The significance of wootz steel to the history of materials science

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Introduction

The melting of steel proved to be a challenge in antiquity on account of the high melting point of iron. In the 1740s Benjamin Huntsman successfully developed a technique of producing steel that allowed it to be made on a much larger commercial scale and was credited with the discovery of crucible steel. However, Cyril Stanley Smith brought to wider attention an older tradition of crucible steel from India, i.e. wootz or Damascus steel, which he hailed as one of the four metallurgical achievements of antiquity. Known by its anglicized name, wootz from India has attracted world attention. Not so well known is the fact that the modern edifice of metallurgy and materials science was built on European efforts to unravel the mystery of this steel over the past three centuries.

Wootz steel was highly prized across several regions of the world over nearly two millennia and one typical product made of this Indian steel came to be known as the Damascus swords. Figure 1 shows a splendid example of the sword of Tipu Sultan. Wootz steel as an advanced material dominated several landscapes: the geographic, spanning Asia, Europe and the Americas; the historic, stretching over two millennia as maps of nations were redrawn and kingdoms rose and fell; and the literary landscape, as celebrated in myths, legends, poetry, drama, movies and plays in western and eastern languages including Sanskrit, Arabic, Urdu, Japanese, Tamil, Telugu and Kannada. South Asian steel held sway over the religious landscapes through trade and other interactions of Hinduism, Buddhism, Zoroastrianism, Judaism, Islam and Christianity. This is unique as no other advanced material can display this multi-faceted splendour.

Fig. 1 The sword of Tipu Sultan

Iron and steel heritage of India

India has been reputed for its iron and steel since ancient times. The Delhi Iron Pillar is a marvellous monument. There are numerous early literary references to steel from India from Mediterranean sources including one from the time of Alexander (3rd c. BCE), who was said to have been presented with 100 talents of Indian steel. Arabs took ingots of wootz steel to Damascus following which a thriving industry developed there for making weapons and armour of this steel, the renown of which has given the steel its name. In the 12th century the Arab Edrisi mentioned that the Hindus excelled in the manufacture of iron and that it was impossible to find anything to surpass the edge from Indian steel. In 1912, Robert Hadfield who studied crucible steel from Sri Lanka recorded that Indian wootz steel was far superior to that previously produced in Europe. Evidence from Kodumanal (c. 3rd century BCE) in Tamil Nadu suggests crucible ferrous processing.

European travellers such as Francis Buchanan in 1807, Benjmain Heyne in 1818, Voysey in 1832 and Josiah Marshall Heath in 1840 observed the manufacture of steel in south India by a crucible process at several locales including Mysore, Malabar and Golconda. By the late 1600's shipments running into tens of thousands of wootz ingots were traded from the Coromandel coast to Persia. This indicates that the production of wootz steel was almost on an industrial scale in what was still an activity predating the Industrial Revolution in Europe. Thus, Konasamudram in Telangana was a world renowned centre to which merchants from Persia and elsewhere flocked long before Sheffield, Pittsburgh and Jamshedpur emerged as steel centres in the modern era.

Indian wootz ingots have been used to forge oriental Damascus swords which were reputed to cut even gauze kerchiefs and were found to be of a very high carbon content of 1.5-2.0% and the best of these were believed to have been made from Indian steel in Persia and Damascus according to Smith. In India, until the 19th century, swords and daggers of wootz steel were made at centres including Lahore, Amritsar, Agra, Jaipur, Gwalior, Tanjore, Mysore and Golconda, although none of these centres survive today.

The role of wootz steel in the development of modern metallurgy

For centuries, iron and steel were thought to be two elements belonging to the ferrous family, just as copper, silver, gold and other metals belong to the non-ferrous family of metals. The recognition that steel is an alloy of iron and carbon came as a result of the chemical assaying of wootz steel in 1774 by the Swedish chemist Tobern Bergman. The Chemical Revolution wrought by Lavoisier received an impetus with the identification of carbon as an element. Indeed, chemistry must in some degree attribute its very origins to iron and its makers.

This single-minded pursuit of an Eastern technological product by Western scientists —the illustrious names include Michael Faraday, Breant, Anasoff, Belaiew— for over a century created the foundations of modern materials science.

The development of wootz steel by sheer empirical practice in Southern India, the fashioning of the steel by thermo-mechanical treatments into fierce and beautiful Damascus swords in India and the Middle East with little knowledge of the underpinning science is a remarkable tale in the annals of metallurgy. When this steel was presented to the Western world, scientists in England, France, Russia and Sweden toiled hard and discovered the composition and microstructure and their relation to mechanical properties. This single-minded pursuit of an Eastern technological product by Western scientists —the illustrious names include Michael Faraday, Breant, Anasoff, Belaiew— for over a century created the foundations of modern materials science.

As studies of wootz progressed it became imperative to establish the phase diagram of the iron-carbon system. The first comprehensive construction is due to Roberts-Austen in 1898. This was the first phase diagram of any alloy ever to be established. Such a diagram made it evident that it is possible to distinguish different products such as wrought iron, plain carbon steels, ultra-high-carbon steels and cast irons on the basis of their composition (Fig. 2). It was also possible to identify various phases such as austenite, ferrite, cementite. The phase reactions such as peritectic, eutectic and eutectoid came to be established. Combination of phases led to microstructures consisting of pearlite and ledeburite. The use of the optical microscope became widespread due to studies of wootz steel.

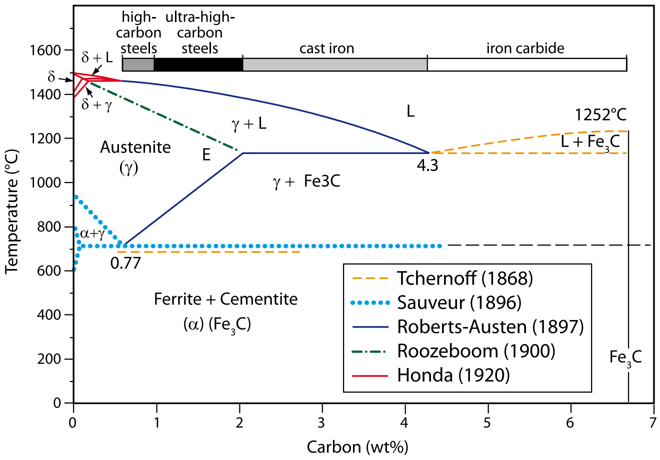


Fig. 2 Iron-carbon (Fe-C) diagram, the first phase diagram of any alloy to be established, by Roberts-Austen in 1898, after whom austenite came to be named. (Courtesy of J Wadsworth)

Deformation and solidification microstructures

Panseri in the 1960's was one of the first to point out that Damascus steel was a hypereutectoid ferrocarbon alloy with spheroidised carbides and carbon content between 1.2-1.8%. Recent studies by Jeffrey Wadsworth and Oleg Sherby have indicated that ultra-high-carbon steels exhibit superplastic properties at warm temperatures and are strong and ductile at room temperatures. The explanation of the superplasticity of the steel is that the typical microstructure of ultra-high-carbon steel with the coarse network of pro-eutectoid cementite forming along the grain boundaries of prior austenite can lead to a fine uniform distribution of spheroidised cementite particles (0.1 mm diameter) in a fine-grained ferrite matrix. John Verhoeven and the blacksmith Alan Pendray collaborated in the production of modern Damascus blades. Verhoeven has proposed that minute amounts of vanadium were necessary to lead to micro-segregation and the formation of banded structures during subsequent processing. Figure 3 shows the banded pattern visible to the naked eye. This texture and its beauty added to the reputation of the Damascus swords.

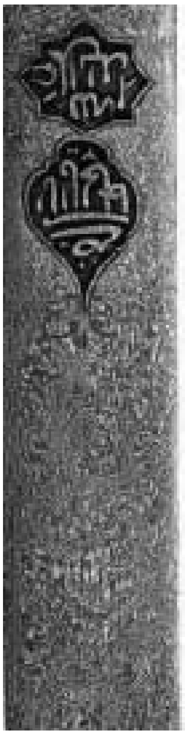
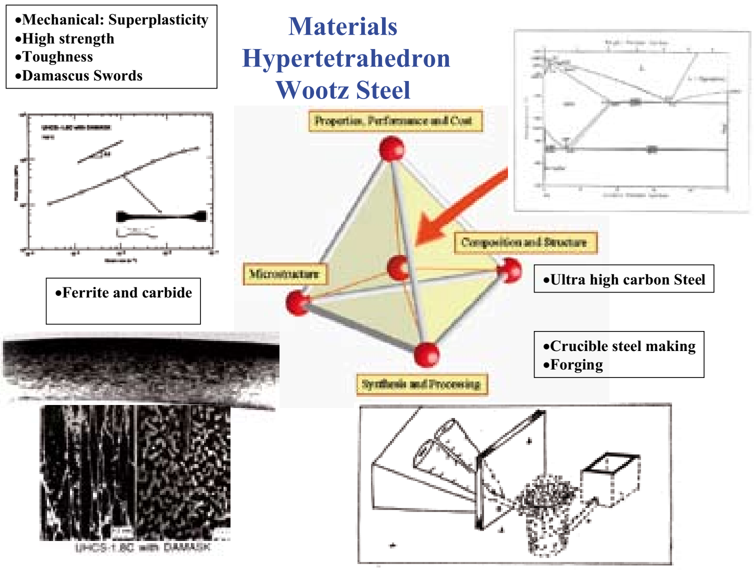


Fig. 3 Ladder pattern (Courtesy of JD Verhoeven)

Materials science tetrahedron and wootz steel

As discussed above, the investigations on wootz steel in 19th century Europe led to the foundations of what we understand today as the central paradigm of materials science. This is based on the idea that the processing of a material leads to a structure, which has a definite combination of properties. This set of properties in turn defines the performance of the possible products that can be made out of these materials. Merton C Flemings and Praveen Chaudhari captured these four defining ideas as the four corners of a tetrahedron. It applies equally well to metals, ceramics, polymers and composites and to materials ranging from sand to steel, nickel to nylon and bone to bronze. It is this powerful generalization that has made materials science a pervasive and enduring concept. The past decade has added one more idea to this quartet of the conceptual framework, namely modelling. As processing, structure and properties become complex, it is possible for us to resort to modelling and simulation. Figure 4 represents such a materials science hyper-tetrahedron for wootz steel. Individual vertices represent processing, structure, properties, performance and modelling. The facets of the Buchanan furnace, the iron-carbon diagram, the microstructure of dendrites in the as-cast state and spheroidised cementite in the forged material, the superplastic elongation, and the Damascene marks are displayed with emphasis on the strong interconnections among them. Materials science came into being due to the investigations into the properties of wootz steel.

Fig. 4 Materials hyper-tetrahedron for Wootz steel (S Ranganathan)



- Mechanical: Superplasticity
- High strength
- Toughness
- Damascus Swords

Materials Hypertetrahedron Wootz Steel

- Ferrite and carbide

- Ultra high carbon Steel

- Crucible steel making
- Forging

Further reading

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