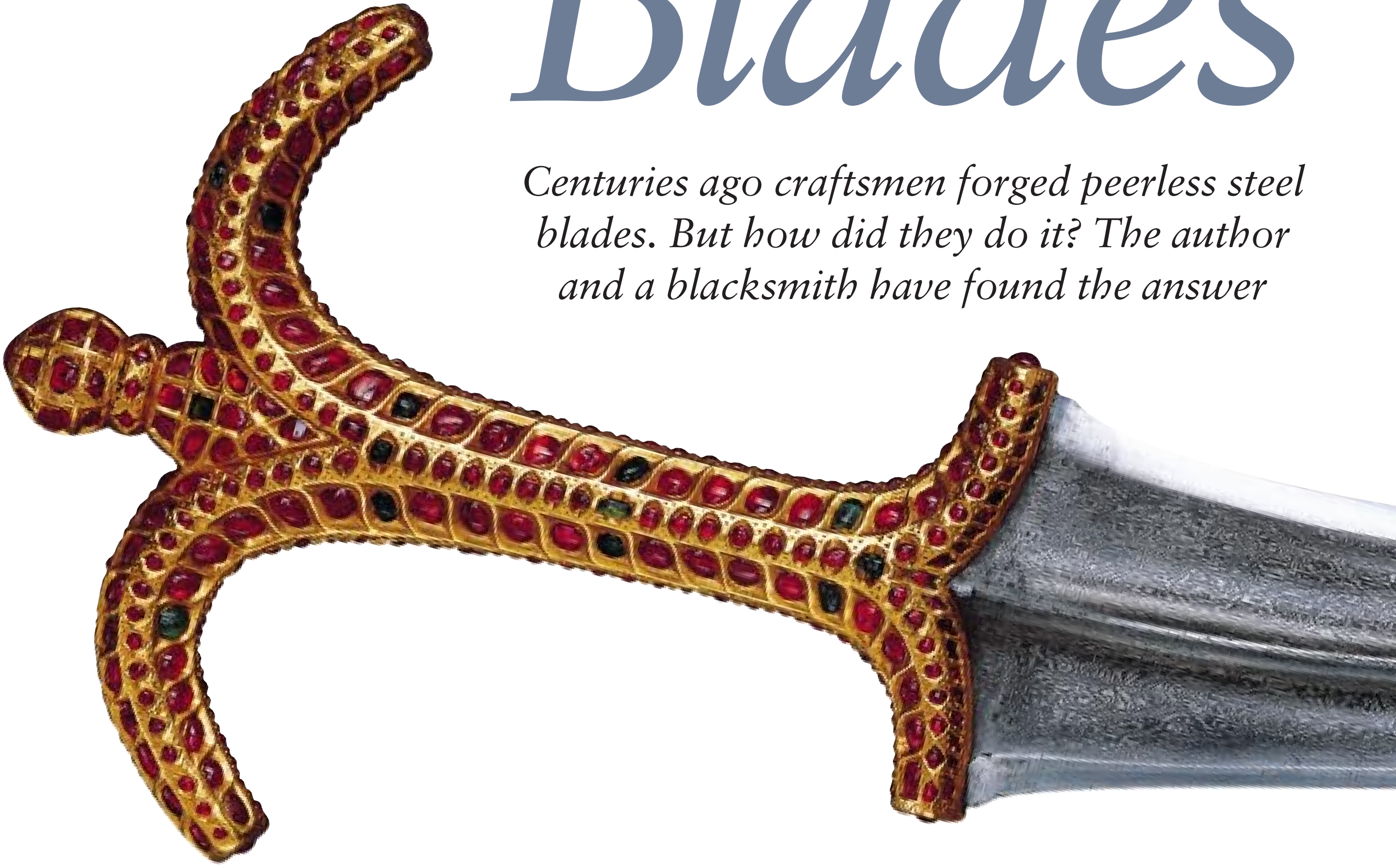
The Mystery of *Damascus Blades*

by John D. Verhoeven

Centuries ago craftsmen forged peerless steel blades. But how did they do it? The author and a blacksmith have found the answer



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From the Bronze Age up to the 19th century, warriors relied on the sword as a weapon. Armies possessing better versions enjoyed a distinct tactical advantage. And those with Damascus swords—which Westerners first encountered during the Crusades against the Muslim nations—had what some consider to be the best sword of all.

Those blades, originally thought to have been fashioned in Damascus (which is now in Syria), featured two qualities not found in European varieties. A wavy pattern known today as damask, or damascene, decorated their surface [*see illustration above*]. And, more important, the edge could be incredibly sharp. Legend tells how Damascus swords could slice through a silk handkerchief floating in the air, a feat no European weapon could emulate.

Despite the fame and utility of these blades, Westerners have never been able to figure out how the steel—also used for daggers, axes and spearheads—was made. The most accomplished European metallurgists and bladesmiths could not replicate it, even after bringing specimens home and analyzing them in detail. The art of production has been lost even in the land of origin; experts generally agree that the last high-quality Damascus swords were crafted no later than the early 1800s. Recently, however, an ingenious blacksmith and I have, we believe, unlocked the secret.

We are not the first to have claimed a solution, but we are the first to have proved our case by making faithful replicas of the revered weapons. To validate any theory of how Damascus swords and daggers were made, replicas ought to be fashioned from the same starting materials as the originals. The finished weapons should also bear the same damask pattern and have the same chemistry and microscopic structure.

What Is Real Damascus Steel?

Genuine Damascus blades are known to have been made in that city—and later elsewhere in the Muslim Middle East and Orient—from small ingots made of steel (a mix of iron and carbon) shipped from India; those starting materials have been called wootz ingots or wootz cakes since around 1800. They were shaped like hockey pucks, about four inches in diameter and a bit less than two inches in height. Early English observers in India established that the wootz Damascus swords were made by forging these ingots directly into a blade shape by many repeated heating and hammering operations. The steel contains around 1.5 percent carbon by weight, plus low levels of other impurities such as silicon, manganese, phosphorus and sulfur.

The attractive surface pattern found on Damascus swords can be created in other ways, however. Modern artist-blacksmiths can "forge weld" together alternate sheets of high- and low-carbon steel into an intricate composite. Such forge welding, or "pattern welding," has a tradition in the West dating back to ancient Rome, and similar techniques can be found in Indonesia and Japan. The internal structure resulting from these techniques is totally different, though, from that of the wootz blades. To avoid confusion between the two types of manufacture, I refer to the forge-welded blades as "welded" Damascus and reserve the term "wootz" Damascus for the weapons of interest in this article.

As early as 1824, Jean Robert Bréant in France and, slightly later, Pavel Anosoff in Russia announced success at uncovering the secret arts of the Muslim bladesmiths; both claimed to have replicated the originals. In this century other solutions have been advanced, the most recent by Jeffrey Wadsworth and Oleg D. Sherby [see "Damascus Steels," Scientific American, February 1985]. But in no case have modern artisans been able to use the proposed methods to produce satisfactory blades that have the exterior appearance and internal structure of the ancient originals.

Efforts to compare the chemistry and microscopic features of modern wootz blades with their older counterparts were long hampered by a curious obstacle. Museum-quality Damascus weapons are valuable art objects and are rarely sacrificed to science for examination of their internal structure. In 1924, though, European collector Henri Moser donated four swords to metallurgist B. Zschokke, who sectioned them for chemical and microstructural analysis. The remaining pieces went to the Berne Museum in Switzerland, which recently donated some of them to me for study.

When I examined the prized specimens, I found that they contained bands of iron carbide particles, Fe_3C, known as cementite. These particles are generally around six to nine microns in diameter, well rounded and tightly clustered into bands spaced 30 to 70 microns apart, which are lined up parallel to the blade surface, like the grain inside a plank of wood. When the blade is etched with acid, the carbides appear as white lines in a dark steel matrix. Just as the wavy growth rings in a tree produce the characteristic swirling patterns on cut wood, undulations in the carbide bands account for the intricate damascene patterns on the blade surfaces. The carbide particles are extremely hard, and it is thought that the combination of these bands of hard steel within a softer matrix of springier steel gives Damascus weapons a hard cutting edge combined with a tough flexibility.

I first attempted to match the microstructures of wootz Damascus steel in the confines of a university laboratory. I soon realized, though, that I would need to work with someone skilled in the art of forging edged weapons. Master bladesmith Alfred H. Pendray had been working independently on the Damascus puzzle. He had been making small ingots in a gas-fired furnace and forging them into blade shapes, and he had often obtained microstructures that were intriguingly close to those of the finer-quality antique blades.

We began collaborating in 1988. Pendray as a youth learned the skills of a farrier from his father and has a deep and patient understanding of the art of forging steel. But to reproduce a technique, we would need to back up our theories with accurate scientific data and rigorous attention to the details of our experiments. In 1993 one of my students at Iowa State University and I went to Pendray's blacksmith shop near Gainesville, Fla., where we set up computer-monitored thermocouple and infrared pyrometer equipment to record the temperatures of the melting and forging processes we were trying.

At first we tried to produce blades using the method put forward by Wadsworth and Sherby, but we failed to produce either the internal microstructure or the surface damascene patterns. Then, over a period of several years, we developed a technique that Pendray can routinely use to make reconstructed wootz Damascus steel blades. He can also replicate the pattern known as Mohammed's ladder [*see illustration on page 79*], found on some of the finest of the old Muslim examples. In this pattern the undulations line up in a ladderlike formation along the length of the blade; it was thought to be symbolic of the way the faithful ascended to heaven.

DAGGER with a Damascus steel blade, from Mughal India, was made in about 1585. The fine-quality blade is thickened near the point to pierce armor; the gold hilt is set with emeralds and rubies.

Our technique is similar to the general method described by the earlier researchers—but with crucial differences. We produce a small steel ingot of a precise composition in a closed crucible and then forge it into a blade shape. Our success—and what enables us to go further than our predecessors—depends critically on the mix of iron, carbon and other elements (such as vanadium and molybdenum, which we refer to as impurity elements) in the steel, how hot and for how long the crucible is fired, and the temperature and skill used in the repeated forging operations.

A Tale of Steel

If you have steel containing about 1.5 percent carbon, add to it one of several impurity elements (at surprisingly low levels, around 0.03 percent), and then put it through five or six cycles of heating to a precise temperature range and cooling to room temperature, you can get groups of clustered carbide particles to form. It is these carbide particles that produce the characteristic surface patterns during forging. Experiments on antique and modern blades show that band formation results from segregation at a microscopic level of some impurity elements as the liquefied ingot cools and solidifies.

Here's how microsegregation happens within the steel. As the hot ingot cools down and freezes, a solid front of crystallized iron extends into the liquid, adopting the shape of pine-tree-like projections called dendrites [*see illustration on opposite page*]. In the 1.5 percent carbon steel, the type of iron that solidifies from the liquid steel is called austenite. In the regions between these dendrites (called the interdendritic regions), liquid metal becomes briefly trapped. Solid iron can accommodate fewer atoms of carbon and other elements than liquid iron can, so as the metal solidifies into crystalline iron dendrites, carbon and impurity atoms tend to segregate into the remaining liquid. Hence, the concentration of those atoms can become very high in the last interdendritic regions to freeze.

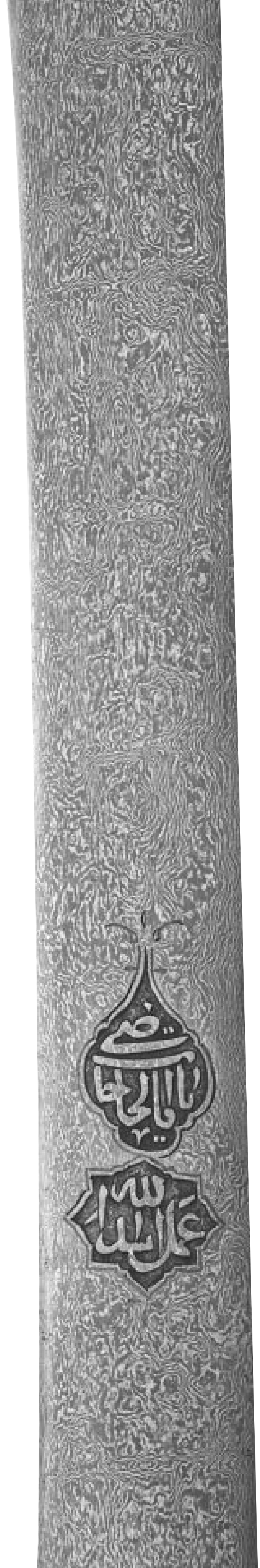
As the iron solidifies and the dendrites grow, the regions between them are left with a lattice of impurity atoms frozen into place like a string of pearls. Later, when the ingot goes through multiple heating and cooling cycles, it is these impurity atoms that encourage the growth of the strings of hard cementite particles that are the lighter bands in the steel. We can show that this lattice is related to the light and dark steel bands in the wootz steel. The distance between dendrite branches is around half a millimeter, and as the ingot is hammered out and its diameter is reduced, this distance is also reduced. The final spacing between dendrites corresponds closely to the distance between bands in Damascus steel.

During forging, it is important to get just the right temperature in the steel to obtain a mix of austenite and cementite particles. When the ingot's temperature falls below a critical point, iron carbide particles (the same cementite particles I saw in the Moser blades) start forming. The lowest temperature above which all the cooling steel remains austenite is called the A temperature. In steels with more than 0.77 percent carbon, the A temperature is termed the A_{cm} temperature. Below the A_{cm}, cementite particles begin appearing, randomly spaced within the austenitic steel.

The Trick of Banding

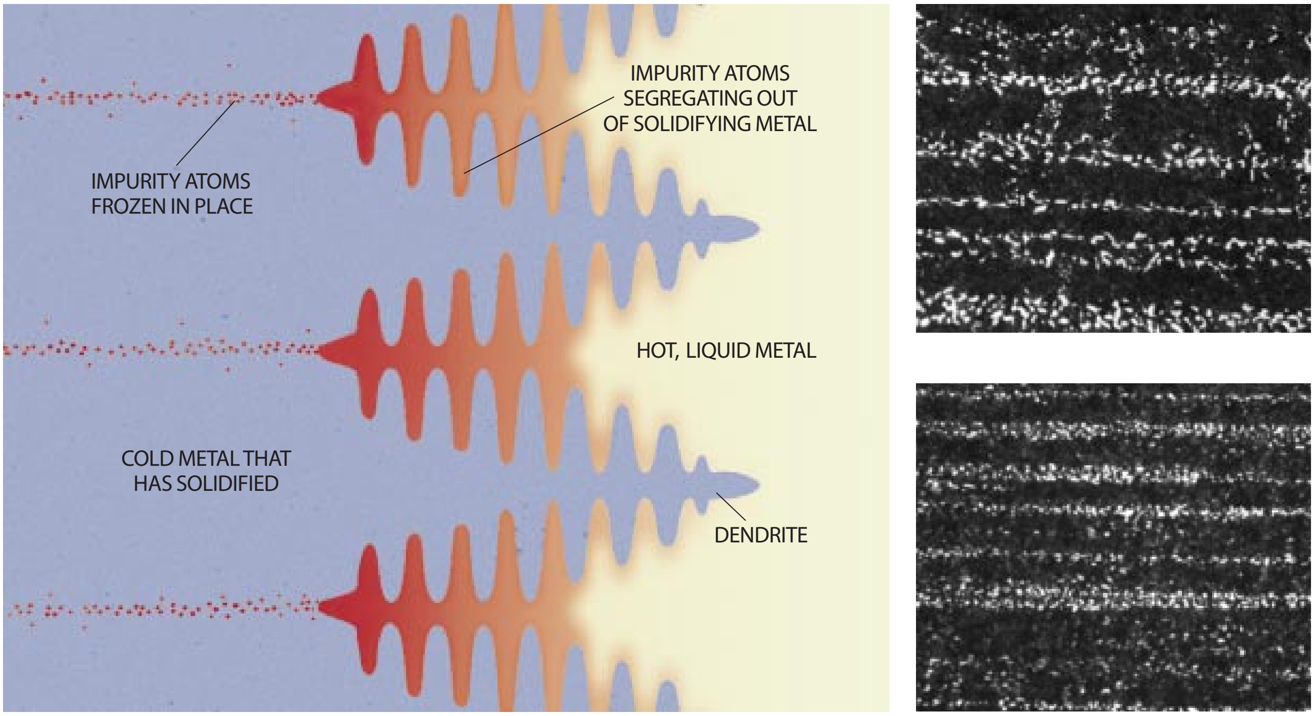
A major mystery of wootz Damascus blades has been how simple forging of small steel ingots into the shape of a blade can cause carbides to line up into distinctive bands. We systematically examined cross sections of the forged ingots as we changed them from hockey-puck shapes to blades. To bring about that change, we heated an ingot to a temperature at which the steel would form a mixture of cementite particles and austenite and then hammered it. While the ingot was being forged, it would cool down from about 50 degrees Celsius below the A_{cm} to about 250 degrees C below the A_{cm}. During this cooling, the proportion of cementite particles increased. We would then put the ingot through another cycle of heating and hammering between the same two temperatures. Based on experience, we found we needed around 50 of these forging cycles to produce a blade close to the size of the originals—45 millimeters wide and five millimeters thick.

This is how we think banding occurs:



DAMASCUS STEEL SWORD from the 17th century shows a classic damascene pattern of swirling light and dark bands. The inscription tells us that this excellent blade was made in 1691 or 1692 by Assad Allah, the most renowned Persian swordsmith of his time.

COURTESY OF BUTTERFIELDS



COOLING INGOT of Damascus steel, on a microscopic level, has a front of freezing metal extending into the molten steel, crystallizing, at first, into pine-tree-like formations called dendrites. Atoms of impurity elements (*red*) such as vanadium rapidly segregate out of the solid iron into the regions between the dendrites, where they freeze into place lined up like beads on a necklace. In subsequent cycles of heating and cooling, these impurity atoms are the basis for the growth of particles of hard iron carbide (cementite), which are the light-colored bands in the Damascus blade. The top micrograph shows light and dark bands in a section through an original Damascus sword. The lower micrograph shows a section through the author's modern reconstruction. The similarity between the two structures indicates that the modern technique is an accurate replication of the original process.

CLEO VILETT (*drawings*); HAL SAILSBURY (*micrographs*)

During the initial 20 or so cycles, the hard carbide particles form more or less randomly, but with each additional cycle they tend to become more strongly aligned along the latticework of points formed in the interdendritic regions. The reason for the improvement is that each time the steel is heated, some of its carbide particles dissolve. But the atoms of the impurity elements slow the rate of dissolution, causing larger particles of carbide to remain. Each cycle of heating and cooling causes these particles to grow only slightly, which is why it takes so many cycles to form the distinct bands. Because the impurity elements are lined up in the regions between the dendrites, the carbide particles become concentrated there as well.

The Right Elements

Although we long suspected that impurity elements played a key role in the formation of bands, we were not sure which ones were most important. We determined quickly that silicon, sulfur and phosphorus, well known to be present in ancient wootz steels, did not appear to be major players. But that information did not solve the problem.

We had a lucky breakthrough when we started to use Sorel metal as one ingredient for the ingots. This metal is a high-purity iron-carbon alloy containing 3.9 to 4.7 percent carbon, produced from a large ilmenite ore deposit at Lac Tio on the St. Lawrence River in Quebec. The ore deposit contains traces of vanadium; hence, the Sorel metal comes with 0.003 to 0.014 percent vanadium impurity. Initially we disregarded this impurity because we couldn't believe such a low concentration was significant. But we eventually (after two years of hitting a brick wall) tumbled to the fact that even low levels could be important.

Adding vanadium in such tiny amounts as 0.003 percent to high-purity iron-carbon alloys yielded good banding. Molybdenum also produces the desired effect, and, to a lesser extent, so do chromium, niobium and manganese. Elements that do not promote carbide formation and banding include copper and nickel. Electron-probe microanalysis has confirmed that the effective elements, when present at only 0.02 percent or less in the ingots, become microsegregated into the interdendritic regions and become much more concentrated there.

To test our conclusion that banding comes from microsegregation of impurity elements leading to microsegregation of cementite particles, we conducted experiments designed to show that if we got rid of the microsegregation of impurity atoms, we could get rid of the bands. We took small pieces of nicely banded antique and modern blades and heated these to around 50 degrees C above the A_{cm} temperature. At this temperature, all the iron carbide particles dissolved away into the austenite. We then quenched the blades in water. The rapid cooling produced the martensite phase of steel—very hard and strong, with no carbide particles. Because the carbide particles had vanished, so had the bands that came from them.

To re-create the cementite particles, we put the blades through several cycles of being heated to 50 degrees C below the A_{cm} temperature and then slowly air-cooled, which gave the particles time to regrow and become segregated. After the first cycle, the carbide particles reappeared but were randomly distributed. But after an additional cycle or two, these particles began to align into

HOW TO MAKE A DAMASCUS BLADE

Master bladesmith Alfred H. Pendray demonstrates the technique in his smithy near Gainesville, Fla.

1 Assemble the ingredients to load into the crucible, including high-purity iron, Sorel iron, charcoal, glass chips and green leaves. The quantity of carbon and impurity elements that end up in the ingot is controlled by the proportions of iron, Sorel iron and charcoal added to the mix.

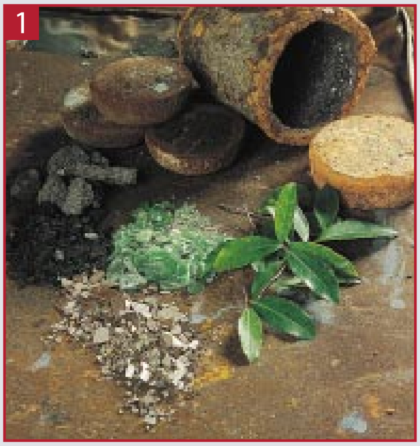
2 Heat the crucible. During this process, the glass melts, forming a slag that protects the ingot from oxidizing. The leaves generate hydrogen, which is known to accelerate carburization of iron. The carbon content of the iron is raised to 1.5 percent, a good proportion for forming the hard iron carbide particles whose accretion into bands gives Damascus blades their characteristic wavy surface pattern. The leaves and glass can be left out, but ingots made without them are more prone to cracking during hammering.

3 When the crucible has cooled, remove the ingot, which bears a resemblance to the wootz cakes used by the ancients.

4 Heat the ingot to a precise temperature. Pendray is using a gas-fired furnace with the propane-to-air ratio adjusted to minimize the formation of oxide scale during forging. Typically, a surface oxide layer of about half a millimeter in thickness forms, and the final grinding operation must be sufficient to remove it.

5 Forge the ingot (deform it slightly with hammer blows while it is still hot). When the ingot gets too cold to deform without cracking, heat it up and forge again. Four separate stages of the ingot are shown here; each stage is the result of several cycles of heating and forging. A total of about 50 cycles may be needed to bang out the blade shape from the ingot—a highly labor-intensive process. Pendray uses a modern air hammer. A handheld hammer works, too, but it takes longer.

6 Cut the blade to final shape and hand-forge to add finer details.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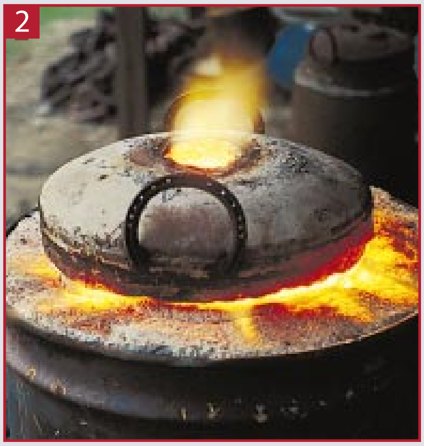
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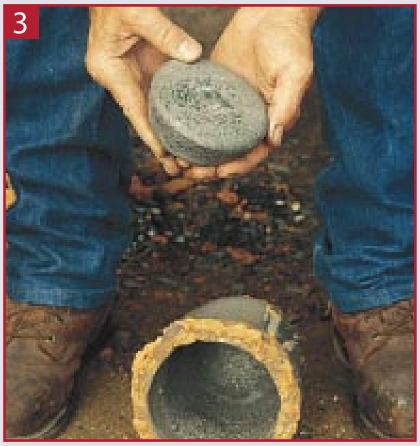
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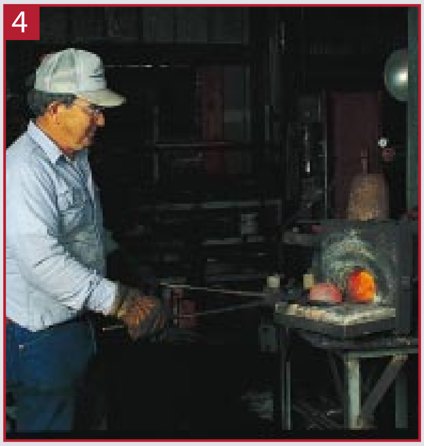
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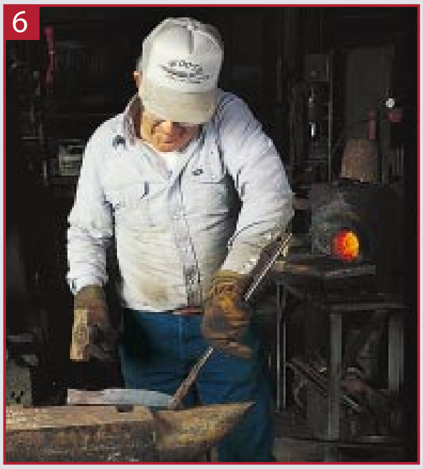
7 Remove the excess steel and the decarburized surface metal. Pendray is using an electric belt grinder for this step.

8 Cut grooves and drill holes into the surface of the blade to create Mohammed's ladder and rose patterns, if desired. Forge the blade flat again and polish the surface to give the blade its near final form.

9 Etch blade surface with an acid to bring out the pattern; the softer steel darkens, and the harder steel appears as brighter lines.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FINISHED BLADE shows the Mohammed's ladder and rose patterns.

weak bands, and after six to eight cycles the bands became quite distinct.

In one test, we cranked up the heat well beyond the A_{cm}—to 1,200 degrees C, just below the melting point of the steel—and held it there for 18 hours. Subsequent thermal cycling of the steel did not bring back the bands of cementite particles. Calculations show that this high-temperature treatment completely removes the microsegregation of impurity atoms by diffusion.

Pendray and I also tried carefully controlled experiments in which we left out the impurity elements altogether. Even after many cycles of heating and slow cooling, these ingots did not produce clusters of carbide particles or bands. When we added the impurity elements to the same ingot and put it through the heating and cooling cycles, the bands appeared.

Our re-creation of the Damascus blade helps us to answer another question: How did the ancient smiths generate the Mohammed's ladder pattern? Our work supports one theory proposed in the past—that the ladder rungs were produced by cutting grooves across the blades. The ladder pattern visible in the bottom photograph above was made by incising small trenches into the blade after it had been forged to near its final thickness [*see illustration 8 above*], then subsequently forging it to fill in the trenches. Such forging reduces the spacing between light and dark bands on the final surface, especially along the edges of the trenches. The round configuration between the rungs, known as the rose pattern, is also known from older scimitars. It comes from shallow holes drilled in the blade at the same time the grooves are cut.

Why was the art of making these weapons lost sometime around two centuries ago? Perhaps not all iron ores from India contained the necessary carbide-forming elements. The four ancient Moser blades that we studied all contained vanadium impurities, which is probably why the bands formed in these steels. If changes in world trade resulted in the arrival of ingots from India that no longer contained the required impurity elements, bladesmiths and their sons would no longer be able to make the beautiful patterns in their blades and would not necessarily know why. If this state of affairs persisted, after a generation or two the secret of the legendary Damascus sword would have been lost. It is only now, thanks to a partnership between science and art, that the veil has been lifted from this mystery.

The Author

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Further Information

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