Scandinavian Journal of Metallurgy 2001; **30**: 65–68

SCANDINAVIAN
JOURNAL OF METALLURGY
ISSN 0371-0459

Reproduced wootz Damascus steel

Juha Perttula

Tampere University of Technology, Institute of Production Engineering, P.O. Box 589, FIN-33101 Tampere, Finland

The best Damascus blades were forged in Persia from Indian wootz steel having a carbon content of about 1.5%. They became famous for their high quality and distinct surface patterns which resulted from small cementite particles arranged in parallel layers. The last highest-quality blades were made perhaps in the 18th century, after which the art was temporarily lost. Recently, it has been rediscovered. In this paper, it is shown that this ancient steel material can be reproduced by a modern foundry. The addition of about 0.5% Cr is essential. The interdendritic segregation of Cr and thermal cycling lead to the formation of the characteristic layered microstructure in forged specimens. Cr also prevents graphitization.

Key words: wootz, Damascus, segregation, Cr, reproduction.

Accepted for publication 18 May 2000

Damascus steel takes its name from the place where medieval Europeans first encountered it. The best Damascus blades, however, were made in Persia from Indian steel which was called wootz [1–3]. The production of wootz Damascus steel started in 500 AD or earlier and the last highest-quality blades were made perhaps around 1750 AD, after which the quality decreased. In recent years, many important factors concerning the manufacturing process have been scientifically determined and some excellent blades have been successfully prepared [4–7]. In Fig. 1 is shown a blade forged by the author. Carbide-rich zones are etched light.

Genuine Damascus steel was very hypereutectoid in nature. Its carbon content varied between 1% and 2%, but was typically 1.5%. The distinct feature of this steel was beautiful surface figures which were formed from numerous small globular cementite particles lying in parallel layers. Usually the blades were not hardened and the structure of a matrix was pearlite or spheroidite, depending on the cooling rate. The air-cooled blades could undergo a transition from spheroidite at the thick back to pearlite at the thin edge. If the cooling rate was accelerated, for instance, by boiling water or oil, a fully pearlitic matrix was attained. Despite some exceptions, generally no free graphite existed [6]. In Fig. 2 is shown a typical microstructure with a pearlitic matrix and parallel carbide-rich layers whose spacing is about 40 μm.

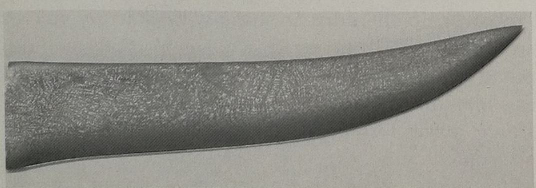

Fig. 1. Reproduced wootz Damascus blade, length 15 cm.

The secrets of Damascus steel have fascinated bladesmiths and scientists for centuries [1–3, 8]. Many opinions on the origin of the damask pattern have been presented, such as whether it is due to a proeutectoid carbide network on austenite grains or the inhomogeneous structure of an incompletely molten crucible charge. Undoubtedly, Damascus steel was made in several different ways [1], but the most likely explanation for the origin of the highest-quality structure has been presented by Verhoeven et al. [4–7]. In the original wootz process a hypereutectoid carbon level was achieved by melting a mixture of iron sponge and wood for carbonization in small closed crucibles (ca. 2 kg). Good Damascus blades were forged from ingots which were solidified slowly from the molten state and therefore had a coarse dendritic microstructure. Due to the interdendritic segregation of certain impurity elements, thermal cycling during the forging process caused the dissolution of carbides in the intradendritic regions and the collecting of carbides in the interdendritic regions. After several forging cycles, the carbide-rich layers parallel to the deformation plane were formed.

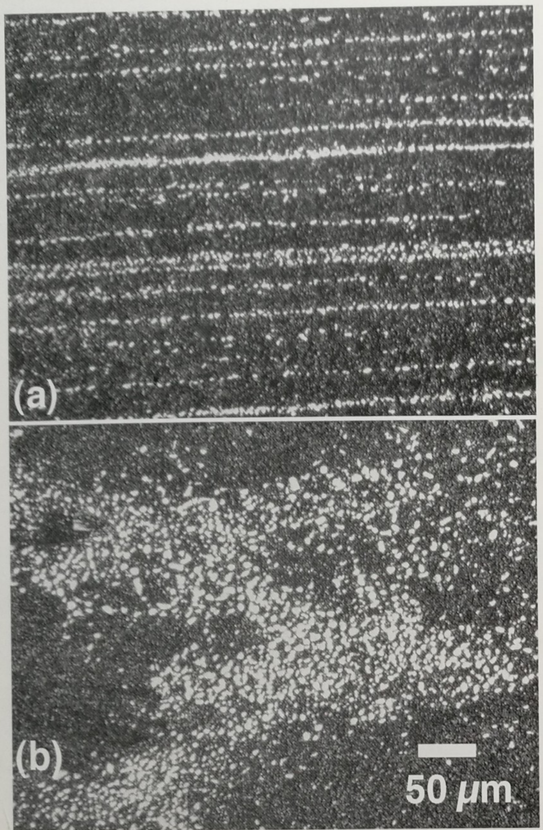

Fig. 2. (a) transverse section and (b) surface of a blade.

Genuine Damascus steel is often confused with welded steel in which alternating sheets of different grades of steel or iron are forge-welded together. A high number of layers is attained by repeating the folding and welding cycles several times. Stainless Damascus steel emerged a few years ago (Damasteel Ltd., Sweden). It has carbide-rich layers similar to its ancient counterparts. However, the layers are produced by utilizing powder metallurgy. Both it and welded steels are quite common today, whereas modern-made wootz is a very rare material. The purpose of this study is to show how ancient wootz Damascus steel can be reproduced by present-day techniques. It also helps to give an understanding of the nature of the ancient blades.

Steelmaking

In Table 1 are listed chemical compositions of steel materials used in the ancient blades (Old), the preliminary tests (New1, New2) and the current study (New3). The preliminary tests showed that a good damask could be achieved by melting scrap (New1). When commercially pure iron was used (New2), an inferior damask pattern was obtained accompanied by graphitization. Scrap contained 0.18% of Cr and small amounts of other carbide formers, which obviously prevented graphitization and resulted in the formation of the desired patterns. It should be pointed out that the ancient blades did not contain appreciable quantities of Cr, but they contained small amounts of V, which has similar effects as Cr [6].

Table 1. Chemical compositions of wootz Damascus steels (wt %)

	C	Si	Mn	S	P	Cr	Mo	V	Al	Cu	Ni
Old*	1.51	0.05	0.02	0.01	0.11	0.00	0.00	0.01	0.00	0.10	0.03
New1	1.56	0.38	0.68	0.01	0.01	0.18	0.06	0.03	0.14	0.07	0.14
New2+	1.72	0.17	0.21	0.01	0.01	0.03	0.00	0.00	0.06	0.02	0.03
New3	1.55	0.01	0.18	0.02	0.02	0.46	0.01	0.00	0.03	0.04	0.03

*Average of 7 swords [6].
+Susceptible to graphitization.

The steel used in the current study was prepared by air induction melting of 150 kg pure iron and additions of graphite, ferrochromium, and ferromanganese. Aluminium was used as a deoxidant. A long solidification time giving rise to coarse dendrites was attained using sand moulds which produced steel ingots 50 mm×50 mm×250 mm in size. The ingots were reheated in a furnace at 1140°C for 90 min until cementite and possible free graphite were dissolved. The hot ingots were immersed in water for a few seconds and after that air cooled.

The ingots were cut into pieces 80-mm long which were hammered vertically in a manner that elongated the structure nearly equally in all directions. A traditional blacksmith's forge and power hammer were used. About 15 heating and forging cycles were needed to attain the required thickness of about 5 mm. Temperature was observed by eye. A peak temperature above 1100°C was used in the first three cycles, after which it was decreased to around 900°C. The workpieces were cooled to near 600°C between the forging cycles. The treatment was nearly similar to that used successfully by Verhoeven et al. [4, 5]. However, in the current study a satisfactory microstructure was difficult to achieve by that method. Some specimens had a homogeneous distribution of carbides and in the cases where the layered microstructure was formed there often existed grain-boundary cementite.

It was discovered that a very good layered microstructure was always formed when the specimens

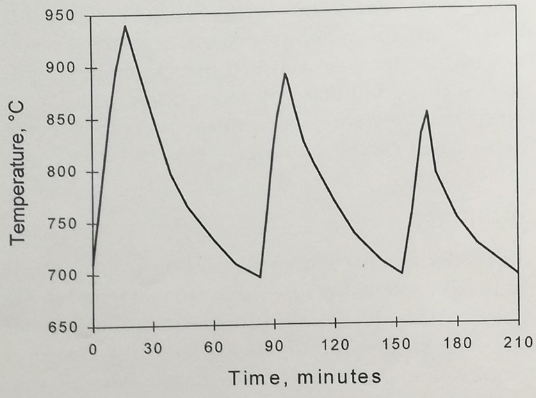

Fig. 3. Thermal cycling treatment.

were first forged and then thermally cycled in an electrical furnace. The cycling treatment is illustrated in Fig. 3. Obviously the very slow cooling rate is essential.

The purpose of the first heating to 940°C is to dissolve all cementite in the intradendritic regions and retain some undissolved interdendritic carbides, which are enriched by chromium. These carbides hinder grain boundaries and therefore more boundary area exists in the interdendritic regions. During the slow cooling, dissolved cementite nucleates on the surfaces of the existing carbides and the grain boundaries evolving the carbide-rich layers and the matrix transforms into very coarse pearlite. In Fig. 4a is shown one layer. Grain-boundary cementite in this case does not form a continuous network but rather blocky particles.

Disadvantageous grain-boundary cementite can be removed by reheating the specimen to 890°C and cooling it slowly. Generally this is a sufficient procedure, but in some cases, an extra heating cycle to 850°C is beneficial. After these one or two cycles, the regions between the carbide-rich layers contain a mixture of coarse pearlite and small spheroidised cementite particles, as in Fig 4b. The slow cooling rate and the fact that austenite remains inhomogeneous at these relatively low peak temperatures favours the formation of spheroidite over pearlite. Softer spheroidite can be transformed into harder pearlite by austenitizing the specimen and cooling it fast in air or oil. The specimen in Fig. 4c has been reheated to 850°C for 20 min and cooled fast by blown air. In this case the pearlite lamella spacing is very small and unresolvable by light microscope.

Third elements

This study supports the theory that the interdendritic segregation of third elements is responsible for the formation of the carbide-rich layers in the Fe-C alloys. Table 1 gives a list of the elements which account for most of the content of ancient blades (Old). The P content is rather high, but it is argued that the small amount of V is more effective [5–7]. Cr is the major alloying element in the steel of the present study (New3). It has been shown that a very small amount (<0.02%) of V can produce a good damask pattern on very clean steel (P and S levels <0.003%) whereas a similar amount of Cr is ineffective [5], but a somewhat higher amount of Cr (0.04%) has a weak effect [7]. According to the results of the present study, the Cr content 0.46% work very well.

The other important function of Cr and V is their

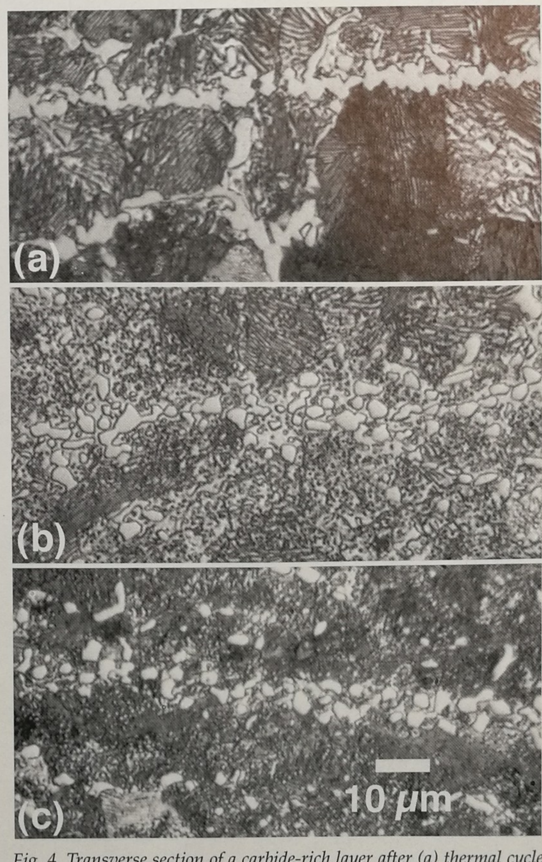

Fig. 4. Transverse section of a carbide-rich layer after (a) thermal cycle to 940°C (b) thermal cycles to 940°C, 890°C, and 850°C (c) reheating to 850°C and fast cooling by blown air.

ability to prevent graphitization. Small amounts of V in the ancient blades perhaps had a slight effect. The relatively high addition of Cr used in the steels of the present study (New3) prevented graphitization very effectively. On the other hand, P and Si have an opposite effect. They strongly promote the formation of graphite (New2). P may also induce severe hot shortness. Thus, forging of the ancient Damascus blades which contained relatively high amounts of P needed very good metallurgical skills. Perhaps V was the most important third element in ancient wootz steel [6], but also other carbide formers like Mo, Nb, Cr and Mn as well as P and S can be responsible for the formation of the damask [7].

Cutting tests

The cutting performance of non-hardened Damascus steel was compared to mild steel and hardened 0.75% carbon steel. Blades with a deep cutting angle of about 20° were made and their ability to cut leather was tested by ordinary users and a leather professional.

The microstructure of the tested Damascus blade is shown in Fig. 2. Its hardness was as high as 46 Rc due to a high carbide content and very fine pearlite. The hardness of mild steel was too low for the Rockwell C hardness meter used. As expected, the Damascus blade retained a keen cutting edge considerably longer than the mild steel blade. In ancient times, similarly, the difference between Damascus and wrought-iron blades was very distinct.

The 0.75% C blades were quenched from 780°C and tempered at 150°C for 3 h and at 220°C for 1.5 h. A Rockwell C hardness of 63 Rc and 60 Rc was attained, respectively. The former blade served considerably longer than the latter blade. It was a real surprise that the cutting capacity of the non-hardened Damascus blade was equal to that of the hardened blade of 60 Rc. Moreover, the non-hardened structure was very tough.

It should be realised that this test tells quite little about the performance of the ancient weapons. However, it is interesting to consider that the best medieval European blades had a hardened high carbon steel edge. Their good combination of hardness and toughness was attained by forge-welding steel and wrought-iron together [9, 10] and quenching the blade by a method which only hardened the edge [9].

It is often claimed that the Muslims' Damascus swords were metallurgically superior to the crusaders' weapons. During the cutting tests it was noticed that the professional found existing differences quite reliably, but the inexperienced users were easily misled by the appearance of the blade. Similarly, it is possible that the ancient Damascus blades felt better than they really were and that their legendary reputation increased in that way. In any case, the test confirmed that very serviceable weapons could be made from ancient Damascus steel.

Summary

The modern wootz Damascus steel developed in this study has a microstructure similar to that found in the ancient blades. Its chemical composition is somewhat improved so that the ingots can be easily cast in a common foundry, they can be forged without precautions, and finally the damask pattern can be conveniently produced by thermal cycling in a programmable furnace. The very slow cooling rate of a cycle is essential. The cutting tests indicate very promising results and the non-hardened structure of the steel is very tough. It is excellent material for blades, but no superior properties compared to the modern steel grades were found in this study. Wootz Damascus steel is an attractive alternative for modern knives, because it have interesting history and fascinating damask pattern can be seen on its surface.

Acknowledgement

The Foundation of Ella and Georg Ehrnrooth is acknowledged for its financial support and Timo Suuniitty, a leather professional, for his help with testing the cutting performance of the blades. The Wallace Collection, London, is thanked for their impressive exhibition of ancient wootz Damascus steel weapons. Bladesmith Pekka Väyrynen is acknowledged because he produces very fine modern wootz Damascus steel blades.

References

1. Smith CS. A history of metallography. Univ of Chicago Press, Chicago 1960: 14–29.
2. Wadsworth J, Sherby OD. Prog Mat Sci 1980: 25: 35–68.
3. Figiel LS. On Damascus steel. Atlantas Art Press, Atlanta 1991.
4. Verhoeven JD, Pendray AH, Berge PM. Mater Char 1993: 30: 187–200.
5. Verhoeven JD, Pendray AH, Gibson ED. Mater Char 1996: 37: 9–22.
6. Verhoeven JD, Pendray AH, Dauksch WE. JOM (Sept) 1998: 58–64.
7. Verhoeven JD, Laabs F, Pendray AH, Dauksch WE. Iron and Steelmaker (Nov) 1998: 65–74.
8. Smith CS. Science 1983: 216: 242–244.
9. Williams AR. Gladius 1977: 13: 75–101.
10. Charles JA. Mater Sci Technol 1998: 14: 496–503.