Reproduction of Damascus steel (wootz), patterns and blade forging.

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Brief history.
There is information in the literature indicating that these steels were already being produced before the birth of Christ. Hanging on a wall in a materials research centre in India is a tapestry showing King Puru handing his sword over to Alexander the Great after being defeated by him in 330 BC (Figure 1). It is said that a piece of steel was packed in a golden casket which in the picture is shown being carried forward and handed over. Later, from before the Viking period until around 1750, edged weapons of high quality were produced, mainly in Persia, with steel imported from southern India. The steel is known in English as wootz. Many people in Sweden have read about the knight Arn who during the Crusades encountered Muslims equipped with sabres, swords and daggers made of Damascus steel. The trading place of Damascus has given its name to the weapons made by forging wootz steel, and the leading blacksmiths were considered to be in Persia. The finished weapons had attractive patterns that were considered to guarantee quality. The history comes to an end around 1750, when the wootz steel that was supplied changed to such a degree that the blacksmiths knowledge and methods developed and passed on from generation to generation were no longer adequate to produce the "Damascus patterns" on finished blades. The Persian blacksmiths methods disappeared because they no longer worked. After just a few generations everything was forgotten and lost for posterity.

About the wootz steel
Weapons from museums that have been studied show that wootz steel is a carbon steel with a carbon content in the range of 1.2 – 2.0% C. The steel is surprisingly pure, that is to say free of slag inclusions, and is made by melting and solidifying in ceramic crucibles. Slow solidification results in a segregated solidification structure with a highly variable carbon content. In subsequent forging layers with a particularly high proportion of free cementite parallel with the forged blade surface is formed. The different layers, or bands, were little deformed by the hammer blows, and when the blade was then ground and polished the surface intersected the bands in such a way that patterns arose. To make the patterns clearly visible, the polished blade was etched. Weapons that have been studied have a pearlitic structure in their cutting edges, while thicker parts of the blade have a structure known as divorced eutectoid transformation (DET) and are tougher than fine pearlite. The weapons do not appear to be water-hardened but rather oil or air-quenched. The proportion of martensite is very low, approximately 5%.
If pure iron and carbon, for example 1.5% carbon, are mixed in a crucible, melted together, left to solidify and forged into a blade and polished and etched, a pattern is created, but not the real Damascus pattern. The bands do not become sufficiently distinct and the etched figures are therefore wrong, for example only showing a granular pattern.

In the temperature cycles of forging the cementite is dissolved during heating and precipitated out again during cooling in the actual forging process. It has been found that if the alloying element vanadium is added at a very low concentration, for example 0.01%, the vanadium can support the nucleation for the precipitation of cementite to slightly larger and more stable cementite particles. These dissolve less readily during the heating part of the cycle, and in the cooling part they continue to grow and form layers that are determined by how the vanadium has already segregated in the solidification of the crucible ingot. The actual mechanism that produces larger and relatively few cementite crystals in a banded structure is similar to what metallurgists call coalescence. Coalescence explains overageing which in the age-hardening of aluminium alloys has a detrimental effect on the hardening. However, the banding process is more complex due to the thermal cycles and other effects of vanadium.

A likely explanation for the disappearance of Damascus steel around 1750 is that ore from a different deposit in India started to be used and that the new raw material did not have the low concentration of vanadium needed to control pattern-forming. The wootz ingots imported into Persia consequently lacked an important constituent from around 1750 on, and the important "stamp of quality" was consequently lost! As the proven and inherited methods no longer worked, they were forgotten after just a few generations of blacksmiths.

In the last twenty-five years the research of John Verhoeven and Alfred Pendray has yielded the results described above. It can also be mentioned that another research team in the United States, led by Oleg Sherby and Jeffrey Wadsworth, has shown that these high-carbon steels and the technique of divorced eutectoid transformation (DET) typical of Damascus steel acquire superplastic properties in a temperature range around 700°C. The steels are of great interest principally for the automotive industry. The team has also demonstrated the possibility of attaining extremely high strengths, around 5000 MPa. DET results in a very fine-grain structure similar to spheroidised steel and results in greater toughness than pearlitic matrix.

It should also be mentioned that a discussion is taking place on nanotechnical effects in Damascus steel. A research team in Dresden headed by M. Reibold and P. Paufler has found large quantities of nanofilaments of cementite in museum weapons as well as carbon nanotubes. These are thought to contribute a powerful hardening mechanism. These reports are barely one year old, but the findings are very interesting and may perhaps go some way towards explaining some of the historical descriptions that exist of the extreme properties of Damascus weapons in relation to edge sharpness, impact resistance, bendability and toughness.

Direct measurements on museum weapons show, however, that the mechanical properties are roughly equivalent to modern tool steels and were far better than in mediaeval weld-forged European "damasced" weapons. These were developed firstly to resemble Damascus weapons in appearance, by using two different steels which after repeated welding and folding produced patterns in the completed blade, and secondly as far as possible to minimise the effect of the large quantity of slags these steels had. The slags were finely divided with repeated folding and weld-forging which entailed very substantial total deformation. Damascus forging from a wootz ingot, on the other hand, meant minimal forging deformation.
Our own work in the forge and material laboratory

Our cooperation, which has been in progress since 2004, started with a discussion on an old Swedish article (written in old Swedish spelling) that described the successful attempts of the "engineer" P. Anossov to recreate Damascus steel in the mid-19th century at a weapons factory at Slatust in the Urals. Anossov used ceramic crucibles and a blast furnace to melt batches of a few kilograms.

We produced crucibles and lids from refractory ceramic materials, conducted a literature study and designed and built a first furnace set-up with good control of temperature and blast air flow. Figure 2 shows the first furnace, which was partly sunk into the floor of the forge and was provided with both thermoelectric temperature measurement and a pyrometer instrument. You can also see how the supply of blast air is arranged from two holes in the bottom of the furnace. During operation a "chimney" that extended the visible rectangular tube and connected with the roof extractor of the forge was installed. Coke was supplied intermittently through the rectangular tube.

The first crucibles were made of refractory castings, which are normally used for furnace parts and repairs in the steel industry. Figure 3 shows the furnace setup after a run where the crucibles are lifted out and the residual heat shows the position of the crucibles during the operation.

The cooled crucibles with lids are visible outside the furnace. It was found that the combination of coke-fired furnace and these crucible materials did not work satisfactorily. The formation of slag from the coke redirected the blast air, with the result that the temperature distribution around the crucibles could become so uneven that the crucibles sometimes cracked. The thermal shock resistance of the crucible material was too low.

We initiated a series of experiments with some different crucible materials and two different free-standing types of furnace: one fired by liquefied petroleum gas (LPG) and the other by coke. The LPG-fired furnaces resulted in more even temperature distribution, and crucibles made of refractory materials coped well. But their low thermal conductivity means that long holding times at high temperature are needed to melt the steel.

With crucibles in which graphite has been mixed into the ceramic, known as clay graphite crucibles, higher thermal shock resistance is obtained and they cope in coke-fired furnaces without cracking. In addition, they have higher thermal conductivity and lead to shorter melting times and consequently less thermal wear on furnaces as well as better economics. A drawback with these crucible materials, however, is reactions that slowly break the material down and can affect the steel. We have coated the inside of the crucibles with a thin layer of oxide ceramic to minimise the effect on the steel and can control the carbon content in finished steel to reproducible fall within approximately ± 0,05%C from the desired carbon content. However, we are continuing to experiment with crucible materials based mainly on aluminium oxide, quartz and graphite as well as various designs of moulds in order to produce crucibles without any defects.
We melt together high-purity iron with graphite, generally with an ingot weight of 2 kg, and to date we have produced over thirty ingots. Figure 4 below shows an ingot from which a piece has been cut off for structural determination and analysis of carbon content, and Figure 5 shows the segregated solidification structure of an ingot where dendrites (stems and branches) are clearly visible.

Before the forging we generally carry out partial homogenisation, which evens out the carbon distribution but largely preserves the segregation of vanadium.

The forging is performed at precise temperatures and at first very carefully. After forging down to approximately 5 mm we obtain a band structure as shown in Figure 6. The picture shows the structure in a section along the blade and perpendicular to the blade surface. The light stripes are thus sections through layers parallel to the plane of the blade. Figure 7 shows a partial magnification of a light stripe. It can be seen that the light cementite crystals in the band are quite large and rounded and that the structure does not have any grain boundary cementite. The surrounding matrix here is pearlite.

Various methods can be used to harden the blade for use of the steel in knife blades. The historically correct method is to perform pearlite hardening with forced air cooling. With more powerful cooling a larger proportion of pearlite and a smaller proportion of DET structure are obtained. In order to obtain harder edges it is possible instead to carry out bainitic hardening or, if even higher hardness is desired, martensitic hardening and tempering.

At carbon contents of around 1.5% approximately HRC 50 is obtained in pearlitic hardening, HRC 60 in bainitic hardening and HRC 63 in martensitic hardening and tempering at 200°. All three methods keep the cementite crystals intact in the band structure and produce the same Damascus patterns, but the contrast in the pattern is slightly better for pearlitic matrix than for DET, bainite and tempered martensite.

It is known from studies of museum weapons that sabres or swords were often ground from flat blades to evenly rounded blade surface from the broad ridge to the sharp edge. The blade surfaces then cut obliquely through the banded structure at gradually increasing angles. If this kind of grinding is applied to knife blades which are then carefully polished, good conditions in which to etch out Damascus patterns are obtained.

The etching techniques normally employed by knifesmiths on weld-forged "damasced" blades do not work well on Damascus steel. The etching recipes are intended for a mixture of solid layers of both a steel that etches relatively quickly and a steel that can barely be etched at all. It is common to etch very forcefully to obtain high-contrast relief patterns. It can be seen from Figure 7 that the surface of a genuine Damascus blade contains "showers" of small cementite crystals, most smaller than 0.01 mm.

Each such cementite crystal is a small face-ground and polished mirror and the "shower" of mirrors is perceived by the eye as a bright area. If the surrounding matrix is etched down too much, the
cementite mirrors easily detach. The new cementite crystals that show up below the detached are not bright-polished small mirrors, so no new bright areas are created and the blade surface is perceived by the eye as almost black. An attractive pattern of the light and bright cementite particles that sit like bumps on the blade surface may be obtained, but if the blade is wiped with a cloth the particles detach and what remains is the dark background, that is to say the blade surface becomes black and devoid of pattern.

We have experimented with a number of weak etching recipes and quite long etching times in order to obtain good control of when the etching should be discontinued. Figures 9 - 16 show examples of etching on knife blades where these refined methods have been used. It is not easy to photograph the etched blades. Quite advanced lighting techniques are required in photographing the double-curved and bright surfaces for the pattern of the whole blade surface to appear with just the right level of contrast. Thomas Holmgren, an art teacher at the Rinmangymnasiet upper secondary school in Eskilstuna has carried out the photography. The pictures show the patterns on some knife blades, forged, ground, polished and etched by students at Mälardalen University. The forging was carried out during a laboratory assignment in materials technology at Faktotum in the Faktorimuséet museum in Eskilstuna. Figure 8 shows the forging of the knife blade which is shown in etched condition in Figures 9 and 10. The blades in Figures 9-13 are the first forgings made by four students.
Figure 13. Etched knife blade, student. Ingot B

Figure 14. Etched knife blade, Torsten Almén. Ingot C

Figure 15. Etched knife blade, Torsten Almén. Ingot D

Figure 16. Etched knife blade, Torsten Almén. Ingot D                               Photo: Thomas Holmgren, layman@algonet.se

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