Replication of Wootz "Damascus" Type Steel

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Abstract

In recent years, the Damascus steel making process is once again being examined in an effort to understand more about the striking patterns on ancient Damascus blades. Wootz is generally manufactured by the forging of a dendritic crucible steel. It is during the forging process and the associated heat treatments that the two phases of a wootz blade become pronounced. Information on the production of crucible steel is available, yet very little is known about the hammer forging techniques, or the cutting edge durability of the steel. In order to understand more about the effects of hammer techniques, a wootz crucible steel was produced and forged using several methods of fullering to draw out bar lengths. Metallographic studies of the test specimen's longitudinal face, and transverse face are characterized in the experiment. The replication of ancient blade bevels is obtained by the comparison of two knife edge making methods. Edge durability of the replicated wootz blade is tested in a similar fashion to the American blade smith standards for knife edges.

Acknowledgements

I am ever thankful to Diane and Tom Obach for the encouragement and support while I was immersed in this project. I'd like to thank John Anderson and Rio Tinto Iron and Titanium Inc for providing the high quality cast iron used in making good wootz steel. I'm also extremely grateful to the people at Sudbury branch of RHI Canada Inc., who were very helpful to me. RHI products were used in the design of an outstanding crucible furnace. I am especially thankful to my supervisor, Dr. Patrick Julig, for his patience, support, and expert knowledge in the field of Archaeology.

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Introduction

The development of steel has been a major factor in the history of human conquest, and which civilizations won out (Diamond, 1997). The sword has been an outstanding weapon, being thoroughly recorded in historical literature and poetry. Legends are sometimes made of Sword arms and the soldiers that carried them in conflicts. The Crusades brought back accounts of the Orientals carrying sharp swords made of wavy blue steel. European blade smiths tried desperately to replicate the steel and it's properties but were largely frustrated in their attempts. Robert Breant in 1824 published his attempt at making this type of steel. The steel was highly carbureted and would crumble under the hammer when not forged properly (Breant, 1824). Al Kindi, Al Bairuni, and Al Tarsoussi have contributed treatises about Damascus blades but little has been recorded about the forging process (Zaki, 1953). The information the Arab philosophers have written characterizes the varieties of Damascus blades and their significances. Rarely has the forging procedure been mentioned in any of the published accounts of ancient "Wootz" Damascus. It is the goal of this study to replicate and understand more about the forging of the Damascus type steel called "Wootz".

Wootz Damascus can be described as a slowly cooled crucible steel with a carbon content of 1-2.1% (Wadsworth, 1980). " The inner structure of the steel is created when the molten charge begins to solidify and impurity elements such as Mn, S, Si, and P are the first elements to form a network by segregating between the austenite dendrites. The dendrites are deformed into planar arrays parallel to the blade surface during the forging procedure. The surface patterns are created when the preferred precipitation of cementite particles from the austenite form along the planar arrays during the thermomechanical treatment of hammer forging" (Verhoeven et al., 1993). In this statement, Verhoeven et al. have characterized the hidden properties of "Wootz" steel but there is still some research to be done on the third elements (Mn, S, Si, P) and the mechanisms for pattern formation.

The ancient smiths made "Wootz" steel for many of the utility items that were required in everyday life. The steel was traded as cakes from many regions and was forged in several countries such a Persia, India, Russia, and others (Gilmour and Allan, 2001). The method of Wootz manufacture was generally the carbonization of iron in a clay/rice husk crucible (Lowe, 1990). Within the clay crucible, the iron and carbon charge is enclosed by a lid and left to melt over a long period of time. Later the iron cake was released from the crucible after it was slowly cooled to a solid. Now the steel ingot was placed back in the fire and left to anneal till the smith was satisfied with it’s gray color and uniform surface mottlings (Massalski, 1841). Once the color of the ingot met the Blade smith's demands it was forged into a watered steel sword. It is the endeavor of this study to help shed some light on the "Wootz" Damascus steel making process and characterize the forging procedure. The core of the experiment will be the actual replication of the steel and the forging of blades. Blades made from the steel are further tested for physical properties and visual characteristics. A brief comparison will be made with literature descriptions of "Wootz" blades and the surface characteristics.

The experiment in making and forging "Wootz" steel ingots was done by The Writer at his home. The blacksmith shop was a small 10 by 12 foot forge area with the standard equipment found in a very basic smithy. Tooling for the blacksmith shop was generally an anvil, coal forge, many different size hammers, and tongs to hold the hot steel ingot while forging to shape. The crucible furnace was home built out of a 45 gallon barrel for the purpose of manufacturing "Wootz" ingots. Plastic refractory bricks were used to line the inner core of the barrel and a large propane burner supplied the heat for melting the ingredients. Clay graphite crucibles were purchased and used to contain the ingredients of the steel melt.

Experimental Method

This section explains a method in which the "Damascus type" crucible steel was produced for the experiment and the testing of the steel visually and functionally. This general overview of the smelting process is followed by an in depth explanation of the hammering and forging of the ingot material, to produce a "Wootz" Damascus type steel blade. This section will then be followed by actual results of the steel and the blades produced.

Producing the Wootz Ingot

1) A crucible furnace powered by propane gas was built and used to generate the heat energy needed to reach the melting point (1535 cel.) of iron.

2)The ingot of steel consisted of 1010 iron and a high carbon cast iron that were added together in the right proportions to attain a mixture of 1.5% carbon. The individual components within the steel were selected to be within the typical range of genuine Damascus sword (Verhoeven 1993:189), as listed below.

C % Mn % Si % S % P % Cu % Cr% Ni %

1.34-1.87 .005-.14 .005-.11 .007-.038 .05-.206
.04-.06 trace .008-.016

3) The charge was put into a "A6" clay graphite crucible and covered with a cup of green glass.

4)The charge was then heated to liquidus within 40 to 90 minutes followed by a "ramp down" temperature. The charge was not left to boil for any length of time due to the possibility that extra carbon would be absorbed from the crucible. The furnace temperature was lowered in such a manner as to cool the liquid steel to solidus in a slow fashion. The general cool down time was within 10 to 20 minutes of the initial temperature ramp down.

5)The furnace burner was then closed when the charge was at a solid state and left to cool in the furnace.

6)After 6 hours, the charge was removed from the crucible and cleaned of the fluxing glass (Figure 8.). The color of the wootz cake is noted. If a very brassy appearance is present, this could indicate that the carbon content is too high. The over carburization of the ingot will turn the steel into cast iron and render it virtually impossible to forge. The wootz cake was then examined for dendritic patterns on the surface of the steel. The dendrites are a key sign of the quality of a wootz ingot. The dendritic strings of cementite nodules are a noticeable feature of surface morphology on the ingot (Figure 9.).

7) The wootz cake is then put into a steel crucible filled with iron oxide scale. The crucible is then lowered into the furnace at the temperature of 1100 celsius and allowed to slowly cool 5 to 10 hours. This procedure was to produce a low carbon steel rim around the high carbon steel inner core before hammer forging. The thermal treatment also helps to anneal the product and produce a finer microstructure in the ingot.

8) The wootz cake is then removed from the crucible and examined for a

decarburized and ductile iron shell or rim surrounding the charge. The appearance of the wootz cake will now have a very dull and mottled gray surface color.

10) The cake is now ready to be forged into blade shapes.

Forging the Damascus Type Blade

Now that a wootz cake has been sufficiently processed and prepared, it is possible to begin forging test blades to shape. Several methods of forging are tested to try and reproduce the similar internal structures and surface "waterings" reported in genuine damask swords.

1)Three rectangular bar blanks are forged to similar blade lengths.

2) The individual bars are forged using different degrees of "fullering".

Fullering is a method of deformation to draw out a length of steel by hammering a small depression in the barstock with a specially shaped hammer, and then flattening out the whole surface of the metal (Figure. 4).

3) The first bar is fullered using a very aggressive angle and flattened with an 8 lb hammer.

4) The second bar is fullered with medium sized fuller and flattened with an 8 to 12 lb hammer.

5) The third bar is drawn out with a round faced hammer (a very mild form of fullering).

6)The very thin soft iron rim produced from the iron oxide anneal is now removed from the outer surface of the blade blanks by using a high speed belt grinder. The end section of the blade is cut transversely to examine the inner grain structure. The surface of the wootz billets is then sanded with emery cloth from 80 to 1500 grit to produce a very smooth area for the ferric chloride etch. The etch is used to reaffirm that the dendritic pattern of the wootz steel is present.

7) Once the blanks have been ground properly, a brief (20 second) ferric chloride etch is applied to the surface, and the surface lightly cleaned and neutralized in baking soda. The knife surface is immediately oiled to prevent oxidation of the blade.

8) Each blade is then examined visually and recorded in a 6x photograph. The results visually compared with the micrograph preformed by Verhoeven (1987:156) and Peterson (1990:362). The cementite banding and the angles of sheeting are the main objectives of the observation and comparison in the experiment.

<u>Two Damascus Forged Blade edges</u>

In the previous section, two blade blanks are forged from a wootz cake. The two blanks are then used to make a comparison between a forge blade edge and a "stock reduced" or ground blade edge. The process is to better understand the morphology and metallurgy of the blade edges and try to learn which methods may have been used in antiquity to produce such edges.

1) The first blade blank is forged into a rectangular billet.

2) The decarburized rim is then ground off the billet.

3) The bevel of the blade edge is now stock reduced into the profile by

the use of a belt grinder.

4) The second blade blank is processed differently in the forging stage.

The blade bevel on this blank is forged into place at a similar angle to the stock reduced bevel of the first blade.

5) The second blade is ground to remove the decarburized rim around

the billet.

6) The blade is heated to critical temperature (cherry red in color and

non magnetic) and quenched in a light oil. A temper is drawn to a brown gold surface oxide color on the surface of the blade, by re-heating the blades in an electric oven.

7) Both blades are sanded with fine grit abrasives in order to provide an

acceptable surface for the final ferric chloride etch.

8) Ferric chloride is used to reveal the banding on the beveled blade

edges of the two billets. The banding is observed on both blades and compared to the edge micrographs of genuine Damascus blades.

<u>Blade Edge Durability of Damascus steel</u>

To test the cutting ability of wootz Damascus steel, the blades are then evaluated with a similar test to the American Blade Smith standards for knives.

1) The first test is called the rope cutting test. A free hanging hemp rope of 1 inch in diameter is hung from a secure overhead fixture. The rope is then struck with the cutting edge of the blade, 6 inches from the free hanging end. Successfully cutting through the rope indicates good edge geometry and sharpness of the blades.

2) The second test is a wood chopping test. The wood was spruce purchased from the local hardware store. A construction grade 2 inch by 4 inch softwood board length is struck with the blade edge of the knives. The board must be cut twice and then an examination of the edge is performed. The test demonstrates edge toughness of the forged blade.

3) The last test demonstrates edge retention. The sections of the blade used in the previous test must be able to shave hair to show that enough of the edge remains keen and shaving sharp.

Detailed Hammer Forging Procedure of "Damascus Type" Blades.

1) In this section an indepth procedure of the hammer forging process is presented, as considerable skill and precision is needed to avoid many potential forging errors. The goal of forging the ingot is to produce a square bar from which a blade profile can be made. Potential errors may occur when wootz is initially forged at a cooler temperature or allowing the formation of improper ingot morphology. Initial temperatures below an orange color may result in the formation of cracks in the steel. Caution must also be taken not to forge the ingot in a bright yellow color or the steel will also deteriorate. The forged ingot must remain in a continuous and fattened (convex outer profile) shape avoiding the formation of an hourglass ingot profile (Figure 2.) The hour glass profile will lead to severe cracking and de-laminations.

2) The first step is to begin heating the ingot with the face towards the coal fire at the proper temperature. The proper temperature to heat the ingot is determined by comparing the ingot material to the Iron-carbon phase diagram in Figure 1 (Verhoeven. Jones, 1987). The ingot is held at the specific temperature, between Acm and A1, making sure that the blackbody radiation is uniform over the whole surface. The temperature must never exceed Acm or else severe cracking will occur. It is important to heat the ingot on the perpendicular sides to the ingot face that will be forged. The ingot remains in the forge for a holding period of 7 minutes to ensure that the core of the steel is sufficiently heated. The holding period generally depends on the size of the ingot. After the holding period has

expired, the ingot is withdrawn from the forge to the anvil with a pair of blacksmith tongs and hammered with an 8 to 12 lbs sledge hammer.

3) Figure 3 shows the techniques and corrections needed to form a good ingot shape. Once the ingot has been shaped into a square billet, it can now be drawn out into a long bar length appropriate for a sword or blade profile. To draw out the square billet, the steel is now fullered and flattened in the direction of forging. The fuller in this experiment was preformed by 3 different shaping methods as follows :

A) "planishing" with hammer face – only the hammer face is used to draw out the bar length. The hammer face has only a very mild curvature.

B) medium fuller- a medium face used to dimple the steel prior to being flattened out with a flat hammer face, as in Figure 4(b). The circular medium fuller face is 13.5 mm in diameter of curvature.

C) aggressive fuller- a sharper hammer face used to dimple and depress the steel prior to being flattened out with a flat hammer face. The circular aggressive fuller face is 7 mm in diameter of curvature.

Figure 4. is a visual illustration of how the hammer is employed in properly drawing out the billet. In forging the billet it was found that maintaining a bar length that has radius or rounded edges was important, as shown in Fig 5.

In order to reduce the chances of forming a wrinkle or initiating a crack, it is critical to maintain a square or slightly rounded bar shape during the entire drawing-out process. During the forge cycle it is also very important to heat the bar length from a temp near Acm 1 down to a low red color prior to beginning another heating cycle. "Heat cycling" the bar length in this manner apparently promotes the creation of the best surface waterings. The surface patterns or "waterings" is an important aspect of "Wootz" steel.

Once the bar is of appropriate length to form a sword, it must then be profiled into the blade shape, prior to working on forging the blade bevels. The bar length is heated on the profile side then removed from the fire to form the tip on the blade edge. It is important to hammer on the blade edge only when the bar length is hot. After shaping on the profile, immediately correct any wrinkles that occur on the side of the blade edge by hammering them out. (See Figure 6 for an in depth illustration of the hammer techniques and processes.)

It is now prudent to begin forging the tang of the blade. Hammer the tang profile only when the steel is sufficiently hot and quickly correct any wrinkles on the side of the steel, as shown on Figure 7. Once these steps are finished you may forge in the blade bevels in a standard manner used by most bladesmiths. The blade bevels are forged into place by holding the blade at an appropriate angle to the anvil surface. The edge is now hammered into place by a similarly angled hammer strikes to the blade. The edge is forged into both sides with an even amount of hammer blows, making sure to overlap all the strikes.

4) The steel is now ready to be quenched in an medium weight oil bath. The piece is heated in the coal fire evenly over

the blade surface till it reaches a non-magnetic state (cherry red color).

After the color is evenly distributed on the steel, it is quenched

vertically into a barrel of light warm oil. The blade remains in the

quench till it is cool to the touch, and then removed for cleaning.

Cleaning the oil and oxides off of the blade surface is important

before proceeding to the next step, the tempering of the steel.

5) The bare steel blade is now ready to be tempered in an oven.

Generally the oven is set at 350 degrees Fahrenheit and the blade

remains in the oven till a yellow brown oxide color is visible over the

entire blade length. Once the temper is even colored, the blade is

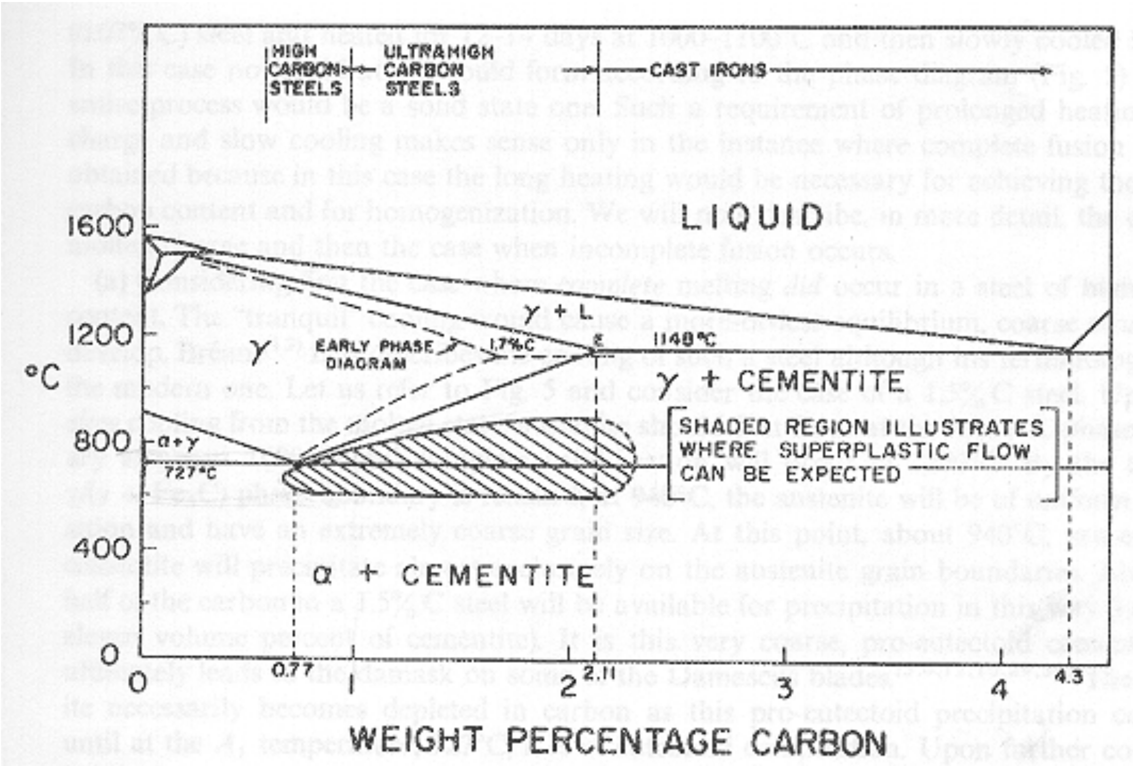
quickly removed from the oven to prevent further softening of the

blade edge. It is also advisable to further draw a purple or blue temper

color over the tang/handle of the blade, to further soften the steel. The blue temper will reduce brittleness and prevent breakage of the tang during heavy use.

6) The knife is now ready to be hand sanded to a mirror finish, and then

etched with nitric acid or ferric chloride. The knife is repeatedly dipped into a 4% solution of ferric chloride and distilled water, till a dark pattern is revealed. The oxide is then removed by a light grinding compound on a felt buffing wheel. The cycle is repeated until the desired surface watering is displayed on the blade.


HIGH CARBON STEELS
ULTRAHIGH CARBON STEELS
CAST IRONS
LIQUID
1600
1200
800
400
0
°C
γ + L
γ
EARLY PHASE DIAGRAM
1.7%C
1148°C
γ + CEMENTITE
α+γ
727°C
SHADED REGION ILLUSTRATES WHERE SUPERPLASTIC FLOW CAN BE EXPECTED
α + CEMENTITE
0
0.77
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WEIGHT PERCENTAGE CARBON

Figure. 1.

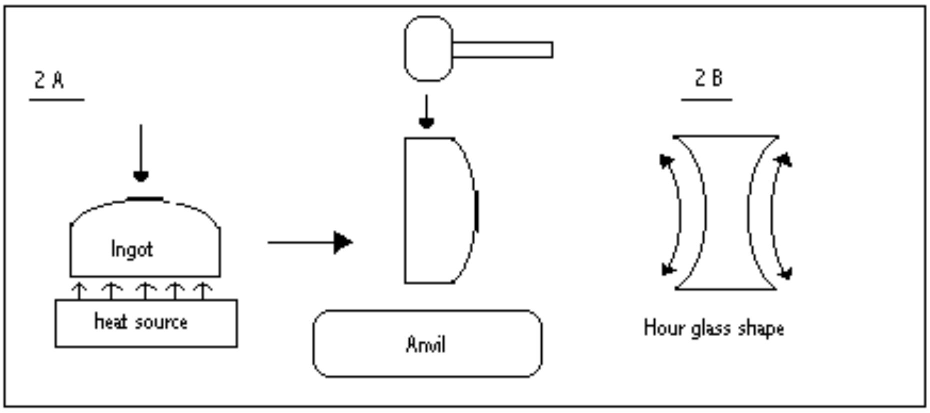

Figure. 2.

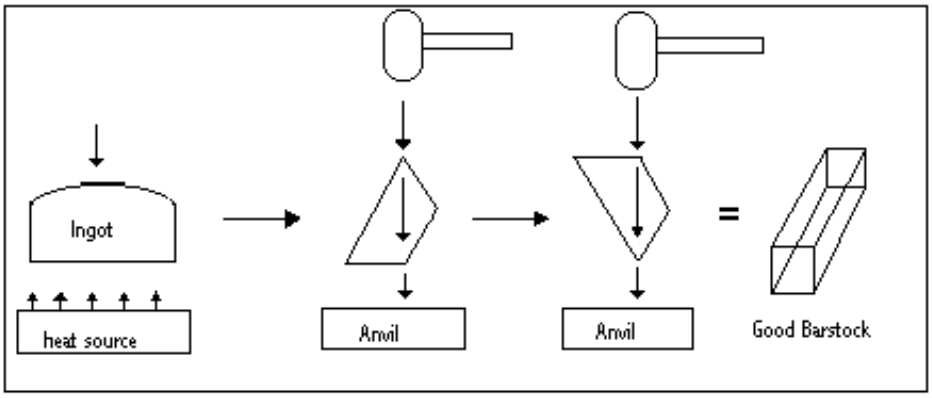

Figure. 3.

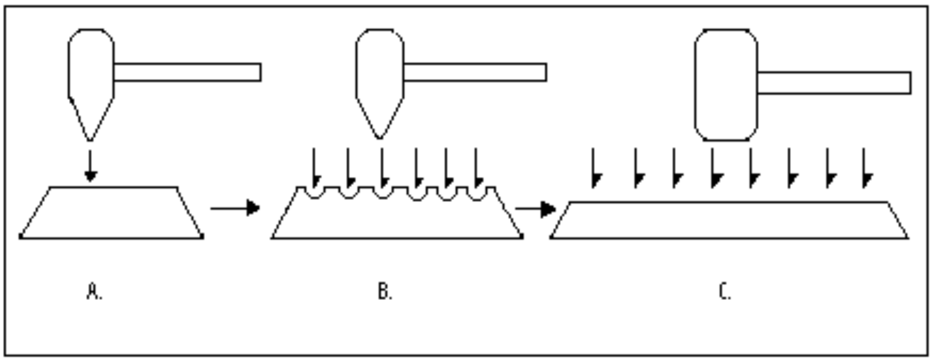

Figure. 4.

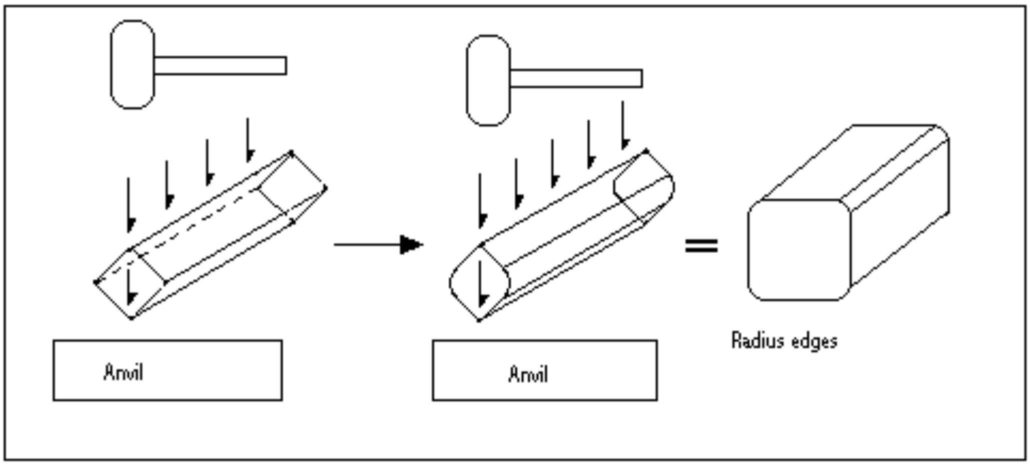

Figure. 5.

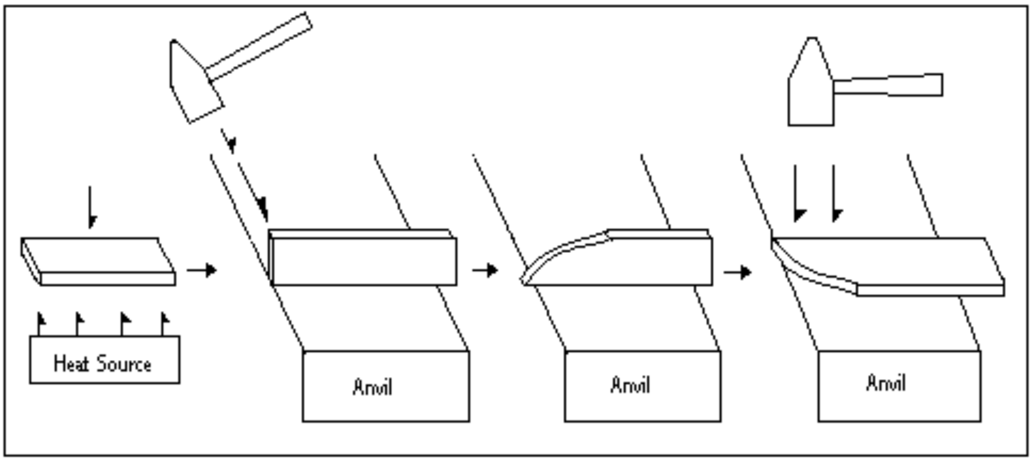

Figure. 6.

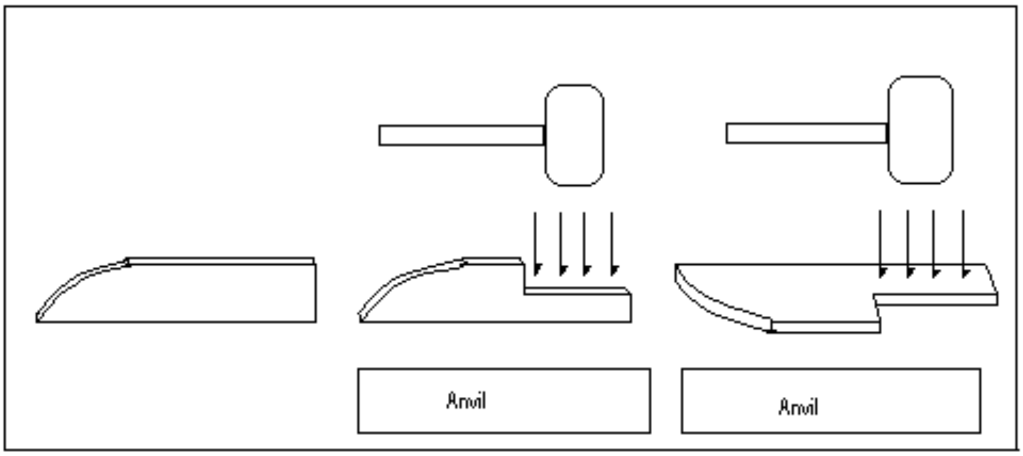

Figure. 7.

Results

Wootz Ingot Morphology

A primary characteristic in the production of Wootz crucible steel is the dendritic patterns displayed on the surface of the steel ingot. The dendritic pattern in the ingots results from microstructural distribution of cementite and impurity elements (Verhoeven, and Jones 1987). The following pictures seen in Figures. 8-9. display the profile and surface dendritic patterns achieved in the experiment. The steel ingots produced in the experiment on average weigh 6 lbs. The ingots have a height of 6.5cm and a width of 9.5 cm, resulting from the A6 crucible size used.

Figure. 8. Side view of an ingot from A6 crucible

In Figure. 9. a magnified picture of the ingot surface is shown and the dendritic pattern is seen. It is this coarse dendritic network that after forging, ultimately leads to the visible surface markings on the Damascus swords (Sherby, Wadsworth 1985).

Figure 9. Surface Dendrite displayed on top of ingot, 6X magnification,

after removal of glass flux.

Planar Sheeting and forging observations

The results of the three different hammer forging processes explained in the experimental methods section are noted and photographed. The alignment of the planar sheets is recorded on the longitudinal face of the blade spine by the linear direction of the cementite particles. The cementite particles are made visible by a selective etching process.

In Figure 10, as the result of very mild fullering, the longitudinal section of a hammer planished blade is shown. The planar sheeting and cementite particles on the spine of the blade visibly exhibit a relatively linear orientation and an apparent direction parallel to the longitudinal face.

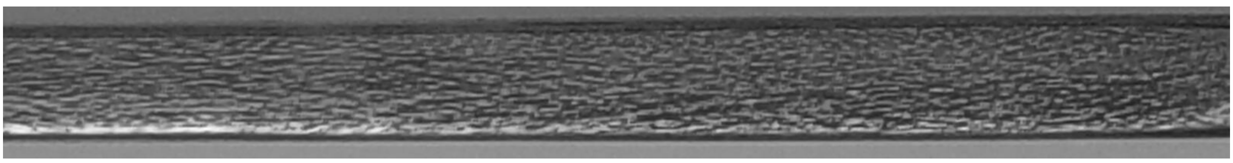

Figure 10. Etched longitudinal face of blade 1. Hammer planished and treated with ferric chloride. The spine is observed under a 6x magnification.

The second blade specimen was hammer forged using a medium fuller to draw out the ingot. All three examples were derived from the material of one large ingot. The blade in Figure 11 shows a mild curvature or "s" pattern in the cementite particles visible on the spine and is visibly more wavy than the previous example. The overall direction is still roughly parallel to the longitudinal face with some visible curvature to the planar orientation.

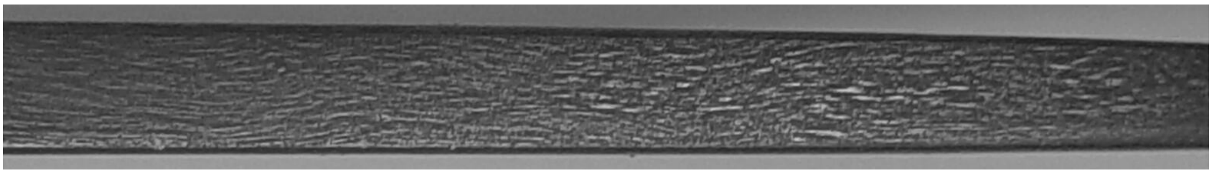

Figure 11. Etched longitudinal face of blade 2. Hammer forged with a medium fuller and etched with ferric chloride. The spine is observed under a 6x magnification

The third wootz blade seen in Figure 12 was forged using a more "aggressive" fuller. The aggressive fuller draws out the ingot into bar length in a rapid fashion. On the visible longitudinal face, the cementite particles in the planar sheeting are aligned in a very aggressive and chaotic "s" pattern. The direction of orientation is still parallel to the longitudinal face but recorded in more of a meandering pattern. This method seems to provide a closer approximation to the reported Damascus type steel. The longitudinal etch is very similar in morphology to the Damascus blade characterized by Peterson et al. (1990).

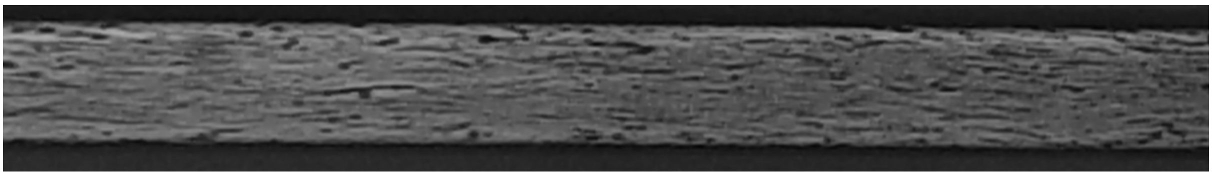

Figure 12. Etched longitudinal face of blade 3. Hammer forged with an aggressive fuller and etched with ferric chloride. The spine is observed under 6x magnification.

<u>Edge Morphology and Watered Patterns</u>

Two methods of forming the edge on a Damascus blade are characterized in this portion of the results. One method of forming the blade edge is to hammer forge the bevel angles and edges during the process of shaping the overall blade. The second method of producing a blade edge is to grind the bevel angle with an abrasive stone or modern belt grinder on the profile of the blade.

The first edge to be characterized is the hammer forged edge seen in Figure 13.

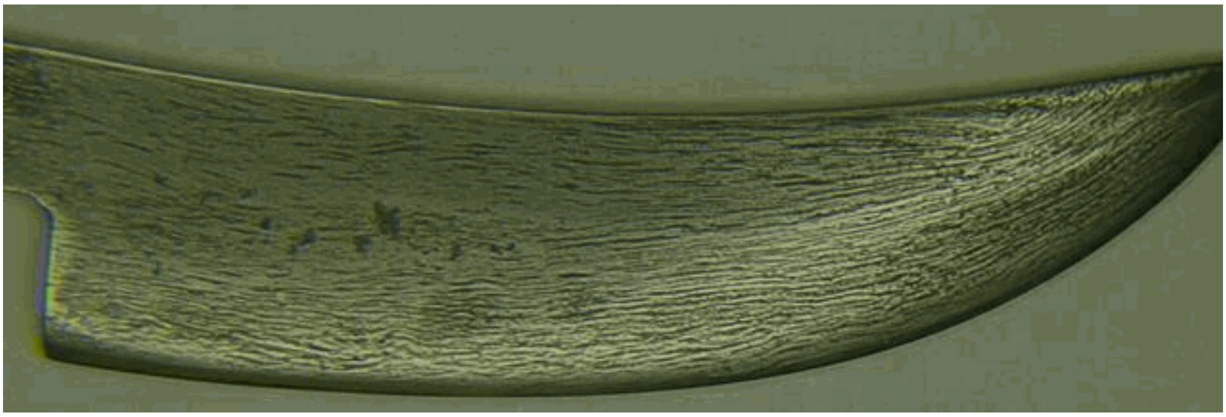

Figure 13. Nitric acid etched blade, hammer forged bevel on blade edge, 2x magnification.

The second edge is shown in Figure 14. displaying an edge morphology that has been ground into the Damascus blade. The ground blade edge can be observed in the top portion (1/5 th) of the blade seen in Figure 14. In this example the wavy "watered steel" is absent near the edge where the blade was ground.

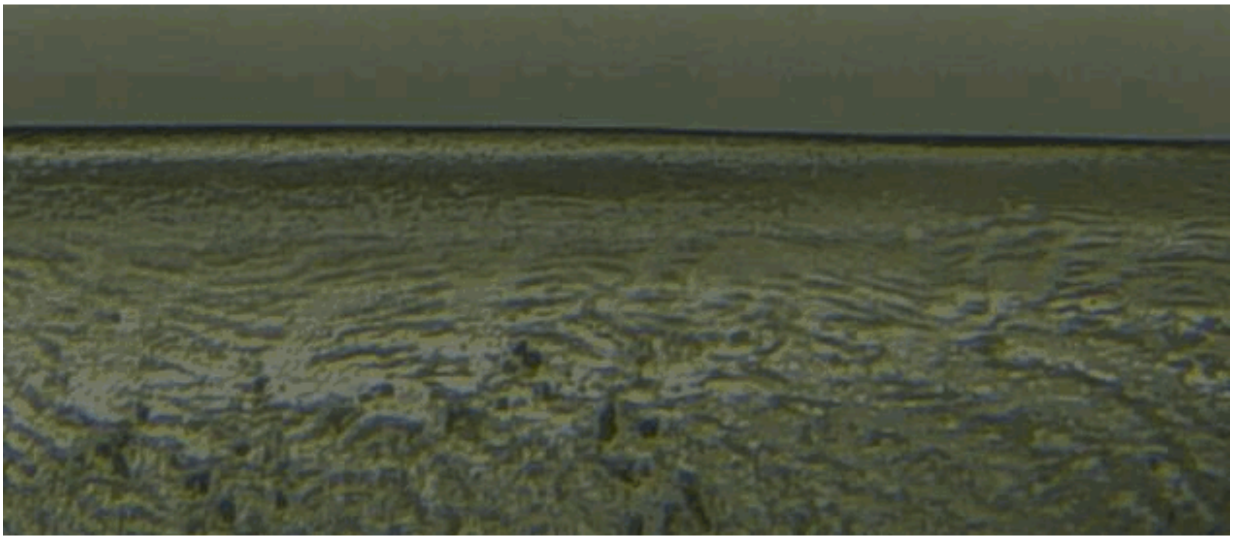

Figure 14. Nitric acid etched blade, ground bevel edge, 2x magnification.

The two pictures provide the possible patterns observed by the methods employed when reconstructing the edges of ancient Damascus type blades.

Cutting Edge Durability of Wootz

The beginning of this section is devoted to testing the edge retention and cutting ability of a wootz knife blade. The first test is the ability of a knife to cut through a free hanging 1-inch hemp rope. The process of edge testing used is similar to the test detailed by the American Bladesmith Journeyman exam. The exam information is further explained on the http://www.americanbladesmith.com/ABS_JSTest.htm website.

The knife used in this test was a wootz bowie knife forged out of similar steel to the prior test pieces. The bowie knife had an edge ground onto the bevel with a 600 grit aluminum oxide paper and sanding block. Once proper technique was used, the knife was able to cut through the rope on 3 occasions.

On the second part of the second part of the test, the blade was used to chop through a spruce 2 inch by 4-inch board length twice. The edge test was performed three times and showed no signs of a chipped or compacted blade edge. The blade carried no visible damage from the previous tests.

The final test was to shave hair, showing that the keen edge has remained intact through the previous tests. The knife remained largely sharp on the vast majority of it's surface and could shave hair. The hammered bevel blades performed the tests with the same results as the ground in edge knives.

Discussion

The experiment involving the planar sheeting and hammer forging was performed to better understand the relationship between these two aspects of wootz blades. It was known that the dendritic (Wootz) steel aligns in clustered sheets of cementite (Verhoeven, Pendray, Berge 1993). The distinct waviness in the cementite sheeting was thought to have been created when the bladesmith used a fullering tool to draw the steel out into blade length (Peterson, Baker, Verhoeven 1990). If the method of forging was recorded in the waviness of the planar sheeting, ancient blades could provide some of the missing details of the old hammer forging techniques. Experimentation with different forging techniques on modern materials and a comparison between both ancient and modern blades could provide some of the forging information. The results of the experiment shown in Figures 10-12. indicate that the pattern of waviness does increase with the aggressiveness of the hammer or fullering technique. The first test piece of "Wootz" Damascus type steel was forged with the flat face of a hammer (Figure 10). The flat method of hammer forging is a very slow manner in which to draw the steel out to bar length. The method is recorded in the planar sheeting is the direction and shape of the cementite particles, which are very flat and linear, oriented towards the blade tip and tang. The distinctive waviness of "Wootz" Damascus type steel is lacking.

The second wootz blade was forged using a medium fuller (Figure 11). The medium fuller is a mild method by which to draw the steel out into bar length. Planar sheeting in the spine of the 2^{nd} wootz blade showed a very gradual "s" shape cementite pattern, somewhat indicative of the "Wootz" pattern.

The third blade was aggressively fullered and drew out to bar length in a quick manner (Figure 12). The cementite particles were still oriented towards the blade tip and tang but showed a chaotic or meandering "s" shaped morphology. A similar distinct waviness is described by Peterson et al. (1990) in the characterization of an ancient "Wootz" Damascus steel sword.

Upon examining the three blades it can be shown that the method of fullering is recorded to a degree in the planar sheeting. Understanding this principle can shed some light on the forging methods used by bladesmiths on ancient wootz swords. The methods and techniques used by ancient smith's to forge wootz are rare and lack detail. The only publication where the forging particulars are mentioned was by J. Abbot made in Jullalabad (Piaskowski, 1978).

In addition to the previous experiments, two more blades were produced to look at the relationship between a hammer forged bevel for the blade edge or a ground/stock reduced blade edge. The hammer forged bevel was produced while "hot forging" the knife and a side profile is shown in Figure 13. It is clear to see that the surface waterings on the knife are similar on the blade bevel and the broad flat of the profile. The second blade was forged to near completion with a rather thick edge. The edge was then ground to a sharp bevel with the use of a high speed belt grinder. After the edge bevel was ground into the knife, it was then etched to show the carbide pattern. Figure 14. displays the side profile of the knife, with the top 1/5 of the blade representing the ground edge. A definite change in blade waterings and pattern morphology has occurred with the ground knife edge. The edge shows a pattern resembling the sheeting pattern spine on the knife and not the large, long and flowing pattern on the side of the blade. It is possible from the experiment to determine whether the ancient bladesmiths used either method to create the edge on ancient blades.

The third part in the examination of replicated wootz steel blades, a cutting test was performed on the blade edge. The blade was used to cut a free hanging hemp rope and chop through a 2 by 4 inch pine board. The wootz blade edge was observed for compaction or chipping. The edge showed very little disparity or damage after the tests were completed. The test is a good example of the durability and function of the knife during normal use of a blade. The tests were performed with both a ground edge on the knife and a forged bevel. The different blades performed with very similar outcomes through out the process of edge testing.

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