Microstructural Analysis of Heat-Treated Steel

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***Abstract*—To address the needs of bladesmiths throughout history, various processing techniques have been employed to create hard yet ductile, sharp and tapered blades. This project sought to investigate how a variety of heat treatment techniques (forging, normalizing, and hardening) alter the microstructure and thus material properties of AISI 5160 alloy steel. Each heat treatment was performed in the laboratory setting using a muffle furnace and the resulting sample was analyzed using Vickers hardness testing, Continuous cooling transformation diagrams, and optical microscopy. The result of this experiment suggests shaping/forging a tool, then quenching after the shaping process for best results.**

***Index Terms*—Steel alloy, heat treating, forging, normalizing, hardening, microstructure**

I. INTRODUCTION

Steel is a commonly used alloy of iron and carbon that is essential in modern transport systems, infrastructure, housing, manufacturing, agriculture, water and energy industries (World Steel Association, 2012). Different percentage combinations of iron and carbon can yield drastically different physical properties, which are uniquely sought after by manufacturers. For example, steel used in construction must have high strength and stiffness. An artist's steel, by contrast, should have ductility, softness, and appearance prioritized.

A common use of steel throughout history has been the creation of strong, sharp, and ductile weapons. The exact production methods have changed over the centuries, although two components have stayed the same: steel and heat. This project is an exploration in how different heat treatments affect the end result of steel material properties. Many knifemakers seek a hardened steel in the spine and outer edges of a blade, to improve impact and wear resistance, with a soft interior to reduce brittleness and unwanted shattering. The primary query that this paper seeks to answer is:

What heat treatments satisfy this product end goal?

A variety of induced microstructures and their physical properties were examined in the context of knife-making.

The central manufacturing process of this experiment was the forging of steel. Forging a piece of metal involves heating it to an orange-hot state (900°C), hammering into the desired shape, and repeating. Between rounds, the metal (which cools quickly in open air) reheats to the desired temperature in the forge. The most obvious result of the forging process is the ability to shape what is normally a hard and strong metal. However, the physical properties of the metal can be changed as well. Different microstructural compositions can arise in the same steel compositions, depending on how they were processed.

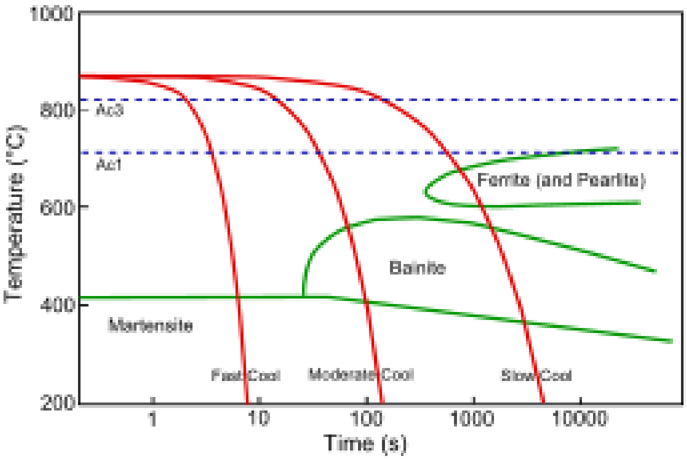

Fig. 1. Steel Continuous Cooling Transformation (CCT) diagram.

A. *Microstructures of Steel*

Depending on the methods used in its preparation, the same steel sample can take on any number of microstructural characteristics. The simplest way to relate these is through a continuous cooling transformation (CCT) diagram (Figure 1). Common steel microstructures are:

1) Martensite: Martensite is the hardest, most ordered, and most brittle microstructure of steel that is generally easy to produce. Its body-centered tetragonal structure created by cooling the steel extremely rapidly, usually through quenching the sample in a water or oil bath.

2) Ferrite: Ferrite is a body centered cubic (BCC) structure of iron. It contains very little carbon; ferrite can only dissolve up to .021% by weight of carbon and at high temperatures it becomes austenite, so it only exists as a single phase in the very bottom left of the iron-carbon phase diagram. Ferrite is most often found combined with other microstructures.

3) Pearlite: Pearlite consists of alternating layers of ferrite (88 wt%) and cementite (12 wt%). It occurs when austenite is cooled relatively slowly. Pearlite is a softer microstructure of steel.

4) Bainite: Bainite occurs from moderate cooling of austenite, a slower rate than is needed to form martensite but faster than to form pearlite. Its hardness also falls in between that of martensite and pearlite.

II. EXPERIMENTAL PROCEDURE

All processed and analyzed samples were AISI 5160 alloy steel cut to be $\frac{1}{4}$” thick, 1 $\frac{1}{4}$” wide, and approximately $\frac{1}{2}$” long. Each sample was treated in two stages, for a total of six different testing conditions. In the first stage, each sample was either forged or left as raw stock.

The forging process entailed heating a sample to 1000°C in a furnace until bright orange (approximately two minutes), and then removing and hammering to shape. When the sample reached the black heat stage (approximately 650°C), it was set back in the furnace to reheat. When in the black heat phase, hammering the sample is no longer beneficial. Visually, this stage is observed by the color of the sample changing from bright orange to a dull black. This phase can also be detected by ear; when the sample is struck in the black heat phase the sound changes from a dull thud to a ringing tone. If a sample in the black heat phase or cooler is struck the probability of cracking or breaking the sample is higher.

Each sample went through eight rounds of forging. In the final round of forging, the samples were again hammered until the black heat phase. Instead of being placed back in the furnace for another round, they were quenched in water. This is standard forging procedure.

In the second stage, three heat treatments were tested on these two varieties of stock: untreated, normalized (heated to 870°C and air-cooled on a large anvil cooling block), or hardened (heated to 840°C and quenched in oil). One sample was prepared for each of the six conditions.

III. ANALYSIS OF SAMPLES

For each sample, the team sought to relate physical properties (hardness, color, microstructure) with the stresses (heat treatments) they were placed through. This process entailed collecting detailed micrographs of our samples, along with microhardness measures.

A. Sample 1: Raw, Untreated Stock

The first sample considered here is a section of untreated stock. Using a Buehler hardness tester, the microhardness taken at the center of the sample’s cross sectional area was 326.9 on the Vickers hardness scale. This information can be utilized to draw a hypothetical curve on the material’s CCT diagram (Figure 2).

According to this hypothetical curve, the phase transformation of this steel stock may have consisted of austenization at or above 850 °C, and formed pearlite upon cooling. Pearlite consists of colonies in which grains are all oriented in the same direction, though this direction varies from colony to colony (Callister, 2007, p. 294). The majority of the visible grains are pearlite grains, in alternating layers of light and dark (see Figure 3). The very small and thin grains that look white are probably proeutectoid ferrite, which forms above the eutectoid temperature. Because this sample was not heated to above this temperature, only extremely amounts of this microstrucutre should be visible. This can be confirmed visually (Figure 3)

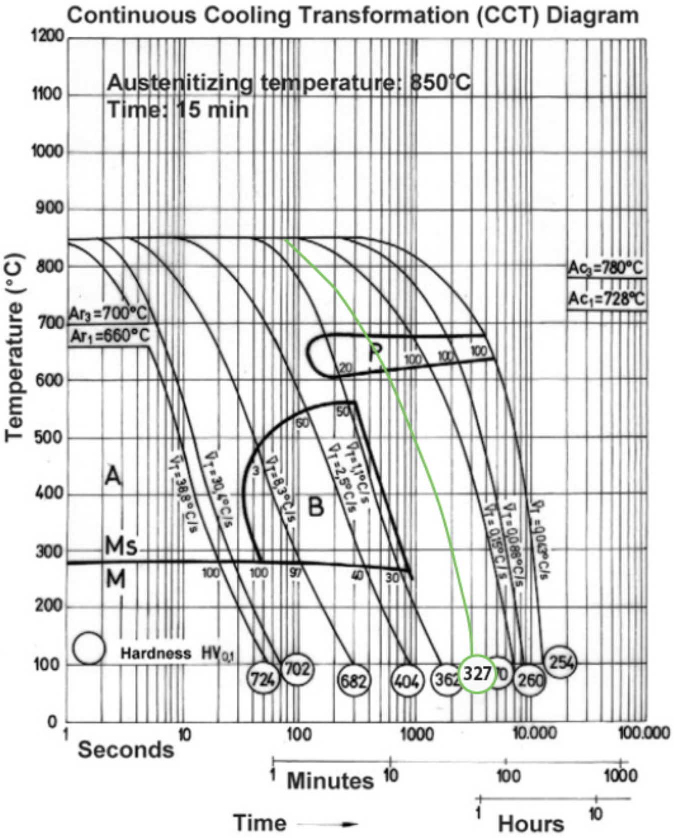

Fig. 2. CCT diagram for 5160 Steel. Green line shows hypothetical cooling for hardness of 326.9 HV (Sample 1).

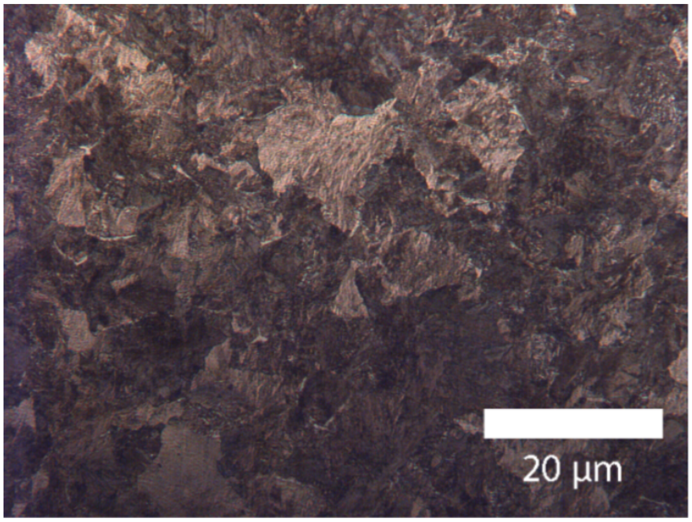

Fig. 3. Optical micrograph of the center of untreated raw 5160 alloy steel (Sample 1), showing pearlite grains in alternating layers of light and dark with small white grains of preutectoid ferrite. 2 % Nital etch.

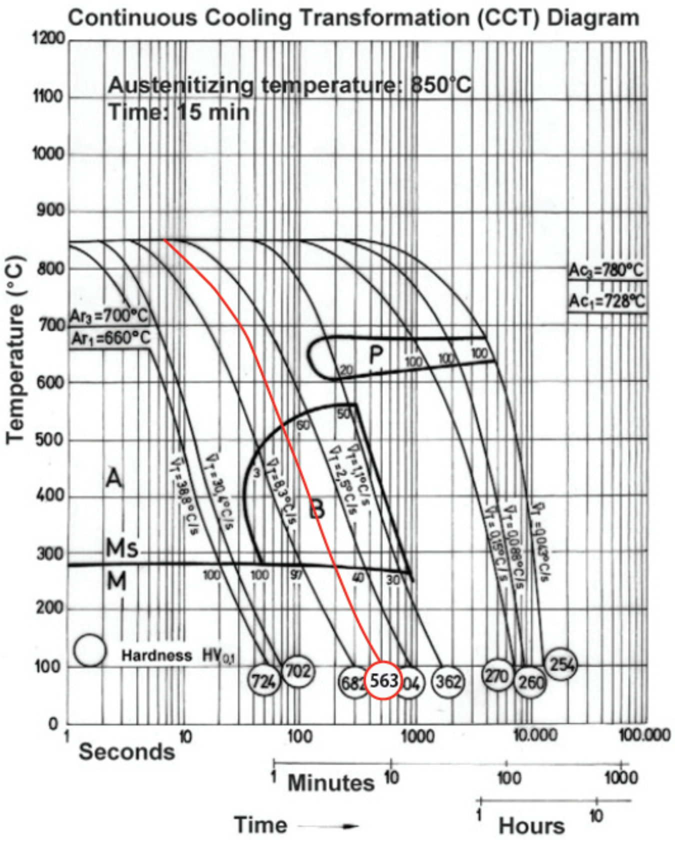

Fig. 4. CCT diagram for 5160 Steel. Red line shows calculated cooling curve after normalization, for hardness of 562.5 HV (Sample 2).

Mechanically, pearlite has properties intermediate between the soft, ductile ferrite and the harder, brittle cementite. Since this is raw stock, this softer structure is by design and makes the metal easier to machine and work with.

B. Sample 2: Raw, Air-Cooled Stock

Sample two was austenized by heating to 870°C and holding this temperature for approximately one hour. The sample was then normalized by placing it on a large anvil to be air-cooled. It took less than a minute for the sample to change color from orange-red (870°C) to black heat (500°C) suggesting a cooling rate around 4.5°C/s. This is represented by the red cooling curve on the CCT diagram shown in Figure 4.

Microhardness measurements for this sample returned a Vickers hardness value of 562.5 (Rockwell C: 53), which matches the hypothetical red curve on the CCT diagram. Reading the curve shows that bainite and martensite both form. The clumps of dark, needle-like shapes are characteristic of bainite. Martensite here can be seen as the needles that form larger light clumps around the bainite.

Martensite is the hardest microstructure in steel, and it can reach a hardness of 63 Rockwell C untempered. Bainite has a hardness between pearlite (quite soft) and untempered martensite. When sample two was heat treated, there was an observable shift in the structure from pearlite to a bainite-martensite combination; this corresponds to the sample becoming significantly harder (33 to 53 Rockwell C).

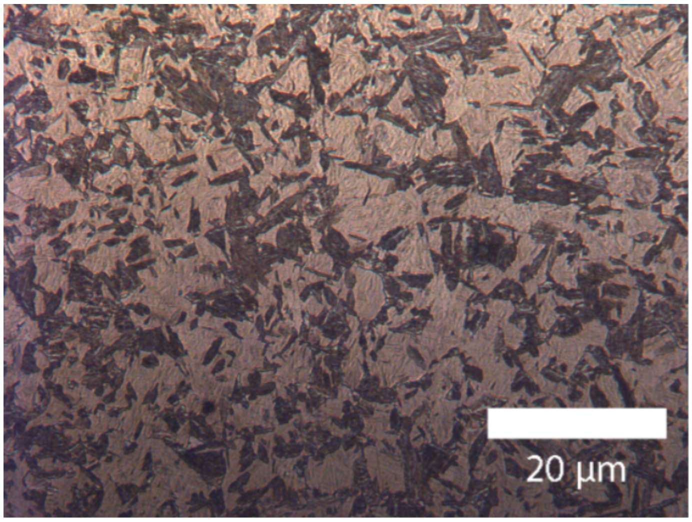

Fig. 5. Optical micrograph of the center of normalized 5160 alloy steel (Sample 2), showing light clumps of martensite surrounding dark, needle-like bainite. 2 % Nital etch.

C. Sample 3: Raw, Quenched Stock

The third sample was a cut piece of raw stock that was heated to 840 °C, then quenched in oil. Hardness testing revealed that the center was 752 HV, and the edge was 680 HV.

Reading the curve for these hardness values shows that the quenched sample core should be entirely martensite. The light-colored grain is characteristic of martensite with the etching technique used, and it is relatively homogeneous in color.

The sample is entirely martensite, which is shown by the hardness results and confirmed by the micrographs (Figure 7).

D. Sample 4: Forged, Untreated Stock

The next three samples repeated the same three heat treatments, but on forged samples instead of raw stock. After these samples were forged according to the procedure, they were tested in accordance with the previous techniques. The fourth sample was left untreated after forging.

The hardness test results returned a Vickers Hardness of 831 in the center of the cross-section and 788 on the edge. Mapping this on a CCT diagram lands the sample squarely in the full martensite region. This analytical result matches the observed thin, needle-like grains.

E. Sample 5: Forged, Air-Cooled Stock

Forging a sample of metal not only shapes the piece, but also changes the microstructures. Retreating a piece, either through normalization, quenching, or some other process, will allow the metal to keep its shape, but take on the microstructural properties of the most recent heat treatment. For this reason, this sample and the next share similar properties to the heat-treated versions of the raw stock. The center of sample five

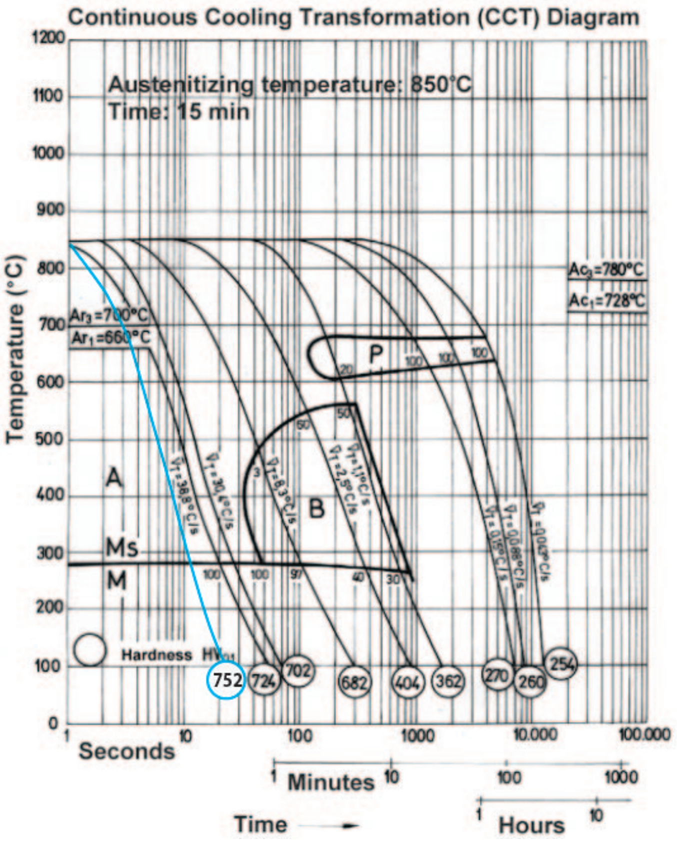

Fig. 6. CCT diagram for 5160 Steel. Blue line shows calculated cooling curve after normalization, for hardness of 752 HV (Sample 3).

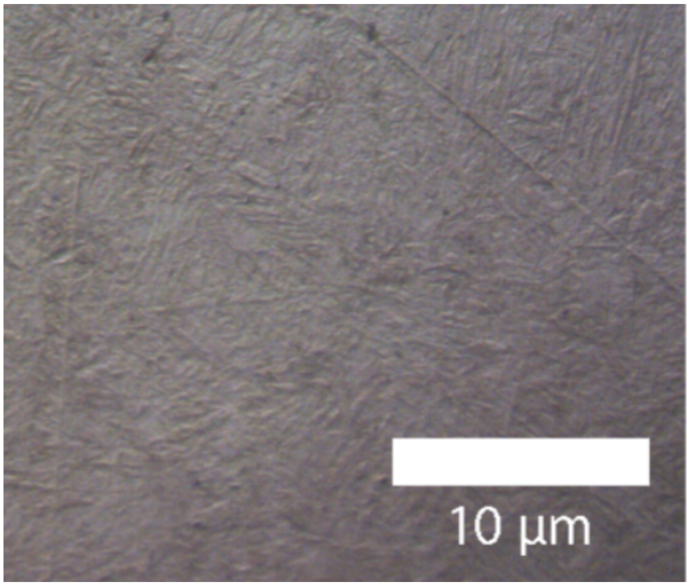

Fig. 7. Optical micrograph of raw quenched 5160 alloy steel (Sample 3), showing all martensite. 2% Nital etch.

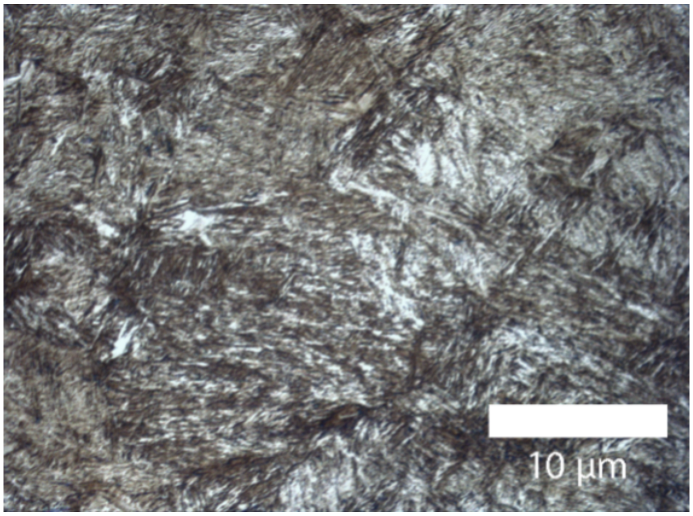

Fig. 8. Optical micrograph of the center of untreated forged 5160 alloy steel (Sample 4), showing thin needle-like grains of martensite. 2 % Nital etch.

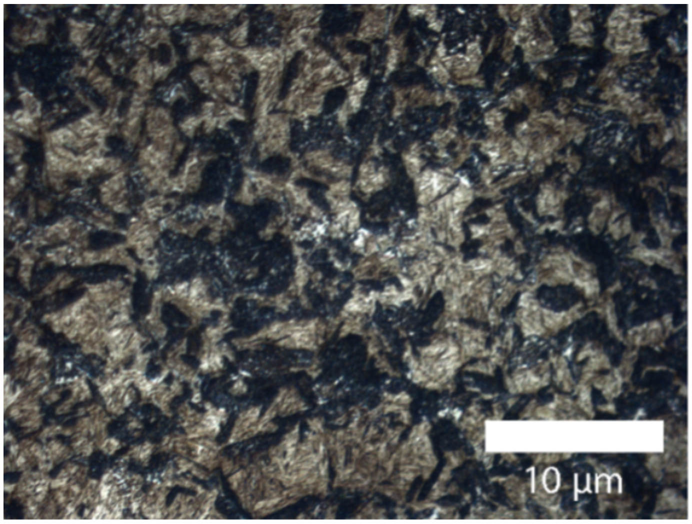

Fig. 9. Optical micrograph of the center of normalized forged 5160 alloy steel (Sample 5), showing dark bainite and lighter surrounding martensite. 2 % Nital etch.

returned a hardness of 552.9 HV, comparable to the raw, air-cooled sample's hardness of 562.5 HV.

F. Sample 6: Forged, Quenched Stock

The sixth sample was forged using the same process described above, and was later reheated and quenched in oil. Quenching a sample makes the metal harder, and more brittle. Hardness testing on this piece yielded results in alignment with this: the center of the sample tested to 781.2 and the edge tested to 828.6. In quenched samples, the edges are observed to be harder than the center due to an increased cooling rate at the edge.

Forging a piece also aligns the inclusions in the sample. The small inclusions that are present in the raw stock are brought together in this sample. Figure 10 from the optical microscope

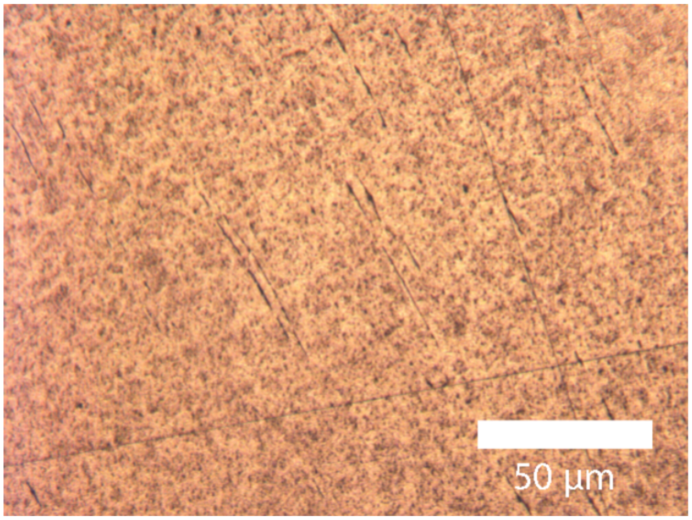

Fig. 10. Optical micrograph of the center of quenched forged 5160 alloy steel (Sample 6), showing long aligned inclusions. 2 % Nital etch.

TABLE I
TABLE OF DIFFERENT VICKERS HARDNESS VALUES FOR HEAT TREATMENTS PERFORMED.

	Vickers Hardness Value			
Treatment	Unforged Center	Unforged Edge	Forged Center	Forged Edge
Untreated	326.9	183.6	831.1	788.1
Normalized	562.4	398.2	552.9	559.7
Quenched	774.9	688.9	781.2	828.6

shows several large-scale inclusions. Due to this, forged pieces are more likely to break. The larger an inclusion is, the more likely it to manifest into a crack.

IV. HOLISTIC ANALYSIS

Steel hardness is one of the top factors to consider when picking a material. Different types of knives must be harder and more brittle or softer and more ductile. These characteristics can be dictated by different heat treatment procedures. Table I contains the the different treatments and hardness testing results performed for this exploration.

The quenched samples are the hardest, because they cooled the fastest and therefore contain the most martensite, which is the hardest mircostructure commonly found in steel.

The untreated forged sample also has a relatively high hardness value, because it was quenched, but at a lower temperature than the treated ones. One reason why the edge is softer than the center is because the sample was air cooled until it reached the black heat phase before quenching.

Normalized (air-cooled) samples were generally found to be softer than quenched samples, because they were left in the open air to cool. This means that the core would have cooled faster as heat conducted to the edges and then convected into the atmosphere last, giving the edges a slower cooling rate.

The unforged untreated sample was the original stock from the supplier. It was designed to be softer and therefore easier to machine and work with, as well as allow for further hardening and heat treating later. The team does not have any information about the forming process for this metal, but it had a longer cooling process than any of the samples in this experiment.

V. CONCLUSION

From these observations of micrographs and hardness of the given samples, the team theorizes that heat treating and quenching forged steel is would be the most effective process for making a knife as it results in a hard outer casing and a soft spine. This means that the hard outer casing would be more durable, less likely to be nicked or scratched. Normally harder materials are at greater risk of cracking, as was seen in some of the reported samples. However, by quenching a larger piece, the softer spine of the knife would make it more ductile and less likely to crack. If one were to create a knife as described here, they would have to shape, heat treat, surface treat, grind, polish, and sharpen the metal for optimal results.

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