

Damascus Steels

They contained more carbon than most modern steels. Along with skillful forging, this property accounted for the renowned strength and toughness of Damascus swords and for their beautiful markings

by Oleg D. Sherby and Jeffrey Wadsworth

In *The Talisman*, a fictional account of the Christian crusaders' adventures in Palestine, Sir Walter Scott tells of a meeting between Richard the Lionhearted and the Saracen king Saladin. The two adversaries were extolling the virtues of their swords. To demonstrate the strength of his heavy, two-handed straight blade, Richard cleaved a steel mace. In reply Saladin took a silk cushion and "drew [his] scimitar across the cushion... with so little apparent effort that the cushion seemed rather to fall asunder than to be divided by violence." The startled Europeans suspected a trick, but Saladin then emphasized his point by slicing through a limp cloth veil in mid-air. As Scott describes it, the Saracen's marvelously sharp and wieldy weapon had "a curved and narrow blade which glittered not like the swords of the Franks, but was, on the contrary, of a dull blue color, marked with ten millions of meandering lines."

Although this description contains some poetic license (Saladin's sword could not, for example, have been a scimitar, because curved blades were not introduced until several hundred years after the purported encounter with Richard in 1192), it is a substantially accurate portrait of a type of blade used throughout Islam in Saladin's time. These blades were exceptionally strong in compression—that is, they were hard enough to retain a sharp cutting edge—but they were also tough enough to absorb blows in combat without breaking. They owed their mechanical virtues, as well as their beautiful wavy surface markings, to the material from which they were forged: Damascus steel. By the time of the Crusades, Damascus swords and armor were the stuff of legend. For centuries thereafter they remained objects of fascination and frustration for European smiths, who tried in vain to reproduce consistently the distinctive damask, or surface pattern.

Uncovering the secret of Damascus swords was a challenge that also attracted the attention of eminent European scientists. Among them was Michael Faraday, a blacksmith's son, who attributed the unique properties of a Damascus steel he analyzed in 1819 (before he invented the electric motor and the electric generator) to small amounts of silica and alumina. Although his conclusion was erroneous, Faraday's paper inspired Jean Robert Bréant, Inspector of Assays at the Paris Mint, to undertake a series of experiments in which he added a variety of elements to steel. It was Bréant who first realized, in 1821, the essential metallurgical point about Damascus steels: that their uncommon strength, toughness and beauty arise from their high carbon content. Bréant identified the white areas in the damask as "carbureted steel"; the dark background he referred to simply as "steel."

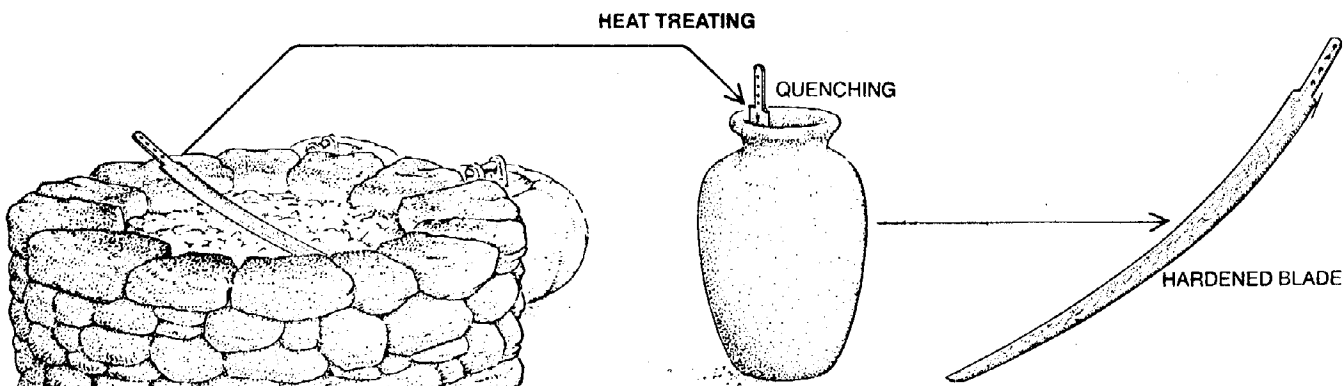
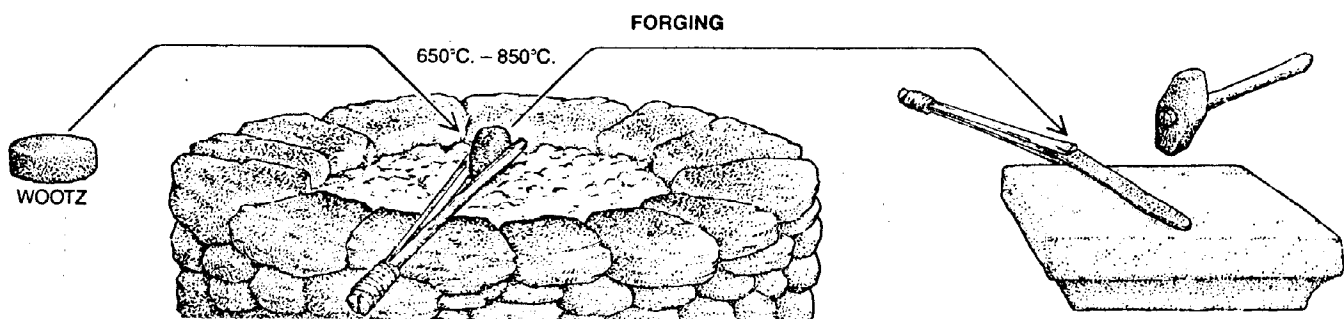
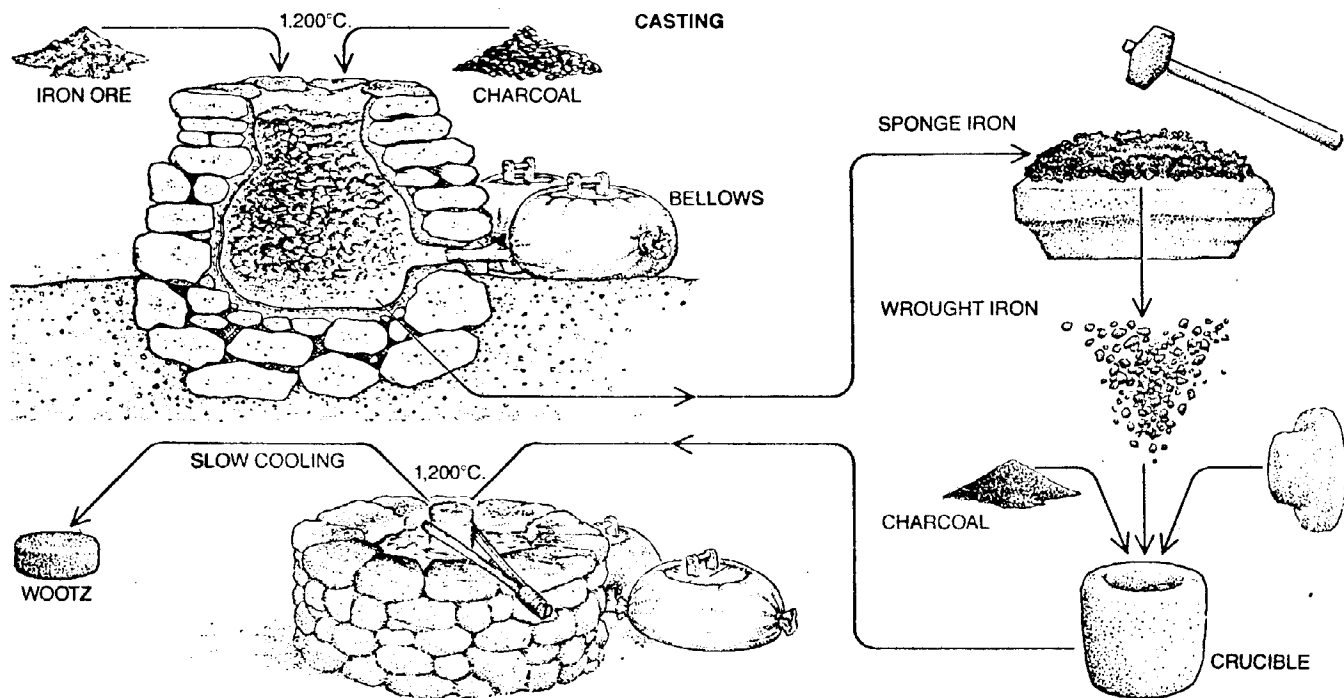
Bréant succeeded in making swords with a damasklike pattern, but he never explained the procedure in detail. Moreover, he could not have understood the importance of all the steps involved. The basis for a complete scientific understanding of Damascus steels was not established until the turn of the century, when a series of investigators worked out the phase transitions that steels undergo as a function of temperature and carbon content. Even today, when the iron-carbon phase diagram is well known, the art of Damascus swordmaking is a patentable discovery under American law.

Our own interest in the subject stems from our research on modern ultrahigh-carbon steels. Such steels, which contain from 1 to 2.1 percent carbon, are rarely used in commercial application because they are assumed to be brittle. The proportion of carbon in Damascus swords, however, ranges from 1.5 to 2 percent. Their undisputed reputation for toughness suggests that the brittleness ordinarily induced

by high carbon content can be avoided through proper processing. At Stanford University we have manufactured ultrahigh-carbon steels that, like the swords, are both strong and ductile at room temperature. We have also been able to reproduce the legendary damask. The procedures followed in our laboratory are essentially similar to those invented in the smithies of the ancient Near East.

The earliest description of Damascus blades dates from A.D. 540, but they may have been in use as long ago as the time of Alexander the Great (about 323 B.C.). Their name derives not from their place of origin but from the place where Europeans first encountered them during the Crusades. The steel itself was made in India, where it was known as wootz. It was widely traded in the form of castings, or cakes, that were about the size of a hockey puck. The best blades are believed to have been forged in Persia from Indian wootz, which was used to make shields and armor as well. Although the geographic distribution of Damascus steels generally followed the spread of the Islamic faith, they were also known in medieval Russia, where they were called *bulat*.

Like all steelmaking processes, the manufacture of wootz involved the removal of oxygen from iron ore, which is an oxide; the addition of carbon to the reduced iron strengthens it and transforms it into steel. The carbon source was charcoal, wood or leaves. Typically iron ore and charcoal were mixed and heated to about 1,200 degrees Celsius in a stone hearth. Oxygen was removed from the ore by reactions with carbon in the charcoal. Depending on the amount of charcoal in the mixture, the product was a wrought iron, which has a very low carbon content, or a pig iron containing more than 4 percent carbon. The Indian steelmakers manufactured wootz either by



TYPICAL MANUFACTURING PROCEDURE for a Damascus sword began with the casting of an ultrahigh-carbon steel, called wootz, in Indian foundries. Iron ore and charcoal were mixed and heated to about 1,200 degrees Celsius in a shallow stone hearth. The iron was reduced (stripped of oxygen) by reactions with carbon from the charcoal, and it acquired a spongy consistency. Impurities were expelled from the sponge iron by hammering; the result was bits of wrought iron, which has a low carbon content. The carbon content was then increased by heating pieces of wrought iron with charcoal

in a clay crucible, which was sealed to prevent the iron from oxidizing again. When a sloshing sound indicated the presence of some molten matter, the crucible was allowed to cool slowly in the furnace. Wootz was widely traded in the form of cakes several inches in diameter. Near Eastern smiths forged a Damascus blade from an individual cake that was probably heated to between 650 and 850 degrees C.; ultrahigh-carbon steels are ductile in that temperature range. The craftsmen hardened the finished blades by reheating them and then quenching them in water, brine or some other liquid.

adding carbon to wrought iron or by removing carbon from pig iron.

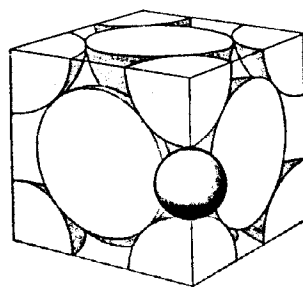
The procedure for producing wootz from wrought iron is better understood than the procedure for producing it from pig iron. Small pieces of the metal were mixed with charcoal in a sealed clay crucible about three inches in diameter and six inches tall. The crucible was then heated to roughly 1,200 degrees C. At this temperature wrought iron is still solid, but its crystals have a face-centered cubic structure that can accommodate carbon atoms in the spaces between the iron atoms [see top illustration at right]. Thus carbon diffused gradually into the iron, forming an alloy known today as austenite.

The addition of carbon lowered the melting point of the metal. When the carbon content at the surface of the wrought-iron pieces had increased to about 2 percent, a thin molten layer of white cast iron began to form on each of the pieces. The presence of molten matter was recognized by a "sloshing" sound as the crucible was shaken; it indicated that a significant amount of carbon had dissolved in the iron.

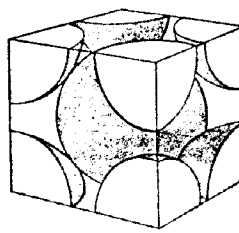
At that point the crucible was cooled very slowly, sometimes over a period of days. The slow cooling produced a homogeneous distribution of from 1.5 to 2 percent carbon throughout the steel. When the temperature of the metal fell below about 1,000 degrees C., some of the carbon precipitated out of solution, forming a network of cementite, or iron carbide (Fe_3C), around the austenite grains. Because the slow cooling allowed the grains to grow relatively large, the cementite network was coarse.

It was this coarse network that ultimately led to the visible markings on Damascus swords. Cementite, however, has certain negative qualities. Although it is very hard, it is also extremely brittle at room temperature. The brittleness would have been made worse by the network structure, which provided ready avenues for crack growth. Yet Damascus swords were the opposite of brittle: they were tough. Wootz acquired toughness only after it had been forged and the cementite network had been broken up by extensive hammering.

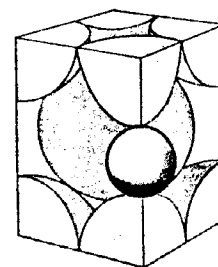
Damascus steels were apparently hammered into blades at a fairly low temperature. Medieval blacksmiths could not precisely measure the temperature inside a hearth or a forge, and so they used the color of the metal as a guide. The forging range for steels typically extended from white heat (1,200 degrees C.) down to orange (900 degrees), but wootz seems to have been



AUSTENITE

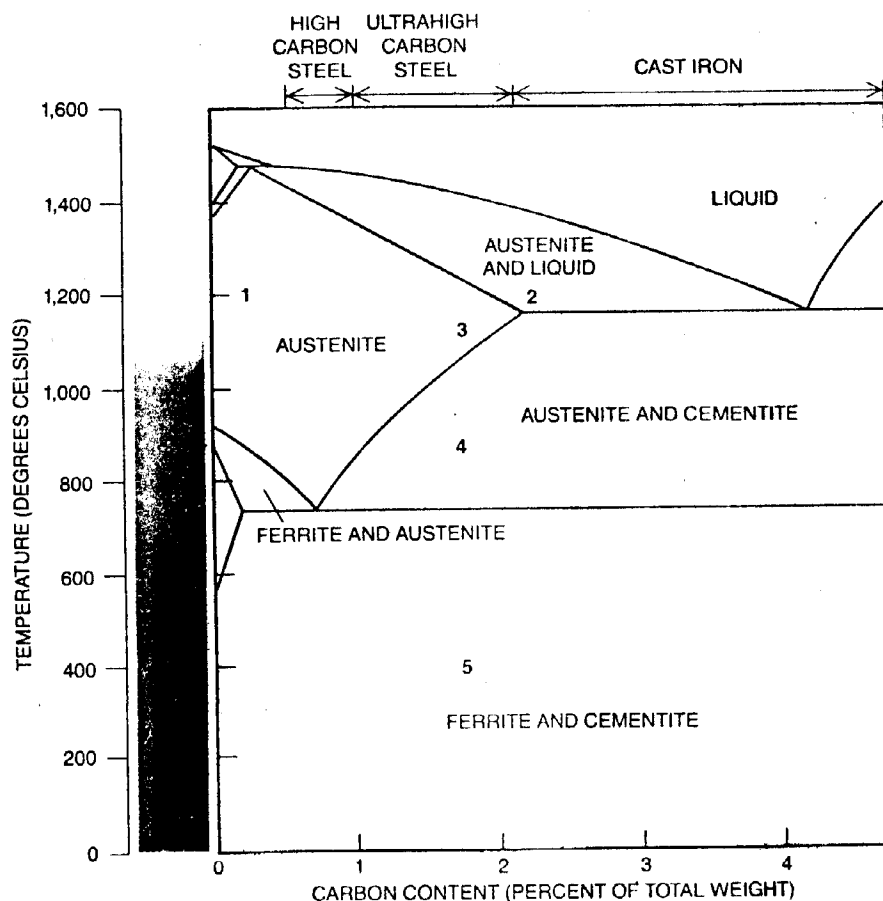


FERRITE

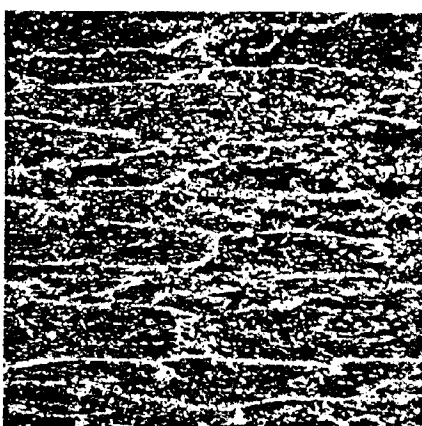
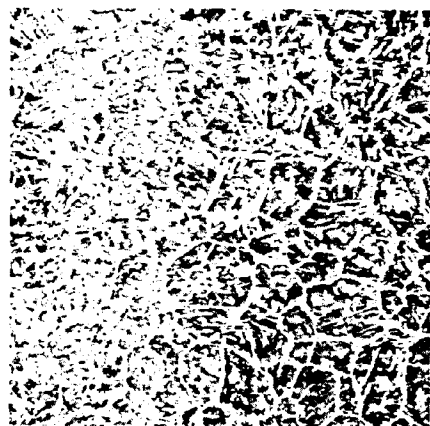
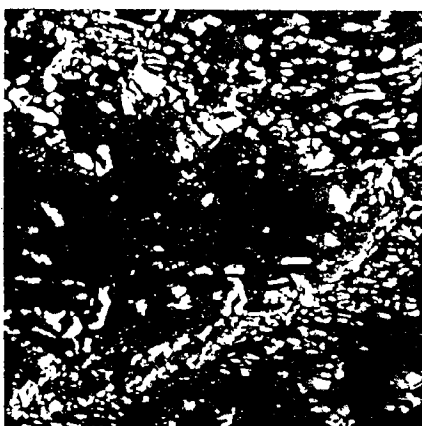
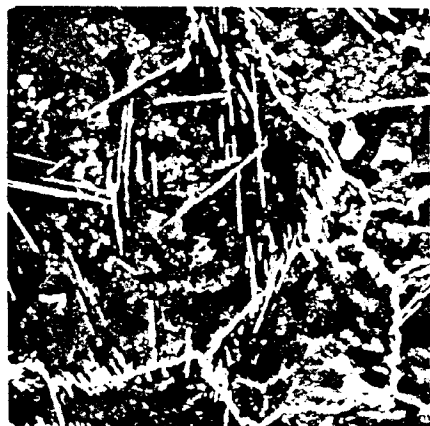


MARTENSITE

IRON CRYSTALS in ultrahigh-carbon steels can exist in three forms. At temperatures above 727 degrees C. the stable configuration is a cubic lattice with iron atoms at the center of each face. The face-centered arrangement can accommodate carbon atoms (dark balls) between the iron atoms. Thus at high temperatures carbon dissolves in the iron; the solution is called austenite. If the steel is then cooled slowly to room temperature, the iron crystals convert into a body-centered cubic form in which there is little room for carbon; this phase is called ferrite. If the steel is cooled rapidly (quenched), carbon atoms are trapped in distorted, tetragonal body-centered crystals, called martensite, that are harder than ferrite.



IRON-CARBON PHASE DIAGRAM is the basis for understanding the properties and the manufacturing process of Damascus swords. When wrought iron and charcoal were heated to 1,200 degrees C. in a crucible, the iron converted into face-centered austenite (1). Carbon from the charcoal could then dissolve in the iron, decreasing its melting temperature. Molten cast iron formed at the surface of the iron particles when the carbon content of the surface layer exceeded 2 percent (2). Slow cooling allowed the carbon to diffuse through the metal, producing a steel with an average carbon content between 1.5 and 2 percent (3); it also allowed the austenite grains to grow to a coarse size. When the temperature fell below about 1,000 degrees C., carbon precipitated out of solution as cementite at the grain boundaries (4). The coarse cementite network was the source of the whitish damask markings. As the temperature fell below 727 degrees, face-centered austenite converted into alternating layers of cementite and carbon-poor, body-centered ferrite (5). The blades were hardened by being reheated above 727 degrees and then quenched, which converted austenite into martensite. Medieval smiths gauged the metal's temperature from its color.

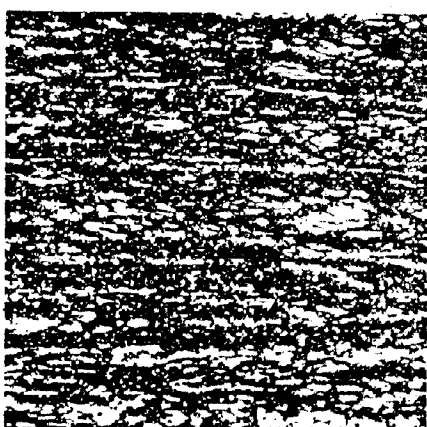
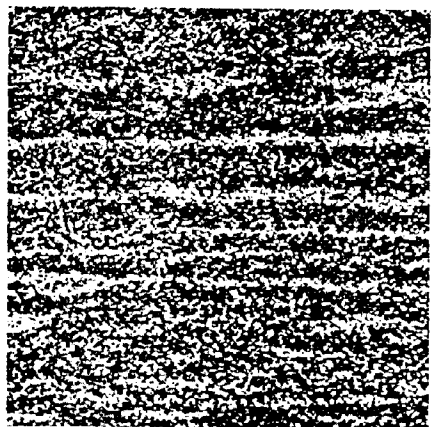


EFFECTS OF FORGING on Damascus steels were simulated by rolling a modern ultra-high-carbon steel. The steel is shown magnified 130 times (*top*) and 6.5 times (*bottom*). Before rolling (*left*), the light cementite network is continuous; its dimensions are roughly the same in all directions. After rolling (*right*), the network is elongated in the rolling direction and is broken up into spheroidal particles. As a result the steel is tougher (less brittle).

forged at temperatures between cherry (850 degrees) and blood red (650 degrees). Higher temperatures would have caused the cementite to dissolve again in the austenite. Hammering the wootz cake at a temperature below 850 degrees, on the other hand, broke

up the continuous cementite network into spheroidal particles. The carbide particles still served the function of strengthening the steel, but because they no longer formed a continuous network, the metal was not brittle.

Damascus swords show evidence of



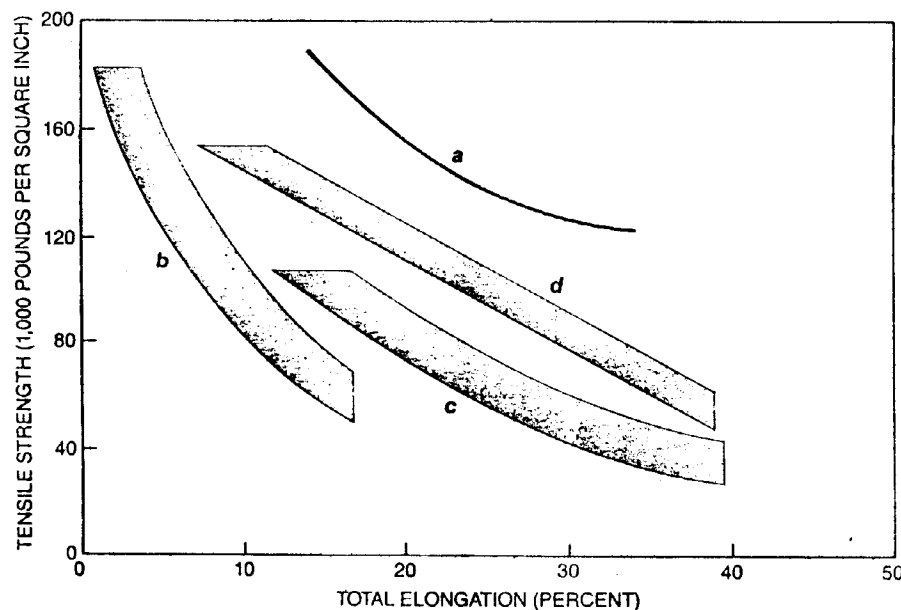
THICKNESS SECTIONS of a Damascus blade (*left*) and of a rolled ultrahigh-carbon steel (*right*) show similar microstructures, suggesting they were processed in a similar way. Mechanical working compresses the cementite network; the space between the layers is about 100 micrometers. Rolled steels have a less intricate damask than the forged blades.

having been well forged; the height of the ingot seems to have been reduced by a factor of three to eight in the pounding out of the blade. An experiment we did demonstrated that ultra-high-carbon steels are indeed ductile and easily forged at a temperature of 850 degrees C. We subjected ingots with carbon contents of 1.3, 1.6 and 1.9 percent to large strains, compressing them in a single step by a factor of three. None of the ingots showed any signs of cracking. In contrast, a cast-iron ingot, whose higher carbon content (2.3 percent) rendered it brittle, cracked around the edges under the same strain.

One of the reasons European smiths had so much trouble reproducing Damascus blades, even from imported wootz, may have been that they were accustomed to working with low-carbon steels, which have a higher melting point. As a result they may have tried to forge the Indian steel at a white heat, when it would have been partially molten. The likely outcome of such an effort was described by Bréant, who observed that "at a white heat [Damascus steels] crumble under the hammer."

After forging, Damascus blades were usually hardened by heat treatment. Thermal hardening of a steel is achieved by heating it above 727 degrees C. (the temperature at which body-centered ferrite begins to be converted into face-centered austenite) and then quenching it (cooling it rapidly) in water or some other medium. When ultrahigh-carbon steels are allowed to cool slowly from the austenite phase, as in the initial casting of wootz, the austenite is converted into pearlite: alternating layers of soft, carbon-poor ferrite and carbon-rich cementite. If the steel is quenched, however, the transformation of austenite into pearlite is suppressed. The iron crystals become body-centered, but they are stretched from a cubic form into a tetragonal one. This structure, called martensite, still has room for carbon atoms, and so it is hard.

Medieval smiths seem to have followed a variety of procedures in heat-treating Damascus blades, often giving considerable weight to considerations that seem immaterial to the modern engineer. Some smiths, for instance, insisted that swords be quenched in the urine of a redheaded boy or in that of a "three-year-old goat fed only ferns for three days." One of the most detailed descriptions of a procedure for hardening Damascus steel (*bulat*) was found in the Balgala Temple in Asia Minor: "The bulat must be heated until it does not shine, just like the sun ris-



STRENGTH AND DUCTILITY of ultrahigh-carbon steels can be greater than those of conventional steels. Tensile strength is the maximum tensile stress a standard piece of metal can withstand before fracturing. Elongation is a measure of ductility: it is the amount by which the metal can be stretched before fracturing. When ultrahigh-carbon steels (a) are rolled during cooling to produce an ultrafine microstructure, they are stronger (for a given ductility) than conventional low-carbon steels (b) and high-strength steels containing small quantities of special alloying elements (c). They also outperform certain advanced steels (d).

ing in the desert, after which it must be cooled down to the color of king's purple, then dropped into the body of a muscular slave... the strength of the slave was transferred to the blade and is the one that gives the metal its strength."

The instructions may be reinterpreted as follows. The blade was heated to a high temperature, presumably above 1,000 degrees C. ("sun rising in the desert"), and then air-cooled to a temperature of about 800 degrees ("king's purple"). Finally, it was quenched in a warm (37 degrees), brinlike medium.

This particular procedure would probably not have yielded the best Damascus blade. Heating the blade above 1,000 degrees C. would allow the cementite to dissolve again in the face-centered austenite; on being cooled to 800 degrees, the coarse network structure, which had been eliminated by forging, would reemerge. The high temperature would also have generated relatively large steel grains. Both effects would have reduced the toughness of the blade. A sword manufactured according to the Balgala prescription would have been hard, but it might also have been too brittle to survive the impact of a Damascus blade that had been heated to only just above 727 degrees before being quenched. Such a blade would have been tough as well as hard.

In general, according to modern metallurgical theory, the strongest and toughest steels are those with the finest grains and particles. Ironically, this suggests that the best Damascus swords of all might have been ones that lacked a damask pattern. Medieval smiths undoubtedly used the characteristic surface markings as a form of quality control: the damask was evidence both of a high carbon content, which made the blade strong, and of a well-forged structure, which made it tough. A damask would only be visible, however, if the cementite particles in the steel were coarse and unevenly distributed. Blades whose microstructure was so fine that it produced no visible surface markings would have been stronger and tougher still.

In order to test our ideas about the composition and processing of Damascus steels, we attempted to reproduce the damask in the laboratory. First we heated a small steel casting, whose carbon content was 1.7 percent, to a temperature of 1,150 degrees C. (light yellow) for 15 hours. The prolonged heating dissolved the carbon and produced a very coarse austenite. Next the casting was cooled at a rate of about 10 degrees per hour. The slow cooling allowed a coarse, continuous cementite network to form at the austenite grain boundaries.

Finally we reheated the casting to 800 degrees C. and rolled it, reduc-

ing its height by a factor of eight. This step, which simulated forging, stretched the grains in the rolling direction and broke up the carbide network. When the steel was etched with an acid that attacked the iron matrix preferentially over the carbide, a damask was visible to the unaided eye. The microstructure of the casting was strikingly similar to that of Damascus steels [see bottom illustration on page 118].

The procedure described here is one way of manufacturing a Damascus steel; there probably were many others. The Near Eastern artisans may even have made superior ultrahigh-carbon steels that lacked a damask. We did just that in the laboratory by rolling the casting as it cooled from 1,100 degrees C. through the austenite-plus-cementite phase. The mechanical working refined the austenite grains and caused the cementite to precipitate out of solution as fine, uniformly distributed particles rather than as a coarse network. Thus the finished steel bore no surface markings.

Such damask-free ultrahigh-carbon steels are stronger and more ductile at room temperature than conventional automotive steels. Furthermore, they are superplastic (that is, they behave like molasses or semimolten glass) at temperatures of 600 to 800 degrees C. As a result they can be shaped with precision into complicated objects, such as gears, with a minimum of expensive machining and by processing methods that are adaptable to mass production. This suggests they might find wide industrial application.

We are not the first to claim to have rediscovered the lost art of Damascus steelmaking. In addition to Bréant and Faraday, one of our predecessors was the Russian engineer Pavel P. Anosoff, who in 1841 published a two-volume monograph titled *On the Bulat*. So enthusiastic was Anosoff about his findings that he proclaimed: "Our warriors will soon be armed with bulat blades, our laborers will till the soil with bulat plowshares, our artisans will use tools fashioned of bulat, and bulat will supersede all steel employed for the manufacture of articles of special sharpness and endurance."

His forecast was not realized. Today the enormous potential of ultrahigh-carbon steels remains largely unexploited. Although our optimism is more tempered than Anosoff's, we believe the situation will change and the secret of Damascus steel will become common knowledge in modern industry. In the words of an old Russian proverb, "The best of the new is often the long-forgotten past."