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Wootz Damascus steel of ancient orient

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The legendary Damascus blades of ancient Orient are forged from high carbon (ca. 1.5% C) crucible steel, i.e., wootz. The famous damascene surface pattern is formed from carbide particles arranged into parallel layers. The cutting quality and impact toughness of these blades were respectively studied with leather knives and Charpy specimens made from reproduced steel. The advantageous effect of carbides on edge-holding quality may be less than is often believed. It was difficult or even impossible to detect when leather was cut. The steel with a uniform distribution of carbides was somewhat tougher than the steel with carbide-rich layers. Oriental ore often contained a high amount of phosphorus, which presumably made the majority of the blades somewhat brittle, but in the cases when carbon and phosphorus contents are not excessive, wootz Damascus steel can be ductile.

Key words: Charpy, cutting, Damascus, toughness, wootz.

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Woots is ancient high carbon crucible steel whose production started during 500 AD or earlier in India. It was prepared by melting a mixture of carbonisation material (wood, charcoal or leaves) and ore or low-carbon iron in small closed clay crucibles. Wootz was exported from India and many excellent blades around the ancient world were forged from it [1, 2].

The Damascus swords of the Islamic orient are the most famous artefacts made from wootz (Fig. 1). They have had a legendary reputation since they became familiar to the Western world through the crusaders. The characteristic feature of these blades is the surface figures, which are formed from parallel carbide-rich layers aligned along the forging plane. The structure originates from the coarse solidification structure of a wootz ingot.

Damascus blades take their name from the locality at which medieval Europeans encountered them, not from the place of origin [1, 2]. Perhaps the finest survived Damascus blades in museums and collections were forged in the 16th to 18th centuries in Persia from Indian steel. Many fine photographs of such swords are presented in Figiel's book [3]. In the mid-18th century the quality of the damascene patterns started to decrease [4] and the art gradually disappeared [1–5].

Nowadays the term Damascus steel generally refers to all steels having a visible surface pattern. Hence, the genuine wootz Damascus steel is often confused with the forge-welded steel in which alternating sheets of different grades of steel or iron are hammered together. Many blacksmiths use this technique today. A similar technique was also familiar to many ancient cultures. Viking swords, for instance, are known by their pattern-welded blades.

Verhoeven et al. claim that they have revealed the lost art of making genuine Damascus steel. According to them, the formation of the original damascene pattern required that the ore from which the wootz was prepared contained critical impurity elements, particularly vanadium, which segregated between dendrites during the solidification of ingots. The impurity element induced the growth of interdendritic carbides during the forging process and consequently the formation of parallel carbide-rich layers [4, 5].

The author has developed a technique in which the small amount of vanadium (<0.03%) found in ancient steels is replaced by a larger addition of chromium (ca. 0.5%). During a slow furnace cooling, chromium induces the formation of damascene pattern (Fig. 2) and carbide-rich layers (Fig. 3), which are identical to the ancient ones. Chromium also prevents graphite formation, which is prone to occur in hypereutectoid plain carbon steels [6].

The chemical compositions of ancient Damascus steels are listed in Table 1. Verhoeven et al. [4] have reanalysed the famous specimens of Zschokke [7] (Swords 7, 9 and 10) and therefore they are presented twice.

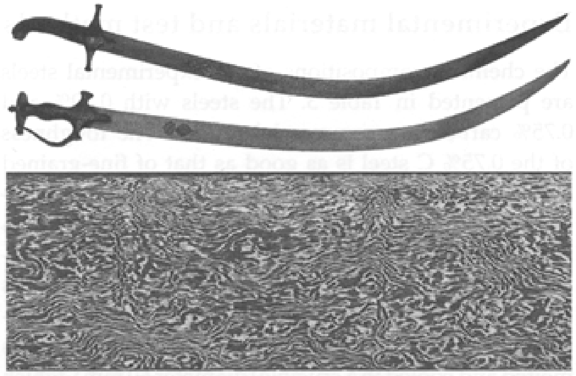

Fig. 1. Persian Damascus sabres from the 1600s and close-up photograph of a blade [3].

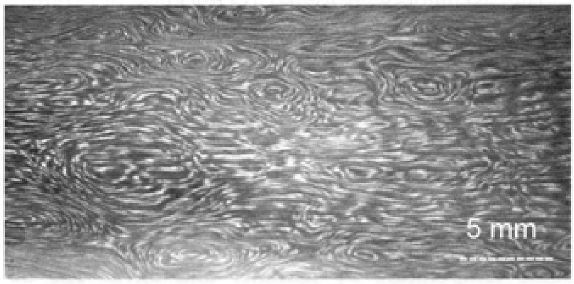

Fig. 2. Surface pattern of a reproduced wootz Damascus specimen.

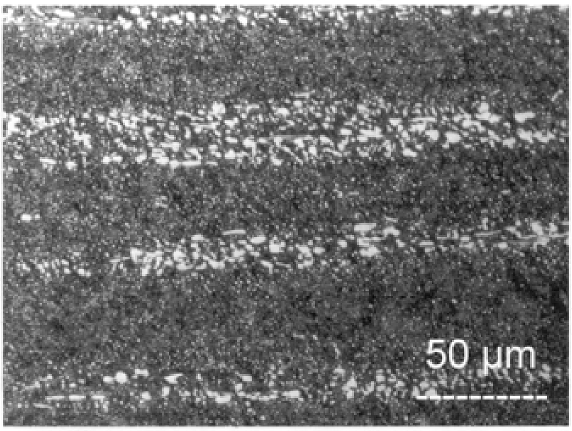

Fig. 3. Transverse section of a reproduced wootz Damascus specimen.

Verhoeven et al. repeatedly found a small amount of vanadium, except in the Voight blade, the damask pattern of which should be formed by different mechanism. In fact, closer examination of this blade has revealed that the microsegregation of phosphorus does not coincide with carbide-rich layers and thus the damascene pattern can not be the consequence of interdendritic formation of cementite induced by microsegregation of impurity elements [8].

Table 1. *Chemical compositions of Oriental wootz Damascus blades (wt%)*

	C	Si	Mn	S	P	V
Verhoeven et al. [4]						
Old B blade	1.51	0.047	0.010	0.005	0.095	0.004
Figiel sword	1.64	0.046	0.020	0.009	0.162	0.004
Voight sword	1.00	0.098	0.050	0.012	0.026	<0.001
Kard knife	1.49	0.050	0.010	0.009	0.144	0.006
Sword 7	1.71	0.035	0.015	0.010	0.101	0.015
Sword 9	1.41	0.050	<0.01	0.006	0.098	0.005
Sword 10	1.79	0.050	0.030	0.016	0.133	0.027
Zschokke [7]						
Dagger 3	1.68	0.015	0.056	0.007	0.086	
Dagger 5	1.58	0.011	0.030	0.018	0.104	
Sword 7	1.87	0.049	0.005	0.013	0.127	
Sword 8	0.60	0.119	0.159	0.032	0.252	
Sword 9	1.34	0.062	0.019	0.008	0.108	
Sword 10	1.73	0.062	0.028	0.020	0.172	
Panseri [9]						
Sword 1	1.62	0.027	traces	0.007	0.087	
Sword 2	1.42	0.110	0.130	0.038	0.035	

Very slowly cooled hypereutectoid steel casting has extremely large grain size with a cementite network at former austenite grain boundaries. Thus, it is very likely that, in some cases, the grain boundary cementite can also act as the source of surface figures. In fact, some blades have the so-called granular damascene pattern, i.e., dark grains surrounded by a light-etching network [2, 3]. However, the majority of the highest quality damascene patterns have the appearance of distorted dendrites, but the distortion may be so large that the dendritic origin can be detected only by an experienced eye.

There are also a numerous amount of smaller carbides between carbide-rich layers, which provide sites for cementite nucleation disturbing pearlite reaction with slow cooling rates. In order to attain sufficient toughness, the heated Damascus blade was not quenched, but was air-cooled or it was wrapped in a wet cloth [1]. Thus a structure containing spheroidised carbide particles on ferrite matrix (spheroidite) is often met, but a pearlitic matrix is also possible [4, 7–9]. A typical Damascus blade has a spheroidised microstructure in thick back, while the thin edge, which cools down faster, has a pearlitic matrix [4].

In 1924 Zschokke compared the performance of the oriental Damascus steel (Swords 7–10 in Table 1) and Solingen pattern-welded Damascus steel (0.61% C–0.059% Si–0.069% Mn–0.007% S–0.024% P) and Solingen melted and worked steel (0.5% C–0.52% Si–0.41% Mn–0.038% S–0.045% P) [7]. The results of mechanical testing are presented in Table 2. Solingen steel specimens outperformed the Oriental ones. Sword 8 with 0.6% carbon is not a typical wootz Damascus blade because the damascene pattern is formed from ferrite layers in a

Table 2. *Measurements of Oriental and Solingen steels by Zschokke [7]*

		Brinell hardness	Breaking angles
Sword 7	Wootz Damascus	201–240	25° 24° 32°
Sword 8	Wootz Damascus	201–249	78° 48° 52°
Sword 9	Wootz Damascus	171–209	24° 18° 14°
Sword 10	Wootz Damascus	235–264	15° 21° 16°
Sample 11	Solingen pattern-welded	313–417	50° 89° 67°
Sample 12	Solingen	451–473	96° 69° 70°

pearlite matrix, but it was the toughest Oriental blade, even though its phosphorus content was highest.

Early medieval Muslim writers thought that Indian wootz was not necessarily the best kind of steel. In the 1600s, European swords sold well in India and were desired due to their superior quality. It was claimed that European blades could bend and become straight again, whereas Indian swords will break rather than bend. Persian sword smiths were preferred to Indian colleagues and thus Persian swords, presumably made from Indian wootz, were also traded to ancient India [1].

The average quality of wootz Damascus blades seems to be inferior, but this does not exclude the fact that some individual blades could be superb. Peterson et al. have executed tensile tests for small specimens made from the Voight blade, with a carbon and phosphorus contents lower than in the average of Damascus steels (Table 1). The matrix is pearlitic. The mean values of three measurements of yield strength, tensile strength, elongation and reduction of area were 740 MPa, 1068 MPa, 10% and 32%, respectively. These values are quite good even when compared to modern steel [8].

Sword blade 2 measured by Panseri in Table 1 is interesting, because the phosphorus content is relatively low while the carbon content is typical for wootz. It is a well-known fact that phosphorus increases fragility and thus the very best Damascus blades were presumably made from low-phosphorus wootz grades.

Because the performance of the highest quality blades is the most interesting, the present study concentrated on the steel with relatively low phosphorus. The study attempts to provide answers to the questions concerning toughness and cutting quality of Damascus swords and knives.

Experimental materials and test methods

The chemical compositions of the experimental steels are presented in Table 3. The steels with 0.29% and 0.75% carbon are commercial grades. The toughness of the 0.75% C steel is as good as that of fine-grained chromium-vanadium tool steels; thus, it represents today's best-quality carbon steel. The steels with 1.58% and 1.70% carbon were air induction melted in the laboratory and the melts were poured into sand moulds (80 × 80 × 300 mm). Only the 1.58% C steel was deoxidised with aluminium. The 1.38% carbon steel was melted and cooled in a crucible (diameter 60 mm), which was placed in an induction furnace. Vermiculite was used as slag.

The cast ingots were forged to a thickness of 15 mm by power hammer. The Damascus pattern was obtained by reheating the forgings to 950°C and cooling by 200°C/h to 700°C and subsequently reheating to 900°C and again cooling slowly. A more detailed explanation of the used technique is published earlier [6].

After this heat treatment the forgings were hot rolled to 6 mm at 850°C temperature, except the crucible-cooled 1.38% C steel, which was hand-forged at the same temperature by hammer and anvil. The obtained spacing of carbide-rich layers was around 50 μm and the carbide particles reached the size of 5 μm (Fig. 3).

The uniform distribution of small carbides (1–2 μm) was obtained by reheating the 1.58% C steel forging to 1160°C where cementite dissolved and then cooling it with water to a temperature of about 600°C and thereafter allowing it cool in air. Final hot rolling to 6 mm was performed at 850°C.

The hardened and tempered 1.58% carbon steel specimens were quenched from 780°C in brine. The heating temperature was 800°C when oil or air-cooling was used in order to produce pearlite or spheroidised microstructure, respectively. The hardened and tempered 0.29% and 0.75% carbon reference steels were oil quenched from 870°C and 800°C, respectively.

In order to reveal microstructure and macroscopic surface pattern, the specimens were polished and etched with ferric chloride in water (10 g/100 ml). The ability of the sword blade to withstand impacts was studied

Table 3. *Chemical compositions of the experimental steels (wt%)*

	C	Si	Mn	S	P	Cr	V	Al
Commercial grade	0.29	0.27	1.18	0.01	0.01	0.33	0.01	0.04
Commercial grade	0.75	0.24	0.72	0.01	0.01	0.17	0.00	0.03
Crucible-cooled	1.38	0.09	0.13	0.05	0.10	0.33	0.02	0.00
Cast in sand moulds	1.58	0.17	0.13	0.03	0.04	0.48	0.01	0.06
Cast in sand moulds	1.70	0.19	0.16	0.02	0.11	0.28	0.03	0.00

Table 4. *Leather knives for cutting tests*

Carbon (wt%)	Hardness (Rc)	Matrix	Cementite particles	Cutting quality
1.58	63	Tempered martensite	Damascene pattern	Excellent
1.58	63	Tempered martensite	Uniform distribution	Excellent
0.75	63	Tempered martensite	–	Excellent
1.58	43	Pearlite	Damascene pattern	Poor
1.58	38	Pearlite	Uniform distribution	Poor
0.75	34	Pearlite	–	Poor
0.75	46	Tempered martensite	–	Worst

using the Charpy impact test with unnotched specimens 5 × 15 × 55 mm in size. The edge-holding quality of the experimental steels was studied by cutting leather. The used test knives were quite similar to surgical knives.

Cutting tests

Any knife blade can be honed extremely sharp, but its ability to retain keen cutting edge determines the quality of steel. The edge-holding quality of seven blades with various microstructures and carbide contens was tested by cutting leather (Table 4). The tests were carried out by an experienced leather professional and the author, who is quite inexperienced in leather work.

Both easily noted that the three hard blades were excellent while the four softer blades had inferior edge-holding quality. However, they could be used for leatherwork, if they were sharpened frequently.

The author found no differences between those blades with almost equal hardness. The leather professional thought that the hard blades were equal. On the softer blades, he thought that the edge-holding quality of the tempered martensite was the worst, even though it was the hardest of the soft blades. Plain pearlite was surprisingly as good as the carbide-rich steels. The quality of sharpening, however, had more effect on edge-holding quality than the microstructure and thus the result is quite unreliable.

In the earlier study, it was found, that a non-hardened wootz Damascus leather knife with hardness of 46 Rc retained a keen cutting edge as long as a hardened and tempered knife with hardness of 60 Rc [6]. It was supposed that the carbides compensated the lower toughness, but in the light of present tests the pearlitic matrix also have an effect.

When the blades were examined under a light microscope, it was noticed that generally only a few carbide particles were located on the ultimate cutting edge, and thus their effect can be assumed to be marginal. This was particularly true with Damascus steel if the carbide-rich layer and ultimate cutting edge did not coincid. On the other hand, in the opposite situation, there was a thick group of carbides on the edge. The Damascus blade may be superb if one can sharpen it so that the carbide-rich layers locate on the ultimate cutting edge.

The cutting test showed that the effect of carbides may be extremely difficult to detect in leather working, even though their virtue is highly appreciated. In the past when superior cutting quality was needed, like razor and surgeon blades, ultra high carbon steel was selected. Even Indian wootz was successfully used in the European high-grade cutting tool business [1]. Many present-day knife smith prefer carbide-rich steel, because they assume that superior edge-holding quality can be achieved.

Impact toughness

The very first impact tests were carried out with air-cooled 1.58% C Damascus steel, which had spheroidised microstructure. The thickness of specimens was 3.5 mm according to the test pieces of Zschokke. However, the specimens did not break in the Charpy impact test machine, instead of which, they became bent and slipped from their position. When the bending was exceeded in machine shop vice, the fracture did not occur until the bending angle reached 120°. The reproduced low phosphorus steel specimens were considerably more ductile than any of the specimens of Zschokke (Table 2). Thus it can be assumed that Zschokke did not test the highest quality swords.

Because consistent Charpy results require that the specimens will break, the thickness was increased to 5 mm. Figure 4 illustrates the impact values of the air-cooled specimens. The results show that Damascus steel can be tough, if the carbon and phosphorus content are not excessive. The measurements of 1.38% C steel have the largest scatter. Obviously it was the result of the most inhomogeneous microstructure, which was due to small crucible-cooled ingot and thereby small forging reduction. In spite of this, the specimens were clearly tougher than those made from the highest carbon and phosphorus containing steel.

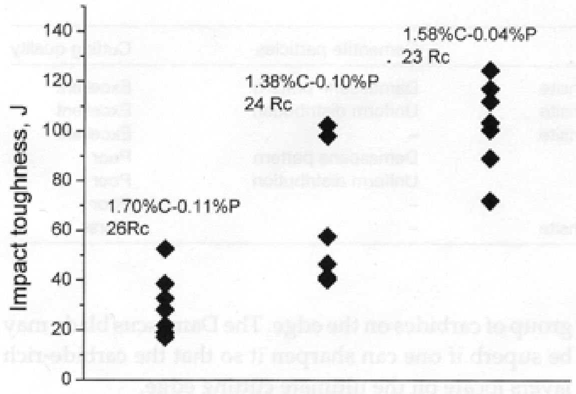

Fig. 4. Effect of carbon and phosphorus on the impact toughness of air-cooled wootz Damascus steels.

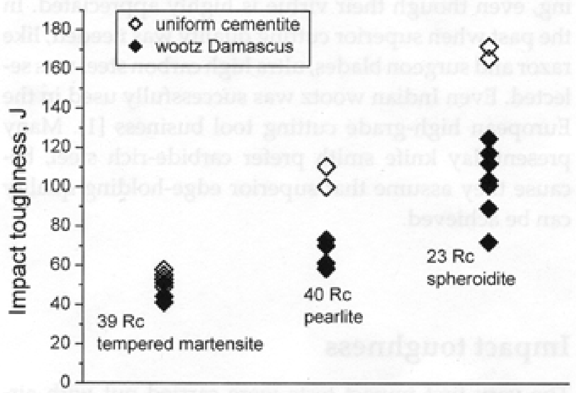

Fig. 5. Effect of matrix microstructure on the impact toughness of 1.58% carbon steel with carbide-rich layers (wootz Damascus) and uniform distribution of carbides.

Generally the microstructure of Damascus blades contains spheroidite or pearlite, but tempered martensite is also possible [10], particularly in knife blades. The impact toughnesses of 1.58% carbon steels with uniform distribution of carbides and carbide-rich layers are compared in Fig. 5. It is clearly shown that the former is tougher, as expected, though the difference seems to be small in the cases of high temperature tempered martensite. With low temperature tempered martensite the difference is relatively larger, as shown in Fig. 6.

Figure 7 illustrates the fact that hypereutectoid carbon steel is a good choice when high hardness is required, but steel with lower carbon content is better when high toughness is desired. The hardness of 63 Rc was attained, when 1.58% C steel was tempered at 200°C or 0.75% C steel at 170°C. At this hardness level the 1.58% C steel with uniform distribution of cementite particles was almost as tough as the 0.75% C steel, but with the lower hardness values the carbon seem to drastically decrease the toughness. The difference is more distinct

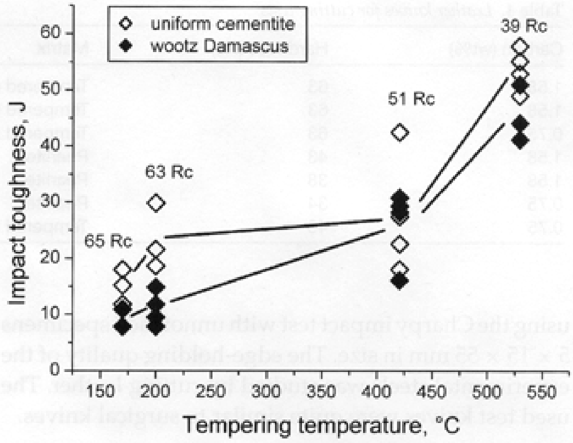

Fig. 6. Impact toughness of tempered martensite of 1.58% carbon steel with carbide-rich layers (wootz Damascus) and uniform distribution of carbides.

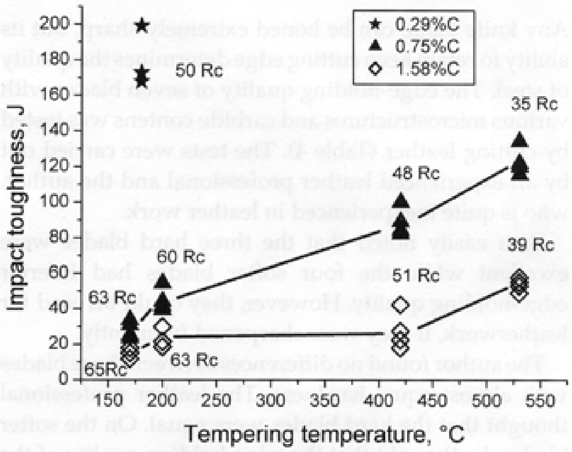

Fig. 7. Effect of carbon content on impact toughness as a function of tempering temperature.

when compared to 0.29% carbon steel at hardness level of 50 Rc.

The Charpy test may simulate a situation in which the side of a sword blade is hit by the edge of another sword. The best Damascus steel specimens had Charpy impact values of around 100 J. The kinetic energy is 100 J if the speed of a sword (1 kg) is sufficient to throw it a distance of 20 m. This very concrete example makes clear that the kinetic energy of 100 J is easily achieved by every swordsman, but more energy than that is needed in order to slice the opponent's sword into two during a battle. A real sword is not fixed in its position and a long blade absorbs more energy prior to breaking than short Charpy specimens.

When steel bars with similar dimensions to a sword blade, were smashed against each other and other hard objects, it was noted that the bars did not break if the

Charpy impact toughness was around 100 J, but they bent quite easily if the hardness was less than 40 Rc.

Conclusions

The effect of cementite particles on the edge-holding quality may be less than is often believed. It was difficult or even impossible to detect when leather was cut by knife. In different kinds of work and knives, however, the carbides may be more advantageous. Practically, hardened wootz Damascus steel is as good knife steel as modern high-carbon steel.

Damascus steel with a large amount of carbon and phosphorus is very brittle even in its soft condition, but in a case where the carbon and phosphorus contents are not excessive, a properly made non-hardened Damascus sword will be ductile and not break during a battle, but it is quite soft and may bend upon impact.

The Charpy impact toughness of steel with uniform distribution of very fine carbides is higher than that of Damascus steel with carbide-rich layers. This, however, may be unimportant, because it is plastic bending, not breaking, which may spoil a well-made Damascus sword during a battle.

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