© 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. 92-103.

4

Iron in Ancient Tamilnadu

B. Sasisekaran* and B. Raghunatha Rao
Department of Metallurgical Engineering, Indian Institute of Technology, Madras.
**Former Research Associate INSA New Delhi, India.*

ABSTRACT

The early Tamil classical literature and the works from the west like Historia Naturalis mention the export of steel from south India to the Roman Egypt and other countries in the west. The Roman literature mentions that the steel imported into Rome from peninsular India was subjected to duty in the port of Alexandria. The archaeological excavations conducted at Paiyampalli, Appukkalu and other places in NorthArcot, Dharmapuri, and Coimbatore districts established a firm datum line for the beginning of iron in Tamilnadu. The iron and steel furnaces from Kodumanal besides a cast iron foundry at Guttur revealed the technological skill attained by the early smelters in Tamilnadu.

Key words: Furnace, Widmanstatten, Pearlite, Ledeburite, Urukku, Ulaikal.

INTRODUCTION

Iron made its appearance in the horizon of Tamilnadu around *c.* 500 BC. The archaeological studies in the districts of NorthArcot and Dharmapuri clearly established the datum line for the Iron Age in Tamilnadu. The historical and literary studies showed that the iron industry flourished in Tamilnadu and the export of steel to the countries like the Roman Egypt. The early Roman literature refers to the import of steel from the Chera country in south India. The maritime trade with the Roman world witnessed the growth of Indo-Roman trade in the peninsular part of the Indian sub continent from *c.* 100 AD to 300 AD. Periplus mentions the kingdom of the Cheras and their port Muziri as the chief port and an active shipping centre on the western coast[1].

The encyclopaedia of the Roman Empire, compiled by the elder Pliny under the title *Historia Naturalis*, refers to the iron from the Cheras[1]. Iron and steel especially wootz from south India was famous from early historic times. The famed south Indian Steel was the most sought after product in the Roman Egypt and other countries in the middle-east. The Roman knowledge of the peninsular kingdoms and especially that of the kingdom of the Cheras seems to have originated from Sri Lanka as it refers to the Cheras as Seres (in the Sinhalese language, the Tamil Chera became Seri).

The Wootz steel, Roman Egypt imported from peninsular India, was high-grade charcoal steel produced in a crucible furnace. The process of manufacturing was jealously held in secret by the producers in the Indian sub-continent and unknown to the Romans and others in the west. Periplus mentions *Ferrum-Indicum* among the list of articles, subjected to duty at Alexandria.

The discovery of an industrial and trade centre at Kodumanal near Karur, the capital of the Cheras, and the later excavations from 1986 to 1996 exposed iron and bead making furnaces at Kodumanal. The ancient industrial site, (*c.* 300 BC to 300 AD), is located on an ancient trade route connecting the West Coast with the east in the early historic time (*c.* 100 BC to 300 AD). Kodumanal was mentioned as a flourishing industrial and trade centre in the early Tamil classical literature Pattirruppattu (*c.* 100 BC to 300 AD, v. 67).

Tamil classical literature (Sangam) indicate the existence of three different varieties of iron viz., Irumbu (wrought iron) (Purananuru v. 170); Urukku (steel) (Purananuru v. 130 irumbu (cast iron) (Kurunthokai v. 155); and weapons made of steel as Ekku or Ekkam (Purananuru v. 61-13, 300).

It also abounds with reference to the blacksmith forge, the smelting operation, and his importance in the ancient war loving Tamil society. Different class of people did the smelting of iron from ore and converting it into steel and manufacturing of weapons from steel. Their relative position in the society is mentioned in the Tamil literature (Purananuru v. 287, v. 170). The iron smelting operation was carried out by people of low caste as against the blacksmith who converted them into steel and made artefacts.

The excavations at Kodumanal corroborate the relative living quarters of iron and steel producers mentioned in the Tamil classical literature. The living quarters of the iron smelters were simple structure with mud flooring and was on the periphery of the habitation area, while the well paved floor of the steel manufacturers was found in the midst of the habitation area.

The blacksmith formed an integral part of the early historic society (classical literary period 1st century BC to 3rd century AD). The blacksmith formed part of a state sponsored workers group in the armies of the Tamil kingdoms. Purananuru (v. 268) states that it is the duty of the blacksmith to manufacture vel or dart for the gallant soldiers. The blacksmith's forge and his instruments are aptly referred to in the classical literature in different context. The *Kollan* or iron-maker or iron-monger cum blacksmith, *Karumkaikollan* –the skilled worker in iron, *ulai* or his

furnace, *turutti* or *visaiturutti* –the hand worked or pedal bellows, *Kuruki* –the blow pipe or nozzle, *ulaikkal* –the stone anvil, *kudam* –the sledge hammer, and *kuradu* –the tongs are mentioned in the classical literature. The blacksmith's forge with all its equipment is mentioned in the classical literature (Ahananuru v. 202). It refers to the sparks flying off the blacksmith furnace (Ahananuru v. 72), the fire in it blown through the blow pipe or nozzle (Ahananuru v. 224) and the work up by the pedal bellows (Perumpanrruppadai v. 207, Narrinai v. 125) operated by treading on it repeatedly with the foot by the assistant and the related shocks that the anvil (ulaikal) receives where the object of work on it is struck by the powerful hammer (Purananuru v. 170).

The remains of a Blacksmith forge consisting of all the necessary equipment from Ujjain excavation (period II, 500-200 BC) such as a groove for the introduction of Nozzle of a bellows, an improvised stand made from the large of a broken vessel to support a water jar to store water for quenching, the use of an anvil and iron tools like pincers (Banerjee[2]), though far away removed in distance clearly reflect the expression given in the early Tamil Classical literature *Manimekalai* The black smith from Ujjain was known and sought after by the early Tamil people is indicated by the literary reference to black smith from Ujjain (Manimekalai XIX, II, 107).

Ahananuru mentions iron and steel by the term *Irumbu* (Ahananuru v. 72) and *Urukku* (Puananuru v. 13) and the superiority of weapons made of steel (urukku). Weapons made of steel were always referred to as "EKKU" or "EKKAM". Purananuru refers to the quenching of iron piece held by the tongs and heated red first in the fire and then plunging into the water (Puananuru v. 21). Other than the weapons of offence and related articles (the ferrules covering the tusks of elephants are generally made of iron) objects of daily use like knife and chisel were all made of steel. Another classical literature Kurunthokai v. 155 refers to the artefact made of iron by casting. It mentions that iron lamps and bells were made by cire-perdue (lost wax) process in the blacksmith foundry (Kurunthokai v. 155).

Iron smelted from the ore was a pasty semi-solid mass with lot of non- metallic inclusions. The iron thus produced requires further treatment to remove non-metallic inclusions. This was done by hammering the red-hot sponge iron on an anvil. When hammered sparks flew in all directions from the sponge, iron, and when sparks ceases the blacksmith knew that the metal had become homogeneous. Tamil classical literature Agananuru refers to the preparation of wrought iron from the bloom. The literature mentions that in the blacksmith's forge sparks flew in all directions when the smelter hammered the red-hot iron on an anvil to remove the non-metallic inclusions (Agananuru v. 202).

ARCHAEOLOGICAL STUDIES

Iron according to Chakrabarti[3] entered the Indian productive system by 800 BC and central and southern India with its rich iron ore and pre industrial smelting tradition seem to show the first evidence of Indian iron. However, the evidence on iron obtained[4] from megalithic sites in Deccan, Karnataka, Andhra Pradesh and Tamilnadu viz., Naikund (BS: 265: 520±100 BC, Habitation mound II, layer

6, Burial no. 7, BS93: 54 ±105 BC), Takalghat (middle phase of megalithic habitation TF 783: 615±105 BC & 555±100 BC,) Bhagimohari (habitation-cum-burial, layer (9) BS 537: 690± 100 BC, BS 536: 750±100 BC). Hallur and Kumaranahalli in Karnataka and Veerapuram in Andhra Pradesh and Paiyampalli in Tamilnadu, indicate the diffusion of iron in Deccan, Karnataka and Andhra Pradesh around 7th century BC and Paiyampalli in Tamilnadu around 6th century BC. The Neolithic-megalithic overlap in phase I at Hallur (T.F573: 955±100 BC) and Kumaranahalli (PRL TL: 50:1140±270) in Karnataka and Veerapuram (PRL 728: 920±140 BC, and PRL 730: 1200±140 BC) in Andhra Pradesh has been dated to *c.* 1000 BC, on the basis of a C^{14} data. However, Iron made its appearance in the middle levels of phase II at Hallur[5]. Based on its occurrence in the middle levels of phase II at Hallur, the introduction of Iron in productive system in Karnataka region can be safely deduced to around *c.* 700 BC[6].

The megalithic people, identified with the authors of Iron in Tamilnadu appeared on the horizon of Tamilnadu during the late phase of the neolithic culture datable to circa. 600-500 BC. The districts of Dharmapuri, Coimbatore and North Arcot bordering Karnataka and Andhra Pradesh formed the nuclear zone of iron age culture in Tamilnadu. They represent a distinctive phase of culture that came in succession to the primitive neolithic culture. The new settlers by their knowledge of mining and metallurgy and their exploitation of rich natural resources enriched the pattern of living in the area of their settlement[2]. The overlap of neolithic–megalithic periods witnessed at Paiyampalli in Tamilnadu has also been observed at Hallur (IAR: 1964-65:31-32) in district Dharwar, Banahalli (IAR: 1983-84: 42-46, IAR: 1985-86) in district Kolar in Karnataka and Hullikalu and Pagidigutta in Andhra Pradesh (Chakrabarti[3]). The excavations at Banahalli have provided a clear cut picture about the developmental stages of the transition from neolithic to iron age (Dikshit: Puratattva 22)[7]. The megalithic period in Tamilnadu had a short span of time and ended with the beginning of early historical period in the late centuries BC, and the early centuries AD But the practice of erecting memorials i.e., hero-stones continued longer and even up to the mediaeval period (Chakrabarti[3]).

The settlement pattern of megalithic habitation sites showed their preference for perennial rivers or their tributaries and in the absence of major river system, they made their settlement near perennial ponds. The Iron Age habitation in Dharmapuri and North Arcot region reveals their concentration along the course of river Pennaiyar and its tributaries. The habitation sites situated near the tributaries of Pennaiyar include Guttur, Mallappadi, Togarapalli, Dailmalai, Mullikkadu, and Chandrapuram in Dharmapuri district, Paiyampalli, Kallerimalai, and Chengam in North Arcot district. There is a wild stream running near the habitation site at Appukkallu. The megalithic folk at the time of their entry had an essentially pastoral economy. The migration from the point of entry to the interior region showed their development from village based economy to the establishment of large towns where trade, commerce, and industry flourished.

Archaeological excavations brought to light iron and steel producing furnaces besides slags in the lowest stratum of the iron age settlements in the sites

excavated in Tamilnadu. The discovery of white cast iron producing furnaces at Guttur in Dharmapuri district datable to *c.* 500 BC and iron and crucible steel furnaces at Kodumanal datable to *c.* 300 BC revealed the technical skill of the ancient smelters. Besides these two industrial sites exposed in the later half of the twentieth century, the excavations conducted in the years 1875 and 1901 at the mounds containing vestiges of ancient iron industry at Nattukkal Palayam and Kannarappalayam brought to light hollow terracotta rings, datable to *c.* 300 to 100 BC. The terracotta rings measured 30 CMS in diameter and provided with a spout. The molten iron might have been poured inside the ring through the spout and was water quenched either to cool fast as revealed from the analysis of artefact from Guttur (Rao and Sasisekaran[8]) or left for sometime to air cool slowly as revealed from the analysis of artefact from Kodumanal[9]. On cooling down the iron would get the shape of the terracotta ring and the cast iron was recovered by breaking the mould. (Rajan[10]).

The excavations carried out at Paiyampalli, Appukkallu, Togarapalli, and other sites in the districts of North Arcot, Dharmapuri, established a firm datum line for the beginning of Iron Age in Tamilnadu.

Paiyampalli

The habitation – cum burial site Paiyampalli (12° 30' N 78° 36'E) lies on Bangalore–Madras trunk road and about 5 km east of Barugur and 8 km west of Natrampalli in Tiruppatur taluk of North Arcot district. The archaeological site is located on the terraces of Talattappamalai hill forming part of Javadi hills. The excavations conducted in the years 1964-65 and 67-68 at Paiyampalli (Rao[8]) brought to light two cultural periods, viz., the Neolithic (period 1) and the megalithic (period II). The carbon–14 determinations of the charcoal samples indicated for period I A date at 1390±100 B.C and for period II at 315±100 BC.

The excavation revealed two phases A (layers 9 and 8) and B (layers 7, 7a, 6, 6a and 5) in period I. The layers 6a, 6 and 5 of phase B in period I, yielded iron artefacts along with megalithic Black and red ware, neolithic Grey ware potteries and polished stone axes in one of the middle terrace (IAR: 1967-68:31). The absence of bone tools and the marked preference for built in huts with floors levelled with stone chips and plastered over with ash- mixed earth showed improvement in the economy of the people in phase B than the earlier culture. The Neolithic settlers at Paiyampalli used to cultivate cereals and pulses. Charred grains of horse gram and green gram were found in those levels where a few sherds of megalithic pottery occurred in an essentially Neolithic habitation-level. The co-occurrence of Neolithic and megalithic elements in layers 6a, 6 and 5 with an occupational deposit of 30 CMS in period I illustrate the existence of these two cultures for a considerable period of time (200 years) before the emergence of iron using migrant as a single dominant culture in period II.

Period II represented the megalithic culture. The megalithic pottery of Paiyampalli is similar to that of other sites, except in respect of the abundance of a comparatively

thin but coarse red ware painted in chocolate, met with at the habitation. The Black and red ware, all black ware and the red ware formed main ceramic of the period II. Russet coated painted ware made its appearance in the late levels of period II. The megalithic people at Paiyampalli smelted iron and produced a large variety of tools and weapons locally, probably from the time of their arrival *c.* 500 BC, is indicated by the enormous quantity of iron slag and ore found all over the site. Sickles spears, chisels, nails, and axes were found in the habitation area (IAR[11]: 1967-68:31). The excavation at Paiyampalli has provided a firm datum for the introduction of iron in the Northwest part of Tamilnadu.

Appukkallu

The excavations at Appukkallu further confirm the migration of iron producing Black and red ware people into NorthArcot region around *c.* 500 BC. The village Appakkallu lies 1 km from Anaicut in Vellore taluk. The University of Madras excavated the habitation site in the years 1977 and 80 (Raman: IAR: 1976-77: 47). The trenches laid on six locations yielded three cultural periods and in this the period 1 yielded megalithic culture with lingering Neolithic elements in the lowest stratum. Though the Black and red ware pottery made its beginning in layer 15 (APKLI), the succeeding, two layers (14,13) formed the peak of its cultural activity at Appakkalu. This was revealed by the profuse occurrence of very fine variety of thin Black and red ware with lustrous polish and all black ware along with a large quantity of iron slag in these layers.

The charcoal collected from a pit sealed by layer 12 in APKL-I, which overlies layer 13,14 and 15 with a cultural deposit of 0.97 metres, has given a C^{14} determination[6] of 300 BC (B.S. 2300±140). The layer 15 yielded along with Black and red ware pottery a few grounds stones of indeterminate shapes devoid of Neolithic pottery (IAR: 1976-77: 47). The lingering of pre-megalithic elements at the beginning of period I is further established at other sites like viz., Mallappadi, Kallerimalai and Malaiyamputtu in North Arcot district. The occurrence of iron slag in large quantities in layer 14 of APKL I indicate that the Black and red ware people at Appakkallu smelted iron and produced artefacts in large numbers locally at a time which is coeval to Paiyampalli *c.* 500 BC.

Togarapalli

The village Togarapalli is situated about 20km South-Southeast of Krishnagiri, on the Krishnagiri - Mattur road. The ancient site is nearly 2km north of the village Togarapalli. The megalithic and early historic settlement are found on the terrace of the hill the Neolithic cultural remains were found on the foot of the hill .A stream, a tributary of Pennaiyar is running 2km west of the site. The stratigraphical section scraping conducted at Togarapalli by Narasimhaiah[12] on the terrace of the hill brought to light megalithic habitation on layers five and six. The charcoal sample collected from layer 5, which overlies the 0.25 mts thick layer 6 has given a C^{14} date of 290 BC, (calibrated). Narasimhaiah[12] concluded that the 0.25 Mts. thick habitation deposit below the layer 5 would make the beginning of the Black and red ware in this region around *c.* 500 BC.

METALLURGICAL STUDIES

Metallurgical study of select iron artefacts from Guttur and Kodumanal revealed the technology that went into the making of these artefacts. The excavation in the year 1982-83 at Guttur 12° 25' N 78° 15' E near Krishnagiri brought to light for the first time in Tamilnadu an industrial centre datable to c. 500 BC where iron articles were produced by casting. The excavation revealed a twin-elongated oval shaped furnace each measuring 2.02mts in length 0.63 mts in weath and 0.45 mts in depth (Fig. 1). The thickness of the wall portion measures 0.04 mt on its northern side and 0.08mt on its southern side. Brick structure was found on either side of the furnace and in between of the twin furnace. The one at the middle was probably used for the bellows and the brick structure on its side for the filling of the furnace fuel and ore while the smelting was in progress. The exposed portion of the furnace showed three openings one on its side and two in front with earthern pipes. The one at the bottom indicates the arrangements for the retrieval of molten iron on its sides. The measurement of the furnace showed that it could have been the largest furnace in operation at that time in India. Prakash quoting Francis Buchanan states that the twin furnace in operation in the Malabar region in the 18th century was the largest furnace with a production capacity of 250 kg per smelting operation. The twin furnace dimensions that Buchanan wrote

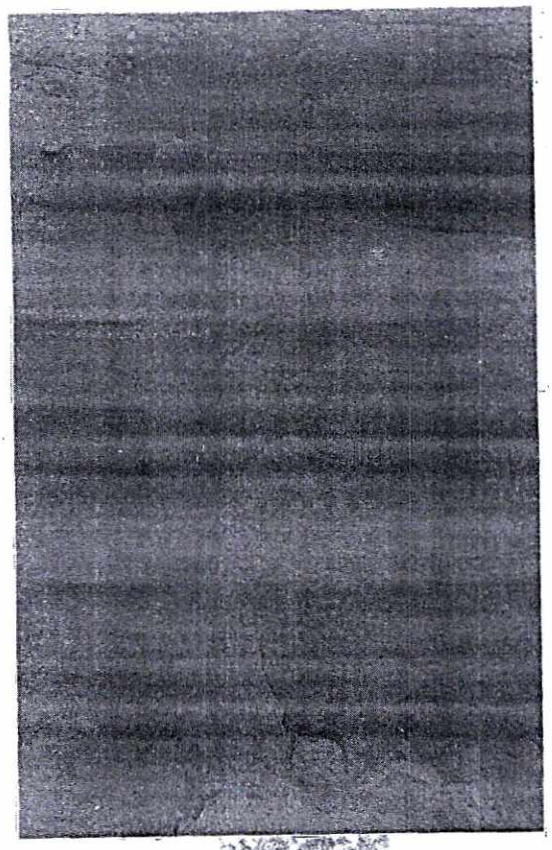

Fig. 1 : Exposed portion of a twin elongated oval furnace.

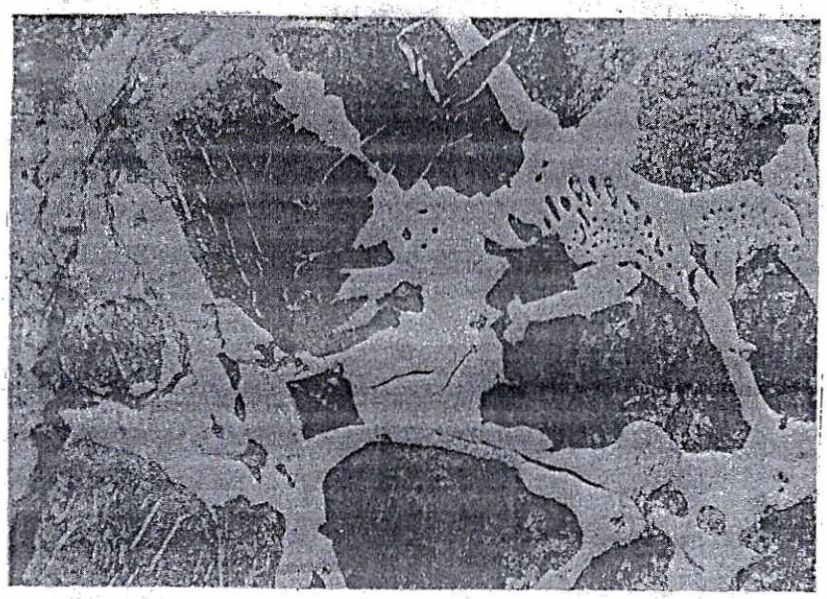

Fig. 2 : Microstructure of the artefact containing cenebtute (white, pearlite (black) and ledeburite with microhardness impressions (280x)

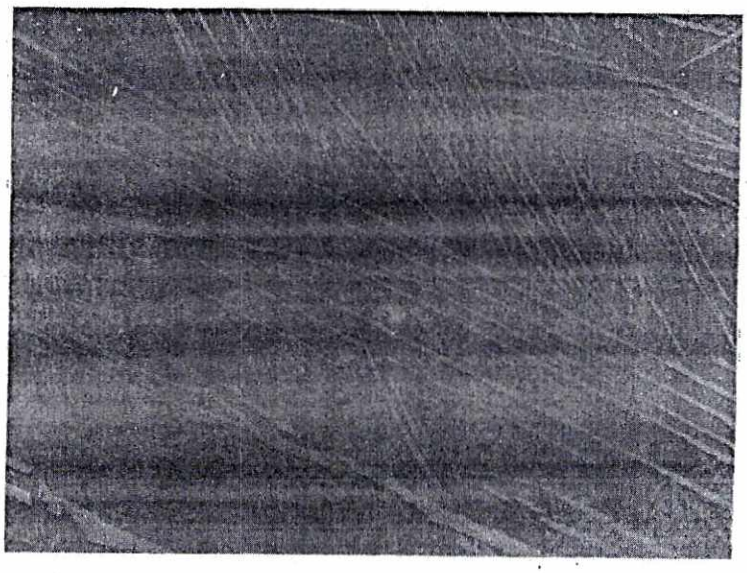

Fig. 3 : Primary cementite platelets in some zones of the artefact (700x).

in his memoirs tally exactly with the one exposed at Guttur (Buchanan[13]). The chemical analysis of the iron artefact showed that it was a cast iron with carbon content varying from 3 to 5%. The microscopic examination across the cross section of the specimen revealed a widely varying structures viz., dark etching pearlite, white etching iron carbide known as cementite and ledeburite (Fig. 2) as well as cementite platelets (Fig. 3) and also martensitic structue[8] (Fig. 4). The microhardness measurements showed that the white etching region, cementite

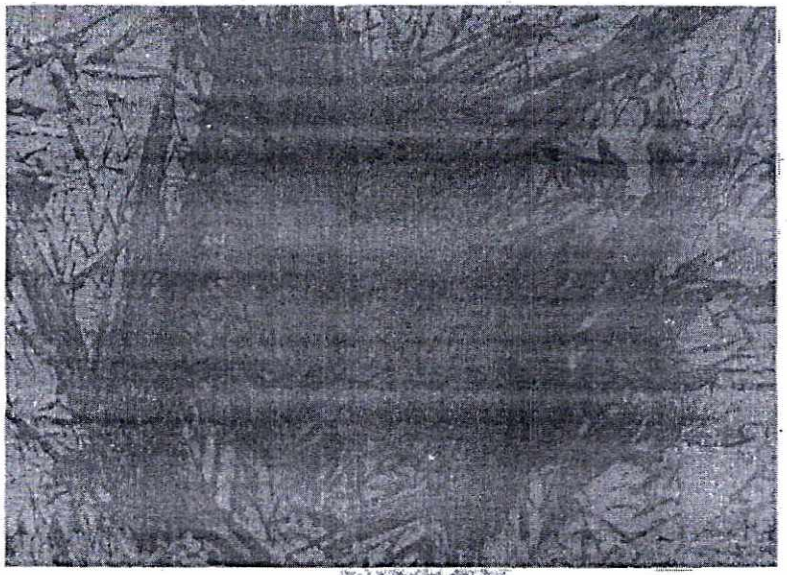

Fig. 4 : Microstructure of acicular martensite observed in a few regions (1400x).

has 900 VHN and the black etching region, pearlite has 190 VHN. The ledeburite structure is a transformation product obtained at 1140°C upon cooling the molten metal from a higher temperature of about 1300°C. From the metallurgical studies made, it appears that the metal artefacts were made from white cast iron and water was splashed during solidification of the metal. The discovery of twin iron furnace and artefact from Guttur datable to *c.* 500 BC indicates the existence of a cast iron industry producing finished iron artefact as manufactured in a modern iron foundry[8]. The archaeological evidence from Guttur and other places was further corroborated by the reference in Kurunthokai an early Tamil classical literature where in it was stated that the ancient metallurgist produced iron objects like bell by cire perdue (lost wax) process (Kurunthokai v. 155). The study of the Indian pre-industrial iron technology has started around eighteenth century AD, when the westerners tried to understand the metallurgical properties and manufacturing process of the pre-industrial Indian steel known as wootz[3]. The term Wootz for the Indian steel was originally derived from the Tamil word Urukku (Purananuru v. 13) meaning fused metal or steel also called Ukku in Kannada and Telugu (Burrow 1961).

The excavations at Kodumanal in Tamilnadu yielded important evidence on the manufacture of steel by crucible process as early as *c.* 300 BC[9]. The excavations exposed two crucible furnaces of which one is found in used condition. These furnaces were found at a depth of 125 cm below the ground, right on the natural soil. The main crucible furnace was surrounded by more than 12 small furnaces as shown in the line drawing of Fig. 5. The main furnace was oval and measured 112 cm-north-south and 100cm-east west. The furnace had a depth of 40cm. The furnace wall had a thickness of 20cm. The top of the furnace wall showed rectangular holes at acute angles. The small furnaces surrounding the main furnace had a diameter of 30 cm at the mouth with a small hole at the centre.

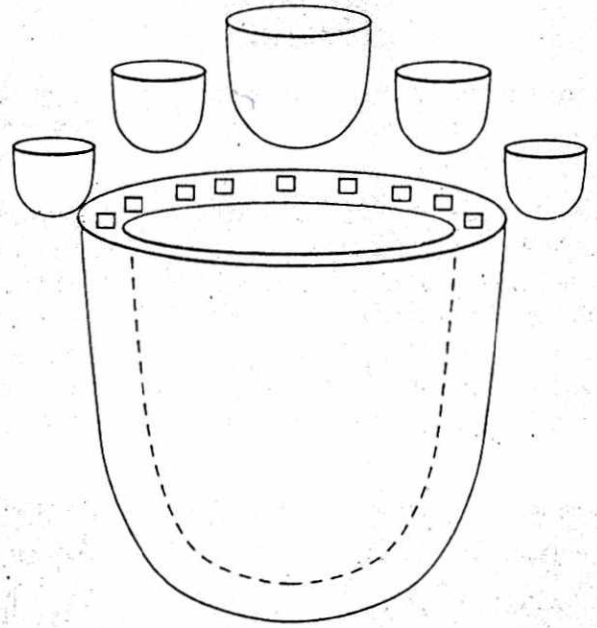

Fig. 5 : Line drawing showing outline of crucible furnace surrounded by small crucible furnaces.

The small furnaces were connected to the main furnace through burnt clay pipes. The absence of tuyeres in the crucible furnace and its link to the small furnaces through clay pipes indicates that the crucible furnace and the surrounding small furnaces were operated by using natural drought for blast. The small furnaces were probably used as fast cooling zone. A partially broken crucible in vitrified condition was found insitu in one of the small furnaces. The bowl shaped crucible had a diameter of 0.9 cm at the top with a thickness varying from 7mm to 9mm

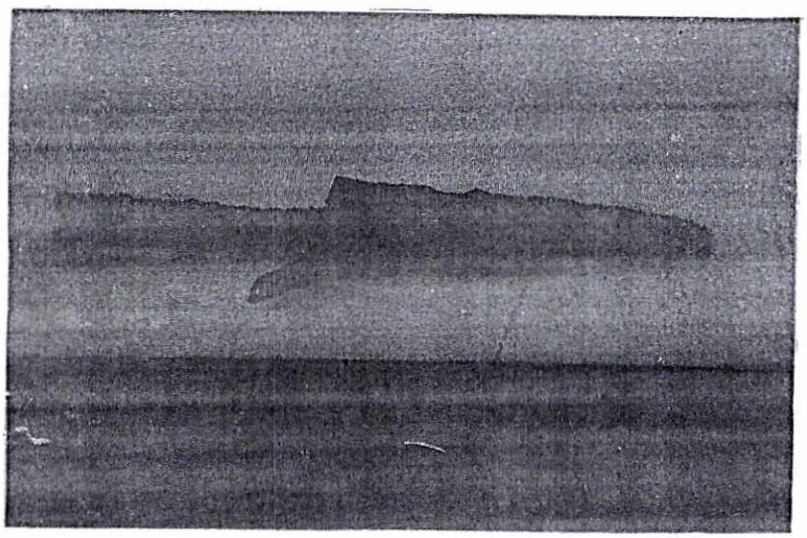

Fig. 6 : Iron arrowwhead excavated from Kodumanal

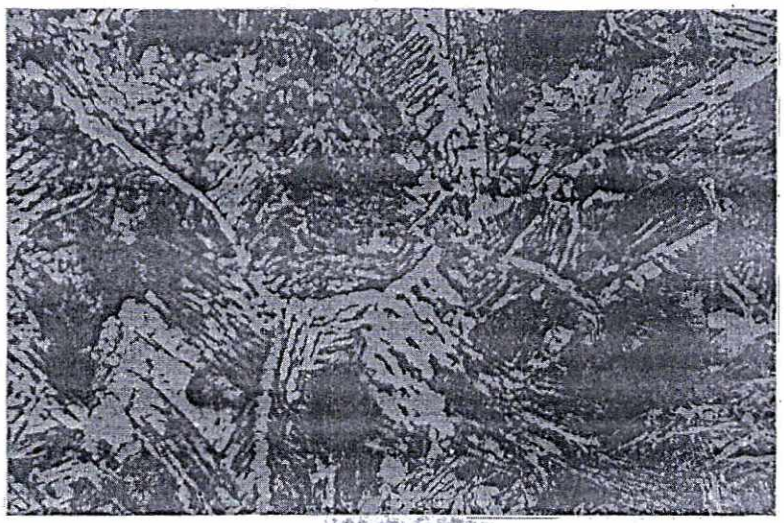

Fig. 7 : Microstructure showing a widmanstatten structure in some regions of the arrowhead 1000x.

from top to bottom of the crucible (Rajan[10]). The nineteenth century accounts on the manufacture of wootz steel in the Salem region describe the use of bellows and tuyere during the operation. They were silent on the use of small furnaces as fast cooling zone. The excavation from Kodumanal amply illustrates the use of natural drought instead of forced drought as in the 19th century crucible furnace in the Salem region. Metallographic analysis of an iron arrowhead (Fig. 6) datable to ancient period c. 300 BC, from Kodumanal revealed widmanstatten structure (Fig. 7). The widmanstatten structure occurs in steels which has been rapidly cooled from high temperature (~1000°C) but not quenched with water. It is formed by the ejection of ferrite or cementite along certain crystal planes forming a mesh like arrangement (Tylecote[14]). The absence of martensite and the presence of widmanstatten structure confirm that it was a fast cooled artefact but not water quenched. The postholes found around the crucible furnace and the floor level indicates that there was a super structure over the workshop. The location of the crucible furnace site in the midst of the habitation area and the relatively better living condition of the smelters making steel than their iron smelting counterpart points to the flourishing market for this value added product. The iron and steel industries at Kodumanal played an important role in Trans-regional trade in ancient period. This is clearly revealed by the occurrence of Sanskritised inscriptions in Brahmi script and punch marked coins and Roman potteries in the habitation area contemporaneous to the iron and steel industries discovered (Rajan[10]).

CONCLUSION

The iron and steel industries and their metallurgy were well developed in ancient Tamilnadu. Many types of artefacts were made and also exported to the Roman world. Three different types of furnaces viz.; bowl furnace, crucible furnace and twin elongated oval shaped furnaces were found to be employed by the ancient smelters.

REFERENCES

1. Schoff, W.H., 1915. The eastern trade of the Roman Empire, Journal of the American Oriental Society, Newyork, Vol. 35.
2. Banerjee, N.R., 1965. Iron age in India.
3. Chakrabarti, D.K., 1992. The Early use of Iron in India, Oxford University Press, Bombay.
4. Deo, S.B., 1994. New Discoveries of Iron Age, In India, Indian Archaeological, Heritage, Agam kala Prakashan, pp. 189-197.
5. Gaur, R.C., 1983. Excavations at Atranjikhera, Motilal Banarasidas. Delhi.
6. Bharadwaj, H.C., 1973. Aspects of Early Iron Technology in India, in D.P.Agarawal and A.Ghosh (Eds), Radiocarbon and Indian Archaeology (RIA), pp. 391-400.
7. Dikshit, K.N.,1992. Iron Age and Peninsular India, Puratattva, 22, pp. 31-34.
8. Rao, B. Ragunatha and Sasisekaran, B., 1997. Guttur-An Iron Age Industrial Centre In Dharmapuri District, I.J.H.S., Vol. 32(4), New Delhi, pp. 347-359.
9. Sasisekaran, B and Rao, B. Ragunatha., 1999. Technology of Iron and Steel In Kodumanal–an ancient Industrial Centre in Tamilnadu. Vol. 34(4), pp. 263-272, Journal of H.O.S, I.N.S.A. New Delhi.
10. Rajan, K., 1994. Archaeology of Tamilnadu (Kongu Country) Book India Publishing House, Delhi.
11. IAR, The Director General, 1964–1980. Indian archaeology A Review The Archaeological survey of India New Delhi.
12. Narasimhaiah, B., 1980. Neolithic and Megalithic Cultures In Tamilnadu, Sandeep Prakashan, Delhi.
13. Buchanan, F., 1807. A Journey from Madras, Vol. 3, London.
14. Tylecote, R.F., 1962. Metallurgy in Archaeology, Edward Arnold, London.