Metallurgy of Ancient Indian Iron and Steel

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Early ideas about the Aryan migration theory and the introduction of iron into India from the West have now been proved to be incorrect. For example, Pleiner (1971) proposed that so-called Aryans had no iron production until the second half of the first millennium BCE, and that there was no iron export to the West from the area of the Aryans, whom he assumed to be "the Sanskrit speaking people." However, there are firm dates for the advent of iron in the Indian subcontinent before this period. The independent origin of iron has been convincingly argued by Chakrabarti (1992). Agrawal and Kharakwal (2002) have compiled radiocarbon dates of excavated iron manufacturing sites in the Indian subcontinent. The earliest available date, 3050–90 BP, is from Raja-Nala-Ka-Tila in Uttar Pradesh (Tiwari 2003).

The primacy of iron technology in the Indian subcontinent is well established and there are several published books on the state of ancient Indian iron technology (Neogi 1914; Chakrabarti 1992; Biswas 1996; Tripathi 2001; Balasubramaniam 2002). The metallurgy of iron and steel in ancient India is the topic of this article, which includes the working of iron, the extraction of iron and salient features of ancient Indian iron. Some objects illustrating the skill of the Indian blacksmiths are provided. The Delhi Iron Pillar (Fig. 1) illustrates the pride of Indian blacksmithy skills.

Metal Extraction

The direct reduction method of iron extraction was used for a fairly long period in India's history. Iron lumps were the starting material for the fabrication of most objects.

Iron melts at 1,540°C and the ancient Indian furnaces were incapable of attaining this high a temperature. The various aspects of construction and operation of ancient Indian iron furnaces (called bloomery furnaces because the end product was an iron bloom) have been discussed in the literature (see Tripathi 2001). The ore for extracting iron was carefully collected by the ironsmiths. Interestingly, specific ore was collected depending on the end application. Preheating facilitated breaking of the ores, and the fine dust was separated by washing or by wind. The preheated iron ore and charcoal were charged in alternating layers, the furnace ignited and slowly heated to the reduction temperature (1,000–1,200°C). Different designs of iron extraction furnaces have been described in the literature. Their heights ranged between 5 and 20 ft. A typical ancient Indian bloomery furnace is schematically compared with a modern blast furnace in Fig. 2.

Bellows placed at the bottom of the furnaces were operated at a controlled rate. The iron ore had to be reduced in order to obtain the iron. Iron ore is essentially oxide of iron and it is reduced by the carbon monoxide (CO) that is produced by the burning of charcoal in the bloomery furnace (or coking coal in a modern blast furnace). The other unwanted oxides, like silicon dioxide (SiO_2), which is commonly found in iron ores, have to be removed and this was possible by the creation of a liquid slag called iron silicate or fayalite $FeSiO_4$ or $2FeO{\cdot}SiO_2$. While some of the liquid slag flowed out of the bloomery furnace during the reduction of iron ore to iron, some of the liquid slag still remained when the hot iron lumps were taken out of the furnace. Therefore, the

Metallurgy of Ancient Indian Iron and Steel. Fig. 1 Delhi iron pillar located in the Quwwat-ul-Islam mosque in the Qutub Complex at New Delhi.

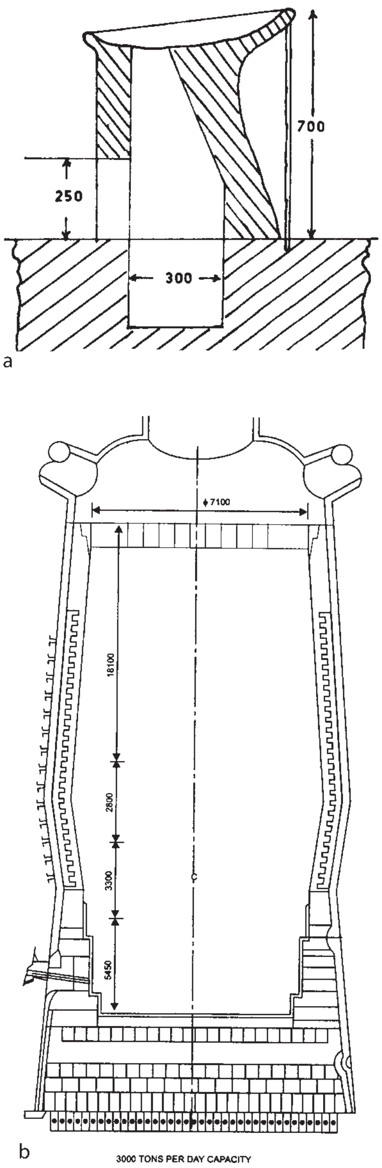

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Fig. 2 Comparison of (a) modern and (b) ancient furnaces for extracting iron from ore.

hot lumps that were extracted from the bloomery furnace at the end of the heat (typically lasting for about 6 to 8 h) were immediately hammered. In this process, most of the entrapped liquid fayalitic slag flowed out of the solid reduced iron mass. However, it was not possible to remove all the entrapped liquid slags and ancient irons produced by the direct reduction process will always contain entrapped inclusions. The inclusions are essentially composed of fayalite, some iron oxides (for example, wüstite FeO) and glassy phases (due to calcium silicon phosphates). As a result of entrapped slag particles and iron oxides in the structure, the specific gravity of ancient irons is lower than that for the purest form of iron (Fe).

The slag present in ancient irons is generally microscopic in nature with a few in larger sizes. As the solid-state reduction resulted in a fine distribution of slag particles, it was difficult to completely hammer the slag out of the metallic matrix. The resulting sponge iron always contained some amount of entrapped slag inclusions and unreduced FeO. These were not of uniform size and also not strictly uniform in composition.

Viewing the production of iron lumps from a powder metallurgical viewpoint, the ancient Indians produced iron "pre-forms" directly from iron ore which implied that the powder production, powder consolidation, and sintering[1] processes were combined into one operation (Dube 1990).

The end product of the extraction process was a lump of iron that was subsequently used for a wide variety of applications, either directly or after further heat treatments. One important heat treatment that was successfully conducted was controlled carburization of iron in specially designed crucibles. The carbon content of steel (i.e., an alloy of iron and carbon) was carefully controlled by subsequent decarburization treatments. It is important to control the carbon content in steel because the mechanical properties of steel are critically dependent on the carbon content. As a rule of thumb, the higher the carbon content, the higher the strength of steel.

The relatively small iron lumps produced in the bloomery furnace were the starting materials for the manufacture of large iron objects. The lumps were also used, after suitable heat treatments, for manufacturing agricultural (hoes, spades, sickles, and weeding forks), household (knives, ladles, spoons, sieves, saucepans, cauldrons, bowls, dishes, saucers, and tripods), building (nails, clamps, staples, sheets, door handles, and spikes), tools (anvils, hammers, scissors, saws, chains, and smithy tools), and warfare (swords, javelins, armor, helmets, and shield bases) items. A marvelous example of a forge-welded object is the gilded Buddha head from the Gupta period (320–600 AD) (Fig. 3).

With the advent of the carburization of iron, a special type of high carbon steel was produced in India from as early as the fourth century BCE. This steel was known as *wootz steel* and it was much prized by warriors because tough swords could be wrought from wootz steel. This has been described in detail by Srinivasan and Ranganathan (2004). There were several applications for wootz steel, like the manufacture of tough

[1] Sintering is a process in which solid wastes are combined into a porous mass that can then be added to the blast furnace. These wastes include iron ore fines, pollution control dust, coke breeze, water treatment plant sludge, and flux.

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Fig. 3 Gilded wrought iron Buddha image of the sixth Century AD, now in Lucknow State Museum.

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Fig. 4 Typical watered blade manufactured from wootz steel.

swords (see Fig. 4), helmets (see Fig. 5), and armor (see Fig. 6).

Classification

Ancient Indians were masters in the production of iron and steel. The method of production of wrought iron directly from the ore by the process of direct reduction continued for a fairly long time, up to the end of the eighteenth century AD. The Indians knew fairly early about the beneficial aspect of carburizing iron to increase its strength. The earliest evidence for carburization of iron dates to about 800 BCE (Ghosh and Chattopadhaya 1982). The second urbanization of India (i.e., settlements along the Ganga) may have been strongly influenced by the steeling of iron.

Three principal varieties of iron were recognized based on the carbon content. Each of these was further subdivided into other varieties depending on the composition and properties (Prakash 1991). Sanskrit literary sources (for example, *Rasa Ratna Samuchchaya* dated to the eighth to twelfth century AD) classify iron into three basic categories: wrought iron (*Kanta Loha*), carbon steel (*Tikshna Loha*), and cast iron (*Munda Loha*). *Rasendrashār Samgraha* also mentions these three classifications and states that "*munda* is ten times better than iron rust, *tikshna* hundred times better than *munda*, and *kanta* million times better than *tikshna* iron." These three basic categories were further classified according to the carbon content, heat treatment, and end use. *Munda* was again subdivided into three varieties: *mridu*, which easily melts and does not break and is glossy; *kuntha*, which expands with difficulty when struck with a hammer; and *kadāra*, which breaks when struck with a hammer and has a black fracture surface. Six varieties of *tikshna* were provided: *khara*, *sāra*, *hrinnāla*, *tārābatta*, *bājira*, and *kālaauha* (black metal). One variety is rough and free from hair-like lines and has a quicksilver-like fracture surface, while another variety breaks with difficulty and presents a sharp edge. Five different varieties of *kanta* were recognized: *bhrāmaka*, *chumbaka*, *karshaka*, *drāvaka*, and *romakāntā*. The variety of iron which makes all kinds of iron move about was called *bhrāmaka*; that which kisses iron was called *chumbaka*; that which attracts iron was called *karshaka*; that which at once melts iron was called *drāvaka* and *romakāntā* was the kind which, when broken, shoots forth hair-like filaments.

The ancient Indian iron furnaces were capable of producing iron of consistent (low) carbon content-

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containing entrapped slag inclusions (Tripathi 2001). Iron meant for corrosion-resistant applications contained higher phosphorous (P) contents. Therefore, it is reasonable to conclude that the ancient Indian metallurgists possessed the art of manufacturing iron and steel according to the desired application and corrosion-resistant steel was one among them. The excellent corrosion resistance of ancient Indian iron can be attributed to its relatively high phosphorus contents. This is due to the absence of CaO (calcium oxide, i.e., limestone) in the charge of the bloomery furnace.

Metallurgy of Ancient Indian Iron and Steel. Fig. 5 A typical medieval Indian helmet fabricated out of wootz steel.

Microstructures

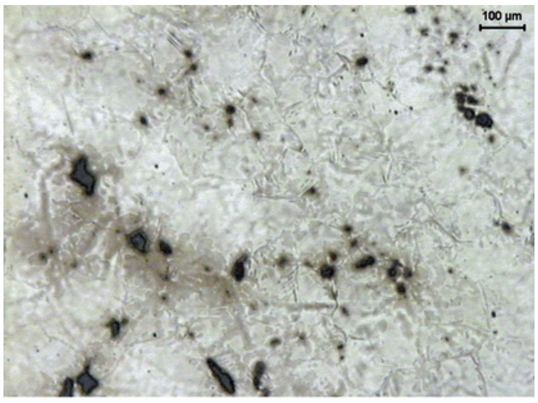
In materials engineering, the close correlation between structure and properties is well known. Structure indicates arrangement of the material. When one views the arrangement of electrons, neutrons, and protons, we call it atomic structure. On a microscopic scale, in the order of micrometers, the grain structure of engineering materials is understood. Finally, the macrostructure refers to observations made in the range millimeters. Structure affects the properties of engineering materials.

The microstructures of ancient irons are highly heterogeneous; the iron normally possesses nonuniform grain structures.

In the unetched condition, the specimens generally reveal slag inclusions irregularly distributed in the microstructure. The end product of the bloomery furnace was a lump of direct reduced iron, which contained phosphorous as the major alloying element. The end product of the ancient Indian direct process of extracting iron can be called phosphoric iron. The end product of modern blast furnaces is pig iron, in which carbon is the major alloying element. In contrast to macrosegregation of P in pig iron, microsegregation of P is realized in ancient phosphoric irons. Fig. 7 shows an optical metallograph obtained after polishing an ancient Indian iron sample to a mirror-like finish and etching it with Oberhoffer etchant. The particular etchant used reveals the distribution of P in the microstructure. The dark areas in Fig. 7 are the regions where the P content is less, while the bright areas are indicative of higher P contents. Notice that P is depleted from the grain boundaries and from the regions surrounding the entrapped slag particles. There are several fascinating insights that can be obtained from the study of microstructures but this is beyond the scope of this article.

The forge-welding method of manufacturing iron objects continued for a long time. Indians did not quickly adopt the cast iron technology that was becoming popular in Europe from the beginning of the sixteenth century. They continued with their traditional method of forge welding to manufacture

Metallurgy of Ancient Indian Iron and Steel. Fig. 6 Typical medieval Indian body protection gear wrought out of wootz steel.



Metallurgy of Ancient Indian Iron and Steel. Fig. 7 Microstructure of Gupta period (320–600 AD) iron revealed using an Oberhoffer etchant. The regions depleted in P appear darker in contrast. The dark structures are entrapped slag inclusions.

Metallurgy of Ancient Indian Iron and Steel. Fig. 8 The massive forge-welded iron cannon called *Rajagopala* located at Thanjavur.

large objects like cannons. One typical example of a massive cannon manufactured by forge welding is seen in Fig. 8. This cannon was fabricated in the early part o the seventeenth century and is located at Thanjavur. There are several other massive forge-welded cannons from the medieval period.

Death of Indian Iron

Indian metal crafts flourished until the end of the Mughal period (1526–1705). After the establishment of the British Empire, restrictions were imposed by them in the form of production taxes and bans on export. It was natural that this industry should die. This disappearance of the ancient technology during the seventeenth to nineteenth centuries was aggravated by the discovery of new alchemical principles and development of new industrial process of metal production in Europe.

The direct reduction process of iron making declined after the advent of the processes for making liquid steel in large-scale in the middle of the nineteenth century. The iron and steel trade from India declined and the ancient method of extraction and processing became extinct by the beginning of the twentieth century.

The British in India made attempts to work on iron ores on a large-scale by modern methods. Several iron and steel works were set up in the country. For example, the Bengal Iron Company was established at Barakar in 1874. It employed 821 people in 1891 and produced 12,000 ton of pig iron (Jaggi 1989). However, these iron works depended on the availability of charcoal and this necessarily meant the destruction of forests and depletion of charcoal supplies. Another factor was also at play. By the end of the century, indigenous iron ceased to be produced because of the import of iron.

Another factor in iron's decline is the fact that certain essential steps were not shared by the master smiths with anybody except their favored apprentices. Traditional artisan communities in India never reveal full details to outsiders and when the communities disappeared, so did the methods. Other factors include the use of the same age-old furnaces, processes, and blowers (*bhathi*) by many tribes. This shows that these process secrets were well guarded and any change in the process or equipment was considered a bad omen. Probably this is one of the reasons for the loss of metal technology.

In the twentieth century, the condition had become so bad that the memory of ancient glory remained only in the form of stories narrated by old men. After independence in 1947 India had to borrow the modern technology from western countries to set up steel plants. The situation is now changing with India again rising to the challenge and hoping to be one of the largest producers of iron and steel in the twenty-first century.

The wishful thinking of Neogi in 1914 is worth recollecting.

> We hope we have been able to give a trustworthy account of the process of the manufacture of Indian steel, which was an object of envy of all nations but successfully imitated by none and which supplied the materials of many a true blade of warriors both in the East and the West. It is sad to reflect that an ancient indigenous industry which attracted merchants from Persia, as narrated by Dr Voysey, barely a hundred years ago, is on the point of extinction; but as even the darkest cloud is not without a silver lining, a distinct ray of hope is visible in the not very distant horizon presaging that India will yet regain her lost iron

industry under modern scientific conditions together with other attendant industries depending upon iron.

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