SFSA Cast in Steel 2025 - Washington's Swords
Technical Report

Michigan Technological University - Washington Wompers

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Executive Summary

SFSA has created this competition to encourage students to learn about making steel products using the casting process and applying the latest technology available. Combining historical inspiration with modern technology, team Washington Wompers was able to design, manufacture, and submit a sword based on an artifact from George Washington's collection. This process included CAD design, solidification simulation, steel casting, heat treatment, and casting finishing. The final sword measures 36 inches with a weight of 1.88 kg. George Washington's collection features a variety of sword types, but the Alte Presentation Broadsword stood out to our team because of its details and shape. The original sword features intricate engravings and a brassy handguard. Our competition sword incorporates modern engineering materials and design considerations, with a custom alloy and heat treatment as well as a cast aluminum handguard and an olive wood handle.

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Historical Background

The inspiration for the sword design was the Alte Presentation Broadsword, which was made in Prussia and engraved by Theophilus Alte, a world renowned Prussian sword maker [1]. Although the design shares many similarities in shape, proportion, and size to Alte Presentation Broadsword, the blade of the sword the team produced tapers slightly more. In addition, to ensure that the sword met the length requirement of 43 inches, the blade length was shortened to 30 inches to accommodate the length of the handle. Other dimensions of the blade were estimated, as these measurements were not provided.

The hand guard and handle of the Alte Presentation and Washington Wompers' sword have similar shapes and proportions to the Alte Presentation Broadsword, but are made of different materials than the original. The original hand guard was made of a combination of brass, copper and gold, the hand guard of the Washington Wompers' sword was made of aluminum. In addition, the handle was changed from leather, wood and copper to olive wood [1]. While the design of each component parallelled the historical sword, these material changes were made to incorporate more modern engineering materials.

Casting Design

Casting design is the most critical process in producing a sound casting. The design process should be informed by the material, part application and foundry which is to be used. The sword was designed to be a near-net shape casting, with only heat treatment and grinding being necessary after casting.

Sword Design

The design of any casting must be informed by the process and material available. For the Michigan Tech foundry, sand casting is the only viable process to produce large castings like a sword. Because of time constraints, the sword needed to be designed as a near-net shape casting; this means that no forging or hipping (hot isostatic pressing) would be performed after casting.

With these considerations in mind, a sword design was created using On-Shape CAD. The sword was designed after the Alte Presentation broadsword because the larger profile of the sword makes the mold easier to fill during casting; the sword design is shown in Figure 1.

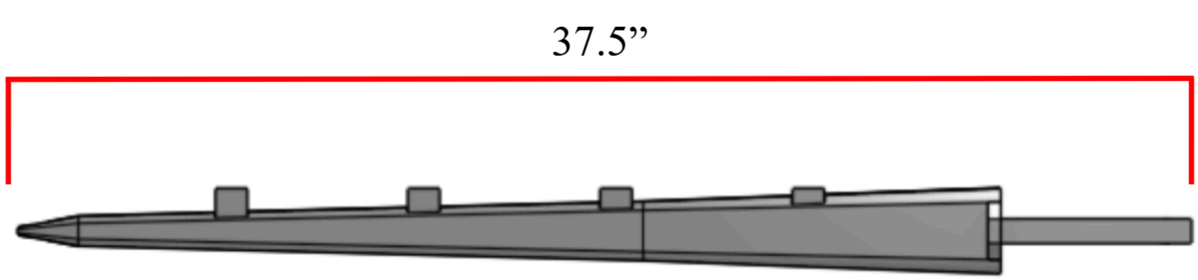

Figure 1*: Sword CAD design.*

It was determined that casting the handguard separately would result in a better final product. This is because a separate handguard casting prevents major shrinkage around the tang which could occur if there was a handguard present on the sword. In addition, it allowed the guard to be made of aluminum, which reduced the weight of the final product relative to a steel handguard. The handguard design (Figure 2) was based on the handguard present on the Alte Presentation sword.

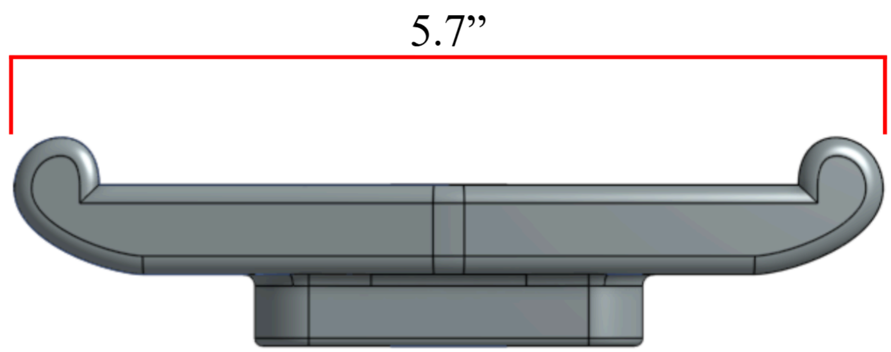

Figure 2*: Handguard CAD design.*

Gating and Riser Design

Gating and risers are used during casting to fill the mold and limit shrinkage porosity. Improper design of the gating can result in incomplete filling, cold-shuts and porosity. Steel also poses challenges in casting due to its low fluidity when compared to other commonly cast alloys. The concern of fluidity was partially addressed by alloying (see alloy design); however, a robust feeding system is also needed to ensure a sound casting.

Because of the extremely thin section size of the sword, multiple in-gates are necessary to properly feed the sword. Risers were added to the original casting design; however, during pattern making, a mistake was made where the risers were placed in the drag side of the casting. This means that the risers would pull molten metal away from the sword casting rather than feed metal to the casting. Because of this, the risers were removed for the actual casting. While this could cause additional porosity, it is generally accepted that for steel-castings of less than 1 in section thickness, risers do not provide significant benefit.

The gating design was done in an iterative manner, and the two initial designs were discarded before the final design was produced. The final design utilized a hand-made wooden runner so no simulations could be performed before casting. The gating designs are shown in Figure 3.

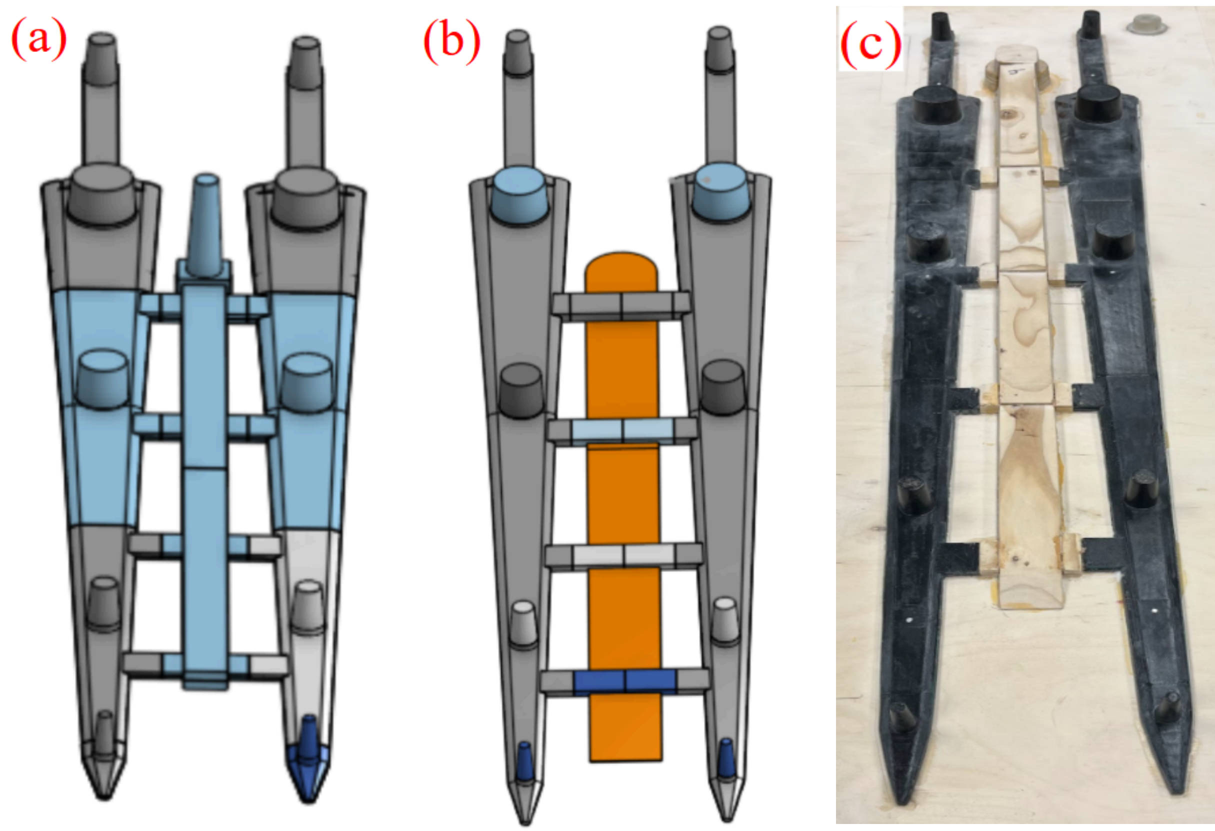

Figure 3, *(a) v1 design - rejected because it was too thin (b) design v2 - rejected due to limited head-pressure (c) v3 design - ensures complete feeding while maintaining head-pressure, runner system hand-made from wood and placed on matchplate*

Casting Simulations

Casting simulations were performed on the blade in order to make improvements to the design before casting. InspireCast solidification simulation software was used to assess the gating and riser design in a no-bake mold with the desired casting parameters before the blade was cast. These simulations were used to verify that the mold would fill with minimal porosity.

Alloy Design

A well-designed sword casting alloy should be strong, tough, and highly castable. Strength defines how much stress the material can withstand before permanent shape change. High strength is important to ensure that the sword can hold a sharp edge and retain its shape. Toughness is a material's ability to resist fracture; this is often defined as the area under a stress-strain curve - with maximum toughness being obtained with high strength, high ductility materials. However, for this application, impact toughness is a better definition. Impact toughness refers to a material's ability to resist fracture during an impact, which is critical to avoid catastrophic material failure. Castability is also crucial because the swords are cast near-net-shape. Castability refers to a material’s ability to produce sound (defect-free) castings, which involves properties such as molten fluidity and shrinkage.

Limitations of Standard Alloys

Alloys commonly used to make swords—such as 4140, 4340, and 5160—are strong, tough, and amenable to forging. These alloys excel in a variety of applications such as crankshafts, heavy duty gears and leaf springs [2]. While they are exceptional for their versatility, these alloys are designed to be highly forgeable, meaning their alloying balances ductility and hardness to enable hot working. Since our process uses a near-net-shape casting, we can optimize for castability, toughness, and hardness without the constraints of forgeability. By modifying the composition, the castability, strength, toughness, and hardenability of these alloys can be improved. 4140 steel was selected as the base composition for the alloy design because it is commonly used in forging and provides a strong base chemistry to build on. The composition of a standard 4140 alloy and the custom alloy “Washington Wompers 4140” (WW-40) are given in Table 1.

***Table 1**: Typical 4140 composition and custom alloy [3].*

Alloy	Fe	C	Mn	Cr	Mo	Si	Cu	Ni	V	Ti	B
4140	bal	0.40	0.88	0.95	0.20	0.20	0	0	0	0	0
WW-40	bal	0.40	0.88	0.95	0.20	1.0	0.3	0.3	0.07	0.05	0.002

Role of Standard 4140 Alloying Elements

The concentrations of carbon, manganese, chromium, and molybdenum were maintained at the same levels as the standard 4140 composition. Carbon is a critical element as it increases hardenability and can form hard carbides with other metals. A concentration of 0.4 wt% C ensures the formation of martensite and carbides while avoiding high carbon concentration which can induce quench cracking [4]. Manganese is crucial to ensure that sulfur forms the relatively benign MnS rather than the highly embrittling FeS intermetallic [5]. Manganese also serves to increase the strength and hardenability of the alloy. Chromium, in concentrations below 1 wt%, increases the strength and hardenability of the alloy. However, if the chromium concentration is increased significantly, chromium carbides may form along grain boundaries, which could be deleterious to fracture toughness. Molybdenum is added to increase the strength and hardenability of the alloy. In concentrations greater than 0.2 wt%, molybdenum may form carbides that would enhance strength; however, in this case, it was deemed that vanadium carbides would be more effective strengtheners, so its concentration was not increased.

Primary Alloy Modifications

Primary alloy modifications are additions to the standard 4140 composition which improve the properties of WW-40 for sword casting. As compared with the standard 4140 alloy composition, WW-40 contains several alloying additions or modifications including silicon, copper, vanadium and boron. Silicon is commonly added to steels in concentrations below 0.3 wt% to act as a deoxidizer. High silicon concentrations are avoided in forging alloys because it reduces hot workability [6]. However, for WW-40, Si concentration was significantly increased in the modified alloy because of its beneficial effects on fluidity, fracture toughness, hardness, and hardenability. Silicon significantly increases the fluidity of molten metal, which is critical to ensure that the mold fills completely during casting. High concentrations (greater than 1 wt%) of silicon are also known to significantly increase the fracture toughness of quenched and tempered steels [7]. Silicon has high solubility in ferrite, which allows it to strengthen the ferrite matrix via solid solution strengthening.

Copper is commonly avoided in steelmaking because it can cause hot shortness and hot tearing. However, if hot tearing is avoided, copper can be used to increase strength via precipitation hardening. This is because copper has high solubility in austenite with very little solubility in ferrite, inducing secondary hardening during the tempering of steels—this principle utilized in the well-known 17-4 PH alloy. Vanadium is another element known for its role in precipitation strengthening. It has high solubility in austenite and very low solubility in ferrite, allowing it to form extremely small precipitates along martensite laths, which significantly increase the strength of the alloy [8]. Boron is a powerful alloying addition due to its ability to act as both a substitutional and interstitial element in ferrite. This allows for a large increase in hardenability to be achieved around 0.002 wt%, which diminishes beyond this point [7].

Secondary Alloy Modifications

Secondary alloying elements were introduced to counteract the negative effects of the primary modifications and to enhance the stability of the microstructure during processing. Nickel was added to counteract the hot shortness caused by copper. In cast steels containing significant copper additions, nickel is required at approximately half the concentration of copper to prevent cracking induced by copper [9]. Beyond its role in mitigating copper-related issues, nickel also enhances toughness, hardenability, and corrosion resistance. Its ability to stabilize austenite ensures uniform hardening during quenching. Titanium was introduced as a nitrogen getter, preventing the formation of boron nitride, which would otherwise render boron ineffective in improving hardenability. Titanium has a strong affinity for nitrogen, ensuring that any free nitrogen is tied up as stable nitrides before boron can react with it. Titanium may also form precipitates during tempering which add to the secondary hardening.

This comprehensive approach to alloy design ensures that WW-40 meets and exceeds the performance requirements necessary for high-quality casting.

Heat Treatment Design

Heat treatment is a critical step in obtaining a combination of high hardness and toughness from cast steels. The heat treatment must be designed in order to maximize both hardness and toughness by making use of the alloying elements present in the steel. For WW-40, it was determined that a three-step heat treatment would be applied of (1) homogenizing followed by air cooling, (2) austenitizing and quenching, and (3) tempering at 482 °F (250 °C) would yield ideal properties.

Homogenizing

The as-cast microstructure of WW-40 is expected to exhibit significant microsegregation due to dendritic solidification where the first to solidify metal is almost completely pure iron, while the last metal to solidify is highly concentrated in solute. This inhomogeneous microstructure is detrimental to material properties as it may result in the formation of deleterious phases which could cause embrittlement.

In the absence of forging, solute redistribution must be completed using a homogenization heat treatment. This involves long heat treatments above the A3 temperature (where the material is fully austenitic). In order to ensure adequate time for diffusion to occur, the sword was held at 1650 °F (900 °C) for 12 hours. The elevated temperatures and extended time of the homogenization treatment allows for redistribution of segregated elements. The as-cast and homogenized and air cooled structures are compared in Figure 1. The as-cast microstructure shows a dendritic structure that grows from the edges of the sample toward the center, while the homogenized sample shows no noticeable directionality.

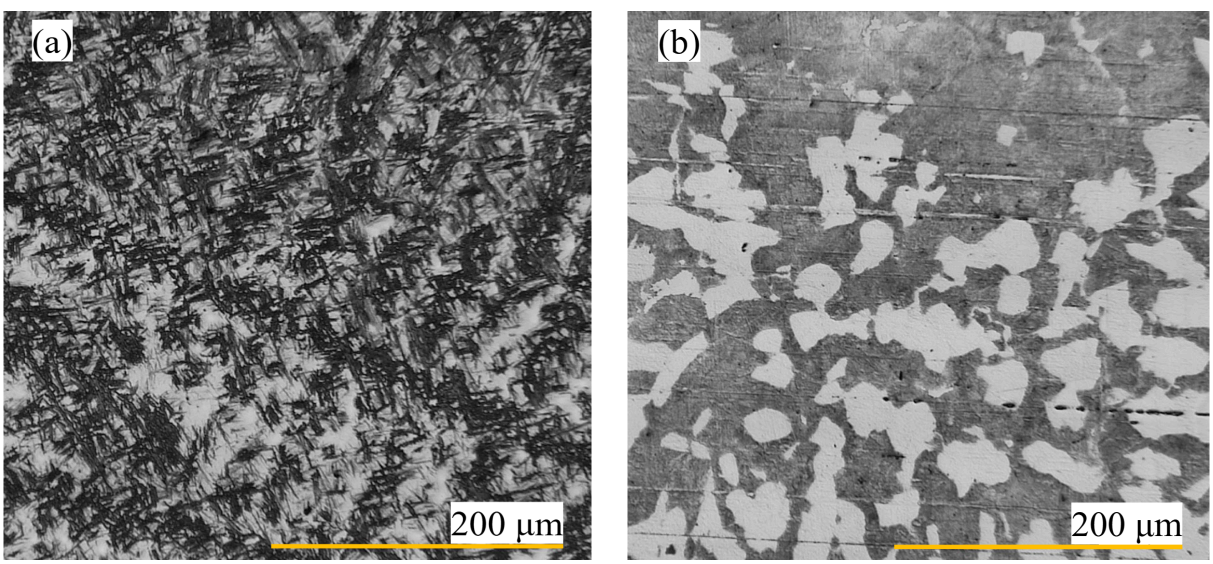

Figure 1: *(a) microstructure of as-cast WW-40 and (b) microstructure of cast, homogenized and air cooled WW-40 - samples are 0.5 in diameter, 0.5 in thick test pucks; etched with 2% nital.*

Austenitizing and Quenching

Austenitizing followed by quenching is necessary to create a blade that is both hard and tough. In order to create a fully martensitic microstructure, the material must be entirely austenitic because only austenite can transform into martensite; the quench rate must also be sufficient to avoid formation of any phases other than martensite. A martensitic microstructure is desirable because it is extremely fine and once tempered, creates a hard and tough material. The formation of martensite is also critical as the shear transformation induces a large number of dislocations because of lattice distortions. These dislocations serve as ideal nucleation sites for precipitation during tempering - this increases the strength induced by secondary hardening [10]. Quenching also prevents dissolved solutes such as vanadium, titanium and copper from precipitation during cooling which allows for fine precipitates to form during tempering.

In order to ensure the sword forms a completely martensitic structure, the cooling rate must be sufficient to reach the Ms (martensitic start) temperature before other phases begin to nucleate. The Ms temperature of WW-40 was simulated using Thermo-Calc and found to be approximately 650 °F (350 °C), as shown in figure 2. Based on the theoretical CCT diagram, the material must be cooled below 350 °C rapidly to avoid pearlite or bainite formation. An oil quench is sufficient to achieve this due to the thin section size of the sword, ensuring a fully martensitic microstructure.

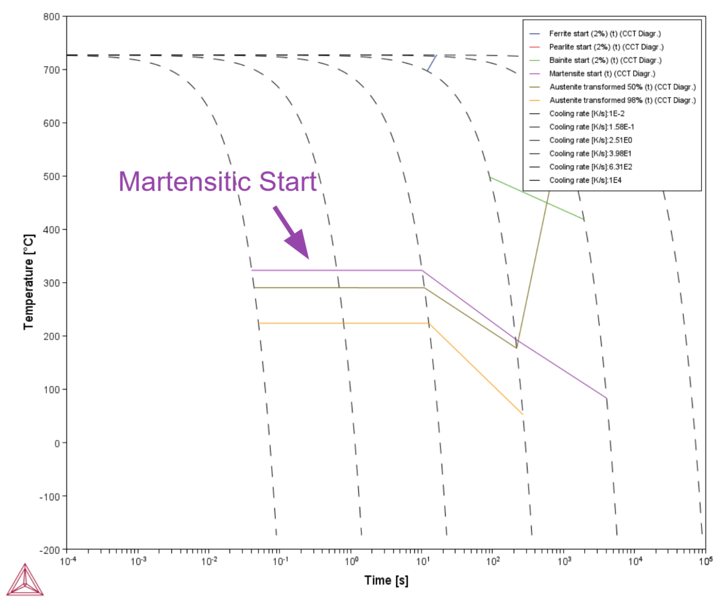

Figure 2: *Simulated CCT diagram of WW-40 showing Ms around 350 °C.*

An oil quench is also desirable as it reduces the risk of cracking compared to a water quench. Quenching was performed by austenitizing the sword and quenching it in oil. The microstructure of the oil quenched sample is completely martensitic; however, some regions of the sample etched lighter while some etched darker. The difference in etching is likely due to segregation of nickel and chromium. This segregation is unlikely to be extremely detrimental as detailed analysis of both light and dark regions show that there is a fine martensitic structure. The microstructure of homogenized and oil quenched WW-40 is shown in figure 3.

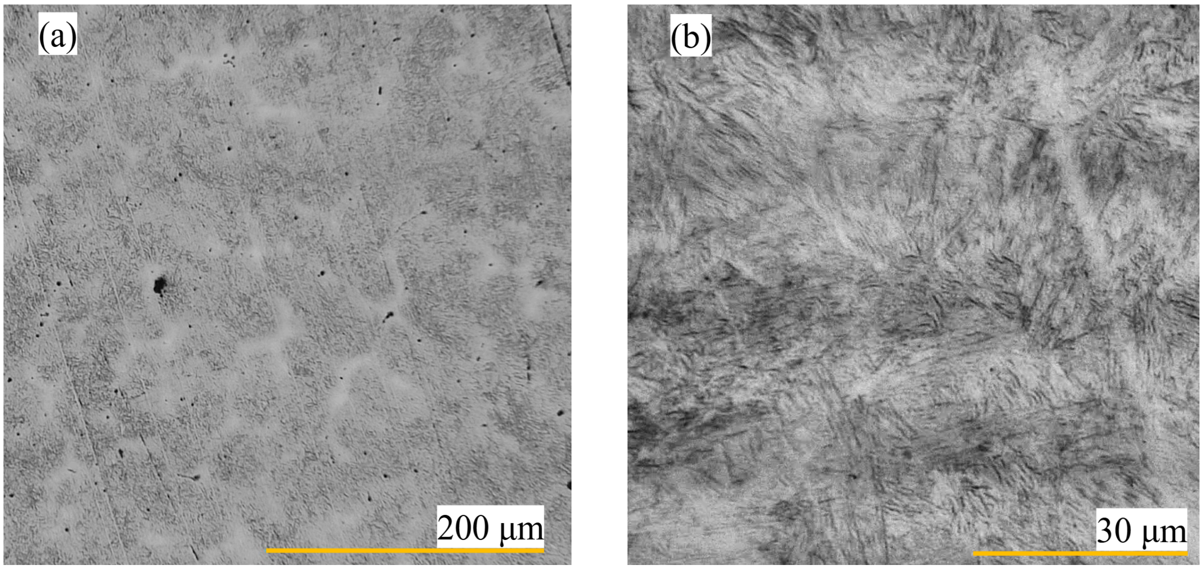

Figure 3: *As-quenched WW-40 (a) showing light and dark etching regions and (b) high magnification showing both light and dark regions with martensitic structure - etched with 2% nital.*

Tempering

Tempering is a necessary step following quenching, while the as-quenched material is extremely strong, martensite has very little ductility which makes the material extremely brittle. The time and temperature at which tempering is carried out must be chosen carefully - as there are a variety of embrittlement mechanisms which can occur during tempering [2]. Over long tempering times, the strength of the material will also be reduced due to coarsening of the structure.

Determining the ideal tempering parameters of an alloy takes a significant amount of experimentation, only some of which can be performed. Ideally, tempering should be performed to achieve a Charpy impact toughness of at least 35-40 J while maintaining a hardness around 50 HRC. A rough estimate of toughness is obtained by following a paper W. J. Nam and H. C. Choi where the effects of silicon, nickel and vanadium on steel were studied [11]. These authors created a steel with the composition shown in Table 2.

Table 2: *Composition of steel studied by W. J. Nam and H. C. Choi with custom alloy also shown [11].*

Alloy	Fe	C	Mn	Cr	Mo	Si	Cu	Ni	V	Ti	B
Nam and Choi	bal	0.60	0.47	0.51	0	1.02	0	1.77	0.18	0	0
WW-40	bal	0.40	0.88	0.95	0.20	1.0	0.3	0.3	0.07	0.05	0.002

While most elements between the compositions are different between the alloys, C, Mn, Cr and Si are close in composition. The major difference is the large nickel addition in the Nam and Choi alloy which may lead to a difference in tempering behavior.

In order to determine if the tempering behavior of the Nam and Choi alloy is similar to WW-40, a tempering study was performed on oil-quenched samples of WW-40. Cylindrical test pucks (approx 0.5 in diameter and 0.5 in thick) were held at 1650 °F (900 °C) for 12 hours. These samples were then air cooled, austenitized for 1 hour and oil quenched. The samples were then tempered for 30 minutes at varying temperatures followed by air cooling. The data from this tempering study is shown beside data from a study performed by Nam and Choi; the compiled data is shown in figure 4. The hardness curves of both alloys match closely in shape which suggests that the tempering behavior of the alloys is similar. The difference in measured hardness is likely due to different quenching oils with the WW-40 alloy quenched in slow-cooling quench oil which will lead to lower hardness.

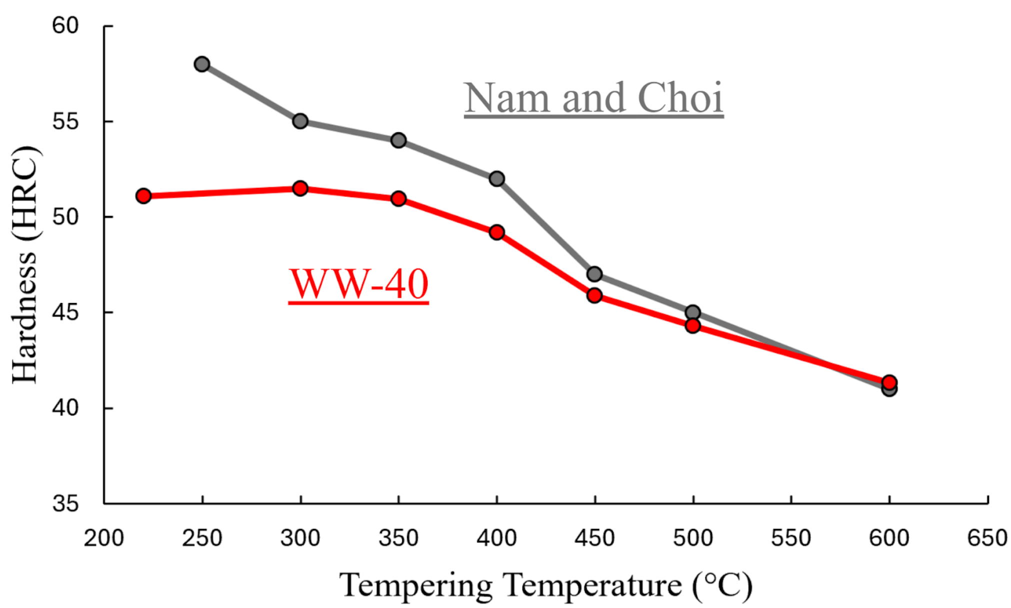

Figure 4: *Effect of tempering temperature on the hardness of homogenized and quenched WW-40 shown beside Nam and Choi alloy [11].*

Nam and Choi also conducted Charpy impact tests during their study. Their study shows that toughness reaches a local maximum of 35 J at a temperature of 570 °F (300 °C) after which it drops to 30 J at 650 °F (350 °C) (see appendix figure 6 “steel C”). The reduction in toughness is likely due to decomposition of austenite into martensite which causes tempered martensite embrittlement.

By tempering at 482 °F (250 °C) the sword should avoid embrittlement while maintaining hardness around 50 HRC. This heat treatment maintains high hardness without risking temper embrittlement. The microstructure of the final heat treated material after homogenizing for 12 hours and air cooling followed by austenitizing, quenching in oil and tempering at 482 °F for 30 minutes is shown in Figure 5. The final microstructure shows a fine tempered martensitic structure.

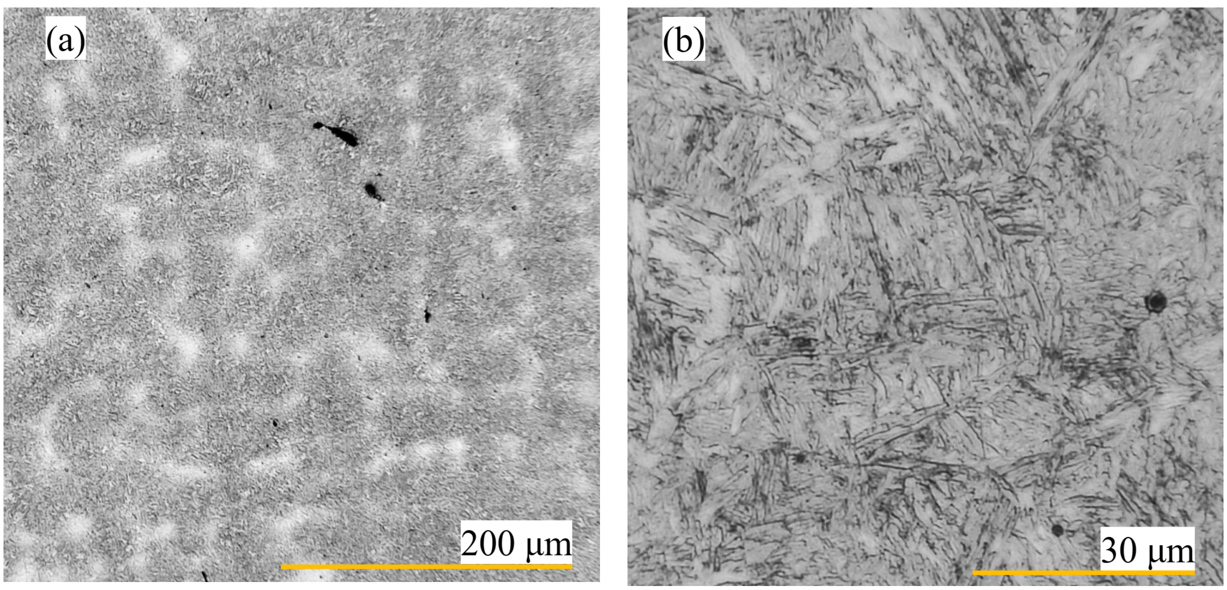

Figure 5: *microstructure of heat treated WW-40 (a) showing light and dark etching regions and (b) high magnification showing both light and dark regions with martensitic structure - etched with 2% nital.*

Summary of Alloy and Heat Treatment Design

WW-40 was designed to optimize castability, strength, and toughness while maintaining the hardenability of traditional forging steels like 4140. Key alloying modifications, including increased silicon for fluidity and toughness, copper and vanadium for precipitation strengthening, and boron for enhanced hardenability, ensure superior performance in the as-cast condition. Nickel and titanium were added to counteract embrittlement effects and stabilize the microstructure.

A combination of computational and experimental methods were utilized to develop the heat treatment. Thermocalc was used to determine critical temperatures of WW-40. A tempering study was performed to determine the effects of tempering on the material properties ensuring a balance of hardness and toughness.

Manufacturing Process

Pattern Making

Once the gating and riser design was finalized and castable, the pattern (Figure 6) was made. Pattern components for the blade of the sword were 3D printed, while those for the gating were created with wood. Each piece of the pattern was sanded until it was smooth, and the 3D printed pieces of each half of the blade were assembled and glued together with methyl ethyl ketone. Then, each blade half was coated in methyl ethyl ketone to ensure that the pattern was smooth. To ensure that the blade was thick enough for the mold to fill, an 0.125 in. thick sheet of ABS was cut to the shape of the blade and glued to the bottom of each blade half. Then, the gating and blade pieces were positioned and glued to each side of the match plate.

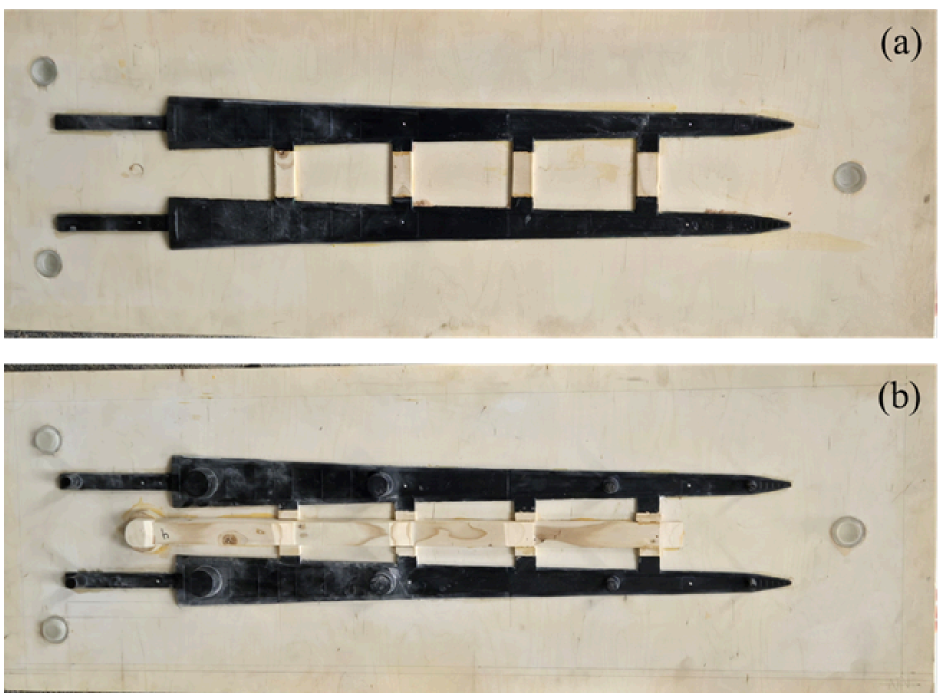

Figure 6: *Completed (a) cope and (b) drag sword pattern*

Three acrylic alignment pins were designed and manufactured to ensure that the cope and drag were aligned. The pins were sanded until they fit together well. Then, holes were drilled into the match plate and the pins were inserted and glued into place.

The hand guard pattern was 3D printed from its CAD model. It was cut along its length into two pieces, and two sheets of 0.125 in. thick ABS were cut to size and glued between the halves of the guard to reflect the change in thickness of the blade. The loose pattern for the hand guard was then sanded to smooth it out.

Mold Manufacturing

For casting efficiency, no-bake resin sand molds were used for both the blade and hand guard instead of green sand molds. This type of sand has a longer shelf life than green sand and allows for advance casting preparation. In contrast, green sand molds would need to be poured immediately. In addition, the surface finish with no-bake molds is superior to that obtained with green sand molds.

Once a mold box had been made for the blades, the pattern was used to create no-bake molds for casting the blade. Because of an error in pattern making where the risers were positioned on the drag, the risers were removed from the molds by filling them with sand. Each mold contained cavities for two swords, and two molds were created and filled for a total of four blades. This was done to ensure that the best possible sword would be completed and judged at competition.

No-bake molds were also created for the hand guard using the loose pattern. Because a loose pattern was used, the parting line for these molds was not plane. Instead, since the pattern was flush with the top of the drag, sand was dug out around the pattern to shift the parting line near the mold cavity to the center of the part. Three hand guard molds were created and filled with aluminum so the best casting could be used on the sword.

Casting

The four blades were cast under argon with a fill time of four to five seconds. The hand guards were cast with 356 aluminum.

Finishing

Once the blades had been broken out of the mold, a wire brush was used to remove the sand from the surface of the blades. The blades were then normalized at 1650°F for 12 hours, and once they were removed from the furnace and allowed to cool, they were cut from the gating.

Although the increased thickness of the blade allowed the mold to fill more easily than a thinner blade, the as-cast swords weighed about 8 pounds each and required significant grinding. A mill was used to reduce the thickness of the blade by 0.12 in. on each side. Then, angle and bench grinders were used to further reduce the thickness of the blade until it was below the 2 kg weight limit. The blade was then quenched and tempered. Once the heat treatment had been completed, polishing was performed.

The cast aluminum hand guards were broken out of the mold and allowed to cool. The best casting was removed from the gating, and the hole was filed until it was large enough that it could be pounded into place on the sword. The handle was made of olive wood in two halves. Once the hand guard was in place on the blade, the handle was wood glued onto the tang and clamped until it dried. The handle was then sanded to its final shape and the blade was sharpened.

Final Results and Compliance with Contest Requirements

The finished product was a steel broadsword with a weight of 1.88 kg and a double edged 30 inch blade. The wooden handle and aluminum guard add another six inches, resulting in a total length of 36 inches. These dimensions were in compliance with the competition limits of a 2 kg weight and 43 inch total length. Our casting was successful, and the finishing process revealed an aesthetically pleasing final product.

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Appendix

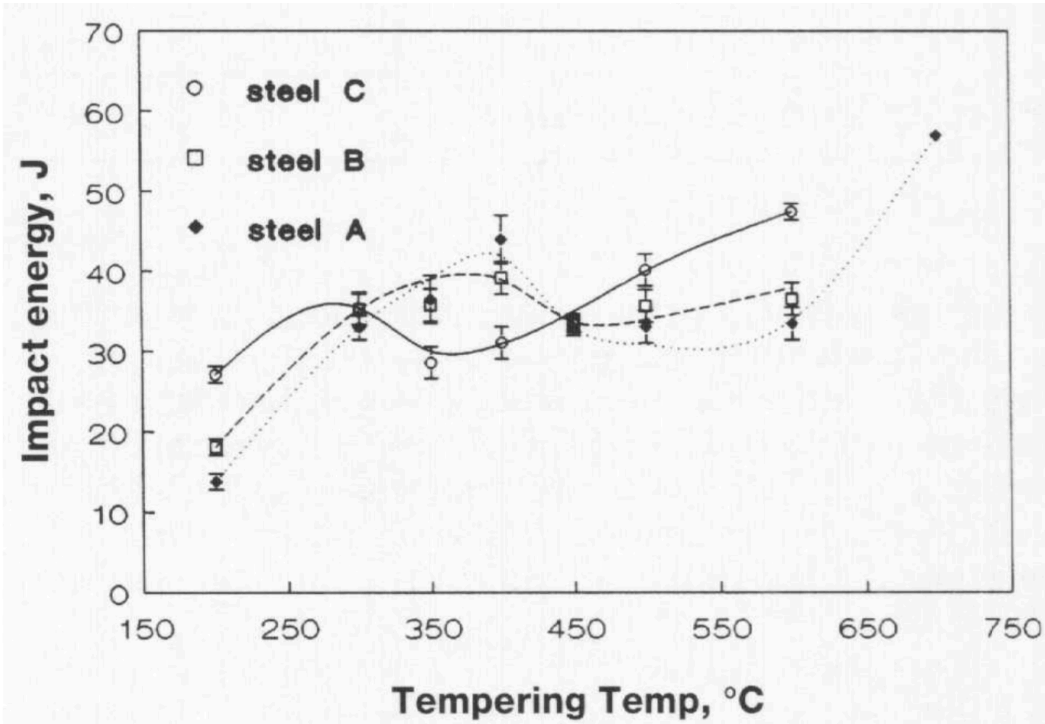

Figure 6, effect of tempering temperature on the Charpy impact toughness of steel alloys, the composition of steel C is given in table 1 [11].