© 2001 NML Jamshedpur 831 007, India; Metallurgy in India: A Retrospective;
(ISBN: 81-87053-56-7); Eds: P. Ramachandra Rao and N.G. Goswami; pp. 52-91.

# 3

# Ferrous Metallurgy in Ancient India

**B. Prakash***
*Formerly Professor of Metallurgical Engineering, Banaras Hindu University, Varanasi, India*

## ABSTRACT

The discovery of fire and its controlled use in Pyrotechnology has been an important landmark in the progress of human civilization and materials technology. The paper discusses the knowledge of the ancient pyrometallurgical process of iron production, the smelting furnace design, construction and its operation used by Munda and Agaria tribes. It also discusses thermo-chemistry and the physico-chemical processes those go on inside the ancient iron smelting furnace and the principles of its process control. The wrought iron produced by the bloomery furnace contained a maximum of 0.4% C which was carburised to produce case carburised, and laminated steel. Another type of steel produced in the country since 400 BC was known as 'ukku' in the southern language and it became world famous by the name of Wootz steel. Two distinct processes viz., (i) carburization of wrought iron and melting carried out inside a closed refractory crucible, and the other (ii) process of manufacture of steel by decarburization of white cast iron by its reaction with synthetic slag have been described. Lastly the paper gives a brief description of the ancient smithy craft used for producing some of the heaviest forgings of the world like iron pillars at Delhi and Dhar, iron beams of Konark and the iron guns of Bijapur and Tanjore. The forging and heat treatment of Wootz steel containing ultra high carbon required special skill known only to the Indian blacksmiths, and latter learnt by Syrians to produce world famous Damascus sword made of this steel. The surface finish known as Watering mark or Damask pattern was the hallmark of original Wootz steel sword.

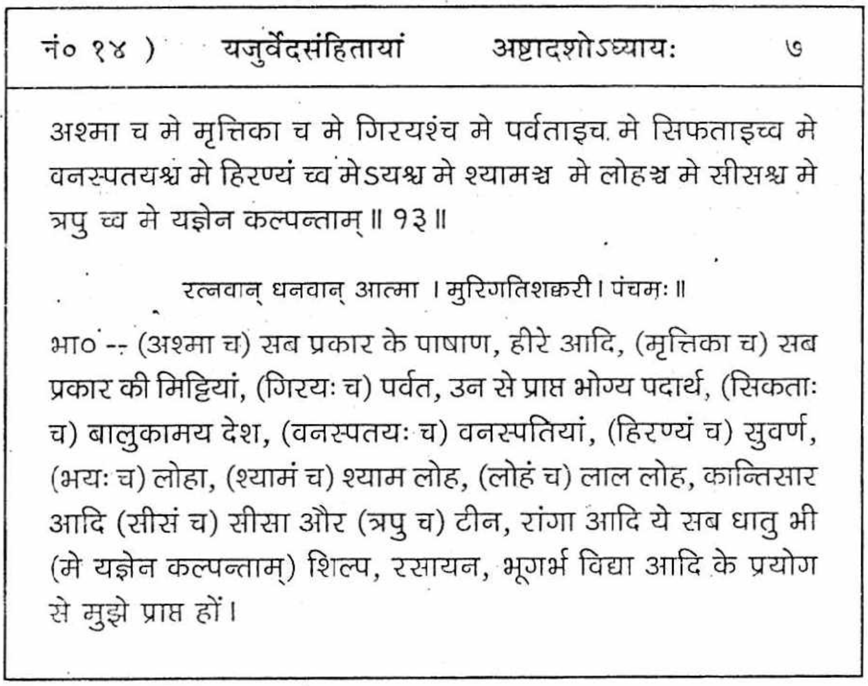
*Key words* : Pyrotechnology, Bloomery iron, Wootz steel, Smithy craft, Watering mark treatment.

---

*Address : Hari Om Shanti, H. No. 3/1005, Gayatri Nagar, Ramnagar, Varanasi - 221008, India.

## INTRODUCTION

The history of human civilization is a continuous endeavour to learn the use of natural resources and this quest for knowledge helped in the progress of material science and technology. In this effort the role of fire has been of prime importance. The first human acquaintance with fire might have been due to the natural combustion of forest, through which, inspite of the devastating effect, man must have learnt about heat and light. The earliest reference to the domestication of fire could be traced to millennia 9000 to 6000 BC, when its lithic and trophic uses must have begun and man must have learnt to start fire with the help of flint stone or fictional heat generated during vigorous rubbing of two pieces of dry wood. Realizing the power of fire man began to worship it by performing havan and making animal sacrifices in the early Vedic period. Rg Veda begins with the worship of 'Fire God'. Prakash[1] has mentioned that the fire alter provided opportunity to learn its physical and chemical properties as well as its controlled use for self protection, quarrying and shaping of flint and other stone tools, production of fired bricks, glasses, cements and mortars as well as design of a variety of furnaces used during pyrotechnology and pyrometallurgical processes. Wertime[2] has mentioned 'Biringuccio'[3] as the shaper of soul of fire as well as mover of the material body. He has been considered as the essential renaissance bridge between the earliest pyrotechnologists and the twentieth century fomenters of the revolution of material science and engineering.



नं० १४ )    यजुर्वेदसंहितायां    अष्टादशोऽध्यायः    ७

अश्मा च मे मृत्तिका च मे गिरयशंच मे पर्वताइच. मे सिफताइच्व मे वनस्पतयश्च मे हिरण्यं च्व मेऽयश्च मे श्यामश्च मे लोहश्च मे सीसश्च मे त्रपु च्व मे यज्ञेन कल्पन्ताम् ॥ १३ ॥

रत्नवान् धनवान् आत्मा । मुरिगतिशक्करी । पंचमः ॥

भा० -- (अश्मा च) सब प्रकार के पाषाण, हीरे आदि, (मृत्तिका च) सब प्रकार की मिट्टियां, (गिरयः च) पर्वत, उन से प्राप्त भोग्य पदार्थ, (सिकताः च) बालुकामय देश, (वनस्पतयः च) वनस्पतियां, (हिरण्यं च) सुवर्ण, (भयः च) लोहा, (श्यामं च) श्याम लोह, (लोहं च) लाल लोह, कान्तिसार आदि (सीसं च) सीसा और (त्रपु च) टीन, रांगा आदि ये सब धातु भी (मे यज्ञेन कल्पन्ताम्) शिल्प, रसायन, भूगर्भ विद्या आदि के प्रयोग से मुझे प्राप्त हों।

*Fig 1 : Sanskrit text indicating the evolution of iron and other metals from Havankund mentioned in Yajurveda.*

Fire wood and charcoal were the two major energy sources used in the early pyrometallurgical processes for shaping the native metals, preparing alloys and extracting metals from their naturally occurring minerals. The ritcha quoted in Fig. 1 is from Yajurveda mentioning the prayer to *Agni* to bless with metals like Au, Ag, Cu, Sn, Pb and Fe in association with minerals occurring in earth and the vegetation i.e., wood providing heat and charcoal (C as reductant). In *Rgveda,* iron has been mentioned several times for its functional use in daily life. The ritcha quoted from Rg Veda (Fig. 2) mentions the production of steel by the association of iron with swan's feather (probably used as carburizer) and the craftsman waiting for the wealthy buyer who could pay its high price. The ancient Sanskrit texts of the country are full of mention of variety of metals including iron and steel.

So far as the archaeological occurrence of iron and steel is concerned, a detailed review has been published by Prakash and Tripathi[4-6] et. al., and many others. Fig. 3 shows the $C^{14}$ dating of iron objects found at various places in India. According to this plot, the iron objects begin to appear during the late 2nd m BC and the development of its extraction process must have begun in the early 2nd m BC i.e., almost simultaneously with the appearance of iron extraction technology at Anatopai. Prakash[5] has examined the possibility of the reduction of iron oxide in *havankund* and proposed a hypothesis of the beginning of pyrometallurgical process of iron making and its gradual transition to the shaft smelting furnace from the *havankund* . India was producing large quantity of iron as well as the world famous 'Wootz' steel and was exporting them to the western countries till the British Government enforced a ban to promote their own trade. As reported by Bhardwaj[7-8], ancient iron industry was flourishing throughout the country till 19th century. In 15th Century AD, iron worth rupees 50,000 to 70,000 was produced in Assam only. The quality of iron was so good that in 1875 more than 50,000

जरतीभि: औषधिभि: पर्णीभि: शकुनानाम्। ऋग्वेद त्रक्ष 9.112.2
कर्मारो अश्मभि: धुभि: हिरण्यवन्तभिच्छति
इन्द्रायेन्द्रो परिश्रव॥

कर्मार यानि लोहार लकड़ी के टुकड़े, को लोहे के खनिज के साथ रखता है। तालपत्र में लकड़ी के टुकड़े रखते होंगे। लोहे के खनिज के टुकड़े और तालपत्र लकड़ी के टुकड़े अर्क (asclepias giganta) यानि आकन्द वृक्ष के पत्तों से (पर्णोभि:) ढकते थे। खनिज के पत्थर, (धुमि: अश्मभि:) लकड़ी के टुकड़े के साथ तपाने से जली हुई लकड़ी का कोयला (कार्बन) लोहे के साथ धुलता होगा, जिससे लोहे का इस्पात में परिवर्तन होता होगा। कार्बन की मात्रा बढ़ाने के लिए शकुन यानि हंस पंछी के पर भी डालते थे। हंस के पंख में 90% वाष्पशील द्रव्य और 10% कार्बन होता है या शकुन पंछी के परों का धौंकनी, निर्माण करने के लिए उपयोग करते होंगे। ऋग्वेदकाल में इस्पात बहुत महंगा होता था। इसीलिए यह लोहार धन-सम्पन्न (हिरण्ययन्तं) व्यक्ति की प्रतीक्षा करता था ताकि उन्हें यह इस्पात बेच सके। इसी लेख में आगे बताया गया है कि उन्नीसवीं सदी तक भारतीय, ऋग्वेद में दी हुई इस ऋचा में वर्णित पद्धति से इस्पात निर्मित करते थे।

*Fig. 2 : Sanskrit text from Rg Veda indicating production of steel and its high price.*

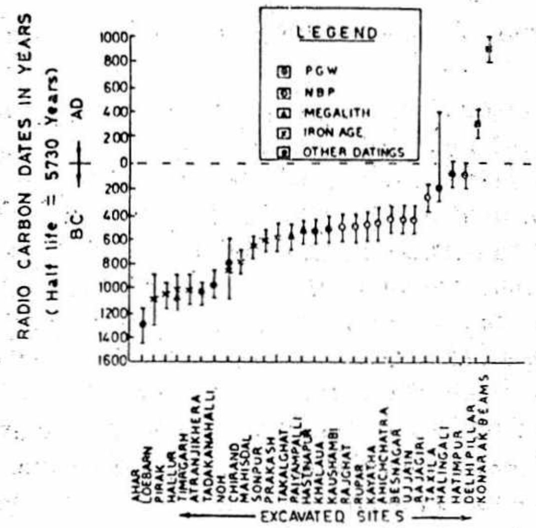


*Fig. 3 : C14 dating of ancient iron objects found at archaeological sites in India*

tonnes were exported to the United Kingdom for the construction of the world famous London Bridge. Elwin[9] recorded in detail about the 'Agaria' tribe and their iron smelting process in India. It is reported that these ancient bloomery furnaces generally had a production capacity of 2 to 10 kg per heat and in some cases larger furnaces such as 'Kothis' of Nagpur had production capacity of 40 kg, the Malabar twin hearth furnaces described by Buchanan[10] had a capacity of 250 kg per heat. After the beginning of the industrialization and introduction of large blast furnaces during 17th century, it is presumed that the ancient process continued in the country till 1960. M.K. Ghosh and K.N.P. Rao[11] of Tata Steel (then Tata Iron & Steel Company) attempted to locate those iron craftsmen of Munda and Asura tribes near Jamehdpur and at two places in Orissa, who could remember the production technology of ancient iron. These persons were successful in operating three different furnaces, one each at Kamarjoda in Bihar and Jiragora and Chiglabecha in Orissa. The operating practice and the logsheet of the raw materials and products were published by Ghose[11]. This was followed by the location of the remains of an ancient furnace at Loharpara in Bastar by Prakash et. al[12]. They could record the details of the furnace operation from a family of Munda tribe. Latter Sharma[13] surveyed eastern Madhya Pradesh and located two old men who remembered the ancient iron making process and after long persuation they constructed a furnace and operated it successfully at Bishunpur under the project 'Vikas Bharati'. Later on a detailed survey of the eastern Madhya Pradesh and neighbouring area of Bihar and Uttar Pradesh was done to locate 'Agarias' and their furnaces. It was found that families of Agaria community still continued their traditional iron making producing iron to the tune of 100 kg per day. A large number of furnaces were found to be operated at Wadruffnagar in Madhya Pradesh. Misra and Chaube[14] have prepared a detailed report on the living traditions of Agarias and their ancient craft. During the years 1993 to 1996 several demonstration were organized by PPST, Institute of Gandhian Studies, Varanasi, IIT (Bombay) and at Anna University, Chennai. These have provided the author an opportunity to study and gain first hand knowledge regarding the operation of these iron smelting furnaces. Recently two major projects have been taken up, one at the Indira Gandhi National Museum of Man in collaboration with RRL at Bhopal and the second at the National Metallurgical Laboratory, Jamshedpur, to study and improve the ancient practice that can be operated in remote areas by the tribal folk and to make it an economically viable process.

## THE ANCIENT IRON MAKING PRACTICE AND PROCESS CONTROL

The ancient process of iron making has been vividly described in the folk songs of *'Chokh Agaria'* from Lapha. One of these songs as translated by Joshi[15] is as follows:

> *She presses down the bellows with the strength of her heels.*
> *He wields the heavy hammer with all his might*
> *From the ground he gets stones.*
> *The fire burns fiercely as the bellows blow.*
> *The little hammer clatters, tinning tanang,*
> *A shower of sparks flies into her breast.*
> *He puts it in black*
> *He pulls it out red*
> *Standing he beats it*
> *The chokh girl blows the bellows at the forge*
> *Like a drum it sounds 'Datur Thunda'*
> *How happy I feel*
> *The chokh boy beats with the hammer*
> *The hammer whistles as he swings it round*
> *And I feel very happy.*

As it appears from the above mentioned song the whole operation was a family affair controlled by the headman and his wife and the technology was maintained as a secret, passed on from generation to generation. The younger generation participated in the activities and when by the age of 17 to 20 they were trained in all the skills of the trade, they were permitted to marry and operate their own furnace. The actual practice of iron making can be divided into the following six steps-

1 – collection of raw material i.e. iron ore, wood and refractory clay
2 – construction of the furnace and the tuyere pipe.
3 – making and fixing the bellows.
4 – drying, firing and operating the furnace.
5 – removal of slag and handling of red hot sponge iron bloom.
6 – secondary refining of the bloom.

The details of the above mentioned steps of the traditional iron making and its process control have been already published by Prakash[16] and Mahmad[17]. Hence, in this paper only some salient features are being highlighted.

## Collection of raw materials

Inspite of the abundantly available rich deposits of hematite in the country the ancient iron smelters preferred to use low grade limonite or magnetite ore available in Assam and Karnataka. The magnetite ore was concentrated by panning or launder washing in the water stream. The ore was generally calcined to remove moisture and the associated organic matter and limonite lumps were broken into small pieces (5mm) to improve its surface area and reducibility.

The charcoal used for heating the ore and generating the reducing gas (CO) was produced from a variety of wood depending upon their availability in the region, and generally no basic flux was used to adjust the properties of the FeO rich fayalite ($2FeO.SiO_2$) slag formed during smelting. The refractory clay and stiff mud are required for making the furnace.

## Construction of the furnace and the tuyere pipe

Elwin[9], Joshi[15], Chatterjee[18], Krishnan[19] and Prakash[20,21] have published photographs and line diagrams of a variety of ancient furnaces constructed and operated in different parts of the country. Fig. 4 shows a reconstructional drawing of one of the oldest iron smelting furnaces found at Naikund dated back to 700 BC. It can be seen that this furnace was constructed using curved bricks made of refractory clay (kaolin). Mahmad[17] has classified these furnaces into two major groups viz., (i) Fosse type and (ii) Aerial Type.

### *Fosse type*

This type of furnace was constructed below the ground level either by digging a small cylindrical pit or shaft as shown in Fig. 5 or a bowl type furnace was constructed in one of the faces of a large square pit as shown in Fig. 6.

### *Aerial Type*

This type of furnace could be further classified into two categories *i.e.*, furnaces having their hearth and the slag pit constructed below the ground level and the tapered circular shaft standing above it. Fig. 7 shows a drawing of this type of furnace constructed at Jiragora. The internal details of the drawing shown in Fig. 8 was constructed completely above the ground level or on a raised platform. Fig. 9 shows the geometrical design of shaft furnace operated at Tendukaira near Jabalpur to smelt weathered banded hematite quartzite ore. The constructional details of this furnace have been described in detail by Mahmad[17]. Fig. 10 shows a photograph of a 40kg furnace known as 'Kothi' operated in Nagpur area. Although these furnaces look crude in appearance they were made with great precision, their dimensions being fixed on the basis of the long experience of the

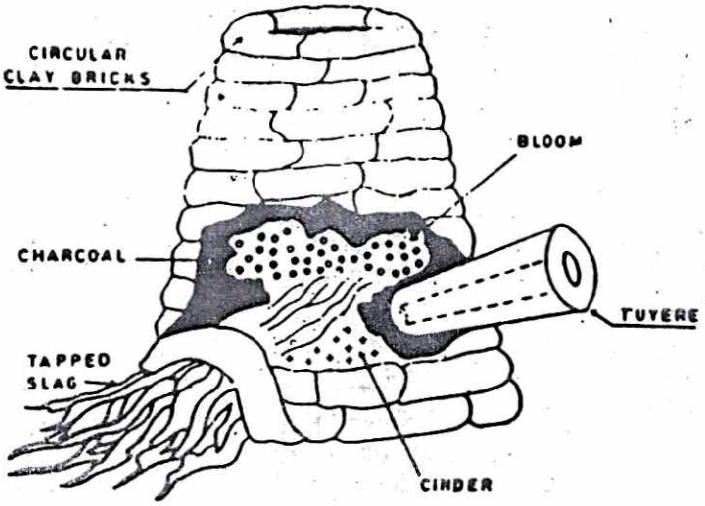


*Fig. 4 : The reconstructional sketch of the iron smelting furnace found at Naikund (700 BC).*

Head smelter. Prakash[22] has examined the design of these furnaces using the empirical relations mentioned by Bashforth[23] with reference to the design of 1000 tonne/day modern blast furnace. The calculated data recorded in Table 1 show that their design criteria like d/D ratio, H/D/2 ratio, stack angle and volume/kg of iron were almost constant in all the furnaces except the furnace inner volume required per kg of iron. This shows that the ancient iron smelters had gained experience regarding the physico-chemical changes taking place during the rise in temperature of the raw material and the reduction of the ore.

The furnaces were constructed using the breadth of man's fingers *'Angula'* (~80mm) as a unit of measurement. The other scales were 'Bitta' i.e., the distance between the tips of the little finger and the thumb in the expanded form (~240mm) and 'Hasta' i.e., the length of the fore arm (~475 to 500mm). In order to measure the

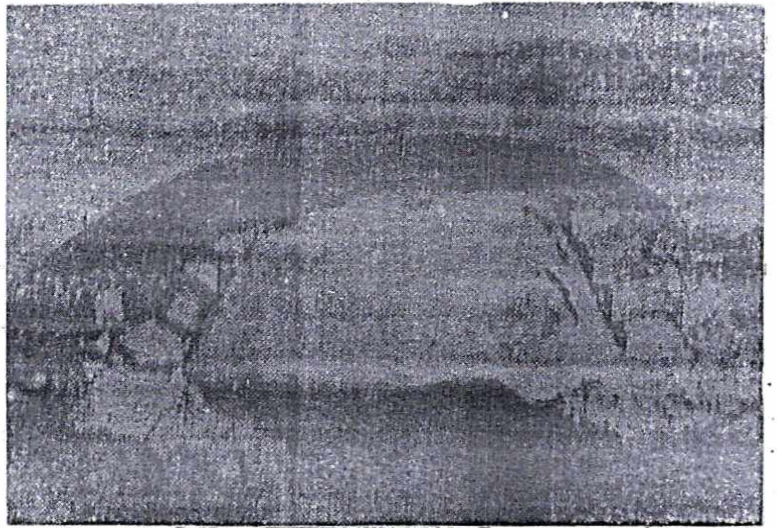


*Fig. 5 : Photograph of fosse type furnace operated in 1963 at Chinglebecha in Orissa.*

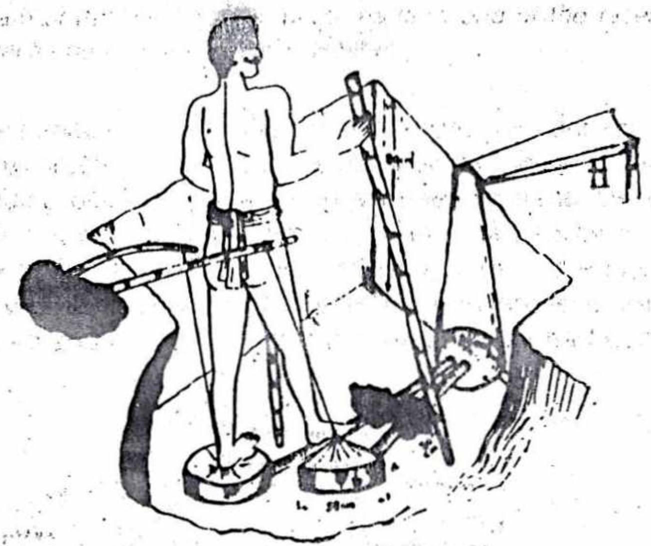


*Fig. 6 : Line diagram of the bowl type furnace made in one of the faces of a pit below ground level found at 'Lohar Para' in Bastar.*

dimensions of the furnace, sticks of the desired length were cut and used as scale. The centre of the circular mouth was determined by placing a stick across its diameter and finding out the centre using a thread to trace the circumference. The centre of the hearth and the shaft taper were marked by dropping a small green clay ball from the central point and the inner edge of the top opening. Thus the verticality as well as increase in diameter at the tuyere level and hearth could be easily measured and controlled. After the furnace wall had partially dried, the

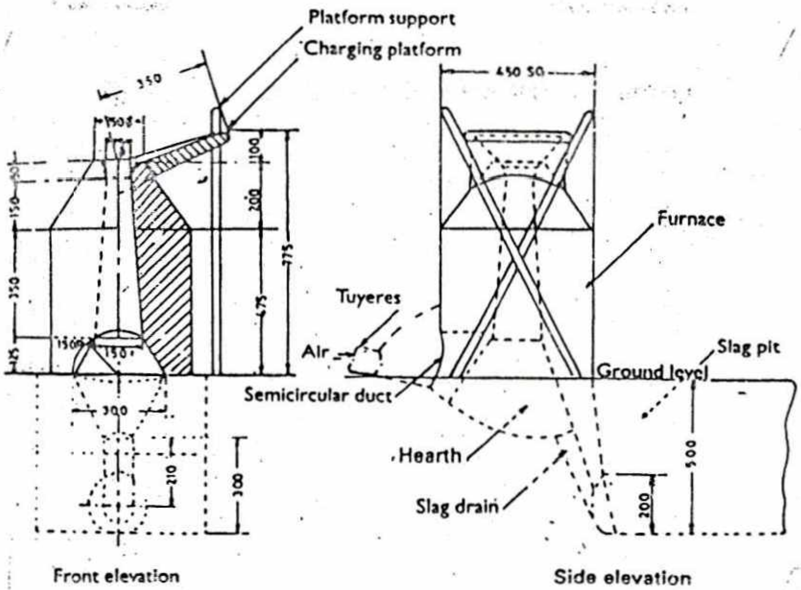


*Fig. 7 : Cross-sectional drawing of Jiragora furnace.*

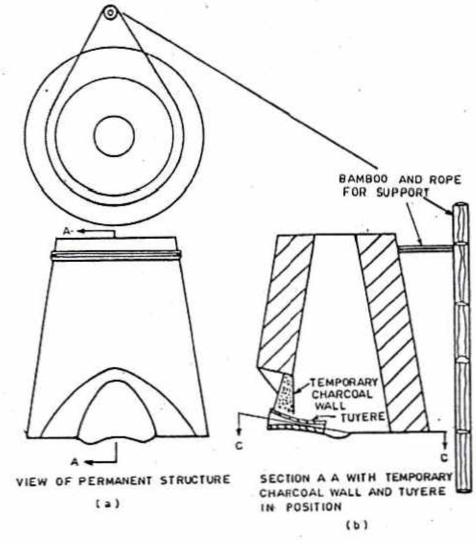


*Fig. 8 : Line diagram of the Bishunpur iron smelting furnace.*

shrinkage cracks and fissures were repaired, the furnace dimensions were checked and corrected, and a large opening was made in the furnace wall at the bottom to prepare the hearth and to fix the tuyere pipe as well as to take out the sponge iron bloom at the end of the furnace blow-in period. While the furnace was drying

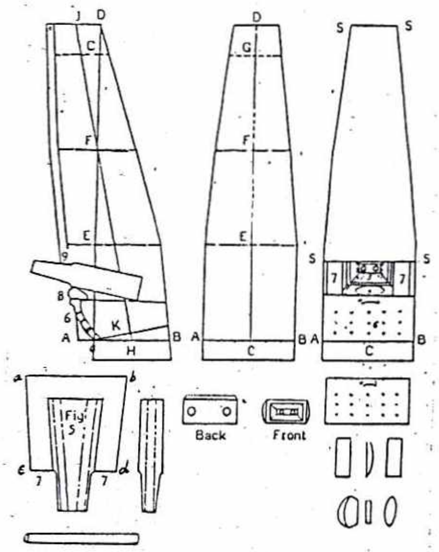


*Fig. 9 : Geometrically designed parts of a furnace constructed at Tendulkaira in M.P.*

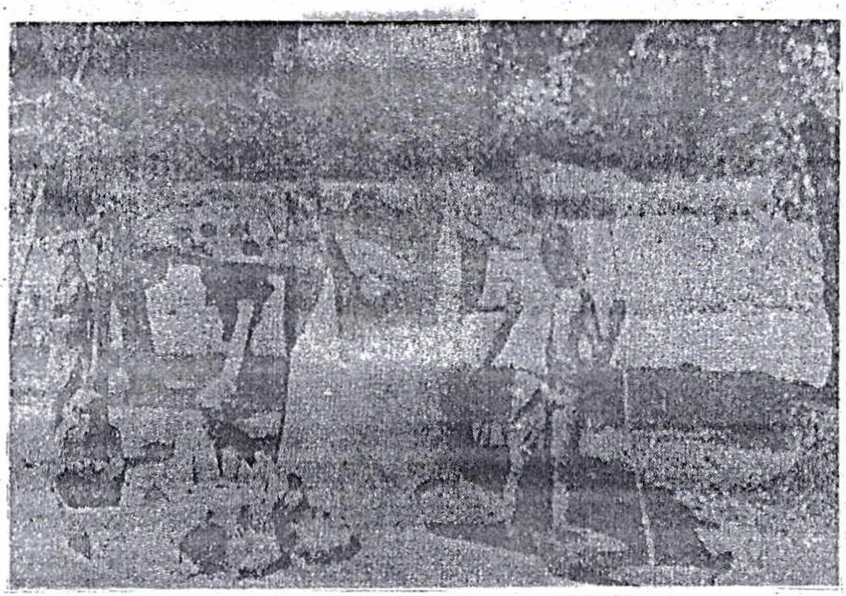


*Fig. 10 : Ancient iron smelting furnace from Nagpur region producing 40 kg of iron per heat and known as 'Kothi'.*

a couple of tuyere pipes designed like a trumpet having about 25mm diameter hole throughout the length (~250-300mm) and an enlarged diameter of 60 to 80mm at the other end, and a wall thickness of 12 to 15mm were prepared from the same clay. These tuyere pipes were used in semi dried condition.

## Making and Fixing of the Bellows

Since the top of the bellows was made of the buffalo hide it had to be soaked in water and bound tightly around the bellow body. The bamboo blow pipes were also examined for any cracks etc. or its burnt out tip and necessary repairs were done. At the same time, the furnace hearth was prepared by lining it with 'Kodon' paddy craft or charcoal powder mixed with clay and then one tuyere pipe was put in position as shown in Fig. 8 and then the front wall opening was closed with the help of charcoal-clay mixture. Now the blow pipes were adjusted in the larger opening of the tuyere and the bellows (two) were fixed. The bellow assembly is shown in Fig. 11.

## Drying, firing and operation of the furnace

After the dried furnace and the raw material were ready the furnace was charged with dried wood chips and then filled with charcoal upto the top. A ritual pooja and *havan* were performed praying for the successful operation of the furnace and then it was ignited using a little of the sacred fire from the havan. This was introduced inside the furnace through the tuyere pipe. When the wood starts burning, the bellows were operated slowly to build the fire inside the furnace. After the yellow flame appeared at the mouth of the furnace the blowing rate was increased to raise the furnace temperature. As the charcoal got consumed, ore was charged and the blowing was continued till a translucent blue flame appeared

Table 1 – Technical analysis of the design of Ancient and modern furnace

| Sl. No. | Location of the furnace | Furnace cross section | d:D ratio | H/D/2 ratio | Stack angle θ° | Furnace Volume($V_1$) $V_1 = \frac{KD^2H}{P.}$ (m³) | $V_2$=cm³/kg of iron (K=0.5) | Remark |
|---|---|---|---|---|---|---|---|---|
| 1. | Madhya Pradesh | Circular | 0.28 | 6.37 | 81.1 | 0.13 | 7916 | Direct |
| 2. | Rajdoha | Circular | 0.28 | 5.77 | 80.1 | 0.14 | 7758 | |
| 3. | Salem | Circular | 0.51 | 3.97 | 75.9 | 0.22 | – | |
| 4. | Mandla | Circular | 0.21 | 2 | 64 | 0.23 | – | |
| 5. | Chiglabecha (Koraput) | Circular | 0.5 | 6.3 | 81 | 0.04 | – | |
| 6. | Jiragora | Circular | 0.3 | 4.6 | 77.8 | 0.02 | 6654 | |
| 7. | Kamarjoda (Hihar | Circular | 0.25 | 4.5 | 77.5 | 0.03 | 30150 | |
| 8. | Baster | Circular | 0.83 | 6.6 | 81.4 | 0.23 | – | |
| 9. | Madhya Pradesh | Rectangular | – | – | – | 0.57 | 5285 | Value of K should be different |
| 10. | Nagpur | Square | 0.4 | 9.76 | 84.1 | 0.16 | 31987 | |
| 11. | Nalanda Valley | Rectangular | 0.28 | 9.76 | 84.1 | 0.24 | 48535 | |
| 12 | Modern Indian Blast Furnace | Circular | 0.7 to 0.77 | 7.0 | 81.9 | 760 | 358 | Indirect reduction. |

D—Maximum diameter (Bosh), d—Throat diameter, H—furnace height, θ°-Stack angle, P—Production kg/heat, K—Constant (0.5) for soft ore, $V_1$—Useful volume, $V_2$—Volume cm³/kg or iron at the top. If this flame was not coming out of the furnace due to any reason it was kindled with the help of a burning wood. The appearance of the blue flame indicated that the furnace has reached a temperature of >1000°C and the charcoal is being burnt to generate CO gas. The operating rate of the bellows was controlled to get this flame of specific height above the mouth. At this stage the furnace was charged with alternate layer of ore and charcoal in the ratio 1:2 and the air blowing rate was adjusted and controlled to maintain steady condition. The temperature inside the furnace was visually examined by peeping through the tuyere pipe and after about one hour the first slag was tapped. The fluidity of the slag, its quantity as well as colour on solidification were indicators of the successful operation of the furnace. The slag was either tapped periodically or continuously throughout the furnace operation.

When sufficient charges of ore had been made, it was followed by few blank charges of charcoal only, and the air blowing rate was increased to consolidate the reduced iron into a large porous lump and separate it from the FeO rich fayalite ($2FeO.SiO_2$) slag. The measured temperature at this stage was found to be 1500°C in front of the tuyere. When the charcoal has almost completely burnt, air blowing was stopped. One heat took about 5 to 6 hours and at this stage preparations were made to take out the hot iron sponge.

## Removal of slag and handling of sponge iron

In case of bowl furnaces, generally the slag was allowed to get collected and solidified at the bottom of the furnace. In the case of other furnaces, it was tapped out through the slag hole known as 'Hagan'. After the smelting period was over, the bellows along with blow pipes were removed and the temporary wall for closing the front opening was removed and the partially melted tuyere was taken out with the help of a tong and a wooden pole. It was placed on a large granite stone anvil and hammered to consolidate and remove the molten slag filled in the pores.

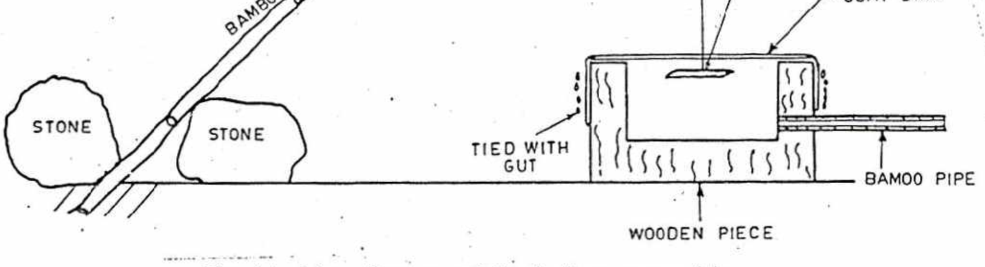


*Fig. 11 : Line diagram of the bellow assembly.*

Fig. 12 shows this being forged on an anvil. The furnace was allowed to cool and it was reused after necessary repair and preparations.

## Secondary refining of the iron bloom

This most important and exclusive Indian practice was carried out to remove the slag trapped inside the iron block. For this, the iron bloom was reheated in a smithy forge to almost white hot (>1250°C) condition and silica sand was sprinkled upon it. This reacted with the remaining FeO and helped in forming fluid $2FeO.SiO_2$ slag which flowed out of the iron block. The iron block was taken out of the furnace and forged to increase its density. This process was repeated till the bloom was converted into 12 to 15mm square/circular rod. This refined rod containing 0.2 to 0.4% $SiO_2$ almost free from the slag inclusion was cut into 150 to 180mm long pieces and sold to the blacksmiths or 'Lohars' for reshaping them into useful objects. Table 2, gives the chemical analysis of sponge iron, refined iron and slag produced at Bishunpur. The microstructure of refined iron consisting of ferrite grains, a little of pearlite and slag stringers is shown in Fig. 13.

The whole process of ancient iron production seems to be very simple but successful operation of the furnace requires utmost care at every stage and a little deviation from the traditional practice resultes into production of only slag and no metal. This fact has been confirmed by Avery[24], who has mentioned that in Europe, in the absence of the ancient operator, the reconstructed bloomery furnace could not be blown satisfactorily by even the experienced scientists and archaeologists. He along with his team travelled to Buhaya (land of Haya tribe), Tanzania in Africa to gain first hand experience of the traditional practice of operation of bloomery furnace. In order to understand the physico-chemical conditions prevailing inside the furnace and appraisal of the ancient iron making technology the process is being examined with the help of modern science and technology.

## THERMOCHEMISTRY AND TECHNOLOGY OF ANCIENT IRON MAKING

From the point of view of thermo-chemical study, the whole smelting operation could be divided into three main steps: The combustion of charcoal to $CO-CO_2$ gases and the solid state reduction of iron oxide to iron in the furnace shaft. The direct reduction of FeO to Fe and formation of FeO rich fayalite ($2FeO.SiO_2$) slag in the tuyere zone. The slag metal reaction controlling the 'C' and metalloid content of the iron sponge. The reduction of $Fe_2O_3$ to Fe being topo-chemical; it gets reduced in the order $Fe_2O_3 \rightarrow Fe_3O_4 \rightarrow FeO \rightarrow Fe$ irrespective of the chemical reaction being carried out by solid 'C' (direct reduction reaction) or by CO gas (indirect reduction reaction). The optimum thermochemical conditions required for the reduction process could be determined from the Fe-O-C equilibrium diagram (Fig. 14) plotted as a function of $CO/CO_2$ ratio and temperature. From this diagram it is obvious that as the temperature increases, the stability of CO gas also increases with respect to $CO_2$ and beyond 1000°C only CO gas is found in the gas generated at the tuyere level. Hence, the rate controlling step for the com-

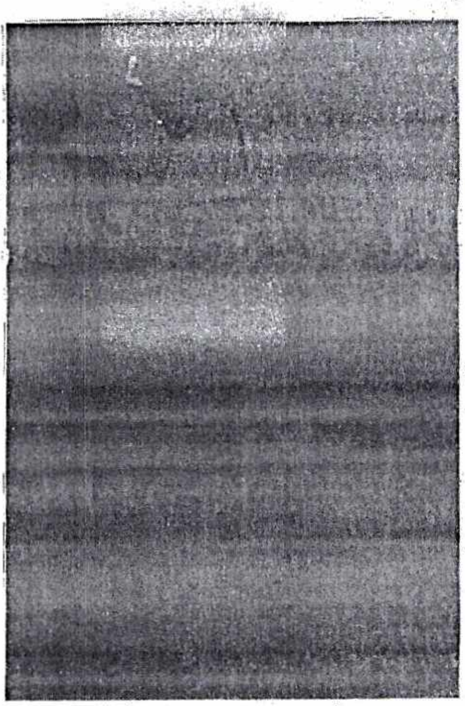


*Fig. 12 : Forging and consolidation of hot sponge bloom being carried out on an iron anvil, a granite block used as an anvil is also seen in the picture.*

bustion of carbon is

$$CO_2 + C \rightarrow 2CO \qquad \ldots \quad (i)$$

The $CO/CO_2$ equilibrium line crosses the FeO-Fe phase boundary at point 'P' which represents the minimum conditions for the reduction of iron oxide to iron.

*Table 2 – Chemical analysis of iron sponge, refined iron and slag in percentage from Bishunpur*

| Constituent | Sponge Iron | Refined Iron | Slag |
|---|---|---|---|
| Fe (T) | 54.99 | 96.25 | 50.64 |
| Fe (M) | 22.53 | 94.21 | 3.7–52.87 |
| C | – | 0.16 | 0.21 |
| Mn | – | 0.057–0.043 | – |
| P | – | 0.02 | – |
| S | 37.31 | 0.007–0.2 | 0.033 |
| FeO | 4.90 | 1.55–0.013 | 59.12 |
| $Fe_2O_3$ | – | 1.18 | 4.53 |
| $SiO_2$ | – | 0.30 | 11.82 |
| $Al_2O_3$ | – | 3.034 | 9.71 |
| CaO | – | Trace | 7.84 |
| MgO | – | Trace | 1.92 |
| $P_2O_5$ | – | – | 1.99 |
| Alkali | – | – | 0.765 |

Based on the studies on reduction kinetics of iron oxide in $CO/CO_2$ gas mixture, the optimum temperature required for fast reduction is between 900 to 1100°C, shown as shaded area in the diagram. In this temperature range the $CO/CO_2$ ratio is 80:20 i.e., 4:1.

Hence the equilibrium reduction reaction could be written as :

$$Fe_2O_3 + XCO \rightarrow 2Fe + 3CO_2 + (X\text{-}3)CO \quad \ldots \quad (ii)$$

where the $CO/CO_2$ ratio is 4. Thus the reaction feasible under equilibrium condition is

$$Fe_2O_3 + 15CO \rightarrow 2Fe + 3CO_2 + 12CO \quad \ldots \quad (iii)$$

using this reaction (iii) and the operation data for the Jiragora furnace collected by Ghosh[11] the material balance and heat balance were calculated as shown in Tables 3 and 4. From the study of these tables the following observations could be made:

(a) The furnace was charged with a definite ore: charcoal ratio and the charge balance was satisfactory for the production of low 'C' wrought iron.

(b) The fayalite – rich slag required addition of $SiO_2$ and $Al_2O_3$ as flux to produce fluid slag of recorded composition and quantity.

(c) The heat balance indicates that the air supply by the foot operated bellows was sufficient to generate theoretical adiabatic flame temperature of 1940°C. This temperature calculated by Avery[24] for the Buhaya furnace was 1800°C. The measured temperature in front of the tuyere was found to be 1500°C by Avery[24] as well as Prasad et. al[25]. This temperature was found sufficient to produce low 'C' wrought iron sponge and fluid FeO rich fayalite slag.

As the iron ore descends down to the shaft, it gets partially reduced to FeO and Fe by the chemical reaction with the hot CO rich gas as well as by the preheated charcoal. In the bottom part of the shaft at 1100 to 1300°C, the following chemical reactions take place.

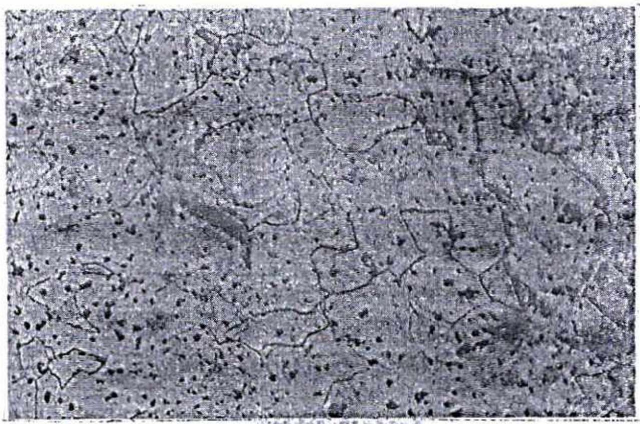


*Fig. 13 : A typical microstructure of wrought iron showing some pearlite and slag inclusions in a matrix of ferrite.*

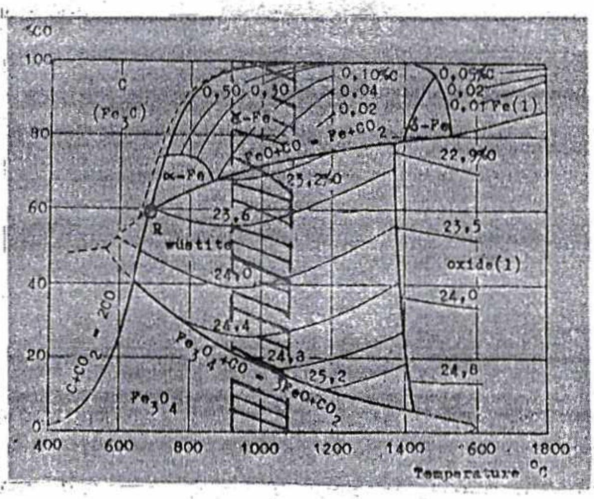


*Fig. 14 : Fe-O-C equilibrium diagram showing the optimum conditions for the bloomery furnace opeartion, indicated by hatched band.*

$$2FeO + C \rightarrow 2Fe + CO_2 \qquad \dots \text{(iv)}$$

and

$$CO_2 + C \rightarrow 2CO \qquad \dots \text{(i)}$$

The overall reaction being

$$FeO + C \rightarrow Fe + CO \qquad \dots \text{(v)}$$

Simultaneously FeO begins to react with $SiO_2$ and other gangue material present in the ore to form FeO – rich fayalite slag. $FeO.SiO_2$ phase diagram is shown in Fig. 15 and it shows that FeO forms an eutectic phase with fayalite at 1175°C. Hence, the slag will be fluid enough even at 1300°C to drip through the solids and react with the charcoal ash present in the tuyere zone before getting collected at the bottom of the furnace. As the iron travels further downwards, it picks up 'C' to form $Fe_3C$ i.e., carburization of sponge iron takes place. This reaction can be written as :

$$3Fe + C \rightarrow Fe_3C \qquad \dots \text{(vi)}$$

Fig. 16 shows schematically the conditions prevailing in the tuyere zone and the hearth. As shown in this figure all the three phases viz solid, liquid and gas are present in this zone and they react with each other. The air blown through the tuyere gets preheated to 600°C as it passes through the red hot part of the tuyere pipe protruding inside the furnace. This hot air creates an oxidizing atmosphere in front of the tuyere and burns charcoal to $CO_2$ and CO and also preheats the $N_2$ content in the air. In this zone while the oxidizing atmosphere tends to stabilize FeO and promote the formation of slag the presence of the hot charcoal and CO gas tend to produce a reducing atmosphere promoting the reduction of FeO to

*Table 3 – Material balance for ironmaking from Jiragora (M.K. Ghosh)*[7]

| Material | Analysis (%) | Calculation | Metal Fe (kg) | Therotical Composition | Actual Composition (basis 21kg) | Gases (kg) | Remark |
|---|---|---|---|---|---|---|---|
| Ore-24kg | | | | | | | Metal composition |
| Fe($Fe_2O_3$) | 63.4 | 24x0.634x0.302 | 5.5 | 9.7 | 9.66 | 2.357 | C-0.4% |
| $SiO_2$ | 2.44 | 24x0.0244.0.021 | 0.01 | 0.565 | 5.68 | 1.387 | Si-0.2% |
| $P_2O_5$ | 0.01 | – | 0.0004 | – | – | 0.114 | Fe–rest |
| $Al_2O_3$ | 1.66 | – | – | 0.446 | 1.41 | 0.026 | Slag composition |
| CaO+MgO | 0.5 | – | – | 0.12 | 1.29 | – | $SiO_2$–27.08% |
| MnO | 0.9 | – | – | 0.20 | 0.21 | 0.888 | $Al_2O_3$–6.72% |
| Lol | 3.7 | – | – | – | – | – | Fe–46% |
| Total | | | 5.5104 | 11.031 | | | MnO–1.026% |
| | | | | | | | CaO–5.0% |
| Oxygen in iron as FeO | | | | 2.77 | | | MgO–1.16%<br>$SO_2$–0.075% |
| | | | | | | | $O_2$–12.98% |
| Charcoal 30 kg | | | | | | | 5.54kg of Iron will be associated with 21 kg slag |
| F.C. | 75.8 | | 0.022 | | | 22.718 | Theoretical |
| Ash | 3.2 | | | 0.96 | | | slag wt. = 14.76kg hence $SiO_2$+ $Al_2O_3$ added as flux = 6.24kg. Theoretical charcoal for reduction = 16kg. |
| V.M. | 21.0 | | | | | 6.3 | |

Furnace trial show 24 kg of ore/30 kg of charcoal. Time of reduction and smelting 6 hrs. Reduction effiency 36.2%.

Fe and its carburization. Haba[26] has called these conditions the 'opposing principle in the bloomery furnace'. In this boundary zone a pseudo equilibrium is attained between the oxidizing and the reducing reactions taking place under a steady working condition. Considering the temperature of this zone being at least 1300°C and the $Fe_2O_3$/FeO + $Fe_2O_3$ content of the slag being about 10% the oxygen partial pressure $pO_2$ will be of the order of $1 \times 10^{-10}$ to $10^{-12}$ atm. as determined from the FeO-$Fe_2O_3$ phase diagram shown in Fig. 17. Nagata[27] has measured the temperature as well as $pO_2$ in front of the tuyere in his experimental 'Tatara' furnace and in presence of the slag containing 75.8% FeO, the $pO_2$ has been found to be $1 \times 10^{-11}$ atm. at 1300°C and $pO_2$ of $1 \times 10^{-5}$ t at 1100°C prevailing 25 cm above the tuyere level. Fig. 18 shows the temperature profile as measured by Nagata[27] in his furnace and the $pO_2$ measured with the help of the solid electrolyte is shown in Fig. 19. If this $pO_2$ ($1 \times 10^{-10}$ to $1 \times 10^{-12}$ atm.) is plotted on the oxide Ellingham diagram as shown in Fig. 20, then it can be seen that this $pO_2$ is too high for the reduction of $SiO_2$ or MnO or $MnO_2$ inside the bloomery furnace. This is the reason that the resulting iron contains very low Si or Mn content and because of the use of charcoal the 'S' and 'P' contents are also low. This zone begins below the tuyere and in this zone the reduced iron gets sintered to form a spongy mass and travels downwards due to its own gravity till it reaches the bottom of the furnace. At the same time the liquid slag trickles down through the porous iron to get collected below it. The slag formed in the bloomery furnace has been found to contain more than 55% FeO as determined by Haba[26] and Nagata[27] and this FeO rich slag reacts with $Fe_3C$ present in the sponge iron and thus decrease the 'C' content of the bloomery iron. This reaction can be written as:

$$Fe_3C + FeO \rightarrow 4Fe + CO \qquad \text{... (vii)}$$

*Table 4 : Heat balance of ironmaking furnace at Jiragora (M.K. Ghosh)*[7]

| Heat Input | k Cal | Heat Output | k Cal |
|---|---|---|---|
| Heat generated by combustion | 81, 011.5 | Heat for heating ore to 1000°C | 4,920.00 |
| | | Heat for endothermic reduction | 5,451.87 |
| $CO/CO_2$=4 | | Heat content of metal at 1200°C | 1,385.00 |
| Total | 81,011.5 | Heat content of slag at 1200°C | 6,300.00 |
| | | Heat in outgoing gases | 48,026.28 |
| | | Heat lost by conduction and radiation by difference | 14,928.22 |
| | | % Radiation loss = 18.5% | 81.011.5 |

Theoretical Flame temperature = 1.928°C

Blowing Rat : Air blown in 6 hrs. = 203 $m^3$

Air blowing rate = 564 litres/min.

No. of strokes for blower size

(280 mm dia., 100 mm. ht.) = 87/min.

Note : Maximum capacity of worker = 300 strokes/min.

Bloomgren et. al.[28], have confirmed the role of FeO rich slag in controlling the 'C' content of the bloomery iron, and they have shown that the addition of CaO as in modern blast furnace decreases the FeO content of the slag resulting in the increase in 'C' content of Fe and production of cast iron.

The success of the ancient iron production technology depended very much on the selection of the raw material and the maintenance of the critical balance between the reducing and oxidizing reactions in the 'Boundary zone'. Based on these considerations, Prakash[20,21] has emphasized the importance of the control of air blowing rate as the most important factor in overall process control and based on the calculations of the material and heat balances, shown in Tables 3 and 4, he has predicted the operating rate of the bellows for the Jirogora furnace as shown in Table 5. This predicted rate of operation of the bellows was verified and found comparable during the operation of the Bishunpur furnace as reported in the same table. The predicted changes in the air blowing rate was also verified during the Agaria furnaces operated at Varanasi and Chennai. At these two places the furnace was also operated successfully with the inferior grade of charcoal available in the local market. For this, the air blowing rate was modified based on the desirable colour (blue) and height of the CO gas flame above the furnace mouth and also the observation of the slag properties. If the air blowing rate was increased, then it invariably resulted in the increase of the furnace temperature and production of molten white cast iron which came out along with the slag. It was considered to be a bad omen, because in the ancient times this highly brittle material could not be shaped by forging. It was a waste material till the processes of cast iron casting and malleablization were developed in China and the process

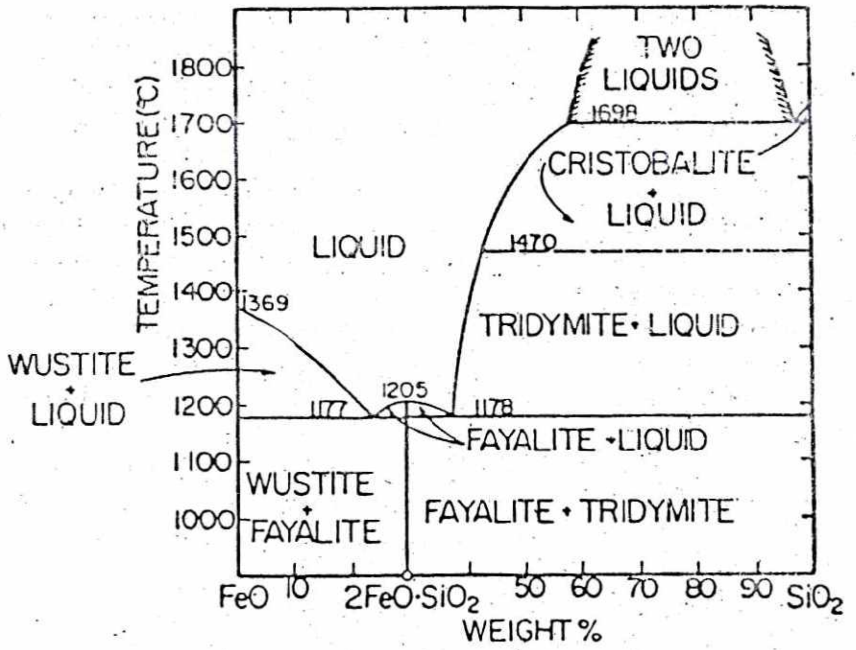


Fig. 15 : FeO-$SiO_2$ binary phase diagram.

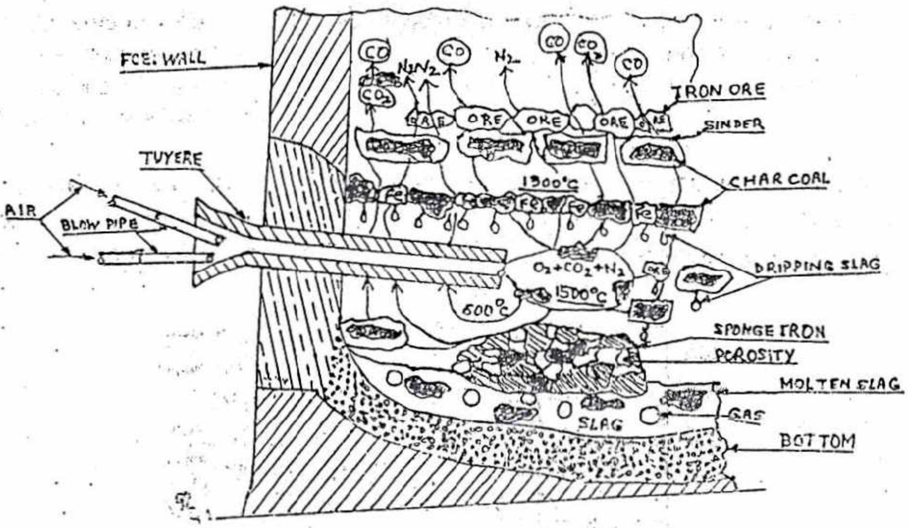


*Fig. 16 : Schematic of thermo-physical conditions prevailing in front of the tuyere and hearth in a bloomery frunace. It shows the preheating of air (~600°C), combustion and gasification of charcoal, direct reduction of iron ore to iron sponge and formation of fluid $2FeO.SiO_2$ based slag.*

of 'Wootz' steel production using the white cast iron was perfected in south India. The chemical composition of some of the important iron objects of the country and the iron produced by the Jabalpur and Bishunpur furnaces are given in the Table 6.

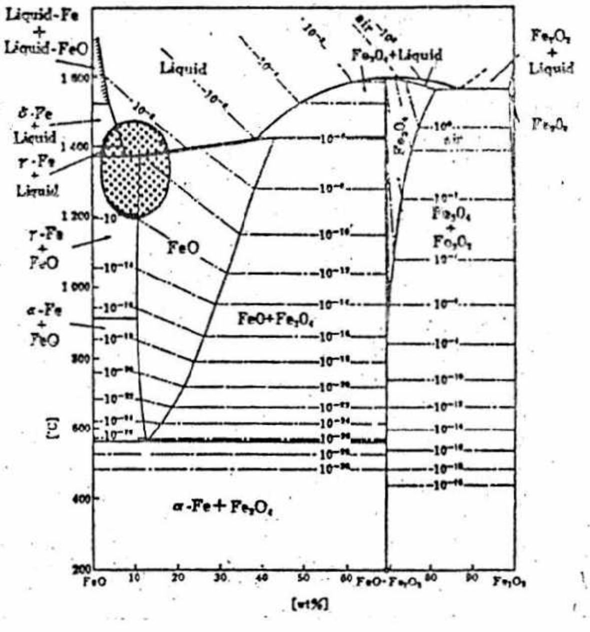


*Fig. 17 : FeO-$Fe_2O_3$ binary phase diagrams with $pO_2$ occurring at various temperatures. The shaded area shows the $pO_2$ in equilibrium with the ancient bloomery furnace slag.*

Table 5 – Comparison of operatins parameters of Jiragora and Bishunpur iron making furnaces

| Operation | Time | Materials charged |  | Blowing Rate | Remaks |
|---|---|---|---|---|---|
|  |  | Ore | Coal |  |  |
| *Jiragora Furnace* |  |  |  |  |  |
| 1. Furnace Preheating | 1 hr | — | 8 kg | Faster than 87 strokes/min. | See Table 1 |
| 2. Reduction stage | 4 hrs | — | 14 kg | 87 strokes/min | Sequence of ore and charging |
| 3. Consolidation stage | 1 hr | — | 8 kg not available | Vigorous blowing |  |
| 4. Total operating time | 6 hrs | — | — | — | — |
| 5. Total material charged and metal produced | — | 24 kg | 30 kg | — | 5.6 kg of iron |
| *Bishunpur Furnace* |  |  |  |  |  |
| 1. Furnace Preheating | 1.25 hrs | 2.5 kg | 3.25 kg | 40-50 kg strokes/min. | Fce. Temp. 550°C |
| 2. Reduction stage | 4 hrs | 8 kg | 16 kg | 60-70 strokes/min | 950°C |
| 3. Consolidation stage | 0.5 hrs hr | 1 kg | 2 kg | 110 strokes/min. | 1500°C |
| 4. Total operating time | 5.75 hrs | — | — | — | — |
| 5. Total material charged and metal produced | — | 11.25 kg | 21.5 kg | — | 2.5 kg of iron |

## STEELING IN ANCIENT INDIA

Generally the iron produced from the bloomery furnace had a maximum carbon content of 0.4%, which had poor hardenability. The other range of Fe-C alloy produced in the country contained 0.7 to 2%C. In the ancient Sanskrit texts it has been mentioned as 'Vajraloha'. The solid state carburization of wrought iron was known as 'steeling' and the resulting material having a high carbon surface (case) could be quenched and tempered to produce a hard and sharp cutting edge necessary for many tools and war weapons. Hadfield[29] has mentioned the possibility of the use of Indian steel chisels and craftsman in the construction of Egyptian pyramid. Ghosh et. al[30]., have reported an iron sickle found at Barudih in Bihar dated back to 810 BC which contained 0.35%C. The microstructure consisted of ferrite and pearlite and it also showed the presence of tempered martensite at the sharp edge. Hadfield[31] had a chance to analyse several iron objects from 'Taxila' and he found many of them to contain 1.3 to 1.5%C. According to him many features of these object suggested deliberate production of steel. The process of carburization of wrought iron could be carried out by any one of the following methods:

1. Carburization of wrought iron inside the bloomery furnace
2. Carburization of wrought iron during secondary refining.
3. Case carburization by packing the iron pieces in charcoal powder and heating to high temperature
4. Cementation of iron bars having different carbon content.

By these processes the carbon content could be raised upto 0.9% which could be easily hardened, but in these processes the slag inclusion present in the

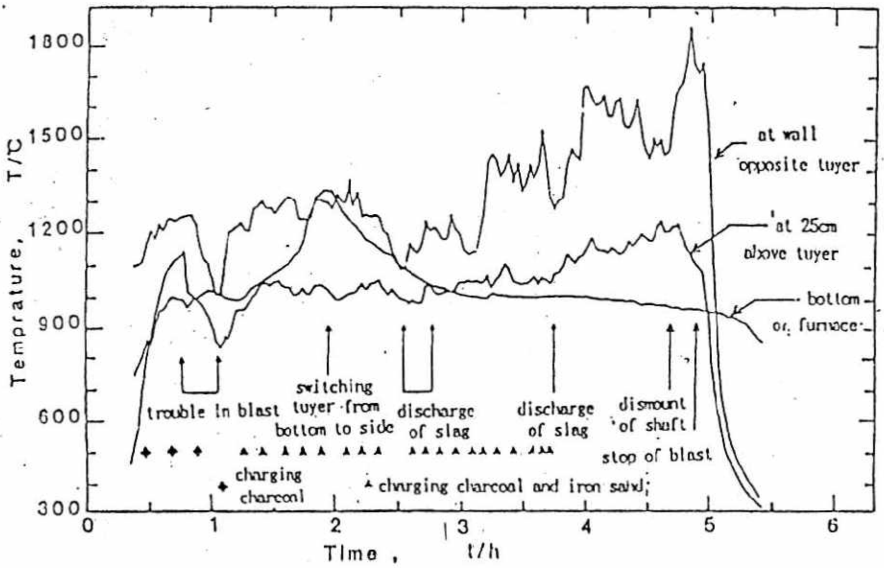


*Fig. 18 : Temperature changes measured inside the experimental 'Tatara' furnace during its operation. Ref. 35.*

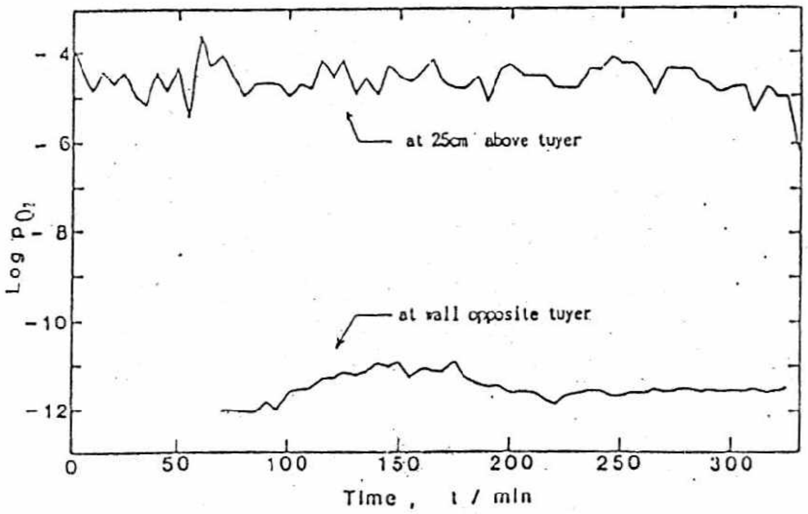


*Fig. 19 : $Po_2$ changes measured inside the the experimental 'Tatara' furnace during its operation. Ref. 35.*

bloomery iron could not be removed and they caused lower tensile strength as well as fracture toughness. Varahamihira[32] has mentioned in detail the process of carburization of swords and their hardening and tempering processes. Agrawal et. al[33]., have reported the process of production of steel by lamination of low and high carbon steel bars which produced a variety of surface designs after polishing and etching of the finished objects. A modified and improved version

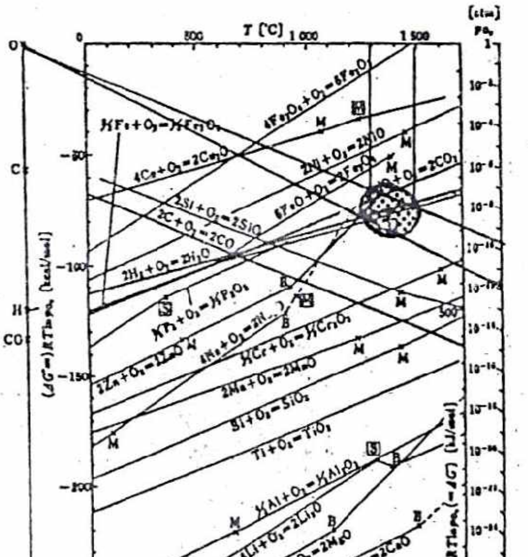


*Fig. 20 : Ellingham free energy diagram for oxides, the shaded area shows the Po2 = 1x10-10 to 1x10-12 prevailing inside the bloomery furnace and its effect on reduction of oxides. Ref. 21.*

of this process became famous in the Western countries by the name of 'Pattern Welding.' This process produced better strength and edge properties as well as a variety of designs on the finished surface. It was extensively used for making swords and war weapons during the medieval period.

## WOOTZ STEEL

A better quality of steel produced in India since ancient times (the exact period is not known) was known as *'wootz'* steel, a name derived from the word *'Ukku'* in the south Indian languages. The literary accounts suggest that this steel from south India was known in the Arabian countries and Europe by the names 'Bulat', 'Faulad' and Hinduani steel. This steel containing between 1, to 2% C had no parallel in the world and its production and processing had reached its zenith during the 18th century. The process details have been published by Buchanan[10]. Heyne[34], Voysey[35], Rao[26], Prakash[4,16], Bronson[37], Lowe[38], Craddock[39], Yater[40], Srinivasan et. al.[41], and many others. By 17th century large shipments running into thousands of wootz steel ingots were exported from Coramandal Coast to Persia. Although the processes of wootz steel making were developed and perfected at Konasamudram near Hyderabad and at Salem in then Mysore, Malabar and Golconda, by the end of 18th century wootz steel objects were being made at many centres including Varanasi, Amritsar, Lahore, Agra, Jaipur, Gwalior, Tanjore and many other places but none of these centres are surviving today and the ancient technology has been forgotten.

Even in the early days of its production Syrians had come to know about these ancient centres of Wootz steel making and they used to travel all the way to India and carry these ingots to Damascus where they used to trade it to blacksmiths who had learnt the secrets of forge welding, forging technique of this ultra high carbon steel and its heat treatment. During the medieval period the swords made at Damascus had become very famous in Europe and they were in great demand. The original Damascus sword was recognized by 'watering mark' or Damask pattern visible on the sword. Fig 21 shows a picture of this pattern looking like crumpled silk and a similar pattern developed by the 'pattern welding' process. The difference is very obvious. Wootz steel was made by two distinctly different processes viz., (i) Process of carburization and melting steel and (ii) The decarburization process.

### Process of carburization and melting of steel

In this process steel was made by packing about 350gms of wrought iron pieces with about 35gms of wood chips of Avaram (Cassia Auriculata) and other specific plants in a refractory crucible and cover it first with green leaves and then close the crucible top with clay having a small hole at the centre. Fig. 22 shows a photograph of a new crucible made from the mixture of refractory clay with charcoal powder and some iron oxide powder. This crucible could easily withstand handling at temperatures exceeding 1500°C. Bronson[37] and Joshi[42] have described in detail the variety of crucibles used in the ancient India for metals technology and in Ayurveda. The charged crucibles were allowed to dry in Sun and 20 to 25 such crucibles were heated in a big charcoal hearth gradually to

*Table 6 : Chemical composition of iron produced by ancient Indian furnaces.*

| Source | C% | Si% | Mn% | P% | S% | Others |
|---|---|---|---|---|---|---|
| 1 Delhi Iron Pillar | 0.23 | 0.066 | _ | 0.18 | Traces | $N_2$-0.0065 |
| 2 Konark Iron Beam | 0.27 to 0.45 | 0.05 to 0.11 | Traces to 0.04 | 0.015 to 0.10 | 0.006 to 0.15 | Cr-0.90%<br>Ni-1.6% |
| 3 Orissa iron | 0.3-0.6 | 0.18 to 0.20 | Traces | 0.02 to 0.03 | Traces | _ |
| 4 Bastar Iron ex. (100 years old) | 0.25 to 0.45 | _ | _ | _ | _ | Other element in traces |
| 5 Jabalpur iron (recent) | 0.59 | _ | 110 ppm | 40 ppm | - | Cu-340 ppm<br>Ni-353 ppm<br>Others in traces |
| 6 Bishunpur iron(recent) | 0.016 to 0.043 | _ | 0.057 | 0.02 to 0.2 | 0.007 to 0.013 | _ |
| 7 Agaria Iron | 0.78 | 0.075 | 0.1 | 0.14 | Traces | _ |

a temperature of 1450 to 1500°C obtained with the help of a pair of large bellows made of full buffalo hide. Fig. 23 shows a drawing of the furnace described by Buchanan[10] and another type of furnace used for the same purpose described by Holland[43] shown in Fig. 24 and another one described by Voysey[35] is shown in Fig. 25. In principle, the design of these furnaces is same but they differ in the construction details.

As the temperature of the furnace was raised, the crucibles were shifted from the colder zone (900°C) to the centre of the furnace where temperature of >1400°C was attained. The whole operation took about 6 hours and during this period the leaves were charred producing a gaseous atmosphere ($CH_4$ + CO) inside the crucible through which the solid state carburization of wrought iron took place picking up carbon from the wood chips. Ultimately the carburized iron got melted inside the crucible and any entrapped slag floated on the top of it. The presence of liquid steel inside the crucible was judged by shaking the crucible during shifting it from the centre of the furnace. The crucible containing the molten steel was replaced at the edge of the furnace for slow cooling. Srinivasan[44] has mentioned that at Kodumanal a separate small hearth furnace was used for slow cooling of the crucibles. The slow rate of cooling produced a coarse grained structure containing thick needles/plates of cementite in a matrix of transformed Ledeburite and pearlite. After the crucible has cooled to room temperature, the wootz steel ingot was taken out by breaking the crucible and sold to the blacksmith after cleaning it free from the adhering slag. Fig. 26 shows a steel ingot inside a crucible and the macrostructure of the wootz steel ingot published by Tylecote[45] is shown in Fig. 27. As reported by Lowe[46], the microstructure of the used crucible was found to consist of distribution of graphite flakes in a matrix of mullite with small prills of iron embedded inside the wall.

### The Decarburization Process

In this method developed at Konasamudram near Hyderabad and Trichinapalli the steel was produced by refining of white cast iron (> 2.5%C) prills or small pieces by chemical interaction with highly oxidizing synthetic slag. As stated earlier prior to the development of this process the production of cast iron by the smelting furnace was considered to be a bad omen. This process of steel making was carried out in a double chambered furnace shown in Fig. 31 and described by Voysey[35]. In this double chambered furnace, made below the ground level in the smaller chamber a charcoal fire was built and a synthetic molten slag was prepared by melting magnetite mixed with silica or the bloomery furnace slag. The fire built in the second chamber to preheat it also heated the air as it was supplied to the reaction chamber. Once sufficient molten slag having temperature of >1400°C was collected in the bottom of the smaller chamber, well cleaned prills or pieces of white cast iron were charged on top of the charcoal fire. This high carbon iron became molten and got preheated as it passed through the charcoal fire bed and reacted with the molten synthetic slag. The two major chemical reactions taking place could be written as:

$$Fe_3C + FeO \rightarrow 4Fe + CO \qquad \text{... (vii)}$$

and

$$Fe_3P + 8FeO \rightarrow 3Fe.P_2O_5 + 11Fe \qquad \text{... (viii)}$$

The second reaction removes phosphorus content of the iron and both the reaction are exothermic as well as self sustaining. The refined steel being heavier than the slag it got collected at the bottom of this chamber and it was tapped in the second preheated chamber by making a hole in the partition wall. On solidification,

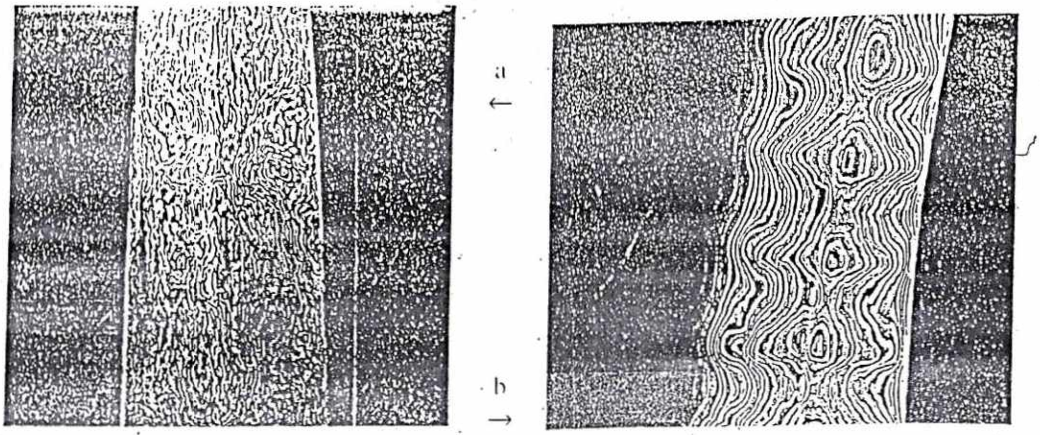


*Fig. 21 : Damask pattern visible on wootz steel sword (a) and (b) the surface finish of a similar design developed on the pattern welded sword.*

a circular pancake shaped steel ingot was obtained. This was cleaned and sold to the blacksmith. Lowe[38] had found a disc shaped ingot during her field study at Konasamudram, which was discarded probably because of over decarburization. Yater[40] has mentioned the process of manufacture of sword using pancake type of ingot and also its export to Europe, U.K. The cast structure is shown in Fig. 29 and the chemical composition of wootz steel and Damascus blades are given in Table 7.

## BLACK SMITHY CRAFT

Indian blacksmiths or 'Lohars' had mastered the smithy craft for producing variety of wrought iron objects as well as Wootz steel weapons as early as 1000 to 800 B.C. They had also mastered the process of forge welding of iron and steel as well as the heat treatment of steel knives, swords and other weapons. Neogi[47] and Prakash[48] have discussed these ancient craft in great detail. The bars of refined iron produced in the form of blocks or bars having 15mm square or circular cross section were purchased from the iron smelters or the Wootz steel ingots purchased from the steel makers were first classified into batches based upon their ductility and appearance of fracture i.e., properties affected by the carbon content of the alloy and then used for producing the suitable article. The knowledge regarding the effect of carbon on the properties of iron is evident from the description given by Susruta[49] for making the surgical knife using high carbon steel and giving it hardening treatment and produce a sharp edge which could cut the human hair into two halves longitudinally. The classification of iron-carbon

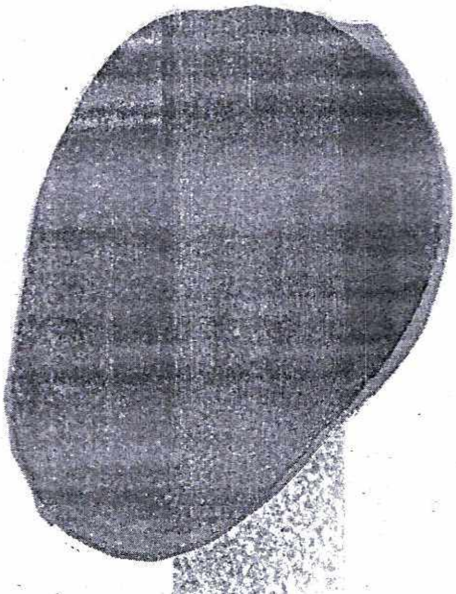


*Fig. 22 : Photograph of a crucible used for wootz steel making (courtesy : Madras National Museum).*

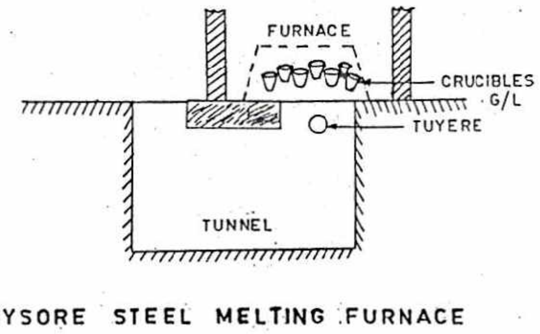


*Fig. 23 : Line diagram of 'Wootz steel' making crucible furnace described by Buchanan.*

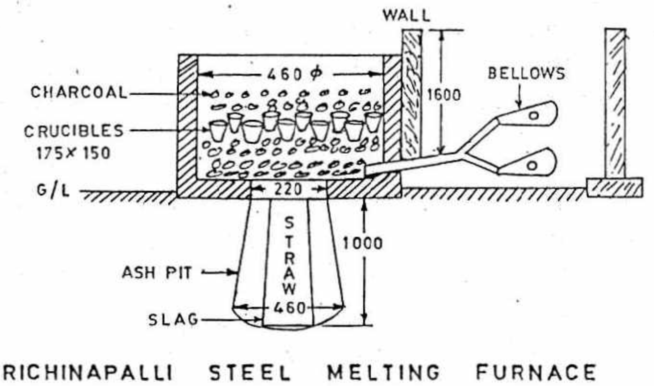


*Fig. 24 : Schematic line diagram of the crucible furnace described by Holland.*

alloy published in *Rasa Ratna Samucca* (8-10 C AD) shown in Fig. 30 has been recently published by Kulkarni[50]. As shown in this figure the Fe-C alloy was classified into three main groups viz., Kanta Loha, Tikshna loha and Munda Loha. While Kanta Loha (wrought iron) and Tikshna Loha (Steel) could be shaped by forging, Munda Loha could be used only for casting purposes and it is classified into three groups based on the appearance of the fracture viz., white cast iron, grey cast iron and mottled cast irons as known today. The ancient blacksmithy craft had reached its zenith as early as 700 BC when the western world did not know even the difference between wrought iron and steel or cast iron. As Samuels[51] has written it was only in 1772 that Reaumur could differentiate between grey, white and mottled cast iron on the basis of the appearance of their fracture.

## Forging and Forge Welding of Wrought Iron

As mentioned earlier, India was producing large quantity of iron and it had found use in daily life. The world famous iron pillar of Delhi belonging to the Gupta period

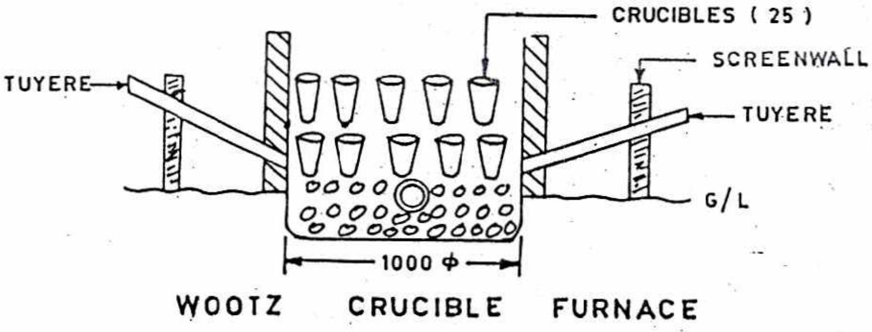


*Fig. 25 : Schematic line diagram of the crucible furnace described by Voysey[35].*

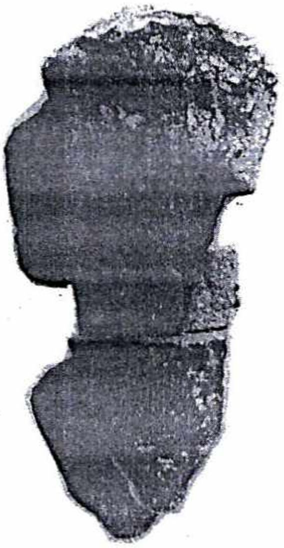


*Fig. 26 : A sectional view of a Wootz steel crucible showing the steel ingot inside it[39].*

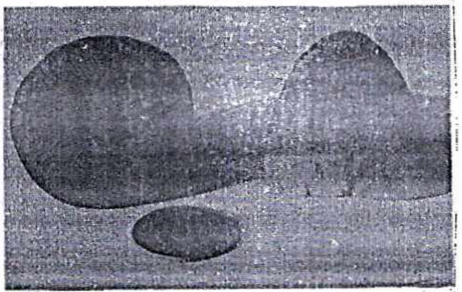


*Fig. 27 : Macro-structure of a Wootz steel ingot[45]*

stands testimony to the forge welding and forging skill of the ancient blacksmiths. For the manufacture of this pillar weighing more than 6 tonnes at least 8 tonnes of wrought iron of uniform composition must have been produced using large number of furnaces and then the blooms must have been forge welded together and given the finished shape. Balasubramaniam[52,53] has described in detail the possible method of the forging of the shaft and the bell capital. Some of the other heaviest forgings of the world are iron pillar at Dhar weighing 8 tonnes (12 C AD) the iron beams of Konark (9C AD), the iron pillar at Kondachari and Iron trident at the Tanginath Temple. These forgings are shown in Figs. 31 to 35 respectively. Fig. 36 shows the base structure of an ancient furnace found at the excavation site at Ujjain. This furnace has been mentioned as a smelting furnace but in the authors opinion it might have been a large forge hearth used for simultaneous

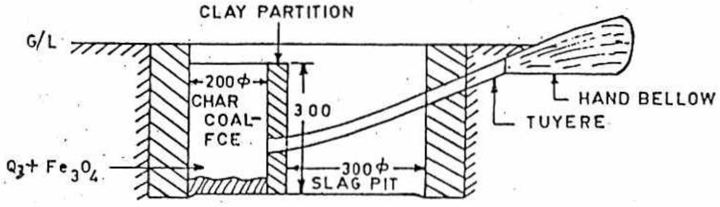


*Fig. 28 : Schematic line diagram of the double chambered furnace used for producing Wootz steel by decarburization of white cast iron.*

heating of four bundles of wrought iron for forge welding them together. Prakash[54] has described in detail the probable method of forging of Dhar iron pillar which is rectangular at the base changing into octagonal and finally circular cross-section at the top. Fig. 37 shows the probable method of joining of 750-1000mm long sections of the forging to complete the length of the pillar. Bonner et. al.[55], have published the ancient account of the money spent during the manufacture of the iron beams of Konark temple. This account maintains the purchase of large quantity of lead and construction of a channel type furnace. It seems that molten lead bath maintained at high temperature in a channel furnace was used for uniform heating of the iron blocks to the welding temperature. The fractured surface of one of the beams clearly shows the use of square sectioned rods in the manufacture of these beams. Neogi[47] has mentioned the process of manufacture of some of the heaviest iron cannons of India like Landa Kesab of Bijapur shown in Fig. 38 weighing about 47 tonnes and the gun barrel of Tanjore shown in Fig. 39. He has mentioned that these guns were manufactured by Hindu blacksmiths. Roessler[56] has made a detailed study of the Tanjore gun barrel and he has found it to be made by shrunk fitting of three layers of iron rings over the rods and forge welding them together. Two smaller guns having 100mm bore hole and made by similar process are kept at the gate of Gujari Mahal in Gwalior fort.

## Forging and Heat Treatment of Wootz Steel

Wootz having 1 to 2%C required special forging skill known only to the Indian blacksmiths and later learnt by the blacksmiths of Damascus, Syria. They used to travel to Hyderabad and Mysore to purchase wootz steel ingots and carry them to Damascus where they prepared swords and other weapons and sell them in the European market. These swords had much superior properties than the Celtic or pattern welded swords. Yater[40] has published a detailed review on the processes of manufacture of the pattern welded swords and compared its structure with that of Damascus sword. Belaiew[57] was probably the first to study the surface structure of Damascus sword and show that it consisted of distribution of $Fe_3C$ nodules or spheroids but he failed to reproduce this structure by his own experience in smithy craft.

Wootz steel being a very hard and brittle material it required special knowledge and skill to hot forge and produce swords and other weapons. The first break-

*Table 7 : Chemical composition of some Wootz steel objects in percentage.*

| | Objects | C | Si | Mn | P | S | Others | Ref. |
|---|---|---|---|---|---|---|---|---|
| 1 | Ingot | 1.68 | 0.43 | - | 0.025 | 0.2 | - | - |
| 2 | Ingot | 1.642 | 0.045 | - | - | 0.181 | - | 12 |
| 3 | Wootz, Mysore | 0.963 | 0.127 | 0.097 | 0.007 | 0.02 | - | 12 |
| 4 | Wootz, Mysore | 0.45 | 0.14 | - | 0.27 | 0.01 | - | 12 |
| 5 | Wootz Sword | 1.33 | 0.045 | - | - | 0.181 | Uncombined carbon 0.31<br>As-0.037 | 43 |
| 6 | Damascus Blade | 1.49 | 0.005 | 0.08 | 0.1 | 0.05 | - | 60 |
| 7 | Dagger | 1.677 | 0.015 | 0.056 | 0.086 | 0.007 | - | 60 |
| 8 | Sword | 1.874 | 0.049 | 0.005 | 0.127 | 0.013 | - | 60 |
| 9 | Sword | 1.42 | - | 0.015 | 0.206 | - | Ni-0.016<br>Cu-0.056 | 60 |
| 10 | Sword | 1.1 | - | 0.71 | - | - | As- 0.005<br>Cu- 0.034 | 60 |

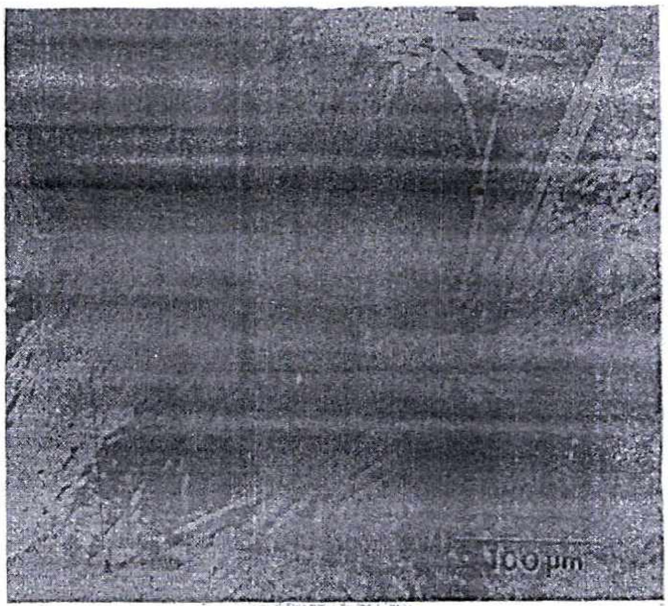
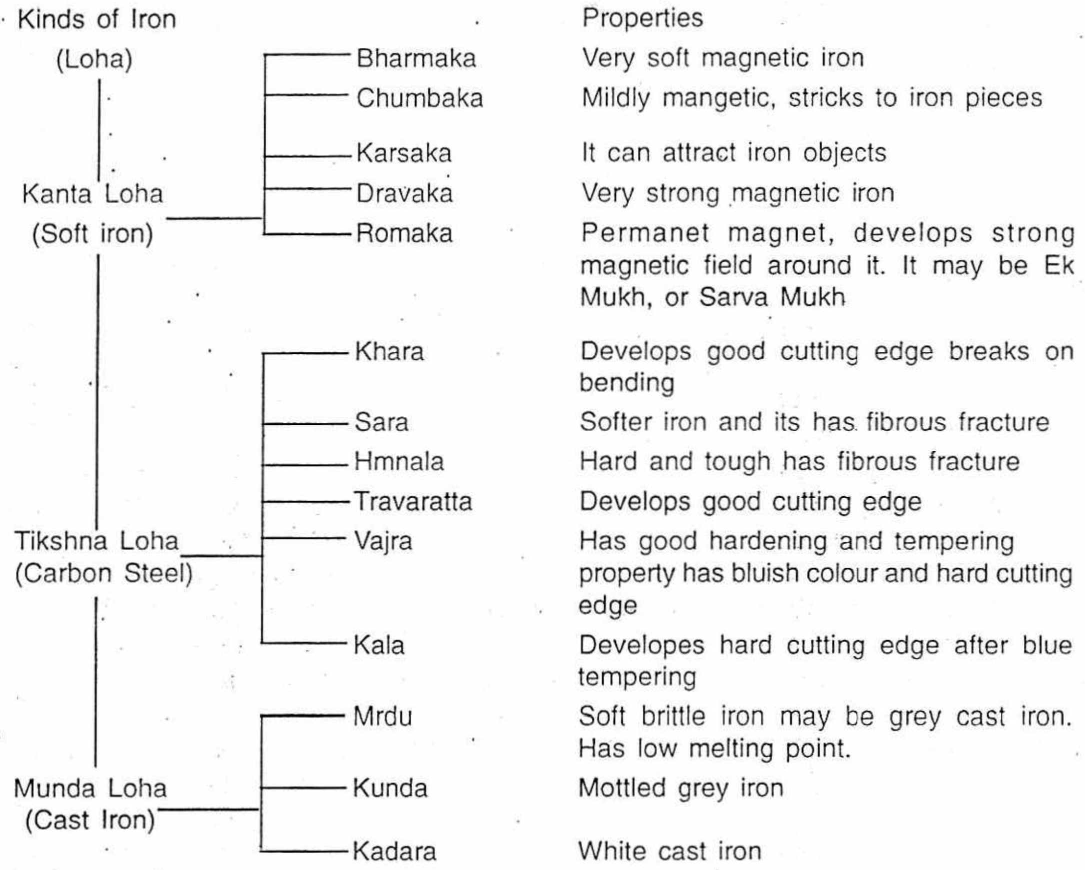


*Fig. 29 : Micro-structure of cast 'Wootz' steel showing thick plate of cementite in a matrix of transformed Ledeburite.*



| Kinds of Iron (Loha) | | Properties |
|---|---|---|
| Kanta Loha (Soft iron) | Bharmaka | Very soft magnetic iron |
| | Chumbaka | Mildly mangetic, stricks to iron pieces |
| | Karsaka | It can attract iron objects |
| | Dravaka | Very strong magnetic iron |
| | Romaka | Permanet magnet, develops strong magnetic field around it. It may be Ek Mukh, or Sarva Mukh |
| Tikshna Loha (Carbon Steel) | Khara | Develops good cutting edge breaks on bending |
| | Sara | Softer iron and its has fibrous fracture |
| | Hmnala | Hard and tough has fibrous fracture |
| | Travaratta | Develops good cutting edge |
| | Vajra | Has good hardening and tempering property has bluish colour and hard cutting edge |
| | Kala | Developes hard cutting edge after blue tempering |
| Munda Loha (Cast Iron) | Mrdu | Soft brittle iron may be grey cast iron. Has low melting point. |
| | Kunda | Mottled grey iron |
| | Kadara | White cast iron |

*Fig. 30 : Classification of Fe-C alloys as described in Rasa Ratna Samucca (8-10C A.D).*

through into this ancient forging technology was by Wadsworth et. al.[58], who established that ultra high carbon steel (1 to 2.1%C) becomes super plastic during warm working at 800 to 850°C. On metallographic examination they found that when forged in this temperature range, the plates of cementite get spheroidized and the steel could be easily forged at slow strain rate. Superplasticity was found to occur at high temperature (800 to 850°C) and it could be formed into any complex shape. For super plastic materials the index of strain rate sensitivity (m) is high, approximately 0.5; and at ideal m=1; the flow stress is proportional to strain rate and the material behaves like a Newtonian viscous fluid. This was followed by the detailed study of Damascus sword by Verhoeven et. al.[59], who tried to develop the 'Damask' pattern on ultra high carbon steel made by modern method and they succeeded in producing similar pattern on a knife. Latter Verhorven et. al.[60], could produce the Damask pattern on forging of original Wootz steel piece obtained by them from India. Prakash[22] got some work done by his students and succeeded in forge welding high carbon steel to low 'C' steel and forge to produce small blade which could be given hardening and tempering treatment by thrusting the red hot steel blade into the green trunk of banana. The sharp edge of such a blade developed a hardness of Rc 45 while the thicker back part had a hardness of Rc 30 only. Varahamihira[32] has mentioned the hardening treatment by plunging the red hot sword in whey into a solution of plantain ashes. Keeping it standing for twenty hours and then taking it out and sharpening the edge on lathe (the grinding wheel). The other method used by Indian blacksmiths was to plunge the red hot blade directly into the plantain tree trunk and allowing it to cool overnight. During this process, at first the quenching action of the plantain sap converts 'g' phase into martensite, which is transformed into tempered martensite due to the flow of heat from the thicker back edge to the sharp edge. The Syrian practice of hardening and tempering consisted of either plunging the red hot sword in slaves belly or running on gallop on a horse holding the red hot sword with the sharp edge in the front i.e., air quenching of the sword blade. The 'Damask' or the watering pattern on the surface of wootz steel swords was revealed by polishing the surface of the finished sword and etching it with sulphuric acid or vitriol.

## DISCUSSION

The multiferous use of pyrotechnology during the Indus valley civilization indicates the knowledge of Indians about the physical and chemical properties of fire. It has also provided ample evidence that pyrometallurgical processes like metal extraction, alloying, metal casting, hot and cold working as well as heat treatment were known to them. As regards the pyrometallurgy of iron and steel, Indians had

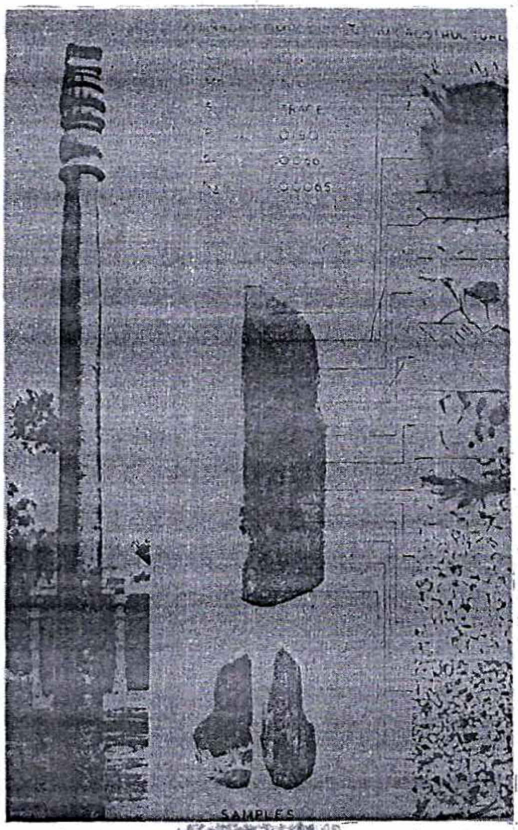


*Fig. 31 : Photograph and micro-structure of iron pillar at Mehrauli in Delhi.*

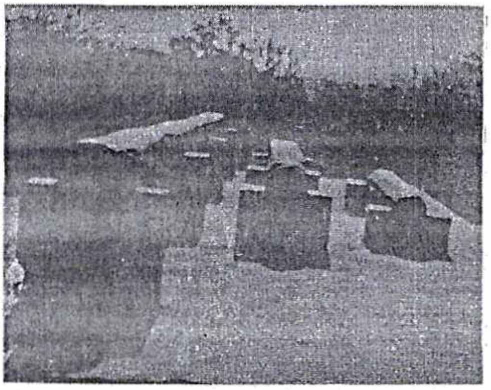


*Fig. 32 : Iron pillar lying in broken condition (3 pieces) at Dhar.*

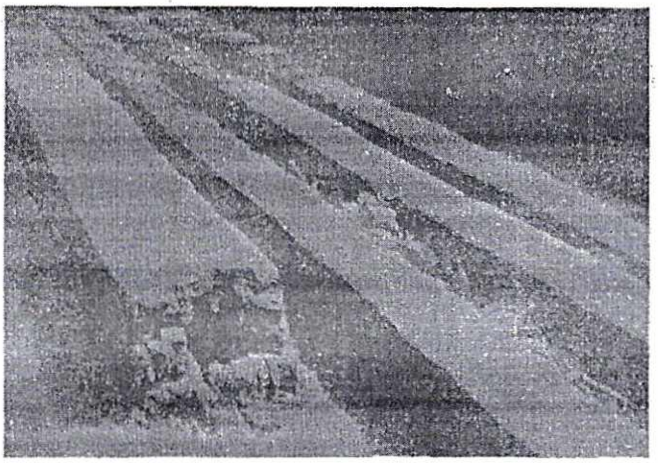


*Fig. 33. : The iron beams at Konark. It also shows the microstructure of the iron beam.*

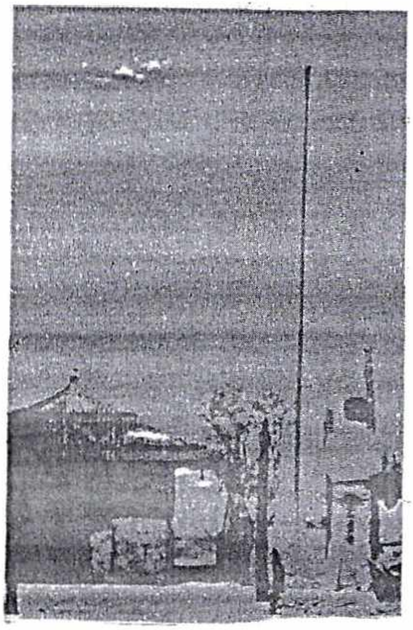


*Fig. 34 : Iron pillar located at Kondachari.*

*Fig. 35 : Iron trident (broken) and its shaft located in the Tanginath temple near Netarhat.*

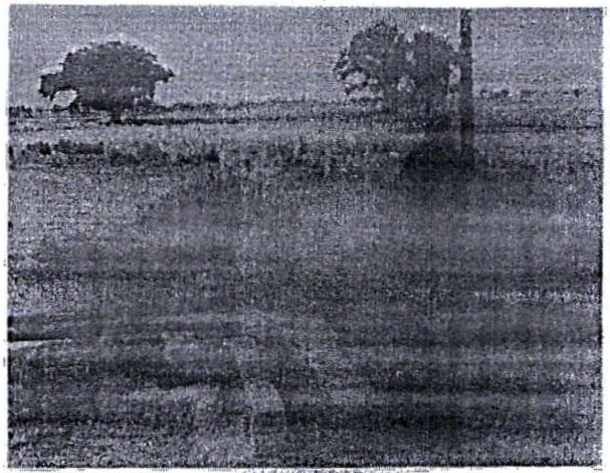


*Fig. 36 : Photograph of a four chanelled furnace found at a site in Ujjain.*

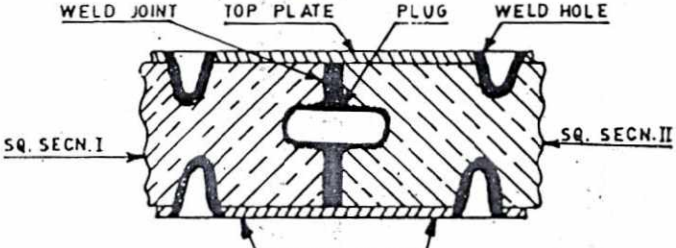


*Fig. 37 : The schematic representation of the probable method of joining forged iron blocks used in the construction of Dhar pillar.*

independent and early beginning and gained high level of skill to operate the iron smelting furnaces, manufacture of Fe-C alloys by carburization and crucible melting and forging as well as heat treatment of ultra high carbon Wootz steel blades. Damask pattern or the watering mark visible to the naked eye was the hall mark of Wootz steel sword. The Indian black smiths had developed the skill to forge weld and prepare heavy forgings like the world famous pillar of Delhi and gun pipes weighing 6 to 50 tonnes. The exquisite design of the bell capital of Delhi iron pillar and its weather resistant property have been a proof of the forging skill and the quality of iron produced by the ancient Indians.

The ancient Indian iron making practice has been described and an attempt has

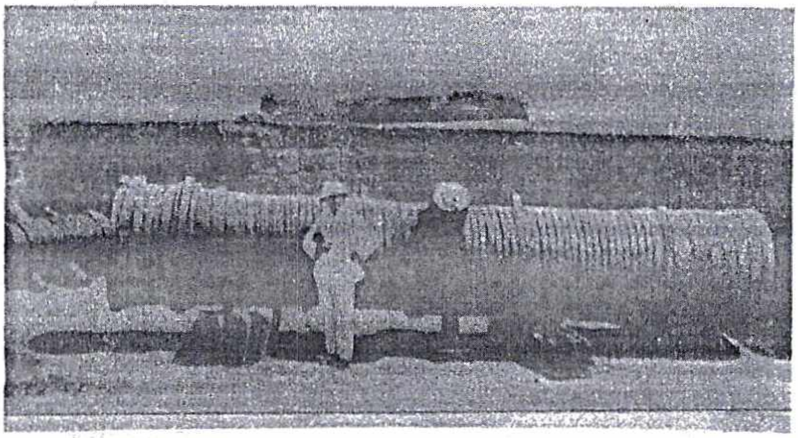


*Fig. 38 : Photograph of 'Landa Kesar' gun lying at Bijapur, weighing about 47 tonnes.*

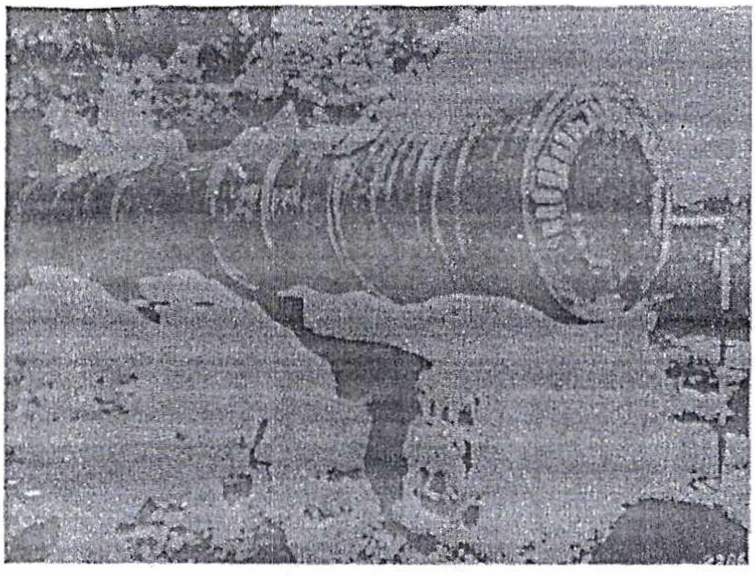


*Fig. 39 : Photograph of the forged gun of iron found at Tanjore.*

been made to interpret the ancient technology taking the help of modern scientific principles applicable to the operation of modern blast furnaces. No doubt the principles of physical-chemistry, thermodynamics and related sciences have helped to develop a better understanding about the operation and process control of the bloomery furnaces but the conditions and the time period taken to develop the bloomery furnace technology only with the help of observational power still remains unanswered.

During the British period a large number of attempts were made to setup iron works at many places in the country e.g., at Kulti, Birbhum, Raniganj, Salem, Porto Novo, Bijapur and Kumaon, but they failed; most probably because of the non-cooperation of the Indian iron smelters. The secret of successful extraction of iron from its ore was maintained in the family and told to no one else. As described by Geijerstam[61], prior to 1856 British engineers had built in Kumaon two charcoal blast furnaces having a bosh diameter of 2000mm and a height of ~6000mm at Khurpatal and one furnace at Devibari, 4 furnaces at Kalidungi. About the same time a Swedish engineer Julius Ramsay took charge of Kumaon Iron works with one iron smelting furnace and a Bessemer converter set up at Dechauri in Kumaon, but they failed to operate these furnaces. It is on record that Ness[62] was the first to produce successful heats of bloomery iron from Indian iron ore in a furnace 2000 mm in diameter and about 7450mm height. After this, in order to promote the British iron industry, the operation of primitive iron furnaces was banned in the country.

As regards the quality of Indian iron it has been certified by Captain Presgrave of Sagar Mint and quoted by Franklin[63] that the properties of Indian wrought iron was better than Swedish or British iron available in the market. McWilliam[64] has tested the mechanical properties of Mirjati iron and has mentioned the yield strength of 256-257.9 Mpa, UTS- 347.5 to 355.2 Mpa and % elongation of 19 to 36, which is comparable to modern wrought iron. As regards the quality of iron produced in various centres in the country Bhardwaj et. al.[7], have quoted from the Sanskrit text of 11th C A.D., *Yuktikalpataru* that (a) Corouncha iron is supposed to be two times better than '*samanya'* (ordinary iron), (b) Kalinga (Orissa) iron is supposed to be eight times better than 'corouncha', (c) Bhadra iron is one hundred times better than Kalinga, (d) Vajra iron is one thousand times better than Bhadra, (e) Pandi iron is supposed to be one hundred times better than Bhadra, (f) Naranga iron is supposed to be 10 times better than Pandi and (g) Kanta iron is supposed to be billion times better than Naranga. This aptly indicates the depth of knowledge gained by the ancient Indian iron craftsmen without the aid or knowledge of modern science or research techniques.

India was also a pioneer in the production of crucible steel i.e., 'Wootz steel' much ahead of the Benjamin Huntsman's crucible steel technology of Sheffield. The process was carried out in refractory crucibles by in-situ carburization of wrought iron using hydrocarbons as the transport media. The crucible has been analyzed by Lowe[46] and it has been found to be made of graphitized mullite, an advanced refractory of today. The wootz steel was ultra high carbon steel requiring special forging and heat treatment skill. How the ancient Indian blacksmiths could determine the narrow range of temperature (800-850°C) suitable for forging using careful hammering is still a mystery. The skill to produce 'Damask' or 'watering mark' on the surface of the swords found only on the original Wootz steel sword speaks volumes about the knowledge of the ancient blacksmiths.

The other process of production of wootz steel by the high temperature refining of white cast iron by reacting with molten synthetic oxidizing high $FeO-Fe_2O_3$ slag has been latter tried by the trade name ' Perrin Process' which was unsuccessful. Latter a similar slag-metal reaction process has been developed by 'ARMCO' Company and it is being used today for the production of wrought iron. Regarding the property of the Wootz steel sword, Charles Wood, the manager of the Proto Novo plant (19th century) has stated that even the best shear of Britain could not cut these swords from the sharp edge side. The simplicity of the ancient processes of Indian iron and steel making and their unique properties have attracted the attention of modern metallurgists and material scientists and efforts are on to improve the productivity of these ancient processes and find out new uses.

## CONCLUSION

From the aforementioned description and discussion of the ancient Indian ferrous technologies, it could be said that ancient Indians were probably far better metallurgists and technologists than those of modern times. Inspite of the availability of modern tools and techniques of research it has taken almost a century to unfold the mysteries of the working of ancient bloomery furnace and Wootz steel making processes. It is beyond any doubt that the ancient manufacturing processes were very precise, and the furnaces were designed and constructed with great accuracy and their products were reproducible.

In recent years, although the super plastic behaviour of the ultra high carbon wootz steel during warm forging process has been rediscovered during the past decade, the forging technique to develop the 'Damask' pattern on the ultra high carbon Wootz steel still remains a mystery. Also in the absence of written records or remains of the ancient smithy shop the exact technique and tools used in the manufacture of some of the heaviest iron forgings of world like Delhi's iron pillar are still a matter of guess and the cause of the rustless property of Indian wrought iron is a challenge to the corrosion scientists.

## REFERENCES

1. Prakash, S., 1965. Foundries of Science in Ancient India, New Delhi, The Research Int. of Ancient Studies.
2. Wertime, T.A., 1982. Early pyrotechnology, Eds. T. A. Wertime and S. A. Wertime, Washington D.C., Smithsonian Inst. Press, p. 21.
3. Biringuccio., 1959. Pirotechnia, Trans. C. S. Smith and Gund M.T., New York, Basic Books.
4. Prakash, B and Tripathi, V., 1986. MM, Sept, p. 568.
4. Prakash, B., 1997. History of technology in India, Vol. 1, Eds. A.K. Bagh, New Delhi, INSA, p. 80.

5. Prakash, B., 1994. Int. Conf. Lafarge Çatalana, Rippoli, Spain, p. 42.
6. Prakash, B., 2000. Conf. on Iron and Steel Production in India and Sweden, History Tech. and Development, Nainital, Mrch.
7. Bhardwaj, H.C and Saran S., 1983. Seminar on metal industries of south India, Thajavour.
8. Bhardwaj, H.C., (1982). IJHS, 17(2), p. 223.
9. Elwin, V., 1942. The Agaria, Calcutta, H. M., Oxford Press.
10. Buchanan, F.A., 1807. Journey from Madras through the countries of Mysore, Canara and Malabar, London.
11. Ghose, M.K., 1964. TISCO, 11(3), p. 32.
12. Prakash, B and Igackhi, K., 1984. IJHS, 19(2), p. 172.
13. Sharma, M., 1990. Vikas Bharati, Bishunpur, Private Communication.
14. Misra, A.K and Chaube, V.K., 1993. Swadeshi Loh aglan (a report), Varanasi, Gandhian Institute for Studies and PPST, Chennai.
15. Joshi, S.D., 1970. History of metal founding in the Indian sub-continent since ancient times, Ranchi, Pub. Mrs. S.S. Joshi.
16. Prakash, B., 1997. Iron and steel heritage of India, Eds. S. Ranganathan, Calcutta, Indian Institute of Metals and Tata Steel, Jamshedpur, p. 29.
17. Mahmad, S.J., 1988. Metal technoogy in Medieval India, New Delhi, Daya Publishing House.
18. Chatterjee, A.B and Altekar, V.A., 1973. The EMR XXVI, 947, p. 47.
19. Krishnan, M.S., 1955. Iron ores of India, Calcutta, Association for cultivation of Science.
20. Prakash, B., 1990. History of science and Technology in India, Vol. 6, Eds. G. Kuppuram and K. Kumudamini, New Delhi, Sandeep Prkashan, p. 53.
21. Prakash, B., 1990. Paleometallugy and culture, Sevenan, France.
22. Prakash, B., 1989. Int. Conf. The Archaeometallurgy of Iron, Results achieved (1967-1987), Prague, UISPP, p. 307.
23. Bashforth, G.R., 1973. The manufacture of Iron and Steel, Vol. 1, Bombay, B. I. Publishers, p. 137.
24. Avery, D.H., 1982. Early pyrotechnology, Eds. T.A. Wertime and S.F. Wertime, Washington D.C. Smithsonian Institute Press, p. 205.
25. Prasad, K.K., et. al., 1996. Metal News, 12, p. 1.
26. Haba, M., (1998). Proc. Intl. Conf. BUMA IV, Matsue, Japan, May, p. 29.
27. Nagata, K., 1998. Proc. Int. Conf. BUMA IV, Matsue, Japan, p. 35.
28. Bloomgren, S and Tholander, E.,1980. Scan. J. Met., 15, p. 151.
29. Hadfield, R., 1912. JISI, 85, p. 34.
30. Ghosh, A.K and Chattopadhyay P.K., 1982. MASCA, 2, 2, p. 63.
31. Hadfield, R., 1975. Optit, TAXILA by Sir Marshal J., Vol. 2, Varanasi.
32. Varahamihira., 1956. History of chemistry of ancient and medieval India, Calcutta, Ind. Chem. Soc.
33. Agrawal, O.P., et. al., 1990. JHMS, 24(1), p. 11.
34. Heyne, B., 1814. Tracts, Historical and statistical on India, London.
35. Voysey, H.W., 1823. J. Asiatic Soc. Bengala, 1, p. 245.

36. Rao, K.N.P., 1989. The Met. & Mat. Tech., 10, 0. 468.

37. Bronson, B., 1986. Archaeomaterials, 1(1), p. 13.

38. Lowe, T.L., 1989. Prnciples of solidification and materials processing, Vol, 2, Eds. R. Trivedi, J. A. Sekhar and J. Majumdar, New Delhi, Oxford and IBH Publishing, p. 639.

39. Craddock, P., 1998. Bull. Met. Museum, 29, p. 41.

40. Yater, W., 1983-84. Anvils Ring, 11(4), P2 and ibid, 11, 4, p. 2.

41. Srinivasan, S and Ranganathan, S., 1997. Iron and steel heritage of India, Eds. Ranganathan S., Calcutta, Indian Institute of Metals & Tata Steel, Jamshedpur, p. 69.

42. Joshi, D., 1971. Rasasastra, Trivandrum, Pub. Div. Ayurvedic college, p.1

43. Holland, T.H., 1893. Imp. Ind. Handbook of Commercial Products, 8, p. 32.

44. Srinivasan, S., 1998. Int. Conf. BUMA IV, Matsue, Japan, p. 79.

45. Tylecote, R.F., 1956. The Met. & Mat. Tech., July, p. 343.

46. Lowe, T.L., 1990. Ceramic and civilization Ed. Kingery, Pitsburg, The American Ceramic Society, 4, p. 237.

47. Neogi, P., 1914. Iron in ancient India, Calcutta, Association for the cultivation of Science.

48. Prakash, B., 1991. IJHS, 26(4), p. 351.

49. Susruta., 1980. Susruta samhita , Varanasi, Chaubhamba Orientalia.

50. Kulkarni, A.D., 1969. Rasatatna Samucca, Delhi, Meherchand and Lakshman Das.

51. Samuels, L.E., 1980. Metallography, 13(1), p. 349.

52. Balasubramaniam, R., 1998. JOM, 97, p. 417.

53. Bakasubramaniam, R., 1999. Bull. Met. Museum, 3, p. 40.

54. Prakash, B., 1989-90. Puratatva, 20, p. 118.

55. Bonner, A., Sharma, S.R and Das, R.P., 1972. New light on the Sun temple of Konark, Varanasi, Chauhhamba Publisher.

56. Rossler, K., 1997. Metal News, 19, p.1.

57. Bellaiew, N.T., 1918. JISI, 97, p. 417.

58. Wadsworth, J. and Sherby, O.D., 1988-89. Progress in Mat. Sc., 15(1), pp. 35, opcit, Scientific America, 252(2), p. 94.

59. Verhoeven, J.D., 1987. Metallography, 20, p. 145.

60. Verhoeven, J.D and Pendray, A.H., 1992. Metals Mat. and Processes, 4(2), p. 93.

61. Geijerstam, J., 2000. Conf. on Iron and Steel Prod. In India and Sweden history, Technology and Development, Nainital, March.

62. Ness, W., 1875. JISI, p. 616.

63. Franklin, J., 1829. Opcit. Indian Science and Technology in the 18th century (1983) by Dharampal, Hyderabad, Academy of Gandhian Studies, p. 269.

64. McWilliams, A., 1920. JISI, 149(2), p. 159.