

Damascus Steel

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The topic of Damascus steel is something that has been on the minds of metallurgists for centuries. They have exceptional toughness and ability to hold a cutting edge (wear resistance), which made them ideal for swords. They also had a characteristic pattern on the surface, known as a “Damask pattern” [1]. For the purpose of this paper, I will refer to these as wootz Damascus, or simply just Damascus. There have been methods to produce specimens with similar surface markings by using pattern welding (forge welding high and low-carbon steels together and then folding them multiple times), but these pattern welded specimens lack the toughness and wear resistance of wootz Damascus. It is generally accepted that the original method for making wootz Damascus has been lost to history [1,7].

In recent years, there has been a lot of work to determine a process to make Damascus steel specimens which rival the strength and toughness of the original wootz Damascus. Two groups, one led by Jeffrey Wadsworth and Oleg Sherby, and the other led by J. D. Verhoeven have produced methods which can make specimens which can produce steel that rivals wootz Damascus. In this paper, I will first examine the history of Damascus steel research and then I will cover the properties and microstructure of Damascus steel. Then I will examine the process developed by Wadsworth and Sherby, along with the process developed by Verhoeven.

History

Historians say that Wootz Damascus steel was being made in the Middle East around A.D. 540, possibly even earlier, using cakes of crucible steel from India called wootz [1]. During the Crusades, the crusaders first faced Damascus steel near Damascus (which is how it got its name, the steel wasn't necessarily made in Damascus) and were impressed by the remarkable properties of Damascus swords, even going as far to claim they had magical properties [2]. Damascus steel continued to be in production until about the 18th century, after which

Damascus steel was no longer made, and the art of producing Damascus blades was lost.

Verhoeven has a theory as to why this happened, which I will cover later.

The modern study of Damascus steel began in Britain in 1795 with George Pearson studying wootz crucible steel. D Mushet continued on this line of study, and correctly concluded that the wootz cakes had very high carbon content, and that this may have an impact on the properties of Damascus steel. Michael Faraday was the next person to work on the topic, although he incorrectly attributed the properties of Damascus steel to silicon and aluminum impurities. However, Faraday's paper prompted Jean Robert Bréant in France to begin a study of Damascus steel. He obtained a sample of wootz, and began testing it. Bréant concluded that the structure of the steel was "a mixture of "pure steel" (or eutectoid composition steel) and "carbureted steel" (or pro-eutectoid cementite)" [1]. The study of Damascus steel continued through the 19th century and into the 20th. In 1918, N. T. Belaiew published a paper on Damascus steel which described the microstructure in detail.

Properties and Microstructure of Damascus Steel

Verhoeven decided to perform destructive tests on a Damascus steel sword analyze its microstructure and quantitatively tests its strength [2]. Damascus steel has an interesting microstructure. Verhoeven has analyzed the microstructure and composition of many different swords, and has come up with the following average composition (concentrations given as weight percent) [2,3]:

| C | Mn | P | S | Si | Ni | Cu | V | Cr | Ti |
|----------|-----------|----------|----------|-----------|-----------|-----------|----------|-----------|-----------|
| 1.60 | 0.56 | 0.107 | 0.02 | 0.043 | 0.012 | 0.048 | 0.01 | 0.01 | 0.002 |

From this, we can see that Damascus steel has a very high carbon content, so it is classified as an ultra-high carbon (UHC) steel [1]. The other constituents are at a low enough level for them to be insignificant in the system (for the most part). If this assumption is made,

then the system becomes an iron-carbon system. Since this composition is hyper-eutectoid, it will be composed of pearlite (lamellar cementite and ferrite) and cementite grains.

The structure of these cementite grains however, is not normal. The pure cementite grains are small (2 to 20 micrometers in diameter [1,2]) and are not randomly dispersed. Instead, they are clustered in large parallel sheets 12 to 30 micrometers thick and tens or hundreds of micrometers apart [1,2]. At the surface of the blade, the cementite sheets are not parallel, but wavy, which is most likely due to the fact that the blade was hammer forged (hammer forging rarely results in uniform deformation, as is the case with most modern forging or rolling operations). These sheets are not quite parallel to the surface, and coupled with the waviness caused by the forging operation, will cause the visible banding pattern that is the most easily noticeable characteristic of Damascus steels. These cementite particles act as barriers to dislocation, increasing the strength of the steels (similar to the way precipitates increase toughness in non-ferrous alloys).

Wadsworth and Sherby also found references to heat treatment of Damascus steel in Belaiew's work [1]. He states that Damascus steel was taken slightly above 727 degrees Celsius (the austenite formation temperature). This temperature is not enough to affect the cementite particles in any significant way, but brings the pearlite into the austenite region, allowing it to undergo a martensite transformation, assuming the steel is not kept at this high temperature for too long. The literature varies from an oil quench to an air cool. This would produce a wide variation in the amount of martensite present. The steel would subsequently be tempered (if it was rapidly quenched, this would decrease the martensite content). Finally, the steel would be polished, and often times etched to reveal the Damask pattern [1]. Sometimes the etching was allowed to continue, and then the swords would be subjected to the Damascene process, to further emphasize the Damask pattern, but this was decorative and did nothing to the actual properties of the steel itself. However, Verhoeven, who put a lot of effort in

researching the microstructure of Damascus steel almost never mentioned heat treatment or martensite formation in the final product, and even says that “The microstructure of [Damascus swords] was not produced by quenching to martensite and tempering” [2], which seems to contradict already existing works in the literature.

There has also been recent evidence (discovered by W. Kochmann and M. Riebold) that the microstructure of Damascus steels contained cementite nanowires, which by themselves could have acted as barriers to dislocations [4,5] which could contribute to better toughness. Further study has uncovered that there may have been carbon nanotubes contained within these cementite nanowires. There is limited information about this phenomenon (and Verhoeven thinks that they may have misinterpreted the data [6]), so I will not focus on it in this paper.

Damascus steel has been known for its strength. However, ultra-high carbon steel is usually not considered to be ductile. Higher-carbon steels tend to be more brittle, which would make them less suitable for swords (which have to survive heavy impacts). However, Damascus steel tends to be different. Verhoeven cut three tensile specimens from different parts of the sword and tested them in tension [2]. The Damascus steel specimens had an average yield strength of 740 MPa, an ultimate tensile strength of 1068 MPa, and 10% strain at fracture (compared to 550 MPa, 965 MPa, and 6% respectively for a hot rolled 1 wt.% plain-carbon steel). This increase in tensile strength is due to the small grain size of Damascus steel and the spherical cementite particles in the pearlite matrix.

The Work of Wadsworth and Sherby

Wadsworth and Sherby didn't begin intending to study Damascus steel. In the late 1970's, they were studying the properties of UHC steels. In their research, they determined that UHC steels are superplastic at “warm” temperatures (600 to 800 degrees Celsius), and with the

proper treatment, can be made strong and ductile at room temperature. During their studies, they noticed that there were many similar properties between their UHC steel and the legendary properties of Damascus steel. Wadsworth and Sherby then began to adapt their own research to develop a method for making Damascus steel. They published their work in a definitive paper, titled "On the Bulat-Damascus Steels Revisited" [1].

Upon consulting the existing literature on Damascus steel (by the authors listed in the introduction), they determined that wootz steel was usually made as ingots. They stated that wootz was made in a crucible from "an iron sponge and wood or charcoal" [1]. This charge is then taken above the melting point, allowing the carbon to become homogeneously distributed through the liquid. The liquid is then poured into a mold cooled very slowly (up to 60 hours) to form a small ingot. This very slow cooling rate allowed equilibrium cooling, so diffusion mitigated the effects of coring. As the metal cooled, austenite grains begin to form in the liquid. By the time the metal is completely solidified, it will be made of large austenite grains. When the austenite/austenite+cementite boundary is reached, cementite grains will begin to nucleate at the grain boundaries. Because of the slow cooling, the cementite particles will be spherical in nature. When the temperature reaches 727 degrees Celsius, the austenite forms pearlite. The final structure of wootz steel would be one of large (equiaxed) pearlite grains, with cementite precipitates at the grain boundaries.

Wadsworth and Sherby state that in order for the cementite particles to remain, the temperature range for forging would be limited to 700 to 900 degrees Celsius. The reason for this is simple, if the temperature crosses the aforementioned austenite/austenite+cementite boundary, the cementite will become austenite again. Also, as stated before, UHC steel is superplastic in this range, making it easier to forge. Wadsworth and Sherby also found some references in literature which stated that the metal not only becomes harder to forge at higher

temperatures (leaving the superplastic region), it also becomes brittle, implying that wootz is hot short. Verhoeven explains this later.

Wadsworth and Sherby decided the easiest way to make Damascus steel from an ingot similar to wootz steel could be made by rolling. First, they prepared a casting of 1.7% carbon. This was subjected to a long heat treatment to mimic the microstructure of wootz steel. Then the steel was then slowly heated to 800 degrees Celsius, where it was isothermally rolled. This causes the austenite grains (which began as large equiaxed grains) to deform into long thin sheet-like grains. The cementite particles which were at the grain boundaries of the austenite move when the austenite grains deform (they remain at the grain boundaries). Because the austenite grains now have a high aspect ratio, with the cementite at the grain boundaries, the cementite is now in layers at the grain boundaries, matching the microstructure of genuine Damascus steel.

The Work of Verhoeven

While Wadsworth and Sherby worked with Damascus steel and compared it to their own work with UHC steels, Verhoeven took a different approach. Verhoeven tried to reproduce the results of Wadsworth and Sherby. However, he came to the conclusion that the Wadsworth-Sherby method was not the correct process, due to the fact that his specimens made with this method did not produce spherical cementite particles, and the cementite sheets were too thin [7]. Wadsworth and Sherby responded in a letter saying that Verhoeven failed to perform the proper heat treatments to his wootz samples [8].

Verhoeven's took a different approach. He instead tried to rediscover the original methods of producing Damascus steel. Therefore, he did extensive studies on genuine Damascus swords, often testing them destructively to determine their composition and microstructure [2,3]. Therefore, while Wadsworth and Sherby used rolling operations to perform

the final deformation, Verhoeven relied on hammer forging, which is not as precise, but should more closely match the microstructure of the genuine Damascus swords.

As I mentioned earlier in the paper, Verhoeven determined the average composition of many Damascus steel swords. He then used this to make his own wootz steel cakes which matched the composition of the genuine swords [7]. He made many different ingots with a few different methods. I will only be discussing “Ingot 41”, which is the ingot which led to the correct microstructure. As mentioned in Wadsworth and Sherby’s research, the wootz ingots were very hot-short (causing them to fracture easily during high temperature forging operations), which occurred in Verhoeven’s ingots as well. Verhoeven attributed the relatively high concentration of phosphorous to the reason for this hot-shortness.

Verhoeven overcame this hot shortness by covering the ingots in iron oxide and putting them in a furnace for 10 hours at 1200 degrees Celsius [7]. This essentially had the opposite effect of case hardening. It decarburized the surface, and also decreased the phosphorous content of the surface to a depth of a few millimeters.

In most of his other ingots, even if a damask pattern was formed, there was also a problem of microporosity in his attempts at making Damascus steel (which doesn’t make sense, because he was subjecting the ingots to severe deformation, which should have welded shut any microporosity). Verhoeven forged his steels above 1000 degrees C to weld shut any microporosity (previous attempts had been performed at slightly lower temperatures). Later forging steps were done between 1000 and 700 degrees Celsius until the final desired shape was achieved [7]. This process successfully produced a damask pattern, and the microstructure (the cementite particle sheets in particular) matched that of genuine Damascus steels.

Verhoeven then mentioned in later papers that minute amounts of carbide-forming elements like vanadium and chromium [3] are crucial to the formation of the damask pattern. He

states that if these elements are missing or in too low concentrations (less than 40 ppm by weight), the Damask pattern will not form. This seems to disagree with the work of Wadsworth and Sherby, which states that the cementite will form on its own, due to the slow cooling process from making the wootz steel. However, as stated before, it is possible that Verhoeven was not following the procedures determined by Wadsworth and Sherby.

However, this also leads to the theory as to why the original method for producing Damascus steel was lost. There is considerable information in the literature [1,7] that wootz steel was produced in a specific region in India. Verhoeven suggests that the mine(s) where the ores were extracted ran out of ores which had the correct amounts of impurities to make Damascus steel. Since the ore was no longer available, the process for making Damascus steel was lost. If this theory is true, then it suggests that the original method for making Damascus steel from wootz was similar to the process developed by Verhoeven.

Conclusion

The different methods put forth by Wadsworth and Sherby and by Verhoeven are two different processes which both seem to produce Damascus steel. While Verhoeven's process is probably closer to the original process for making Damascus steel, it is more prone to variation due to the imperfect nature of hammer forging, and is more prone to variation due to the right amount of impurities required in the wootz. While Wadsworth and Sherby's method is not the same one originally used to make Damascus steel, it would probably produce better and more consistent results.

References

1. J. Wadsworth and O. D. Sherby, "On the Bulat-Damascus Steels Revisited", *Progress in Materials Science*. 25:35-68 (1980).
2. D. T. Peterson, H. H. Baker, J. D. Verhoeven, "Damascus Steel: Characterization of one Damascus Steel Sword", *Materials Characterization*. 24:355-374 (1990).
3. J. D. Verhoeven, A. H. Pendray, W. E. Dauksch, "The Continuing Study of Damascus Steel: Bars from the Alwar Armory", *JOM*, 56-9:17-20 (2004).
4. W. Kochmann and M. Reibold et al., "Nanowires in ancient Damascus steel", *Journal of Alloys and Compounds*, 372:L15-L19 (2004).
5. W. Kochmann and M. Reibold et al., "Discovery of Nanotubes in Ancient Damascus Steel", *Physics and Engineering of New Materials*, 127:305-310 (2009).
6. K. Sanderson, "Sharpest cut from nanotube sword", *Nature news*, 15 November 2006
< <http://www.nature.com/news/2006/061115/full/news061113-11.html> >
7. J. D. Verhoeven and A. H. Pendray, "Experiments To Reproduce the Pattern of Damascus Steel Blades", *Materials Characterization*. 29:195-212 (1992).
8. J. Wadsworth and O. D. Sherby, "Comments on 'Damascus Steel, Part III: The Wadsworth-Sherby Mechanism' by Verhoeven et al.", *Materials Characterization*. 28:165-172 (1992).