SFSA Cast In Steel 2026 – Horseman's Axe Technical Report

University of Tennessee Knoxville – Unbridled Steel

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1. Introduction

The Steel Founders' Society of America (SFSA) Cast in Steel competition challenges university teams to design and fabricate a historically significant weapon using modern casting methods. SFSA has created this competition to encourage students to learn about making steel products using the casting process and applying the latest technology available. This year's objective is to produce a horseman's axe inspired by Robert the Bruce. The competition encourages teams to creatively apply casting techniques to items traditionally produced through forging methods. For this year's competition, teams must produce an axe that weighs less than 3.3 pounds and is no longer than 31.5 inches.

Team Unbridled Steel from the University of Tennessee, Knoxville, is entering the competition for the first time, and by any measure, it has been a strong start. The team consists of Materials Science and Engineering seniors, Sarah Graham and Elijah Hall, and Jake Officer, a PhD student conducting active research in casting. The team is advised by Dr. Dustin Gilmer. In their first year competing together, they have worked exceptionally well and produced results they are proud of.

The team moved quickly from concept to execution by building productive relationships with multiple partners in the foundry industry along the way. Through their connection with Magotteaux Pulaski, the team was introduced to Tennessee Investment Casting Company (TICCO Inc), which performed the casting for the project. Heat treatments were performed at Metal-Tech of Tennessee LLC, and finishing work was done at Replogle Armory which is the home of Jay Replogle, a Forged in Fire champion who specializes in medieval weaponry. This network of industry relationships provided the team with a broader perspective on casting practice and reinforced the value of industry collaboration at each stage of the design process.

The axe was produced using investment casting with 3D printed patterns, selected for its ability to reproduce fine surface detail and high dimensional accuracy. This report documents the historical research, design process, material selection, mold design, casting procedure, and post-processing steps undertaken by the team, as well as results from non-destructive evaluation and material characterization of the final casting.

The final axe from Unbridled Steel weighs approximately 2-1/4 pounds and measures 25-3/4 inches, meeting all SFSA competition requirements.

2. Historical Background and Design Inspiration

The 15th century was an era of great change for military combat. With the increasing use of sophisticated plate armor, traditional swords were no longer effective weapons for mounted combat [1]. Often, strikes would bounce off the armor, leaving the rider in a vulnerable position. This created the ideal conditions for the horsemen's axe to take center stage. The curved blade allowed riders to slash and easily remove the axe as they passed by their enemies, and a stout rear pick was instrumental in piercing and deforming thick plate armor [2].

In the Scottish context, this weapon is inextricably linked to Robert the Bruce's military success as the first King of Scotland. During the Battle of Bannockburn in 1314, he famously utilized a one-handed axe to defeat Henry de Bohun in single combat [3]. While Robert the Bruce's weapon preceded the refined 15th-century models, its effectiveness against a fully armored knight established the tactical blueprint for the horseman's axe in Scotland [4]. Our design reflects the transition to the mid-to-late 15th-century style, featuring a curved blade, a stout rear pick designed to penetrate hardened steel, and the use of languets to protect the wood handle from being damaged by enemy weapons.

2.1. Symbology and Heraldry

The axe's aesthetic is rooted in three interconnected elements of Bruce's legacy. The central motif is a European Garden Spider (*Araneus Diadematus*), referencing the legend in which Bruce, after six military defeats, watched a spider succeed in spanning a gap on its seventh attempt — an inspiration that sent him back into battle. The spider represents determination in the face of failure.

The spider is flanked by the Coat of Arms of the House of Bruce and knotwork from his tomb at Melrose Abbey, marking the axe as both a weapon and a memorial to Scotland's fight for independence. The "web" the spider descends from is rendered in Ogham Script, an ancient Gaelic alphabet used by the aristocracy to establish ancestral legitimacy, which translates to "Seven To Fight." These engravings were cut 0.025" into the face of the axe head, a level of detail achievable only through the combination of fused deposition modeling (FDM) 3D printing and investment casting.

2.2. Handle Construction

Medieval handles used a multilayered composite construction: a wooden core for vibration damping, wrapped with string for compressive strength, and finished in leather for grip. Our handle replicates this design using a hickory core, wrapped and finished in orange and white dyed cowhide leather in a checkerboard weave representing the University of Tennessee and reflecting the quality expected of a nobleman's weapon.

3. Material Consideration

3.1. Axe Head – 4140 Alloy Steel

The axe head material was evaluated against four criteria: castability, hardness, impact strength, and edge retention. After careful consideration of several alloys shown in Table 1, 4140 alloy steel was selected. Its fluid life, low inclusion formation tendency, and well-characterized pouring temperature make it well-suited for investment casting. The chromium and molybdenum content suppresses tempered martensite embrittlement, allowing 4140 to achieve the hardness range needed for bulk structural integrity while retaining sufficient toughness for repeated impact loading. Its edge retention properties allow a hardness differential between the bulk and cutting edge, maintaining sharpness of both the blade and pick.

Name	1060	17-4PH	4140
Castability (Qualitative/fluidity)	●●○○○	●●○○○	●●●○○
Hardness (Vickers)	●●●○○ (280-350HV)	●●●●● (400-450HV)	●●●●○ (350-450HV)
Impact Toughness (% elongation)	●●○○○ (~10)	●●●○○ (7-20)	●●●●○ (~25)
Cost ($)	●●○○○ (Carbon steel)	●●●●● (Cr/Ni/Cu alloy and precipitation hardening)	●●●○○ (Cr/Mo alloying)
Environmental Impact (Qualitative)	●●○○○ (simple alloy, easier to recycle)	●●●●○ (more alloying and energy-intensive processing)	●●●○○ (alloying and heat treatment)

Table 1 Comparison chart ranking of three steel alloys using a five-dot scale. More dots indicate higher performance for castability, impact toughness, and hardness while more dots indicate a less favorable outcome. Rankings are based on representative values found in literature and qualitative assessment.

3.2. Handle – Natural Hickory

Natural hickory was selected for the handle following comparative testing against Dymalux wood composite. While Dymalux offers high strength and dimensional stability, its stiffness resulted in mechanical failure under heavy loading conditions; a material that cannot flex transmits shock to the user rather than absorbing it. Hickory's combination of strength, toughness, and elasticity allows it to flex and recover under load, and it has been well-documented for use as handle material for impact tools which confirm its suitability for this application.

4. Casting Method and Value-added

Investment casting

Investment casting was selected as the manufacturing method because it clearly demonstrates how casting technology adds engineering, aesthetic, and metallurgical value that other methods cannot achieve. An overview of this process can be seen in Figure 1. First, 3D printing enabled the creation of complex internal geometry — specifically a hollow internal wedge within the eye — which mechanically locks the haft while reducing mass to stay within the 3.3-pound weight limit. This integral wedge is a feature that would be extremely difficult to produce by forging or machining. Second, the process delivers the exceptional surface finish required to faithfully reproduce the Ogham runes, the Bruce family crest, and the Dunfermline Abbey knotwork directly in the casting. This preserves the cross-sectional integrity of the blade, avoiding the stress risers that would result from post-process deep engraving, which is a direct manufacturing advantage over forging.

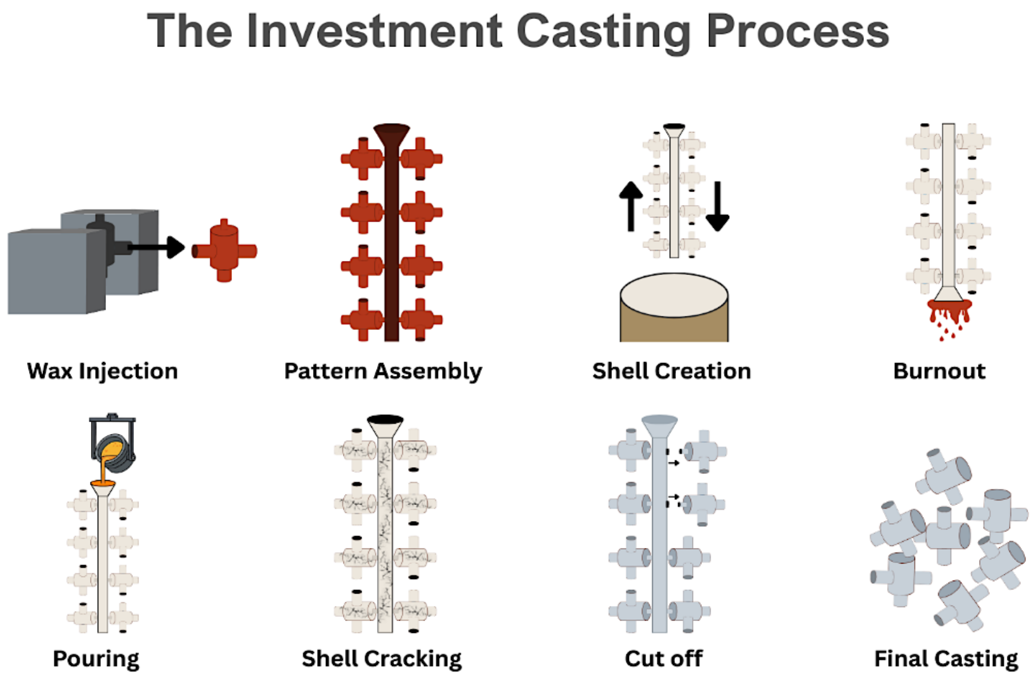

Figure 1 Overview of the investment casting process

5. Design

5.1. Blade and Edge Geometries

The forward blade uses an “appleseed” (convex) geometry. While less sharp than a flat or hollow grind, it provides superior durability for a chopping weapon. The blade has a gentle crescent profile to aid in cutting capabilities on horseback, like the Persian Tabar axe used in mounted warfare around the same period. The casting process requires the printed edge to be thicker than the final geometry, with the final edge profile refined during post-processing.

5.2. Back Spike

The armor-piercing spike uses an elongated diamond profile protruding two inches from the eye. Historically, this geometry was engineered to puncture and peel away plate armor upon impact, allowing deeper penetration on subsequent strikes. The gradual taper maintains a large cross-section to support the fine point. Fully utilized with the momentum of horseback combat, the two-inch penetration would be sufficient to breach plate, gambeson, and outer flesh.

5.3. Eye, Internal Wedge, and Languets

The eye has an elliptical cross-section for forward structural integrity and handle indexing. The axe was designed with an integral cast-in internal wedge that applies outward pressure against the handle, eliminating the most common failure point (wedge delamination) from repeated impact. A center hole accommodates a screw for additional securing if required. Two languets extend from the eye to protect the handle from glancing impacts and distribute interface forces, with their screw securements alternated to prevent stress concentration.

6. Casting

Casting was performed by TICCO Inc. in Bristol, TN, which specializes in low-volume, highly customized investment castings. Sixteen axes were produced in two rounds: one utilizing ceramic filters for controlled filling and one without, to assess whether filters would prevent filling in the thin languet sections. The gating system was assembled using runner wax sprues sized for the alloy volume and required metal head pressure, with venting channels to allow gas to escape and confirm cavity fill. The assembly was dipped in a latex-based slurry followed by zircon sand (3–4 coats for detail capture), then silica sand (5–10 coats for permeability and strength). The shells were then dried in stages – first in a humid environment to prevent cracking, then fully in a separate room before burnout. Burnout involved using a controlled furnace cycle to fully liquefy and drain the wax without causing thermal shock to the ceramic. The shells were then preheated before pouring. After each pour, TICCO's "sugar canning" process was applied: a sugar getter sealed in a metal barrel removes oxygen from the mold while the metal is still molten, ensuring good surface quality for 4140. After cooling, shells were broken off, gates cut, and castings sandblasted and belt-sanded before heat treatment.

7. Heat treatment

The competition axe combines industrial and traditional bladesmithing heat treatment techniques to produce a fully functional weapon. Industrial heat treating at Metal-Tech used electric fluidized bed furnaces with heated alumina oxide for efficient, uniform annealing, quenching, and tempering of the castings.

The axes were then taken to Forged in Fire champion and ABS Journeyman Jay Replogle for grinding and edge treatment. Axes were ground to shape while monitoring weight, then edge-hardened by torch-heating to the alloy's Curie temperature (1330°F) where the loss of magnetization serves as an intuitive temperature indicator for quenching. Blades were quenched in Park's AAA oil, then tempered and prepared for testing.

8. Non-Destructive Evaluation and Characterization

8.1. Computed Tomography (CT)

CT scanning was performed using a Zeiss VoluMax to reconstruct internal geometry and identify subsurface defects. The axe head design exhibited shrinkage porosity near the languets, attributed to insufficient feeding during solidification. The axe head design showed minimal defect volume with no significant cracking observed. Results for the chosen design are shown in Figure 2.

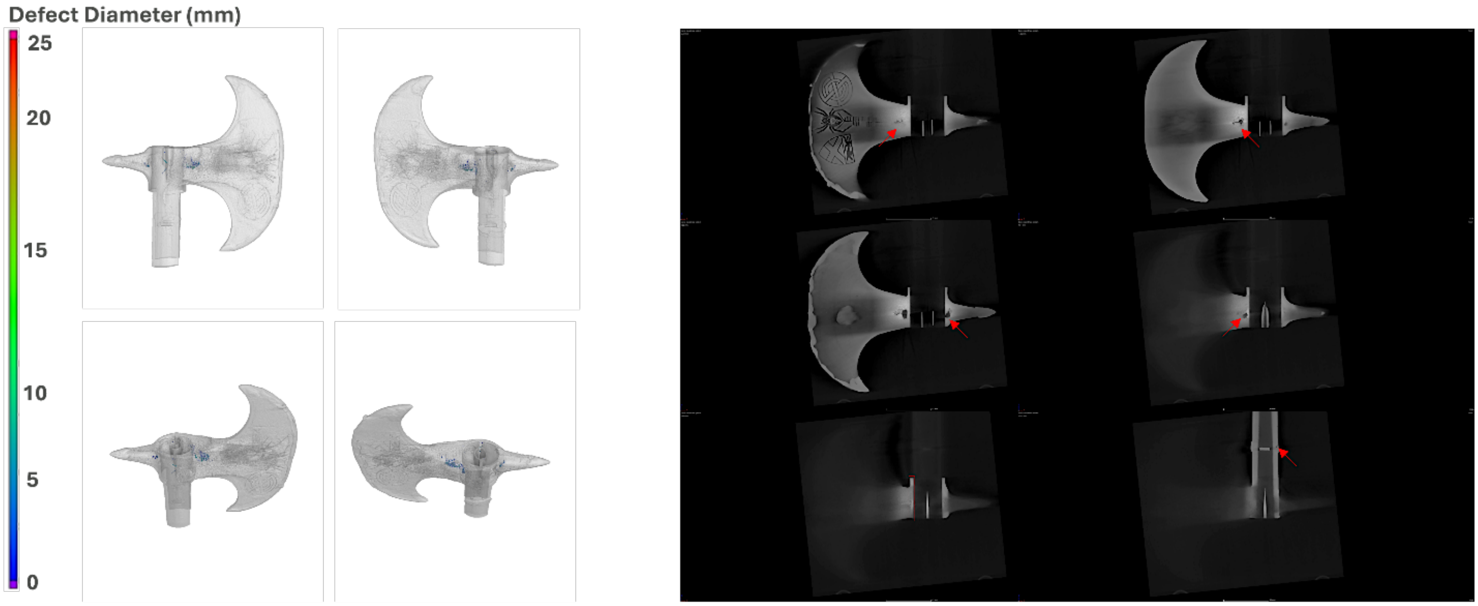

Figure 2 CT reconstruction data showing the range of defect diameters (left) and locations (right) for the axe head.

8.2. Microstructural Analysis

Specimens were sectioned from witness material cast concurrently with the axes, mounted, and prepared via standard metallographic procedure. Samples were etched with Vilella's reagent and examined with a Leica DMi8 M optical microscope. In the as-cast condition, 4140 exhibits coarse ferrite and pearlite with potential Widmanstätten ferrite morphology and dendritic alloying element segregation [5]. Following quench and temper, the microstructure consists of tempered martensite in the bulk and plate martensite near the edge as shown in Figure 3.

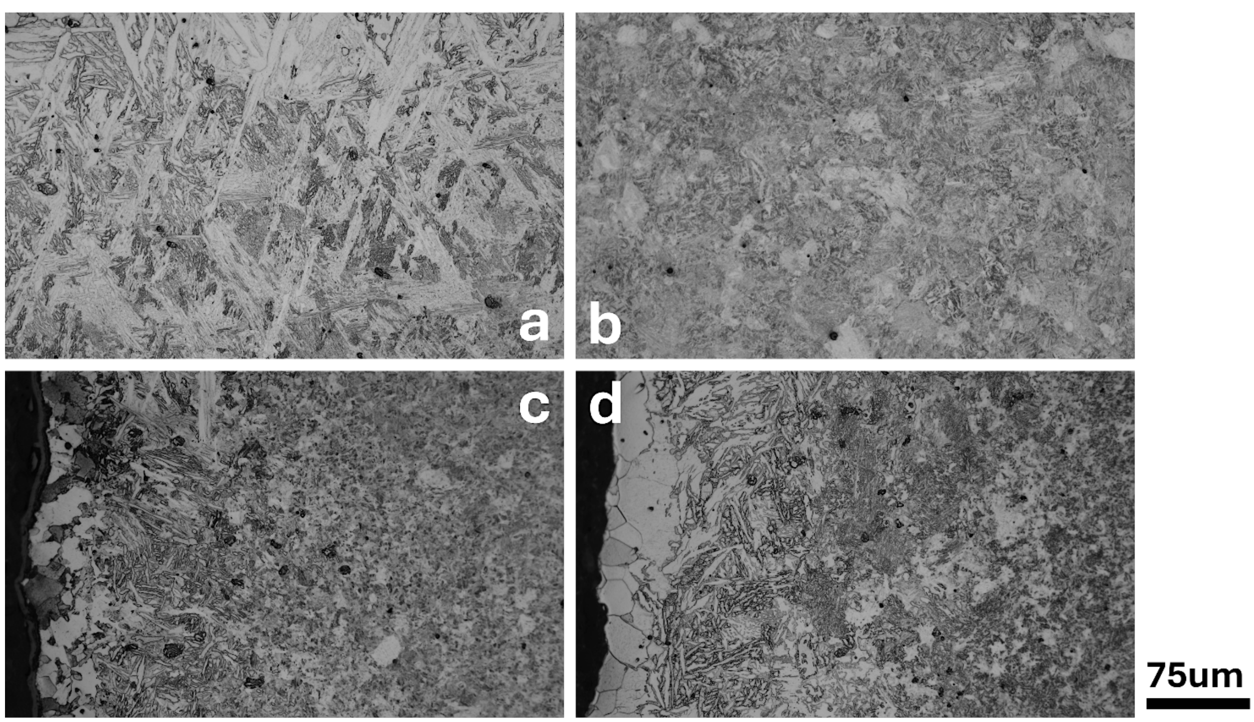

Figure 3 Representative microstructure of the plate martensite (a), tempered martensite (b), evolution of microstructure in both industrial (c) and journeyman (d) heat treatments from edge to bulk region.

8.3. Hardness

Vickers microhardness testing (HV0.5) was performed on witness material specimens using a Leco AMH55. A 5×5 grid of indentations characterized bulk hardness across castings, while linear vectors were used to measure the edge quenched regions. The results validate the microstructural analysis of the differentially hardened blade, where plate martensite along the edge geometry and back pick measured higher hardness than the tempered martensite found in the bulk of the axe head. The hardness variation between samples as well as the differences between bulk and edge hardness are plotted in Figure 4.

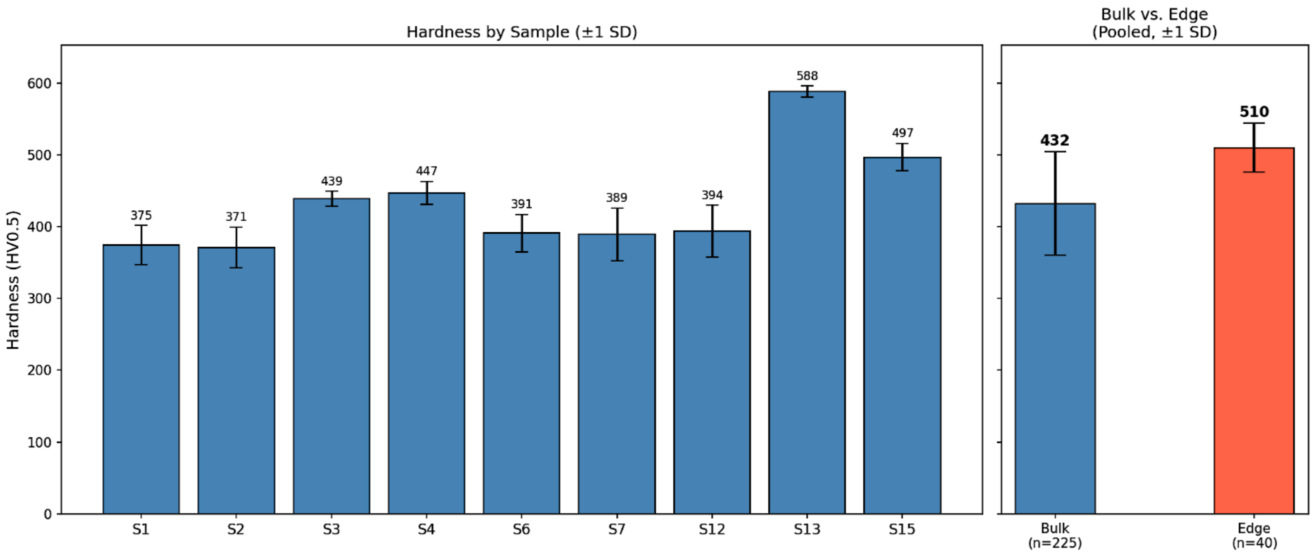

Figure 4 Bar chart showing the variation in hardness between samples (left) and the comparison of cumulative bulk hardness and edge hardness (right).

8.4 Summary

Material characterization using CT scanning, optical microscopy, and microhardness testing confirmed that the axe design, alloy selection, and heat treatment are appropriate for this competition. CT identified shrinkage porosity near the languets; microstructural analysis confirmed tempered martensite consistent with the heat treatment conditions; and hardness testing confirmed bulk hardness within the target range for this application.

9. Physical Testing and Final Assembly

The team originally had two designs: a full axe with tang and an axe head. Throughout the production, analysis, and non-destructive testing phases, both axes performed equally well with each having its own advantages and disadvantages. To decide which axe would be the best for competition and to analyze the performance of the axes, they were subjected to a series of physical tests and evaluated by each member of the team regarding: maneuverability, comfort of the user, and overall damage delivered.

9.1. Impact Testing

The back spike of both axes was subjected to the following tests: penetrating a mild steel electrical box and 1/8” thick aluminum plate to simulate plate armor, a block of 8020 aluminum to test for thicker materials, and a 2’x4’ wood block to simulate shield material. The damage delt by each axe was consistent with the primary difference being the full axe also delt some additional bending damage to the electrical box due to the metal handle. However, the full axe also taxed the user's arm relatively quickly, and the speed of the swing was reduced by the increased weight. During this testing it was also found that the Dymalux wood would not be the best handle material due to its stiffness.

9.2. Edge Retention and Sharpness

The forward edge of the axes was tested in the following ways: slicing hanging vegetables, 1.5” thick rope, wood, and plate. Each axe again performed well with these tests, but the axe head design performed better at cutting the rope due to its lighter weight and wieldability.

9.3. Horseback Testing

To get a real sense of how the axes would be able to be used on horseback; they were taken to a farm and tested while on horseback. While the testing was cut short due to weather and horse temperament, the testing was enough to conclude two things: the axe head design was much easier to use on the horse and allowed the rider to maintain better balance and the teams chosen handle design allowed the axe to be easily stored side saddle.

9.4. Selection and Final Assembly

Based on the results from the physical testing and recommendation from a blind test group, the axe head design was chosen with a hickory wood handle.

The handle was wrapped using a traditional method which involved first using string and resin to create a strong foundation and to help hold the handle together if it cracks. Next, orange and white leather were soaked in a glue and water moisture and hand woven around the handle in a checkerboard handle. As the leather dries, it shrinks and is adhered to the handle and is further secured by the glue as it dries. Next, the handle was laser engraved with the logo of the university and companies that assisted the team to showcase the collaboration that led to the success of the project.

The axe head was mounted on the handle and sharpened using an antique grindstone provided by one of the team members' family. This was not only historically accurate to how these axes would be sharpened but also provided an incredibly sharp edge. Finally, the axe was polished and the inspected to ensure everything was in optimal condition.

Acknowledgements:

Team Unbridled Steel would like to thank the following people for contributing their time, patience, and expertise to this project: John Cory, Jack Hurst, David King, Jay Replogle, Julio Ortega, Vincent Heffren, and Olivia Fowler (and Sadie)

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Appendix

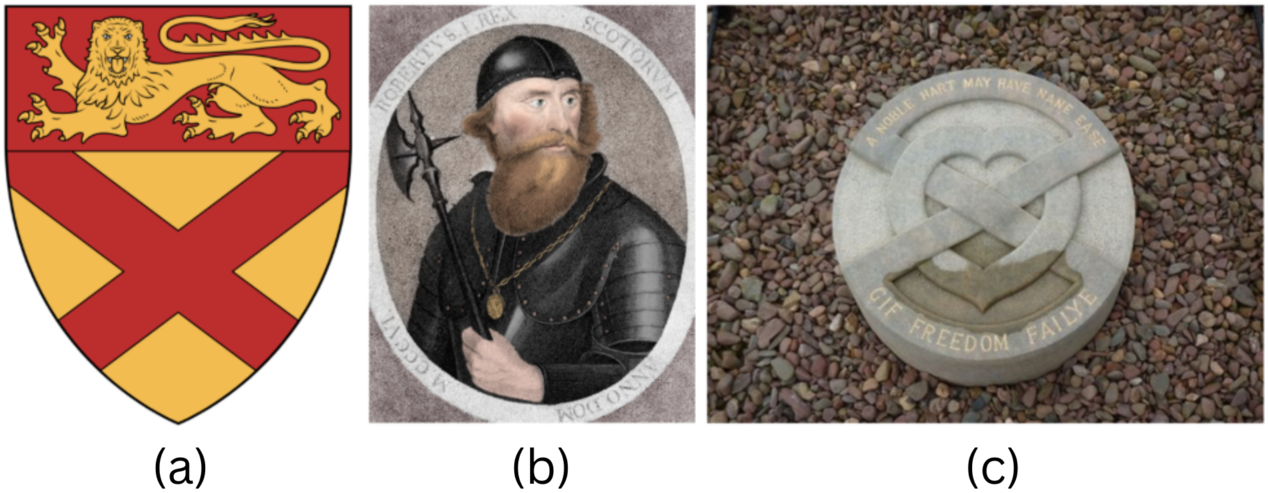
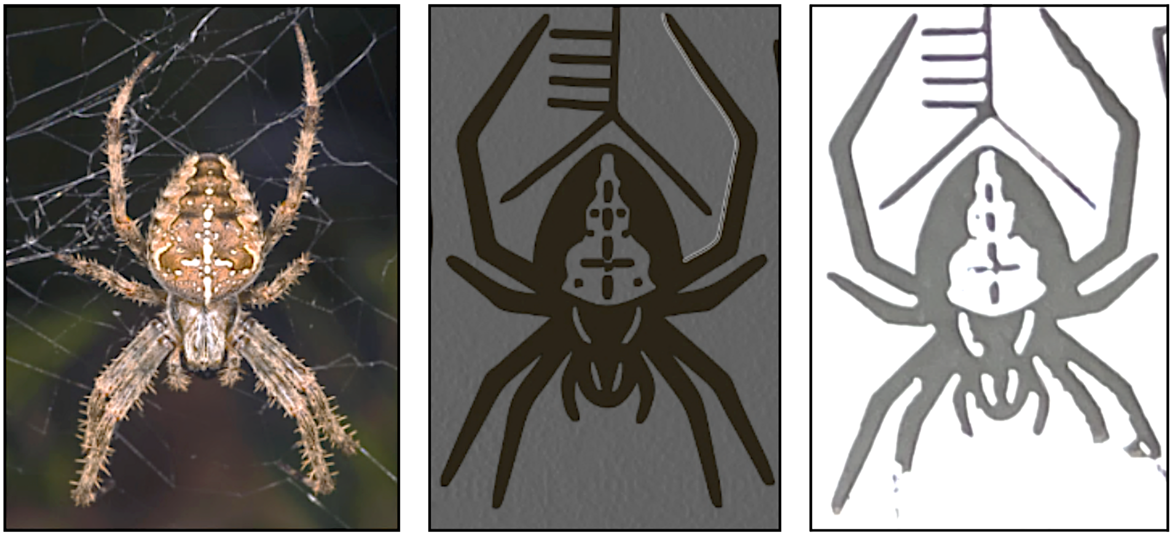


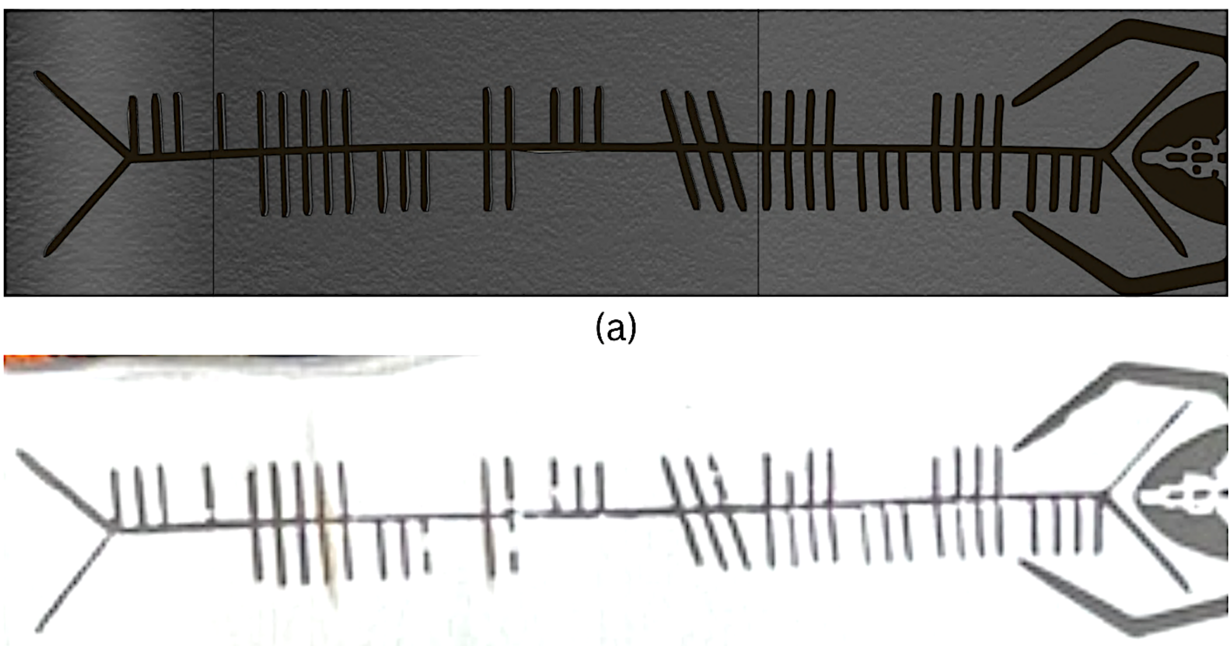
Fig. A1. Robert the Bruce: (a) House of Bruce coat of arms [7], (b) historical engraving [8], (c) heart burial marker at Melrose Abbey [9].

Fig. A2. Medieval battle axe designs: (left) horseman's axe, circa 1540 [10], (right) European battle axe, 13th-15th century [11].



(a) (b) (c)

Fig. A4 A*raneus Diadematus* spider(a) CAD design(b) and final casting (c)



(b)

Fig. A5 Ogham script CAD (a) cast ogham script (b)

Fig. A6 Woven leather handle with orange and white checkerboard pattern

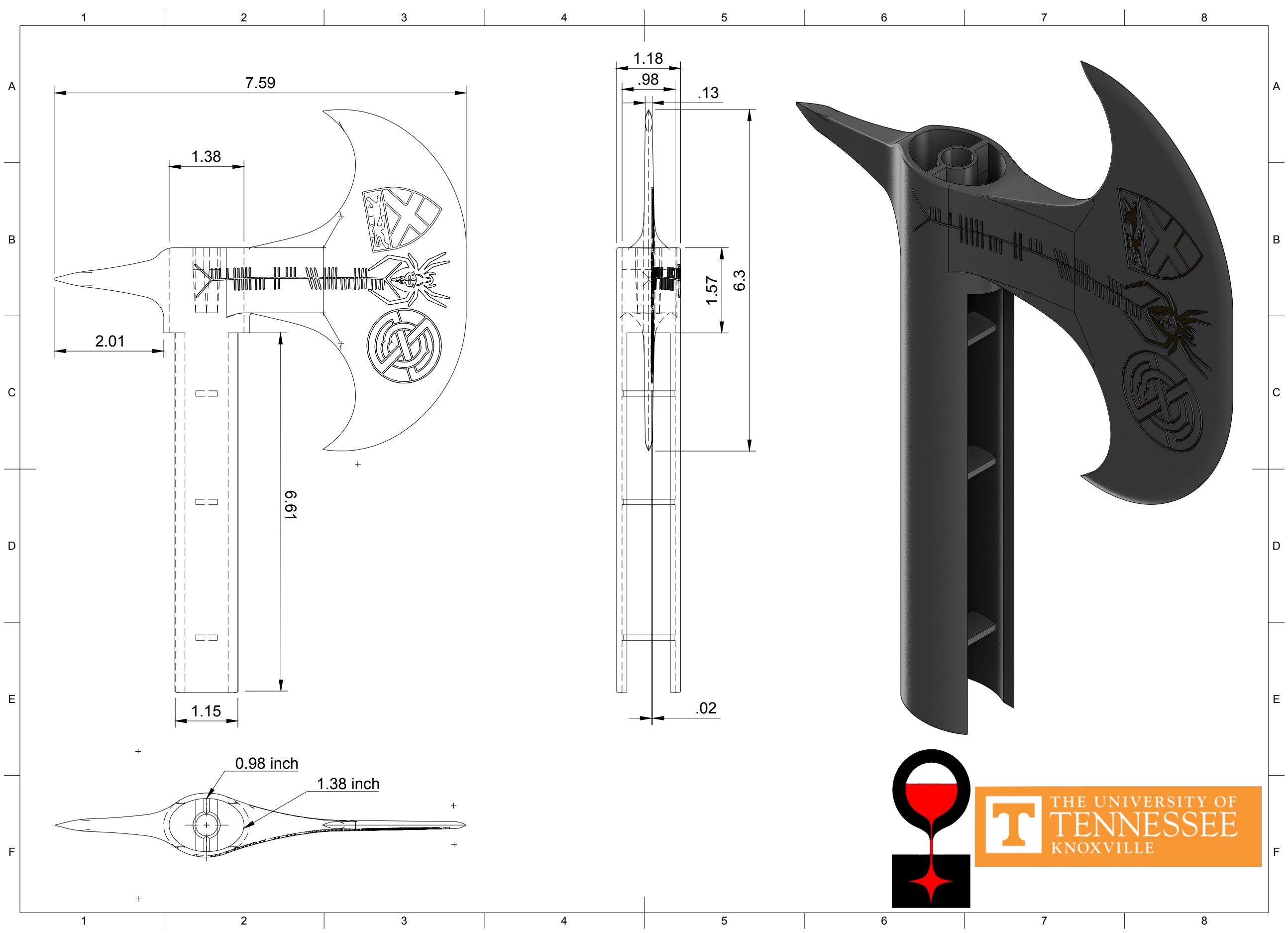
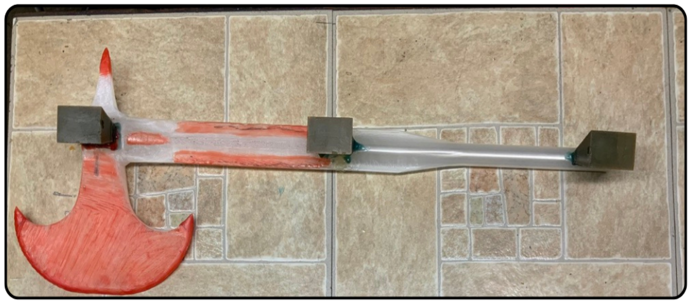
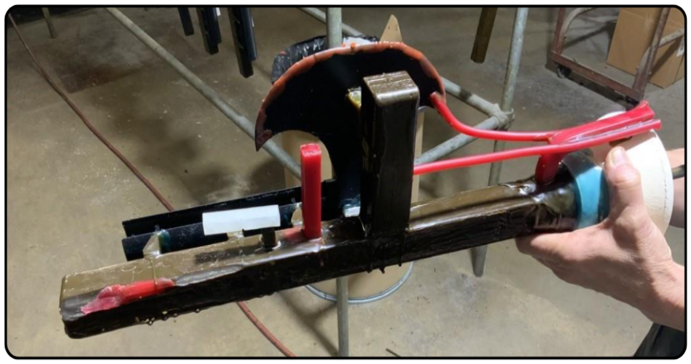


Fig. A7 CAD schematic of axe head



(a)



(b)

Fig. A8 pattern with mounted gates (a) and completed gate system (b).

Fig. A9 Latex based slurry mixer

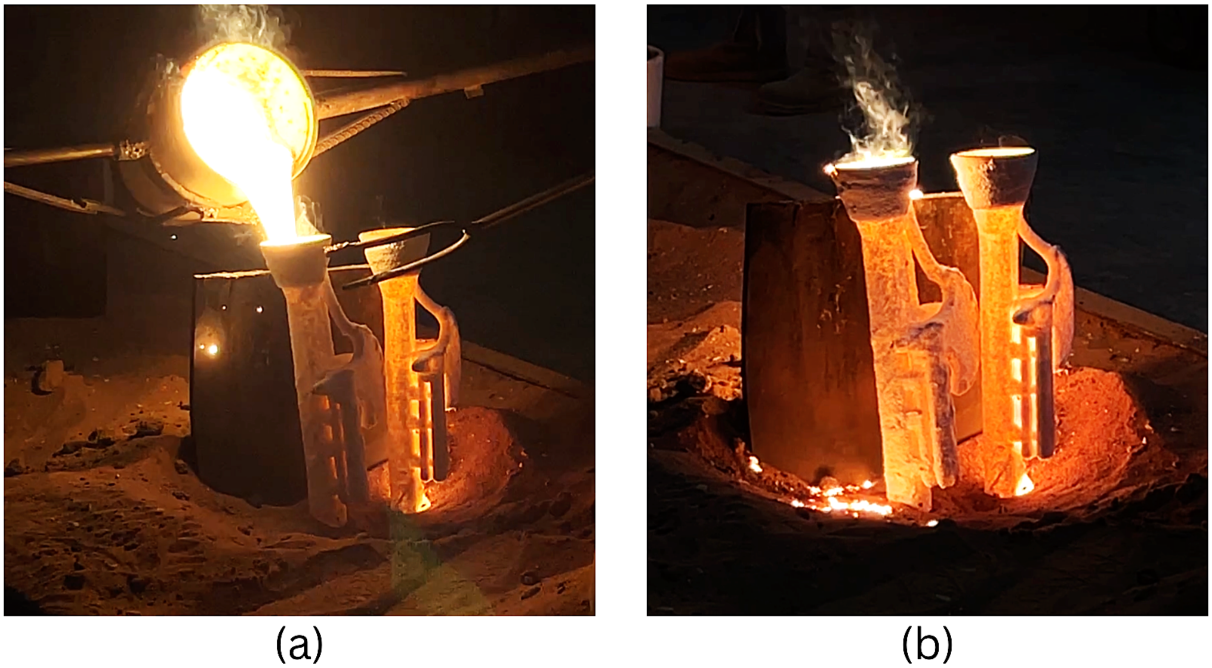


Fig. A10 Axe head molds being filled (a) and solidifying (b)

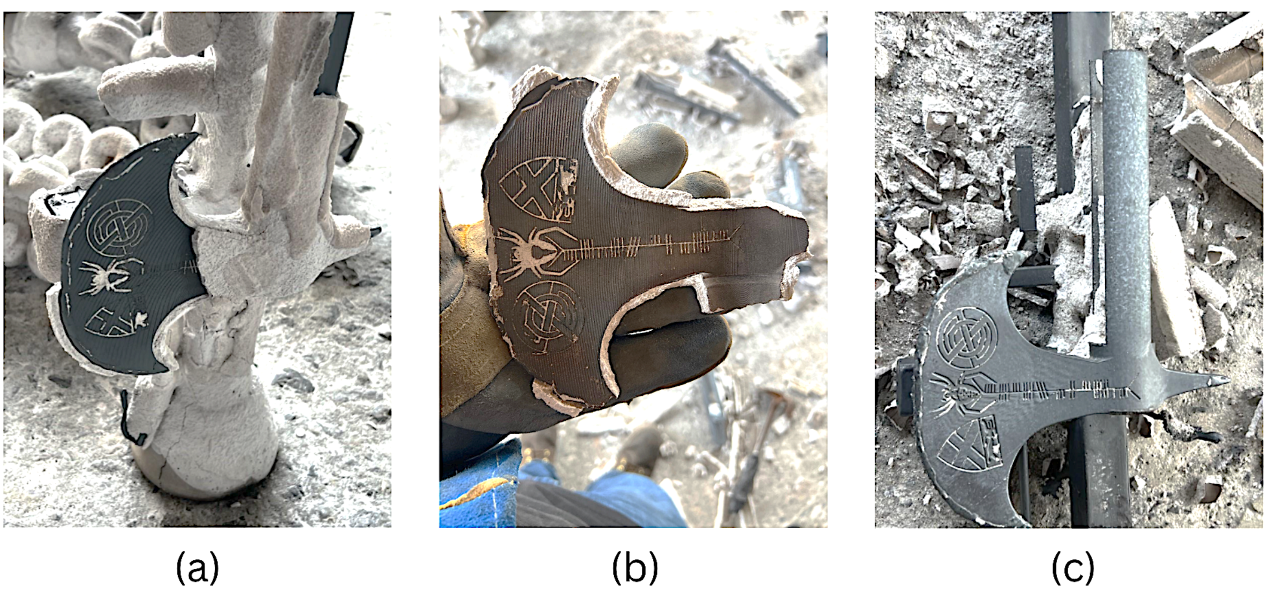


Fig. A11 Shell being broken apart(a) details left in shell (b) completely deshelled axe head (c)

Chemical composition	C	Si	Mn	P	S	Cr	Cu	Mo	Ni	V
	0.38	0.23	0.64	0.019	0.013	0.99	0.17	0.16	0.08	<0.01

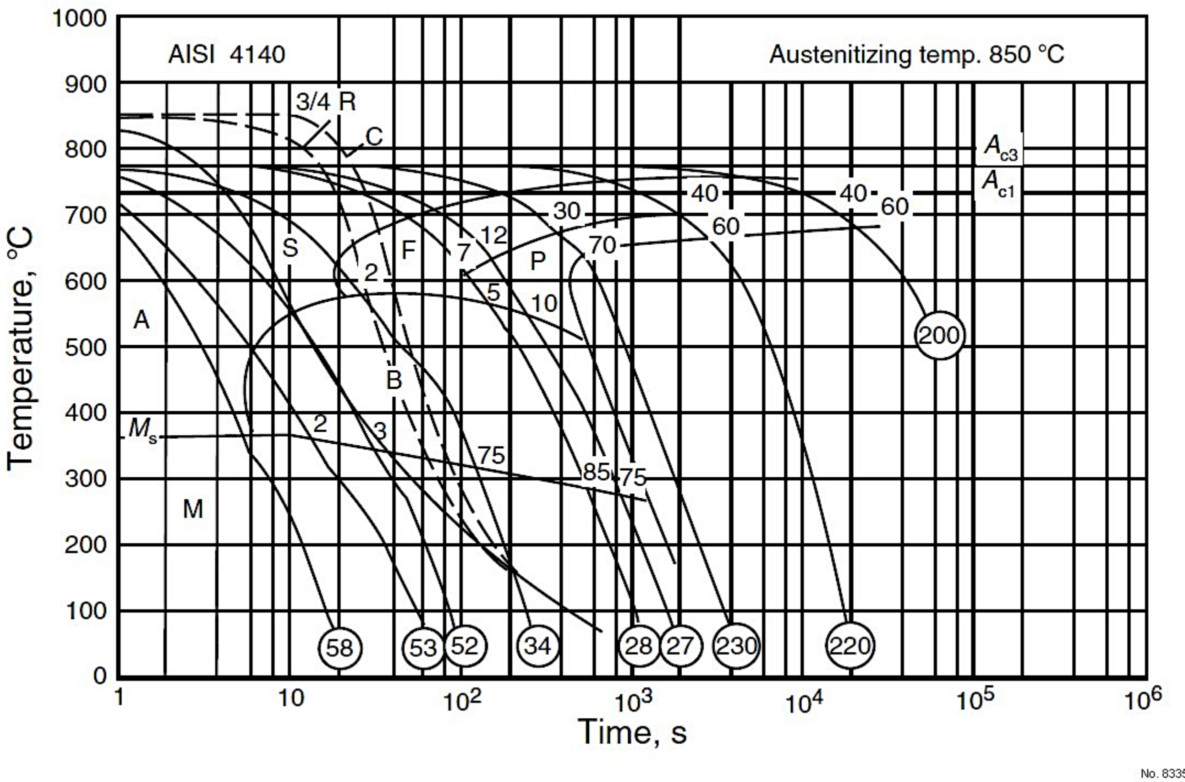
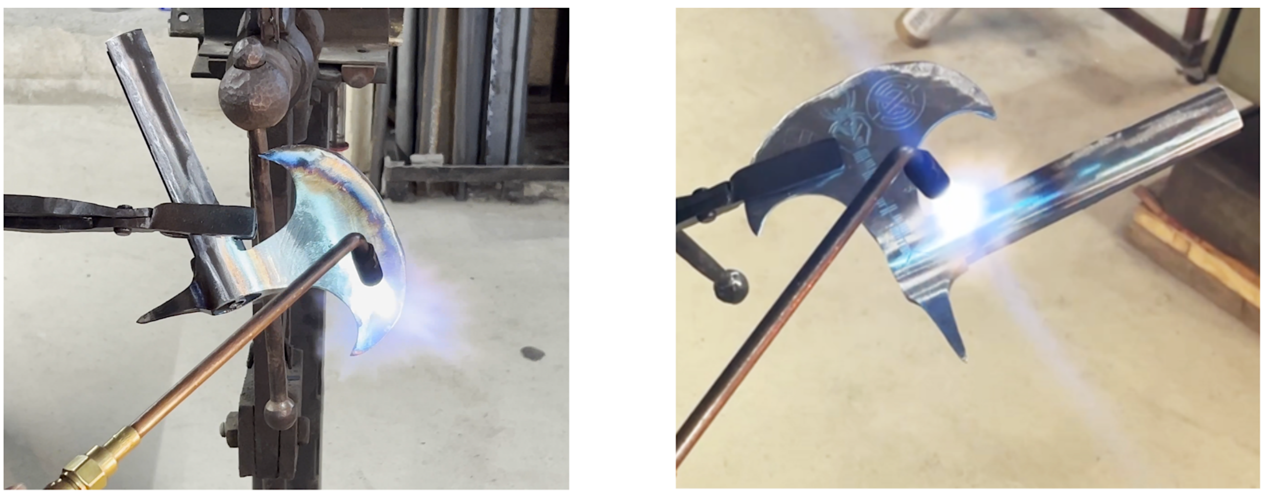


Fig. A12. CCT diagram shows composition of 4140, the temperatures and times for the transformation of austenite to martensite, and the Rockwell C hardness expected for that microstructure. Reprinted from [6].

Fig. A13 Fluidized alumina oxide heat treatment furnace

(a) (b)

Fig. A14 Grinding (a) and filing (b) of the axe head for finishing work



(a) (b)

Fig. A15 Blade (a) and back spike (b) differential heat treatment

Fig. A15 Impact testing of back spike against steel plate electrical box

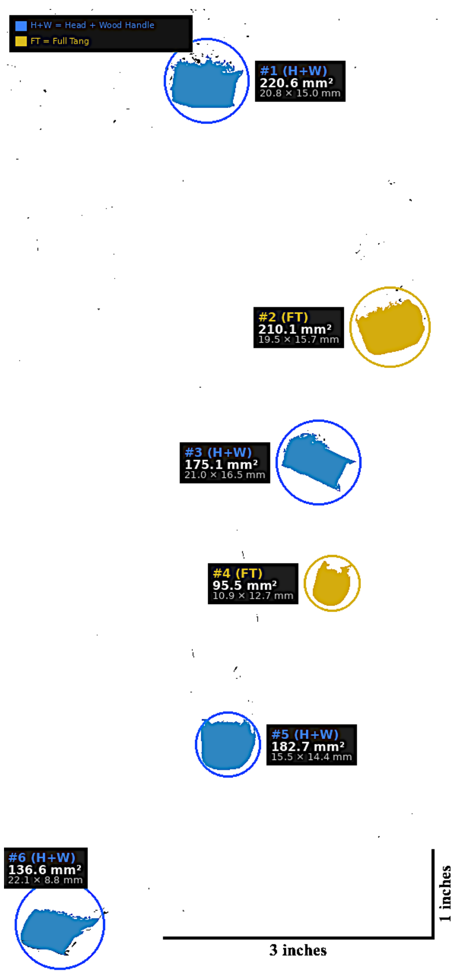


Fig. A16 AI-assisted analysis of impact testing

Fig. A17 Olivia testing the horseman's axe with Sadie

Fig. A18 Axe mounted side saddle

Fig. A19 Woodburning of university and industry partner logos

Fig. A20 Finalized axe