

Bladesmithing at South Dakota School of Mines and Technology

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A Damascus-style layered blade was made by incorporating bloomery iron and crucible steel. A bloomery furnace was constructed and charged with Black Hills, SD bog iron ore, alloys, and hardwood charcoal. At sufficient temperature, the furnace was bottom-tapped to produce a low carbon iron bloom. A high-carbon crucible steel was made in a natural gas-fired furnace using commercial hematite pellets and coke. The steel was cast into sand molds. The two types of iron/steel were forged together using traditional blacksmithing techniques in a coke-fired forge. The forging process continued until the metal could be evenly worked, signifying the homogenization of the two metals. Once homogenized, the metal was shaped into a blade and subsequently ground into near-final shape, heat-treated, and finish-machined. The microstructure and mechanical properties of the blade were characterized using optical microscopy, hardness and tensile testing. The grain structure of the material varied widely and was not entirely homogenous at the welded layers, but the layers themselves were well-homogenized. The finished blade was compared to a common steel (1095) used for bladesmithing and was found to have similar hardness but significantly lower tensile strength.

INTRODUCTION

The objective of this work was to incorporate local Black Hills, SD iron ore into a blade for entry into the TMS Bladesmithing competition. Students recreated two processes of important historical significance: bloomery iron and crucible steel. This paper describes the methods used to make steel for the blade along with the challenges of subsequent thermomechanical processing.

Bloomery Iron

A common method of making iron is through the use of a combustion furnace in which the energy from the exothermic reactions of fuels such as coal or coke with the material (iron and other metals) themselves along with a key component of oxygen to produce enough heat to reduce iron oxides. The following reaction series will take place to produce metallic iron:

- Hot air and coke:



- Reduction of iron oxide with Carbon monoxide (CO).



Students constructed a Catalan-style bloomery furnace is shown in Fig. 1 to make bloomery iron. The furnace consisted of a brick base (plinth) and a refractory stack composed of silica sand, kaolin clay, and cellulose in the form of peat moss.¹ These components were mixed in proportions consistent



Fig. 1. Rigorous dry-out fire.

with literature values and then water was added. The refractory was then kneaded, compacted into balls, and set aside. A form was made from a circular section of plywood and long wood laths in a process akin to the making of a barrel. The form would be later burned out during the dry-out process. The form was then placed on the plinth and leveled. The refractory was made into small bricks, $2\frac{1}{2}'' \times 2\frac{1}{2}'' \times 2\frac{1}{2}''$ (c. $5 \times 5 \times 5$ cm), and placed in circular courses around the form. After each course was finished, a piece of twine was wrapped around the furnace wall to prevent the refractory from slumping. This was repeated until the furnace stood $36''$ (c. 91.5 cm) tall. A buttress (additional refractory for support at the base) was then put around the bottom of the furnace, leaving off $10''$ (c. 25 cm) around the circumference to allow for the tapping arch in the front. The tapping arch is $10''$ (c. 25 cm) wide by $10''$ (c. 25 cm) tall at the peak. The tuyere was placed 90° to the tapping arch, slightly above the peak of the arch, and angled downward at 25° . In order to prevent cracking, the furnace underwent a dry-out consisting of slow initial heating and then an extended high-temperature firing for 2 h, resulting in the refractory baking hard.

In preparation for the furnace run, 90 kg of commercial hardwood charcoal was broken and sized to approximately $<1''$ (c. 2.5 cm) and $>1/4''$ (c. 0.6 cm). The ore, a combination of a local bog iron ore (75%) and commercial iron ore (taconite pellets) pellets (25%), was crushed to $2/8''$ (c. 0.95 cm) or finer until 90 kg was prepared. Iron content of the local ore was unknown, so it was reasoned that a combination of the local ore, flux-forming limonite, and the iron-rich taconite pellets would yield the best chances of

success. The sizing of the ore is a critical piece to allow hot gasses to flow through the stack. A tuyere approximately $10''$ (c. 25 cm) long was made of a 50/50 wt.% mixture of Kaolin and silica formed around a $7/8''$ (c. 2.2 cm) dowel. This refractory mix was then fired at 900°C to produce a tuyere of approximately 79% silica and 21% alumina. Initially, the furnace was completely filled with several charges of hardwood charcoal not included in the 90 kg and fired to bring temperature up slowly and then to a high fire. The charges were then added in alternating batches of approximately 9 kg ore and 9 kg charcoal. A sight-glass in the tuyere was utilized to determine the appropriate times to tap the slag. After the slag tap (removal of viscous gangue material), the arch was sealed back up and ore and charcoal were charged as before. Several more slag taps were performed during the remainder of the smelt (when judged necessary) to keep the slag below the level of the tuyere. Also, the tuyere would periodically be cleared of solidified slag through the use of a thin iron rod inserted through the sight-glass port. After 78 kg of charcoal had been added, the furnace was nearly full, so it was determined to start the burn-down process. The final charges were added and the furnace burden was allowed to burn down. After the furnace burned down to just above the level of the tuyere, the extraction of the bloom was started. The tap arch was removed, and the charcoal fines were removed from beneath the bloom. The bloom was then pried from the furnace and, while still hot, compacted with sledge hammers on a wooden stump. The bloom is easier to work when it is still at such a high temperature and would take significant energy to reheat to forging temperature. The compaction process helps to push slag and other impurities out of the cavities in the bloom, but must not be overworked or it will crack and break apart. The bloom was then split in two for convenience. A small section of the bloom was removed, mounted, polished, and then etched with 2% nital solution. Through metallographic analysis, it was found that the bloom contained significant slag inclusions, as can be seen in Fig. 2.

A small section piece of one of the two bloom pieces was removed. This was brought to a white heat and compacted to a thin strip, resulting in the microstructure found in Fig. 3. This compaction, in line with traditional methods of bloom processing, resulted in a drastic shrinking of the slag inclusions.² Since the microstructure shown in Fig. 3 consists primarily of ferrite, this means that the bloom, at least in this section, contains very little carbon. However, the bloom is very heterogeneous, as qualitative "spark testing" suggests that there are sections of higher carbon content. A larger section of the bloom had to be forged into a billet, folded several times to approximately $2'' \times 12'' \times 1/4''$ (c. $5.0 \times 30.5 \times 6.4$ cm) and the carbon content homogenized before a clear understanding of the composition could be determined.

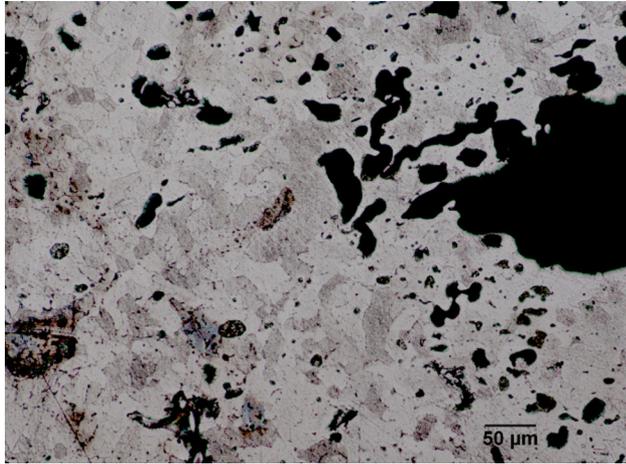


Fig. 2. Micrograph of bloom showing the darker portions as slag and inclusions where the lighter portions show metallic iron primarily ferrite.

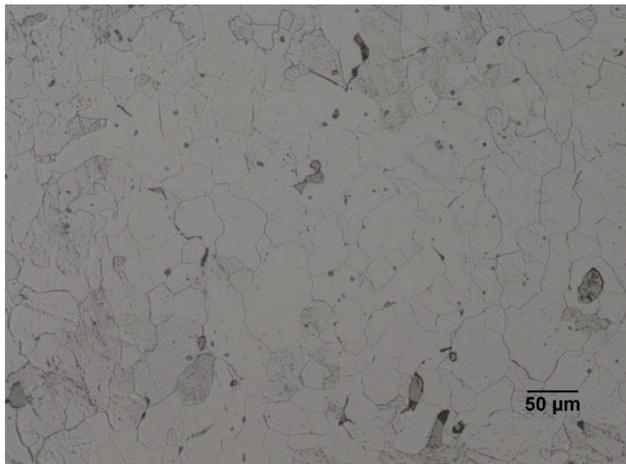


Fig. 3. Cross-section of compacted bloom primarily ferrite with small slag inclusions.

Crucible Steel

The steel-making portion of the project was then commenced. The charge for the crucible was composed of pieces of bloomery iron, white cast iron, black oxide of manganese, and metallic silicon as seen in Table I. The carbon content of the white cast iron was inferred from the ASM handbook by comparing microstructures of white cast irons of known composition. The book *The Steel Foundry* by J.H. Hall was used as a source of experimental data.³ These data were used to infer the expected amount of carbon taken in by the graphite crucible, and to determine the amount of silicon and manganese dioxide to add. The components of the charge were placed in a clay-bonded graphite crucible and placed in a portable caster for firing.

Because carbon is the primary compound that chemically strips oxygen from iron, the entire smelting process must be kept in an oxygen-deficient state

Table I. Crucible charge

Charge component	Amount
Iron from bloom	1850 g
Slag from bloom	443 g
White cast iron	180 g
Manganese dioxide	3 g
Silicon	5 g
Carbon from crucible	~ 0.4 wt.% of melt

to promote the burning of carbon to produce CO instead of CO₂, as in Eq. 1. This was done by using a flux. Melting a flux will create a liquid barrier that allows gas to escape but not to enter the melt, while also bonding to impurities in the raw material. The flux used was composed of 1 part SiO₂, 2 part CaO, and 0.53 parts Al₂O₃. The resulting mix possessed an approximate melting point temperature of 1250°C and a basicity of 1 as determined by a ternary phase diagram. Since the flux was largely made of silica, it will have minimal effect on the clay comprising the crucible. The heat source for the furnace was the combustion of propane and air. The air was preheated by burning oak charcoal in the preheater. The furnace was started first on low power and heated slowly to approximately 600°C to allow for the new crucible to be seasoned according to the manufacturer's recommendation.⁴ After this, the crucible was brought to full power and maintained at a temperature of 1450°C, at which point the air-preheater was started. The furnace then reached a peak temperature of 1550°C. The temperatures were monitored closely using an optical pyrometer and a view port in the furnace to ensure sufficient casting temperature and minimal damage to the furnace. Preparations were then made to cast the crucible charge into a bar. Preparations were then made to cast the crucible charge into a bar. The product was poured into a cinder block that was lined with kerosene soaked casting sand. The product was poured into a cinder block that was lined with kerosene-soaked casting sand. When cooled, the block was broken to free the metal.

Forging

Both the crucible steel and the bloomery iron were broken into pieces and forged into small strips. The pieces were then placed into a 24-gauge 4" × 4" × 10" *c.10 × 10 × 25.5 cm) steel box with thin strips of wrought iron until the box could not fit any more material. This was done because the raw materials of the bloom and crucible steel by themselves were too porous to possess good workability. The pieces were layered so that there was wrought iron inbetween the pieces of bloom and crucible steel to act as an intermediate "glue" increasing forge-weldability. Once placed in the box, it was welded shut with a borax glass flux inside to aid in forge-



Fig. 4. Top Forged blade, bottom semi-finished blade.

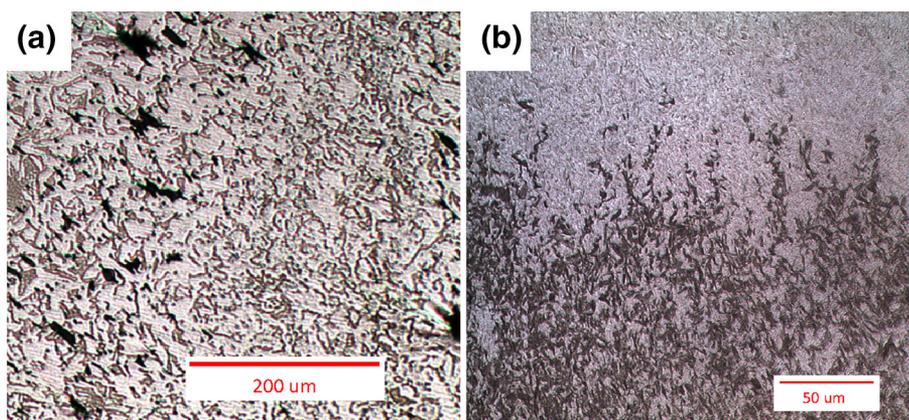


Fig. 5. (a) Quenched martensitic grain structure and (b) tempered martensite grain structure.

welding and placed in the forge. The box ensured all the metal stayed together but was thin enough to oxidize and burn off during the forging process. An iterative process of drawing out the steel, cutting it into sections, and stacking those sections on top of each other before forge-welding them together allowed for the homogenization of the steel into a single bar, later cut and used for the blade and samples.

Once the bar was solid and partially homogenous, the steel was twisted to form a mechanical joint as well as a metallurgical bond between the layers. However, in the beginning stages of forging, the steel was prone to cracking. It is speculated that this cracking behavior could be caused by the large amounts of phosphorous, sulfur, copper, and manganese present in the material, as discussed later in the Results section. After several folds and twists, the steel was homogenized enough where it no longer cracked. At this point, the steel contained an estimated 700,000 layers, the count being estimated by calculating the times the layers were cut and stacked and re-forge-welded each time increasing the number of layers by the layers stacked; the twist was not accounted for in the number of layers. The bar was then ready to be shaped into the knife blank shown in Fig. 4.

Rough Machining

After the forged blank was formed, a rough machining of the final design was performed. The knife was ground to a bowie knife shape, machining out spots for the guard and flattening the blade to allow secure handle and bolster attachment as seen in Fig. 4. The blade was not ground to final dimensions at this point since the blade still needed to be heat-treated. The heat-treating process oxidizes the surface and has a tendency to warp the material.

Heat Treatment

The steel was heat-treated by heating in an electric resistance furnace set at 815°C and quenched in hot oil producing the martensitic structure shown in Fig. 5a. These temperatures were chosen based on literature values for steels of similar chemistry.⁵ Heat treating at 815°C with a 100°C oil quench produced a hardness of 65 HRC in the harder zones and 45 HRC in the softer zones. The samples were then tempered at 220°C for 1 h. Figure 5b shows the microstructure that was achieved after the tempering process converted the original martensite to tempered martensite. The hardness of the tempered martensite areas was measured to be approximately 60 HRC. The final



Fig. 6. Top Blade prepped for etching, bottom etched blade revealing pattern.

Table II. Blade billet chemistries

%	Bloomery and crucible	Bloomery and crucible with wrought iron	Bloomery and crucible with wrought iron	Wrought iron
C	1.34	0.98	0.36	0.08
Mn	4.02	0.88	0.27	0.20
Si	2.46	0.87	0.21	0.28
P	0.000	0.028	0.008	0.025
S	0.060	0.035	0.174	0.010
Cu	0.25	0.28	0.12	0.40
Mo	0.081	0.023	0.364	0.000
V	0.081	0.044	0.050	0.003
Ti	0.077	0.0415	0.0047	0.0092
Al	0.747	0.140	0.049	0.024
Nb	0.196	0.070	0.004	0.000
B	0.950	6.250	0.069	0.012
Ca	0.101	0.083	0.030	0.014
Fe	89.35	90.10	97.63	98.88

blade was tempered for an additional hour, forming a larger percentage of tempered martensite to reduce brittleness and increase toughness.

Finishing

Hand-grinding was performed and the attachment of the bolster, guard, and handle were performed after heat treatment. Care was taken to make sure that the temperature during final grinding did not surpass the temperature used during the tempering process to prevent microstructural changes. The blade was polished to a mirror finish before an etchant was used to reveal the pattern in the steel shown in Fig. 6.

RESULTS

The forging process resulted in various billets that were folded together to produce the final billet. A total of four samples were analyzed by mass spectroscopy shown in Table II: one was from a billet of bloomery plus crucible steel (column 1), a second was from a billet of wrought iron (column 4),

and two were from billets of a combination of all three materials (columns 3 and 4). Column 1 contains the bloomery and crucible iron in the starting stages of the forging process. Because of the very high carbon content and lack of forgability, the wrought iron (column 4) was added. Before homogenization was completed, the billet broke into two pieces because of its brittle nature. Columns 2 and 3 are the chemistries of the separate pieces and indicate how heterogeneous the billet was during the initial forging stages.

Figure 7 depicts a macrograph of the initial billet showing the different high (darker) and low (lighter) carbon areas. The sample was etched with a 3% nital solution revealed the different layers of steel. After macroscopic examination was completed, micrographs were taken of the billet after some forging had occurred. Figure 8 shows the different layers of the preheat-treated billet in greater detail. It has been deduced that the center white band came from the wrought iron since it did not contain enough carbon to produce anything but ferrite. The darker areas are the bloom and crucible steel, which



Fig. 7. Macrograph of layered steel.



Fig. 9. Finished blade.

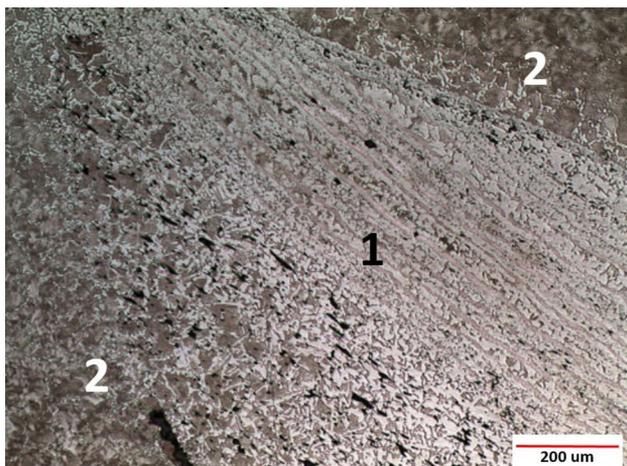


Fig. 8. Micrograph in forged condition area 1 shows the lower carbon area likely produced by the wrought iron where area 2 shows a high carbon content with more pearlite.

both possessed a higher carbon content and therefore demonstrate a pearlitic microstructure. Further metallographic analysis shows areas that are more thoroughly homogenized.

This blade, shown completed in Fig. 9, was forged through the marriage of ancient metal-working techniques with an understanding of modern science.

Mechanical Properties

The hardness of the blade as measured according to ASTM E18 ranges from 40 to 60 HRC.⁶ Table III shows a summary of mechanical properties measured from the blade material after heat treating. These measurements correlate with the large variances in the microstructure of the steel. The lower measurements occurred in the softer regions such as ferrite or pearlite. The harder measurements occurred in the tempered martensitic regions. Prior to tempering, the martensite was measured at 65 HRC. This suggests that blade should be able to hold a very shallow angled cutting edge, which will result in a very sharp blade. Compared to the

Table III. Mechanical properties of the blade material

Sample	Hardness (HRC)	Tensile strength (ksi)	Elongation (%)
1	59	125	4.53
2	58	103	2.07
3	60	107	2.06
Average	59	112	2.89

hardness of a common modern knife-making steel (60 HRC for 1095 steel), the hardness of this blade suggests that it will stay sharper longer. Tensile samples were cut from an excess bar of blade material using a water jet. When tested according to ASTM E8, the engineering tensile strength of the steel was measured to be 112 ksi with 2.9% elongation.⁷

For comparison the tensile strength of 1095 is 365 ksi, suggesting that this blade may be less durable than a modern knife blade. The samples broke very quickly in the machine before significant necking, indicating the presence of cracks, impurities or delamination which caused brittle, premature failure. The tensile strength of the steel made was much less than that of the 1095 comparison steel. This is most likely because the steel being made was not fully homogenized (impurities causing micro-cracks or embrittlement) and the process is not as refined as an industrial manufacturer, as well as the chemistries were different with a lower carbon content.

CONCLUSION

The blade produced in this study was a result of blending modern science and artistic expression and gave unique results. The metallography showed a complex and non-uniform microstructure as a result of the many folded layers of distinct compositions used to construct this blade. Mechanical testing indicated lower strength and ductility values than desired, stemming from less-refined manufacturing techniques, improper chemistry ranges, and

unreliable thermo-mechanical processing. Nevertheless, the student group at South Dakota School of Mines and Technology produced a knife many of those from the frontier people would have been proud to own and use in their everyday tasks.

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