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METALLURGY OF IRON AND STEEL MAKING AND BLACKSMITHY IN ANCIENT INDIA

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Iron Pillars of Delhi and Dhar, Wootz steel swords and many other iron and steel artifacts of our country are testimony to the high level of skill attained by the iron smelters and blacksmiths of ancient India. In the present paper it has been endeavoured to analyse the status of the ancient metallurgical skill in light of the modern knowledge about iron-carbon-oxygen and iron-carbon phase equilibrium diagrams, and thermomechanical behaviour of various iron-carbon alloys. The paper also emphasises the need for involvement of metallurgists and technologists of other disciplines during archaeological excavations so that accurate on-site evaluation of the ancient craft may be done.

INTRODUCTION

The review of archaeological documents has produced ample evidence regarding the demand and trading of Indian iron and 'wootz' steel ingots in the Western countries. Persians have been among the major buyers of 'wootz' steel ingots to manufacture the famous 'Damascus swords' in their country and re-export to the European countries. Lowe[1] has mentioned that one of the Dutch consignments shipped in the 17th century consisted of 20000 ingots of 'wootz' steel from our country. Several other similar exports have been mentioned by Yater[2] and Bronson[3]. The high corrosion resistance of the famous iron pillar of Delhi and many other iron objects of our country is testimony to the quality of ancient iron and steel as well as skill of the ancient blacksmiths. The corrosion resistance of these objects and their quality are still a challenge to the corrosion scientists and metallurgists. Charlswood, then incharge of 'Beypur Iron Works', while discussing a paper of Professor Turner[4] has mentioned that the special shears manufactured in his works had failed to cut the 'wootz' steel swords from the hardened edge side, while the back side of these swords was very soft and easy to cut. These swords were famous for their heat treatability, strength and flexibility. Buchanan[5], Voysey[6], Hadfield[7] and Elwin[8] have published detailed accounts of their surveys of these ancient processes, but the British inventors and craftsmen failed to produce steel of the matching quality even at the Beypur plant.

The present paper is an endeavour to develop a better understanding of the ancient crafts of iron and steel making and blacksmithy with the help of the knowledge of modern Iron-Carbon-Oxygen and Iron-Carbon Equilibrium Phase diagrams and technology of heat treatment.

Production of Iron in India in the Past

The discovery of iron and the beginning of 'Iron Age' in India are still controversial but the archaeological evidences as well as the survey of ancient literature have proved it to begin at least in the 2nd m B.C. The Indian iron making process has been already reviewed by the author[9-12] and many other ancient travellers and archaeologists. Even in the 18th century A.D., throughout India a variety of furnaces having a capacity of producing 5 to 10 kg of iron per heat were in operation and unlike in European countries, where the furnace was destroyed after one or two heats, these furnaces were probably reused several times after minor repairs. The largest furnace as mentioned by Buchanan[5] had a capacity of producing 250 kg of iron per day, operated in the Malabar region (Kerala). Prakash[12] has analysed the designs of these furnaces and they have been found to conform to the design parameters of the modern 1000 tonnes per day furnaces in operation in the middle of the current century. He has also studied the heat and mass balances of the Jiragora furnace operated by Indian tribesmen in 1963 in the presence of Ghosh[13]. These analyses, given in Tables I and II, have shown that the Indian craftsmen applied very strict process control to produce iron containing 0.1 to 0.5% C. The production of iron containing high 'C', i.e. having 2% or more or cast iron was considered to be a bad omen, although this had lower melting point, as shown in Fig. 1. However, the cast iron thus produced was brittle and could not be forged to produce objects like arrow heads, knives, swords, etc. Hence, the air

Table I: Heat balance of ironmaking furnace at Jiragora (M K Ghosh)

S.No.	Heat input	k cal	S.No.	Heat output	k cal
1	Heat generated by combustion $CO/CO_2 = 4$	81,011.5	1	Heat for heating the ore to 1000°C	4,920.00
			2	Heat for endothermic reduction	5,451.87
			3	Heat content of metal at 1200°C	1,385.00
			4	Heat content of slag at 1200°C	6,300.00
			5	Heat in outgoing gases	48,026.28
			6	Heat lost by conduction and radiation by difference	14,928.22
	Total	81,011.5			81,011.5

% Radiation loss = 18.5%

Theoretical Flame Temperature = 1,938°C

Blowing Rate: Air blown in 6 h = 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

Furnace operation practice:

Operation	Time	Coal charged	Blowing Rate
1 Furnace Pre-heating	1 hr	8 kg	Faster than 87 strokes/min
2 Reduction stage	4 hrs.	14 kg	87 strokes/min
3 Consolidation stage	1 hr	8 kg	Vigorous blowing

Table II: Material balance for ironmaking from Jiragora (M K Ghosh). Furnace trial results show 24 kg of ore/30 kg of charcoal. Time of reduction and smelting — 6 hours. Reduction efficiency 36.2%

Material	Analysis %	Calculation	Metal Fe (kg)	Theoretical Composition	Actual Composition (basis 21 kg)	Gases (kg)	Remarks
Ore — 24 kg							**Metal Composition** C — 0.4% Si — 0.2% Fe — rest **Slag Composition** SiO_2 — 27.08% Al_2O_3 — 6.72% Fe — 46% MnO — 1.026% CaO — 5.0% MgO — 1.16% SO_2 — 0.075% O_2 — 12.98%
$Fe(Fe_2O_3)$	63.4	24 × 0.634 × 0.302	5.5	9.7	9.66	2.357	
SiO_2	2.44	24 × 0.0244 − 0.021	0.01	0.565	5.68	1.387	
P_2O_5	0.01	—	0.0004			0.114	
Al_2O_3	1.66	—	—	0.446	1.41	0.026	
CaO + MgO	0.5	—	—	0.12	1.29		
MnO	0.9	—	—	0.20	0.21	0.888	
LoI	3.7	—	—				
Total			5.5104	11.031			
Oxygen in Iron as FeO				2.77			
Carcoal — 30 kg							*5.54 kg of iron will be associated with 21 kg slag. Theoretical slag wt. = 14.761 kg hence $SiO_2 + Al_2O_3$ added as flux = 6.24 kg. Theoretical charcoal for reduction = 16 kg.
F.C.	75.8		0.022			22.718	
Ash	3.2			0.96			
V.M.	21.0					6.3	
Total — 54 kg			5.5324	14.761 theoretical slag wt.	21 kg	33.79	
					54 kg*		

blowing rate and the furnace temperature profile were very closely monitored to carry out only solid state reduction and produce red hot sponge having low carbon. This red hot sponge was taken out from the furnace by breaking the front wall of the hearth area and was consolidated by forging. It was further refined during a secondary treatment and consolidated into a solid bar of wrought iron.

The iron thus produced was classified into two main categories, viz., (i) wrought iron (*Kānta Lohā*) and (ii) carbon steel (*Tīkshṇa Lohā*) and the third category was (iii) cast iron (*Munda Lohā*) which was considered to be undesirable till its refining technique was developed to convert it into 'wootz' steel. In Fig. 1 the carbon range of *Kānta lohā* is shown as 'X' and that of *Tīkshṇa lohā* as 'Y'. As mentioned in '*Rasa Ratna Samuchchaya*'[14], a work dated to 8-12th century A.D., these categories were further classified according to their carbon content and use, as shown in Fig. 2. This type of detailed classification became possible on the basis of the fracture, ductility and probable change in the magnetic property of the iron-carbon alloy, i.e. the proportion of Ferrite and Cementite phases. In contrast to this, the differentiation between grey, white and mottled cast iron on the basis of their fracture was made possible in the West by Reaumur only in 1772, as mentioned by Samuels[15].

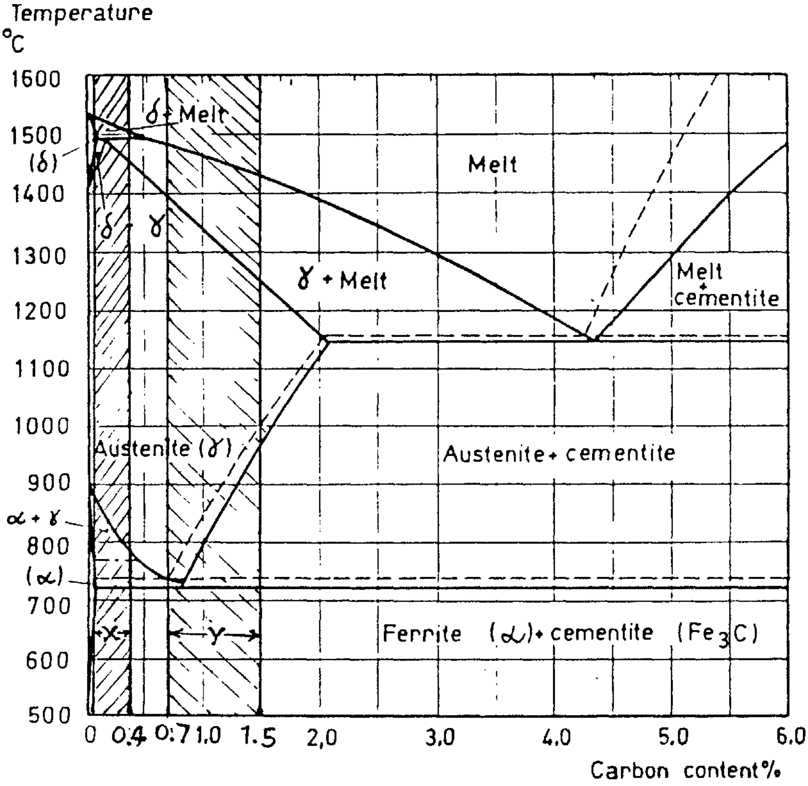
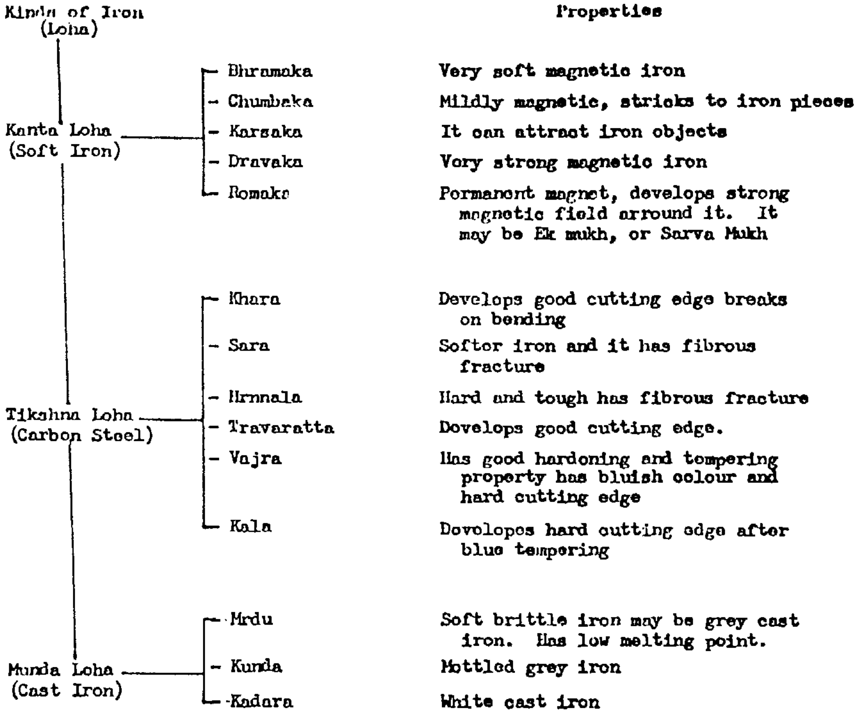


Fig. 1. Iron-carbon equilibrium phase diagram showing the 'C' ranges for *Kānta Lohā* (X), and *Tīkshṇa Lohā* (Y) [----, the stable Fe-C system, —, the metastable system Fe-Fe_3C]



Kinds of Iron (Loha)		Properties
Kanta Loha (Soft Iron)	Bhramaka	Very soft magnetic iron
	Chumbaka	Mildly magnetic, stricks to iron pieces
	Karsaka	It can attract iron objects
	Dravaka	Very strong magnetic iron
	Romaka	Permanent magnet, develops strong magnetic field arround 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 it has fibrous fracture
	Hrnnala	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. 2 Classification of ancient iron-carbon alloys: Their properties (8-12 c A.D.)[14]

The type of process control adopted to produce iron of controlled quality and uniformity can be understood from the study of the Fe-C-O equilibrium diagram shown in Fig. 3. This figure shows the stability regions of Fe_3O_4, FeO and Fe at high temperature and also the $CO_2 + C \rightleftharpoons 2CO$ equilibrium line superimposed on these oxide phases. Fe_2O_3-Fe_3O_4 transformation line has not been shown in this diagram, because it occurs below 250°C. The CO/CO_2 line crosses the $FeO \rightleftharpoons Fe + O$ line at the point 'R' at 750°C which indicates the minimum CO/CO_2 ratio and the temperature required for the reduction of FeO to Fe. The shaded area in this diagram shows the range of temperature in which the smelting furnace must be operated to obtain effective reduction of iron oxide as well as control the carbon content of the hot sponge within the lower limit 'X' shown in Fig. 1. From this diagram it becomes evident that the optimum temperature required for the reduction is 900-950°C and corresponding to this CO/CO_2 ratio of 4(80:20) should be maintained in the gaseous atmosphere inside the furnace. This diagram also shows the topochemical nature of the step-wise reduction, viz. $Fe_2O_3 \rightarrow Fe_3O_4 \rightarrow FeO \rightarrow Fe$ and formation of Fe_3C due to carbon pickup at high temperature.

The two major overall reduction reactions taking place during the reduction of iron ore (Fe_2O_3) Hematite are:

(1) $Fe_2O_3 + 3C \rightarrow 2Fe + 3CO$ (Endothermic)
(2) $Fe_3O_4 + 3CO \rightarrow 2Fe + 3CO_2$ (Exothermic)

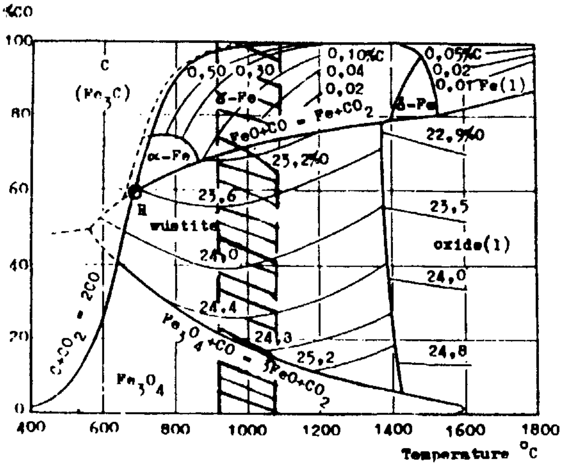


Fig. 3. Fe-C-O equilibrium diagram showing phase boundaries for various iron oxides and the 2CO —> $CO_2 + C$ equilibrium line with temperature on X-axis.

and the CO:CO_2 balance of the furnace atmosphere is governed by the Bouduard reaction, i.e.

(3) $CO_2 + C \rightleftharpoons 2CO$ (Endothermic)

Thus, the reduction reaction taking place in the furnace can be written as:

(4) $Fe_2O_3 + xCO = 2Fe + 3CO_2 + (x-3)CO$
where $CO/CO_2 = 4$

and this reaction (4) has been used to calculate the heat and mass balances given in a Tables I and II for the operation of the furnace shown in Fig. 4.

As the reduction temperature is increased, CO gas becomes more stable, increasing the carbon content at the reaction site, and hence it increases the carbon content of the alloy by the formation of Fe_3C (Cementite). This increase in carbon content of the metal increases the brittleness and decreases the melting point of the alloy as shown in Fig. 1. Thus, we see that solid sponge iron can be produced from its oxide even at 950°C but the slag forming gangue constituents do not melt at this temperature and hence it becomes essential to operate the furnace at a much higher temperature. The study of the ancient iron smelting furnace slags has shown that silica being the major gangue material forms Fayalite (Fe_2SiO_4) which has a melting point of 1205°C with a (FeO-Fe_2SiO_4) eutectic melting point of 1177°C. This means that the smelting furnace should be operated at least at 1250-1300°C, and at this temperature low carbon, 'δ-Ferrite' is prodced (refer to Fig. 2) having a melting point above 1410°C. Thus, in this case the gangue material separates out as molten Fayalite slag and red hot solid sponge having low 'C' can still be produced. Bloomgren and Tholander[16] have studied the constitution of iron smelting furnace slag and the environmental conditions inside the smelting furnace and they have concluded that although due to the formation of iron rich ($2FeO.SiO_2$) slag much iron is lost, the high oxygen activity of the slag acts as a controlling parameter in lowering the carbon content of the metal. The chemical reactions taking place is:

(5) $FeO + C \rightarrow Fe + CO$ (Endothermic)
or
(6) $Fe_3C + FeO \rightarrow 4Fe + CO$ (Endothermic)

Bloomgren and Tholander have also compared the constitution of the low shaft furnace slag with that of modern blast furnace where CaO is added as flux. With the addition of CaO as limestone, the major part of the slag formed is calcium silicate or calcium aluminosilicate which decreases the Fayalite concentration in the slag and also decreases the oxygen potential at the reaction site. This slag also raises the melting point of the slag demanding the operation of the furnace at a higher temperature, i.e. >1500°C, which leads to the increase in 'C' content of the metal and production of cast iron instead of low 'C' wrought iron.

The tribal smelters had been very selective in the collection of the raw material and they had developed great confidence in their processing to produce iron-carbon alloy of desired composition and properties, although their processing technique was shrouded

Fig. 4. Jiragora ironmaking furnace operated in 1963.[13]

by many religious rituals and superstitions. Every care was taken to operate the furnace under strict control of the master craftsman, and any failure to obtain the desired quality of the metal was attributed to the curse of their God *Asur*. As concluded by Prakash and Tripathi[10] from the study of the heat and mass balance (Tables I and II), the ancient Indian smelters added SiO_2 as a flux or used only lean siliceous ores, so that sufficient quantity of Fe_2SiO_4 slag was produced inside the furnace during smelting of the charge. They also executed strict control of the temperature by regulating the rate of operation of bellows as shown in Table I and also observing the colour inside the furnace through the tuyere hole. The Malabar furnace[10] was provided with built-in separate holes for the observation of the progress of smelting operation.

These observations have been recently confirmed during the operation of the low shaft iron smelting furnace by the *Asur Birjia tribe* at Bishunpur[17], where *Vikas Bharati*, a rural development organization has launched a project to revive this craft as an economically viable rural technology. Fig. 5 shows the head craftsman preparing the furnace mouth and its inner profile. Table III gives a comparison of the rate of operation of the bellows during the operation of the Bishunpur and Jiragora furnaces (1963) as well as their total period of operation for the completion of one heat. Due to the operation of these furnaces at 1250 to 1300°C, any appreciable reduction of Si, Mn, etc. was not achieved in the presence of the highly oxidizing and acidic Fayalite slag in the

Fig. 5. Bishunpur iron making furnace operated in 1989-90.[17]

furnace, and this also helped in the control of the carbon content of the hot sponge iron. The sulphur content of the metal was very low and all the phosphorus going into the furnace charge was picked up by the metal. That is why all the primitive iron objects have a higher 'P' content, i.e. >0.1%. Table IV gives the chemical analysis of some of the ancient iron objects and also the iron produced by the Bishunpur furnace.

Table III. Comparison of operating parameters of Jiragora and Bishunpur iron making funraces

Operation	Time	Material Charged		Blowing Rate	Remark
		Ore	Coal		
JIRAGORA FURNACE					
1. Furnace preheating	1h	—	8 kg	Faster than 87 strokes/min	See Table I
2. Reduction stage	4h	—	14 kg	87 strokes/min	Sequence of ore and coal charging not available
3. Consolidation stage	1h	—	8 kg	Vigorous blowing	
4. Total operating time	6h	—	—	—	—
5. Total material charged	—	24 kg	30 kg	—	5.6 kg of iron
BISHUNPUR FURNACE					
1. Furnace preheating	1.25h	2.5 kg	3.25 kg	40-50 strokes/min	Fce Temp. 550°C
2. Reduction stage	4h	8 kg	16 kg	60-70 strokes/min	– 950°C
3. Consolidation stage	0.5h	1 kg	2 kg	110 strokes/min	1500°C
4. Total operating time	5.75h	—	—	—	—
5. Total material charged	—	11.25kg	21.5kg	—	2.5kg of iron

Table IV. 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. Bhubaneswar Iron Beams	0.27 to 0.45	0.05 to 0.11	Traces to 0.04	0.015 to 0.018	0.006 to 0.015	Cr = 0.9% Ni = 1.6%
3. Bastar Iron Axe (100 years old)	0.25 to 0.45	—	—	—	—	Other elements in traces
4. Jabalpur Iron (recent)	0.59	110 ppm	40 ppm	—	—	Cu = 340 ppm Ni = 353 ppm Others in traces
5. Bishunpur Iron (recent)	0.016 to 0.043	—	0.057	0.02 to 0.2	0.007 to 0.013	—

SECONDARY TREATMENT OF THE HOT SPONGE IRON

After the hot sponge (weighing about 3-9 kg.) was taken out from the furnace by breaking the front wall, it was forged to squeeze out the molten slag (Fe_2SiO_4) and also densify the sponge by forge-welding. For further refining, this block was repeatedly heated in a forge hearth and SiO_2 was sprinkled on it, so that the remaining FeO may get converted into (Fe_2SiO_4), i.e., fluid slag and flow out of the semisolid mass. The iron piece was repeatedly forged to further separate the slag as well as convert the spongy mass into a solid rod 15 mm dia × 150 mm. This refined bar was classified into various categories as shown in Fig. 2 on the basis of its ductility and appearance of the fracture. This standard refined wrought iron bar was sold to blacksmiths (*Lohār*) or steel makers for further refining and fabrication of various war weapons and agricultural implements. An assessment of the metallurgical properties of the iron produced by the Bishunpur craftsmen has been already published by Prasad *et al.*[17]. *Kānta lohā* or iron containing more than 2% 'C' did not have any market value or use, because this iron was brittle and it could not be shaped by forging.

PROCESS OF CARBURIZATION

Having understood the effect of carbon alloying on the properties of iron and also the effect of temperature as being one of the controlling parameters, the ancient smiths developed the processes of increasing the carbon content of low 'C' wrought iron bars to a controlled limit to obtain better thermo-mechanical properties. The processes adopted by them can be classified into three categories:

(1) Increasing the carbon content of the hot sponge during smelting by raising the operating temperature and also increasing the time of retention of sponge iron for slightly longer period, as discussed earlier.

(2) Increasing the temperature and time of contact between iron and hot charcoal during secondary refining.

(3) Application of a carburization paste on the edge of the sword, etc. to obtain a hard cutting edge with flexible body. Since processes (1) and (2) increased the carbon content of the iron rod itself or of the whole mass, this selective carburization process was developed.

These processes have been mentioned as early as the *Vedic* Period.[18] Hadfield[7] has also mentioned the possibility of the use of Indian iron chisels and even Indian craftsmen in the building of the 'Pyramids' of Egypt. Suśruta[19] has mentioned the process of carburization by applying a carbonaceous paste on the edge of his surgical knives and heating them to red hot condition followed by hardening and tempering treatment to develop razor sharp edges (700 B.C.). Varāhmihira[20] (~550 A.D.) has mentioned the following processes for carburizing and hardening of iron swords:

i) making a paste with the juice of the plant *arka* (*Calotropis gigantea*), the gelatin from the sheep's horn and pigeon's and mouse dung, applying this paste to the steel after rubbing it with sesame oil, heating the sword in the fire and when it is red hot sprinkling on it water or milk of mares (camel or goat) or ghee (clarified butter) or blood or fat or bile and then sharpening on the lathe.

ii) plunging the steel red hot into a solution of plantain ashes in whey, keeping it standing for twenty four hours, and then sharpening on the lathe (Varāhamihira *Kharglakshanaṁ*, Chap. XVIX, Ślokas 23-26).[18]

The iron treated by the carburization processes suffered from structural heterogeneity, non-consistency of the quality as well as low fracture toughness due to the presence of cementite needles and high amount of slag inclusions. These shortcomings were minimised by the introduction of the process of 'wootz' steel manufacturing technology.

PRODUCTION OF WOOTZ STEEL

Ball[21] writes that 'wootz' steel was much sought after in the Eastern Mediterranian region even earlier than the Christian era. As reviewed by Yater[2] and Bronson[3], this quality of steel was being produced in several places in India and exported to the West for the manufacture of the famous Damascus sword in Persia. This quality sword had attained its reputation for its flexibility, strength, the edge sharpness and for the beautiful quenched and etched pattern developed on surface of the sword. Fig. 6 shows the typical surface structure of the Damascus sword developed by 'Damascurizing' and 'watering' treatments. The development of this type of structure has remained a fascinating mystery in spite of large number of attempts, as reported by Yater[2], Thomsen[22], Kedzierski[23], Anteins[24] and many others through papers presented at the International Symposium on "The Craft of the Blacksmith"[25]. Most of the attempts made to duplicate the properties and structure of this famous sword have been in the direction of pattern welding of several pieces of iron having varying carbon and phosphorus contents. The latest study on the 'watering' treatment and experimentation to develop such structure has been by Verhoevan *et al.*[26] who have reasoned that this pattern was developed due to the carbide distribution pattern in the steel blade, but they also have failed to attain the old perfection.

Bronson[3] in his review on this celebrated steel has questioned the origins of this Indian technology and endeavoured to give credit to Iran or other Arabian countries which were in know of the qualities of this steel and considered it worthwhile to journey to India to procure it. After studying the classification of iron-carbon alloys shown in Fig. 2 (communicated to him by the author), he has acknowledged the origin of the production of molten steel in India. This technology was most probably developed for the first time either in Gujarat or Hyderabad. The English word *wootz* is supposed to be an abbreviation of either the Gujarati word *wuz* or the Telugu word *Hooku*, which means steel or *Pulat* in Persian. The other regions mentioned in the literature are

Tamilnadu and Karnataka where this quality of steel was made by the technique of melting in crucible. In Northern India, crucibles and furnaces similar to those used in South India have been found at Rajghat (Varanasi) and Khairadih (District Ballia) where most probably wootz steel was being produced between 1000 B.C. and 600 A.D.

Two distinct processes of production of wootz steel have been reported by Yater[2], Bronson[3], Prakash[12] and Rao[27]. The first process consisted of carburization of soft iron or wrought iron by packing it with chips of wood and leaves of specific plants, e.g. *Avaram (Cassia auriculata)*, etc. about 1/10th in weight of the iron and then the mouth of the crucible was sealed with clay. Sometimes a hole was made in the cover for the escape of the gases produced inside the crucible. 20 to 25 or sometimes a larger number of such crucibles were heated in a specially designed furnace where the central crucible could attain a temperature of more than 1500°C. The crucibles were shifted in an order to the hottest zone of the furnace where the steel reached the molten state. After this, the crucible was either cooled slowly by keeping it in the low temperature zone or it was water quenched. The details of the process and the time of one such operation have been summarized by Bronson[3]. The wrought iron charge could be carburized in about 2½ to 6 hours and the extent of carburization was controlled by adjusting the proportion of wood chips in the charge, the residual amount of the FeO rich slag remaining in the wrought iron. During the processing and melting of the steel molten slag was separated and a clean steel ingot was obtained, which could be further classified and processed for the production of war weapons, tools, and objects like wires for musical instruments, etc. Table V gives some typical compositions of 'wootz' steel as quoted by Bronson[3] and Percy[28].

The crucibles used in this process had a conical to pear shape and they were very skilfully prepared from a refractory material capable of sustaining such treatment. Several compositions of such crucibles for various uses have been mentioned in the ancient Ayurvedic texts, *Rasa Ratna Samuccaya*[14] and *Suśhruta Saṃhitā*[19]. These

Table V. Chemical analysis of some 'Wootz Steel' objects

Sl. No.	Object	Percentage Chemical Analysis							Ref.
		Combined 'C'	Si	S	P	Mn	As	Others	
1.	Wootz Steel Sri Lanka	1.97	0.07	0.07	0.02	0.07	—	—	2
2.	Indian	1.64-1.65	0.042-0.045	0.17-0.18	—	—	0.037	—	3
3.	Mysore	0.963	0.127	0.02	0.007	—	—	—	3
4.	Damascus Sword	1.677	0.011	0.007	0.086	0.056	—	—	3
5.	Wootz Steel	1.33	0.045	0.180	—	—	0.045	Uncombined C=0.31	28

crucibles were generally prepared from a mixture of some siliceous clay or kaolin mixed with rice husk and iron oxide sand. On firing of these crucibles in reducing atmosphere at first at 400-500°C and then at 1100-1200°C, the rice husk got charred depositing carbon and adding SiO_2 to the clay. As the temperature was raised fusion of FeO to form a Fayalite bond provided strength up to 1200°C and at the same time carbon got graphitised. On further heating, SiO_2 got converted into Mullite and FeO was reduced to iron droplets, but by this time the highly refractory Mullite (M.P. $>1800°C$) network maintained the refractoriness of the crucible and graphite particles imparted nonwettability to the crucible surface. Recently, Lowe *et al.*[29] have analysed and studied the composition as well as structure of many such crucibles collected from the steel melting sites of the Hyderabad region and confirmed the excellent refractoriness of these crucibles having structure as described earlier. It is interesting to note that the use of graphitised refractory and its manufacturing technology are being revived after the lapse of about 200 years and used in the modern steel making furnace lining.

In the second process of steel making, a pool of highly oxidizing molten slag was prepared from magnetite sand and quartz which has a melting point of 1205°C and it was used for refining cast iron by oxidation of carbon and other impurities. For this process, a specially designed compartmentalised pit furnace was made below the ground level and cast iron (rejected from the bloomery furnace) was added in the molten oxidizing slag in the form of red hot small shots. During the process of steel making, the surface of the cast iron reacted with FeO to decarbonise and dephosphorise the iron which became molten steel and got collected at the bottom. The reactions taking place were:

(5) $FeO + Fe_3C \rightarrow 4Fe + CO$ (Exothermic)
(6) $8FeO + 2Fe_3P \rightarrow 3FeO.P_2O_5 + 11\ Fe$ (Exothermic)

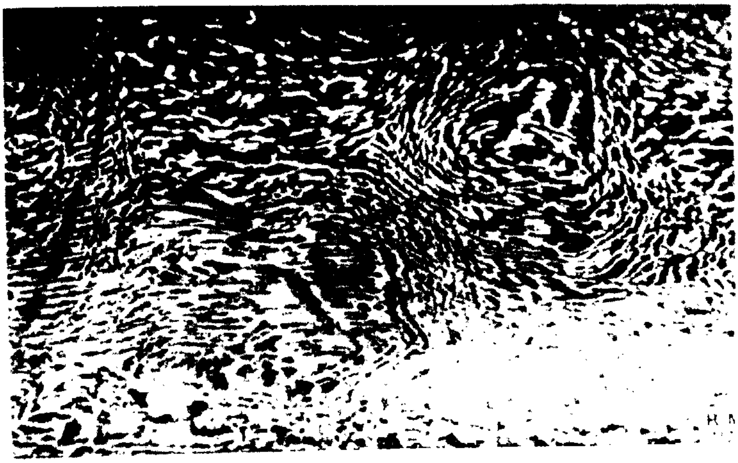


Fig. 6. Typical surface structure on Damascus Swords formed due to watering treatment.[26]

The heat of reaction as well as that generated by the combustion of 'C' and CO gas produced sufficient heat to separate the molten metal into a separate layer which was allowed to solidify in the furnace itself and taken out as clean thick steel plate and tasted for its ductility by making a cut. Probably this steel plate was the 'wootz' steel 'loaves' exported to the West as mentioned by Bronson[3]. Yater[2] has postulated a third process where he assumes that the bloomery iron was first carburised in the solid state to pick up carbon up to 3.5% which became molten in the crucible at 1300 to 1350°C, and then later on the solidified cake was decarburised by the white heat malleablization process. His postulation is most probably based on the combination of the above-mentioned two processes and the process of malleablization developed in the area of Birbhum (Bengal). The author does not agree with such an erroneous process where the energy consuming process of carburization is imagined to be followed by the still more difficult and lengthy process of solid state decarburization. Yater[2] has proposed this process probably because of the prevalent belief that temperature of the order of 1550°C cannot be generated in a charcoal fired furnace. But it has been proved to be possible, as shown in the heat balance given in Table I and also measured by Prasad *et al.*[1] during the operation of the Bishunpur smelting furnace.

THERMO-MECHANICAL TREATMENT AND FORGE WELDING

The details of the iron-carbon phase diagram and the effect of carbon on the structure and proportion of various phases present in any steel are well understood. Fig. 7 shows the change in the structure of five different iron-carbon alloys as attained by normal cooling. This diagram also shows various ranges of temperature to which the steel should be heated to carry out different thermo-mechanical treatments like forging, forge welding, annealing, and spheroidizing, etc., with respect to the phase boundaries of the iron-carbon alloy system. Fig. 8 shows the proportion of ferrite, pearlite and cementite formed as the carbon content is varied in the iron-carbon alloy system and this changes the grain structure, ductility and fracture behaviour of the alloy. The ancient blacksmiths were ignorant about these diagrams and structures but they knew and understood the effect of carbon on properties of iron as depicted by the classification shown in Fig. 2 and proved by the manufacture of such massive iron objects like Delhi's Iron Pillar weighing 6000 kg, which has stood all the tests against time and which has no parallel in the world. In the modern archaeological studies of iron samples, the phase diagrams shown in Figs. 8 and 9 can be used to estimate the carbon content and assess their metallographic and other properties.

The small rods of wrought iron or steel cakes produced by the 'wootz' steel making process were hot forged together to forge-weld them together and shape them to produce the desired product. This must have been possible only why the extensive knowledge about the hot workability of various iron-carbon alloys. As it is well known, low carbon steels or wrought iron are easy to be forge-welded and shaped, but they cannot be used for any object required to have a sharp cutting edge. The structure of high carbon steel (hyper-eutectoid steel) consists of separation of massive cementite at the grain boundary and on Widmannstatten planes, making it extremely difficult to shape the material without cracking or fracture. The ancient Indian blacksmiths had

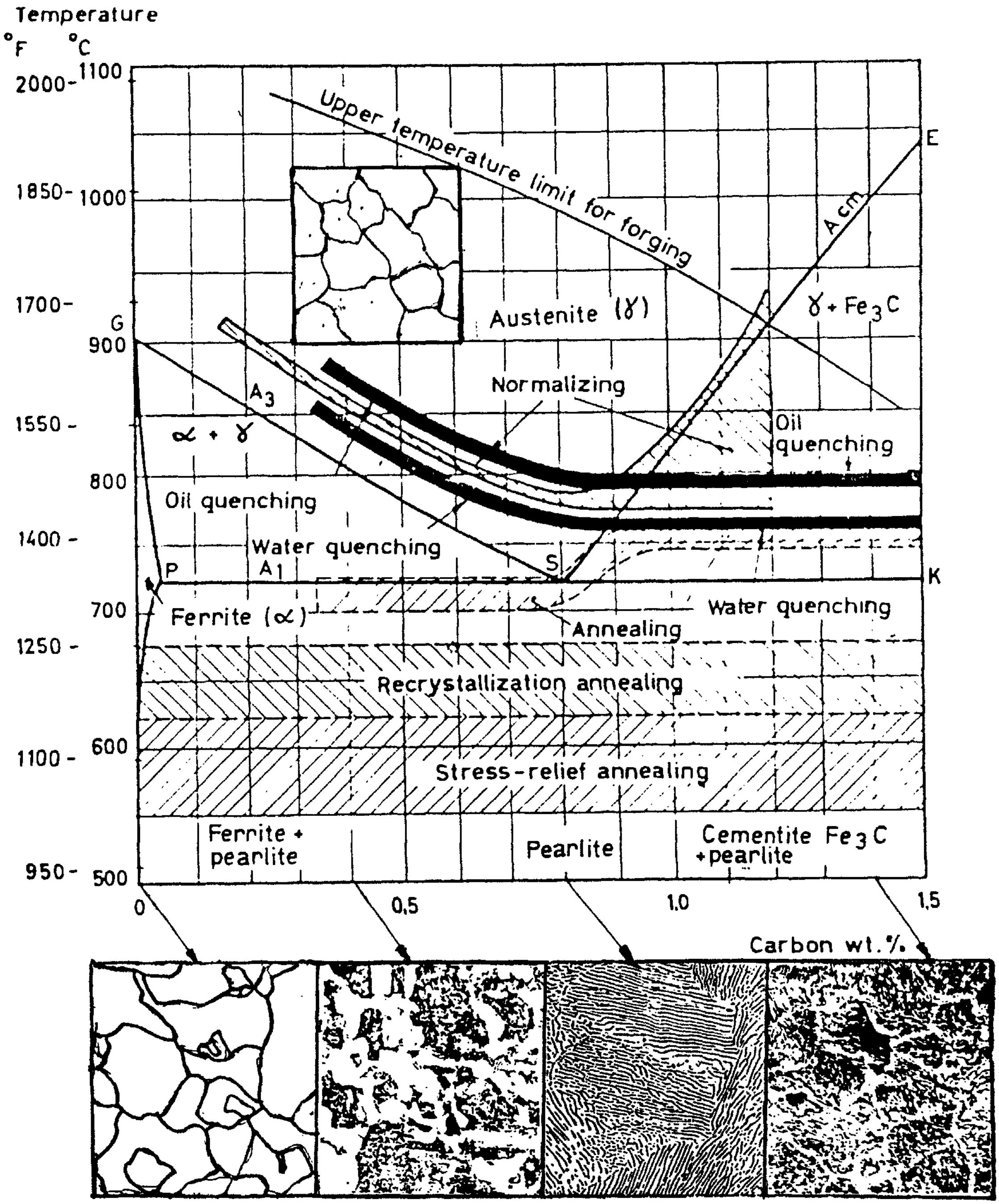


Fig. 7. Fe-C equilibrium diagram showing typical microstructures of Fe-C alloys and various ranges for thermomechanical treament.

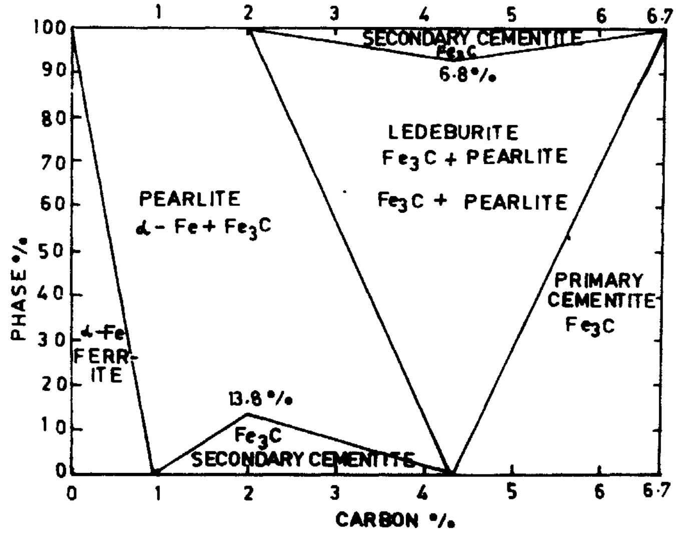


Fig. 8. Proportions of phases formed at room temperature of Fe-C alloys.

attained detailed knowledge about this and that is why they hot-forged such steels with great care and gave long term annealing treatment at cherry red temperature (~700°C). Although much details are not available but as described by Yater[2], the treatment given was most probably spheroidizing, to produce globular cementite in a matrix of ductile ferrite, which can be easily forged to give the desired shape. In modern heat-treatment practice, this treatment is given by repeated heating above 723°C and cooling it below this temperature.

The Indian swords and other war implements were manufactured either by making it by forge-welding and shaping wrought iron pieces followed by carburization of the edge or by skilfully sandwiching a high carbon steel piece between two wrought iron plates and forge-welding them to get a high carbon edge with flexible wrought iron blades. This was further heat-treated by quenching and tempering to produce the hard edge. For the production of the famous Damascus sword either this technique has been used or depending upon the size and weight of the sword blade a number of wootz steel ingots were spheroidized, then forge-welded and hot worked to give it proper shape as well as get a uniform distribution of the carbide. Then the sharp edge of the blade was skilfully given hardening and tempering by numerous ways mentioned in the ancient text and described here in the next section.

Prakash[30] has recently analysed the forging technology of the iron pillar at Dhar and predicted the use of iron pins and punches to weld together 600-700 mm long blocks of iron having a tapered square section of 203 to 260 mm width. Fig. 9 shows a schematic sketch of this technique. The skill of the ancient smiths is visible from the

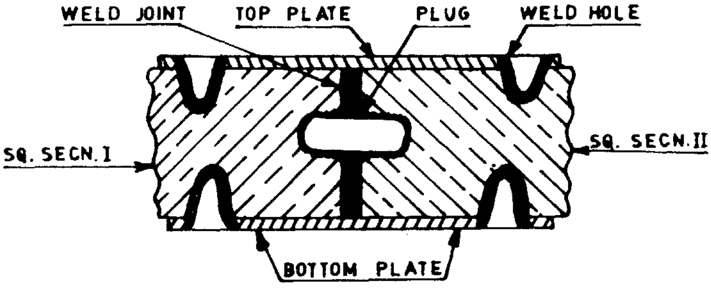


Fig. 9. Schematic diagram showing the hypothetical design of the joints of iron bricks to manufacture iron pillar at Dhar.

ornamented top of Delhi's Iron Pillar shown in Fig. 10. This figure* clearly shows the close fitting of the iron ring on the top section of the pillar as well as the square hole made to fit the Ashoka Emblem or a sculpture of 'Garuda'.

HEAT TREATMENT

The ancient Indian blacksmiths had gained very precise knowledge regarding the grain texture of various iron-carbon alloys, and they knew that the final hardness achieved on any cutting tool is dependent upon the combined effect of the following five variables:

(1) The carbon content of the alloy.

(2) The massivity or cross-sectional thickness of the object.

(3) The final temperature of the object from which it was quenched (900-1100°C).

(4) The severity of cooling achieved during quenching.

(5) Other factors such as control of the phase transformation by arresting the hardening treatment at an intermediate stage.

The ancient smiths were aware that by suitable control of these factors, a combination of properties such as hard cutting edge with flexibility of the blade or extra hard wear-resistant surface could be produced. Today the combined effect of all the above-mentioned variables can be described by the 'S' or TTT curves for various iron alloys. A typical 'S' curve for iron-carbon alloy is shown in Fig. 11[31]. Such Time-Temperature-Transformation curves (TTT) are extensively used to determine the

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*According to an expert N.R. Banerjee, the emblem of the upper part the shaft should not be called an Ashoka emblem. It is in fact an inverted Kalasa (pitcher). It did not have either an abacus or a capital, nor any indication of a Garuda Capital. The emblem of the capital is not called Ashoka emblem, for there is a chronological gap of nearly 700 years between Ashoka and the iron pillar.

Fig. 10. Top view of the ornamented iron pillar of Delhi showing the fitting of the square iron ring on circular end of the pillar.

precise heat-treatment to be given to the steel component to develop the desired property. For example, it is known that with increase in the carbon content of steel, the knee point 'N' of the curve shifts to right increasing the hardenability, i.e. it permits a slower cooling rate to attain the high hardness of Bainite or tempered Martensite. This effect becomes more clear if we consider the four cooling rate curves A,B,C,D in Fig. 12 for the same steel heated to 900-1100°C, and their effect on the final microstructure and property of the steel. If very slow cooling of the alloy is done from Austenite range (W) as depicted by the curves 'A' or 'B' very nominal hardening (Rc 5-30) will be achieved, because the alloy will have an annealed structure comprising ferrite, cementite and pearlite (P) (Refer to iron-carbon diagram shown in Fig. 9). In order to obtain the hardening treatment, a much faster cooling rate has to be obtained, as shown by the curves 'C' and 'D' which do not touch the knee point 'N' of the curve. This is achieved by quenching the red hot iron in water, oil or cold air blowing, etc. Once this is done, the hardness of the alloy will depend upon whether the cooling curve follows the path 'C' to end up with Bainitic structure (B) (Rc 40) or it follows the path 'D' to bring down the temperature below the MS boundary and end up at M_f line. M_s denotes the start of the Martensite structure (M) formation and M_f its finishing temperature. Martensite is very hard and brittle (>Rc 60) and the hardness in the intermediate stage, i.e., between M_s and M_f, depends upon the extent to which the Martensite phase is formed. Generally, this hardening treatment is followed by stress relieving or

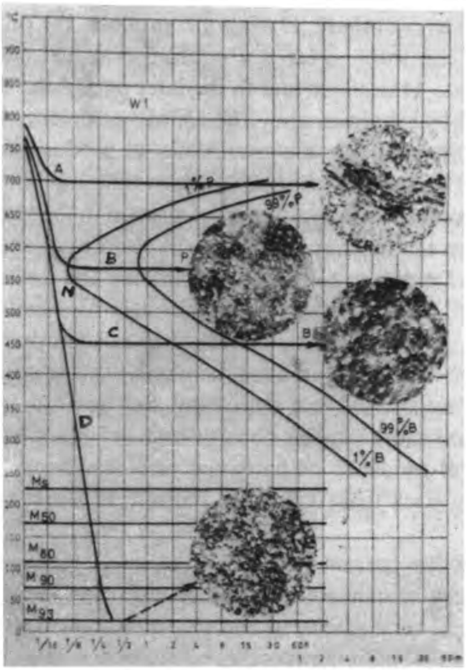

Fig. 11. Time-Temperature-Transformation diagram for hypoeutectoid steel[13] and the changes in structure as affected by the cooling.

tempering by reheating the component, as shown by the curve to the temperature shown in Fig. 7 to give rise to hardness between Rc 40 and Rc 50.

The knowledge gained by the ancient blacksmiths regarding heat-treatment is obvious from the different ways in which this was practised. For example Varāhmihira[20] has mentioned that the hardening of the sword was done by plunging it in whey in a mixture of water and plantain ashes or oil. Another way of achieving the hard edge on the sword was to run fast on a horse holding the red hot sword with its sharp edge in the front. The typical hardening treatment was given by quenching the red hot high carbon steel in water or oil for a few seconds and then withdrawing it to observe as the tempering was achieved due to the flow of heat from the body of the tool. The success of this treatment was judged by the colour (deep blue) attained at the edge of the tool. This typical treatment was called 'watering' of steel. Nevertheless, the process was shrounded by religious beliefs and the water for quenching of the steel has to be brought by a woman possessing certain characteristic features and fulfilling a number of conditions, such as, she should be a young girl, a mother, and she should not be in the period of menstruation, etc. *Rasa Ratna Samuccaya* has mentioned the role of women and their characteristic features in great detail.

The classical heat treatment given to the steel swords was to heat the blade to red hot condition and then insert the blade from the cutting edge side into a green trunk of a banana tree and allow it to cool there. During this process, the organic fluid and water present in the cells of the trunk created a cooling rate fast enough to transfer the Austenite of the edge into Martensite and in the later period the dried wood helped in self-tempering by acting as heat insulator. The cellular structure of the organic material probably reacted with the steel surface chemically to produce the typical 'watering' design found on the 'Damascus' swords, as shown in Fig. 6. Another method of hardening and production of 'watering' mark mentioned in the text reviewed by Yater[2] and Bronson[3] is to wrap the red hot sword in wet cloth to quench and temper it and afterwards produce the Damascurizing mark by etching the surface with a solution of zinc sulphate. If the hardened edge was found to be very hard and brittle, it was further tempered by heating it on fire to the stress relieving and tempering temperature, viz. 250 to 450°C. The practice of hardening and tempering of agricultural implements and other tools is still being carried out following the age-old water quenching and tempering processes and these can be observed at any blacksmith's shop in Indian villages. Archaeological evidence of hardened steel has been found by Ghosh and Chattopadhyay[32] dating back to 810 B.C. at Barudih in Bihar.

From the study of the present paper and the quality of iron and steel artifacts produced in the country it can be easily seen that the Indian iron smelters and blacksmiths had acquired very advanced and precise knowledge about the production technology of iron and steel, their thermo-mechanical behaviour, heat treatment as well as the resultant properties developed as a result of these process control measures taken during production. There is no doubt that this knowledge was confined to individual master craftsmen and they took pride in preserving it by teaching only to their selected disciples. So far there has been lack of archaeological evidence to support the status of the indigenous technology but the evidences collected during the excavations and study of new sites done during the last decade support the hypothesis of indigenous development of the iron technology in India. It is beyond doubt that further studies of the old sites, their findings and discovery of newer sites are required to support the status of the technology presented in this paper, and this can be achieved only by involving technologists and engineers of various disciplines in the excavation team, so that no evidence of technological nature is destroyed due to the ignorance of archaeologists or their workers.

REFERENCES

[1] Lowe, T.L., Ph. D. research report, Private communication.

[2] Yater, W.M., *The Anvil's Ring*, 11, 4 (1983) 2, *ibid*, 11, 4 (1983-84), 2.

[3] Bronson, B., *Archaeomaterials* 1, 1 (1986), 14.

[4] Turner, T., *J.I.S.I.* XLIV (1893) 162, *Ibid* (1894), 179.

[5] Buchanan, F.A., *Journey from Madras through the countries of Mysore, Canara and Malabar*, London (1807).

[6] Voysey, H.W., *Jour. A.S.Soc. Bengal*, I, 245, (1832).

[7] Hadfield, R., Sinhalese Iron and Steel of Ancient Origin, *J.I.S.I.* 85 (1912), 34.

[8] Elwin V., *The Agaria*, H.M. Oxford Press, Calcutta (1942).

[9] Prakash, B., *Bull. Met. Museum* 8, 23 (1983).

[10] Prakash, B. and V. Tripathi, *Metals & Materials*, Sept. (1986), 586.

[11] Prakash, B. and Igaki, K., Ancient Iron Making in Bastar District, *Indian Journal of History of Science* 19, (2), 172 (1984).

[12] Prakash, B, Methods of Iron Making in Early India, International Symposium on 'The Archaeometallurgy of Iron-Results Achieved 1967-1987', held at Liblice, Czechoslovakia, Oct. (1987).

[13] Ghosh, M., *TISCO*, 11, 3, 132 (1964).

[14] Kulkarni D.A., *Rasa Ratna Samuccaya*, Meherchand and Lakshmandas, Delhi (1969).

[15] Samuels, L.E., *Metallography*, 13, 1, 345 (1980).

[16] Bloomgren, S. and Tholander, E., *Scand. J. Met*, 15, 151. (1986).

[17] Prasad, K.K. *et.al.*, *Metal News*, 12,1,1, (1990).

[18] Kulkarni, R.P., *J. Inst. of Engineers (India) (Hindi Section)* 70, 1, 1. (1989).

[19] Suśruta, *Suśruta Sâmhitā*, Chaukhamba Orientation, Varanasi (1980).

[20] Ray, P., *History of Chemistry of Ancient and Medieval India*, Indian Chem. Soc., Calcutta (1956).

[21] Ball, V., *Manual of the Geology of India*, Part III, Economic Geology, Govt. Press, Calcutta, 355, (1981).

[22] Thomsen, R., Pattern welded swords from Illorup and Nydam, *Archaeometallurgy of Iron*, 1967-1987, Symposium at Liblice, Oct. (1987), 371.

[23] Kedzierski, Z. and J. Stepineski, *Ibid*, 387, (1987).

[24] Anteins, A. Results of metallographic examinations of pattern welded swords and lance heads in the Baltic area, *Ibid* (1987).

[25] Scott B.G. and H.Cleere, Eds., *The Craft of the Blacksmith*, Belfast, Sept., (1984).

[26] Verhoeven, J.D. and L.L. Zones, *Metallography*, 145, (1987), *Ibid.*, 153, (1987).

[27] Rao, K.N.P., *Metals News*, 11, (3) 1, (1989).

[28] Percy, J., *Metallurgy of Iron and Steel*, London (1864).

[29] Lowe, T.L., N. Merk and G. Thomas, Symp. on '*Materials Issues in Art and Archaeology*' USA, April (1990).

[30] Prakash, B., 'Archaeometallurgical Study of Iron Pillar at Dhar', Paper communicated to *Puratatva*.

[31] Thelring, K.E., Steel and its Heat Treatment, *Bofors Hand Book*, Butterworth, London (1981).

[32] Ghosh, A.K. and P.K. Chattopadhyay, *MASCA Journal* 2, 2, 63, (1982)