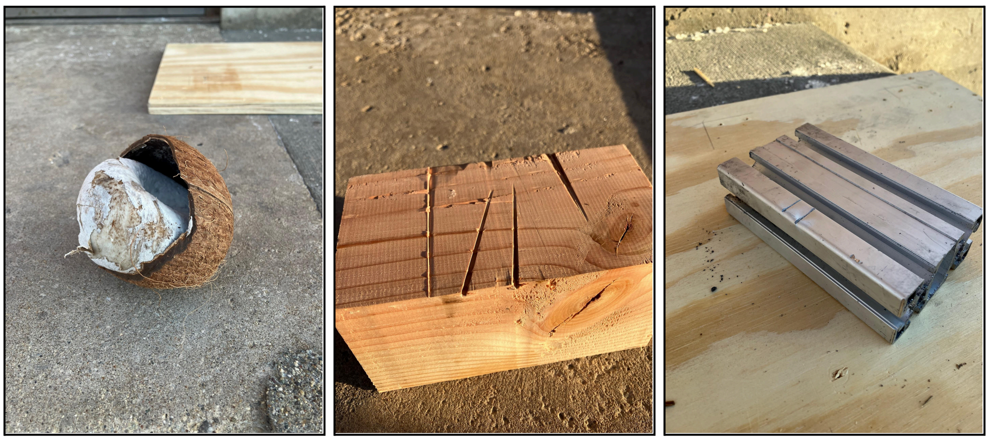


Figure 40: Coconut, Wood Block, and Aluminum Rail after testing (left to right)

As a result of these tests, the weakest blade suffered very little damage (some minor blade bending fixed simply by clamping the blade to a bench). As a result of this, the team decided to move forward with the Mk. 7 as the primary candidate for the competition.

8.2 Sharpness Testing

To test the viability of the edge on the sword, a few different measures were used: first, a light was shown along the edge of the blade. Should the blade have an edge, no light would reflect back towards the source of light (requiring the light and someone's eye to be level with the edge of the blade). Should light reflect, this would mean there is a flat spot and the secondary edge needs to be more defined. This can be seen in figure 41.

Figure 41: Blade Edge

The next test was a 2-fold combination - first, a finger was slid perpendicular to the direction of the blade. This would confirm there was an edge, as well as check the sharpness. Occasionally, as a test, a finger would be run along the length of the blade as well. The majority of times, if no mark was left on the finger, the blade needed to be sharpened. Once the edge

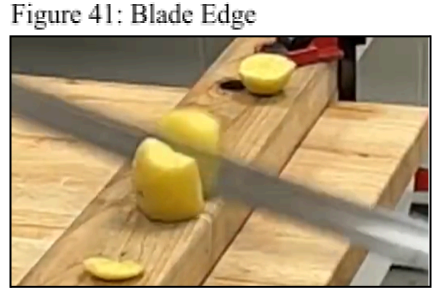


Figure 42: Potato Cutting

was able to cut the finger, the blade was nearly there. The second portion of this test was to use taut paper and slide it against the blade. Initially, the paper would either remain undamaged or tear aimlessly. Once the blade was adequately sharpened, the paper would tear along the length of the edge.

Finally, to test the performance of the edge, the team performed the “potato test”. A raw potato was set on a 2x4 and swung at with the blade. The blade successfully cut through the potato with a clean easy cut, meaning the blade was sharpened. The results of the potato test can be seen on the left.

9. FINAL SWORD MODELS

Mk. 1-4, referenced earlier in the report, were developed in the initial planning and design phases. All of the following blades the team developed and actually created were based on the Mk. 3 blade design. As the blades were being machined, the team decided to make 3 different variations of this design by changing the thickness of the blade and the depth of the fuller. This would allow the team to experiment with how the thickness would handle balancing and performance. The different variations are as described below:

* Blade weight is the weight of the blade alone, not including pommel, guard, or handle

Mk. 5 Model

The Mk. 5 model was machined out of a billet of AISI 4140 steel. Dimensionally it is the same as the Mk. 3 but with a much larger radius of curvature (so the blade appears much straighter along the length as opposed to other blade designs).

Billet: 0.5” x 1.25” x 36”

Blade thickness: 0.23”

Fuller Max depth: 0.05”

Blade weight: ~17 oz

Mk. 6 Model

The Mk. 6 model was machined out of a billet of AISI 4140 steel. Dimensionally it is the same as the Mk. 3 but with a different maximum thickness.

Billet: ⅜” x 2.5” x 36”

Blade thickness: 0.2”

Fuller Max depth: 0.05”

Blade weight: ~14.5 oz

Mk. 7 Model

The Mk. 7 model was machined out of a billet of AISI 4140 steel. Dimensionally it is the same as the Mk. 3 but with a different maximum thickness.

Billet: ⅜” x 2.5” x 36

Blade thickness: 0.155”

Fuller Max depth: 0.035”

Blade weight: ~12 oz

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