

## **Wootz crucible steel: a newly discovered production site in South India**

Sharada Srinivasan

Institute of Archaeology, UCL

### **Introduction**

High-carbon iron alloys are known to have been produced in parts of Asia such as India, where a traditional crucible steel has been produced, (Bronson 1986; Smith 1960: 14-24) and in China, where cast iron was produced (Tylecote 1976: 85), long before they came into vogue in Europe (Lowe 1988). The repute of Indian iron and steel can be traced to Classical Mediterranean accounts (Bronson 1986: 18). European travellers and geologists from the seventeenth century onwards have described the production of steel ingots, in different parts of South India (Fig. 1), by crucible processes. Such accounts were made in the former province of Golconda, Andhra Pradesh (Voysey 1832), the former state of Mysore (modern Karnataka) (Buchanan-Hamilton 1807) and Salem district in Tamil Nadu (Buchanan-Hamilton 1807, Wood 1893); Coomaraswamy (1956: 192-3) has also described crucible steel processes at Alutnuvara in Sri Lanka. This South Indian steel was named wootz, a European corruption of the Telegu word for steel, *ukku*.

Indian wootz ingots are believed to have been used to forge the famed Oriental Damascus swords which have been found to have a very high carbon content of 1.5-2.0% (Smith 1960: 14-6). The Persian Damascus blades, made in Khorasan and Isfahan from South Indian wootz from Golconda, were known to be the finest weapons then made in Eurasia (Bronson 1986: 22-3, Smith 1960: 14-6) and were reputed to cut even gauze kerchiefs (Bronson 1986: 1). The properties of South Indian steel, which became synonymous with Damascus steel, were investigated during the nineteenth and twentieth centuries by numerous European scientists, chemists and metallurgists with the aim of reproducing it on an industrial scale (Smith 1960: 25-9). A typical wootz ingot analysed in 1804 by Mushet (cited in Smith 1960: 22) was found to contain about 1.3 % carbon and had a dendritic structure (Smith 1960: 22). European scientists who were successful in replicating and forging wootz included Stodart who found that wootz steel had a superior cutting edge that of any other steel (Bronson 1986: 30) while Zschokke in 1924 (cited in Smith 1960: 14) found that with heat treatment this steel had special properties such as higher hardness, strength and ductility.

Recent investigations of the Indian wootz process have concentrated on material from the known sites of Konasamudram, Nizamabad district or former Golconda, Andhra Pradesh (Lowe 1990; Voysey 1832) and Gatihosahalli in the Chitradurga district of Karnataka (Frøestone and Tite 1986; Rao 1970). These investigations have shown the existence of specialised, standardised and semi-industrial production techniques dating from at least the late medieval period. During the course of field investigations of copper mining and smelting in South India, the author of this paper came across a previously unrecorded archaeometallurgical site in Mel-siruvalur, South Arcot district, Tamil Nadu,

which investigations have confirmed was a production centre for wootz crucible steel in the Deccan. The find of this production centre supports the idea that wootz steel production was relatively widespread in South India, and extends the known horizons of this technology further.

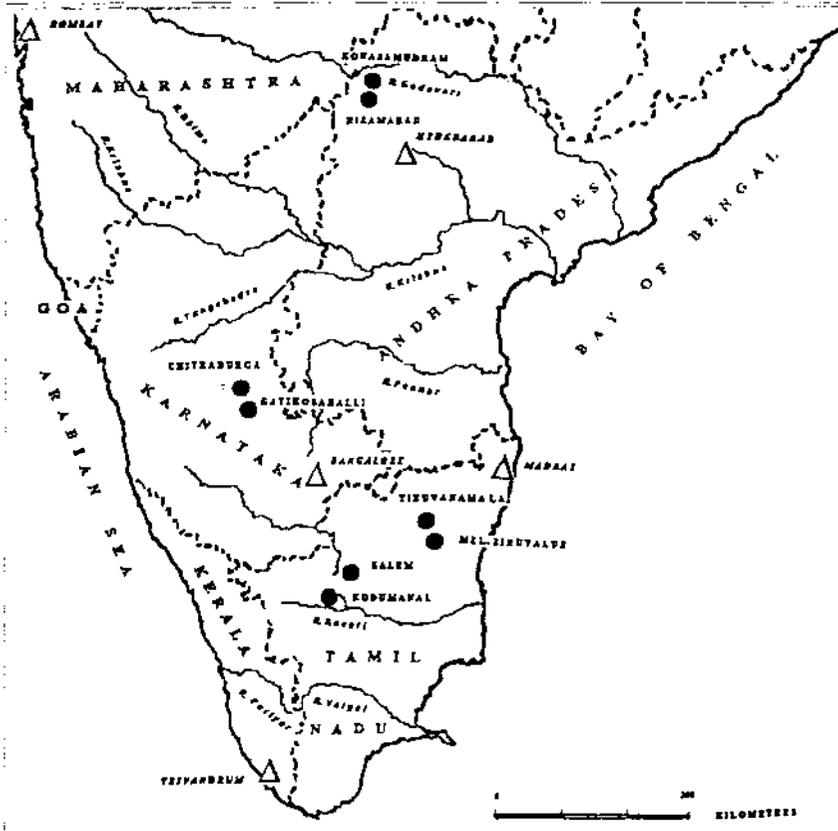


Figure 1 Map of South India indicating sites mentioned in the text.

### History of South Indian steel

Bronson (1986: 18) summarises eight mentions in Classical Mediterranean literature of Indian iron or steel. The earliest of these is that of the Greek physician Ctesia of the late fifth century BC; who mentions the wonderful swords of Indian steel presented to the King of Persia (Bronson 1986: 18; Schoff 1915). The import of Indian iron and steel to the Roman world is suggested by Pliny's *Natural History* which refers to iron from the Seres, identified with the Southern kingdom of the Cheras, while the *Periplus of the Erythraean sea* unequivocally mentions that iron and steel were imported from India (Bronson 1986: 18; Schoff 1915). Although the literary references have not yet been corroborated archaeologically, excavation and investigations on the iron-rich

megalithic sites of Tamil Nadu and the Malabar (mid first millennium BC to early centuries AD) could be revealing: these fall within the domain and period of the Sangam Chera kingdom which may relate to Roman accounts of Seric iron or Chera iron. Indeed recent excavations at an iron age megalithic site at Kodumanal, Tamil Nadu (c. third century BC), close to Karur, the capital of the Chera kingdom of the Sangam era (c. third century BC-third century AD) has revealed furnaces stacked with vitrified crucibles which were found separated from abundant iron slag (Rajan 1991: 98).

More concrete literary evidence of ancient Indian steel is found in later Arab and Middle Eastern sources. Pre-Islamic Arabic literature of the sixth-seventh centuries AD, such as Hamasa's collection of poems, refers to swords of Al-Hind or Hinduwani from India; while Islamic writers such as Jabir Ibn Hayyar of the 8th century and Al-Biruni of the eleventh century AD make it clear that South Asian steel from India and Sri Lanka was used in many places for sword making (Bronson 1986: 19). The Arab Edrisi (cited in Schoff 1915: 232) comments that it was impossible to find anything to surpass the edge obtained from Indian steel. The first explicit documented evidence of the export of wootz steel from South India to make Persian Damascus blades comes from Tavernier (cited in Bronson 1986: 23) who in 1679 mentions the trade in steel from former Golconda near Hyderabad, Andhra Pradesh, which was the only sort which could be damascened by Persian artists, by etching with vitriol.

The considerable European interest in the nineteenth century in wootz steel and Damascus blades contributed greatly to the development of metallography in Europe, as pointed out by Belaiew (1918) and Smith (1960). Such metallographic interest was aimed at understanding the distinctive wavy duplex pattern of the Damascus blades and their relation to the crystalline structure of the wootz ingot from which they were produced. The mechanical properties of wootz steel were also much speculated about, and indeed the steel was replicated with success and used to make surgical and high-grade cutting tools by cutlers like Stodart and Damemme (cited in Smith 1960: 25-6). Attempts to duplicate wootz lead to important experiments, on wootz and alloyed steel, by Michael Faraday in association with Stodart (Smith 1960: 25).

Past observers of the manufacture of wootz steel in India have commented on the process of carburisation of iron to steel in crucibles where a batch of closed crucibles with the low carbon iron charge were stacked in a large furnace and fired in a long 14-24 hour cycle at high temperatures up to 1200 °C in a strongly reducing atmosphere (Percy 1860-1880: 773-6). Three different types of crucible processes have been described by nineteenth century travellers varying from region to region, i.e. the Deccani or Hyderabad process, the Mysore process and the Tamil Nadu process. In the Tamil Nadu process and the Mysore process, the charge consisted of wrought iron produced separately which was then stacked in closed crucibles and carburised in a large furnace (Verhoeven 1987). But while the Mysore process charged the wrought iron with carbonaceous matter, Wood's (1893) observations on crucible processes in Salem and Arcot districts in Tamil Nadu suggest that only iron was charged and the crucible containing the ingot was not fast cooled in water as in the Mysore process (Bronson 1986). The Deccani process was renowned for the best quality wootz

(Bronson 1986) and the process followed here was not of carburisation of a wrought iron bloom but of fusion of two separate pieces of cast iron (i.e., high-carbon iron) and an iron bloom (low-carbon iron) (Voysey 1837: 247) so producing a homogenous alloy of intermediate composition (Bronson 1986: 43; Rao 1970).

The known sites of crucible steel production in South India, i.e. at Konasamudram and Gathiosahalli, date from at least the late medieval period, 16th century. But, although these may be earlier, systematic excavations have not been carried out to determine their antiquity. The existing research on wootz steel at these sites has been more concerned with metallurgical re-construction of the wootz process based on surface finds. The investigation presented here is also from surface finds at a mound in Mel-siruvalur village, South Arcot district, Tamil Nadu.

### **Mel-siruvalur: location and history of the site**

In November 1991 the author made field investigations of old workings at a polymetallic copper-lead-zinc deposit on Kanankadu hillock, 21-22km S.S.W. of Mamandur (12° 00' N; 79° 00' E) in Kallakurichi taluk, South Arcot district, about 40 km south by road from the nearest town of Tiruvannamalai. This polymetallic sulphidic mineralisation occurs in association with meta-anorthosites in the granulitic terrain of the Archaean complex of South India. Iron ores are also found in banded ferruginous quartzite formations in Kallakurichi taluk. The area was visited in the hope of locating evidence for copper smelting based on reports by geologists from the GSI in Madras who had noticed some unidentified metallurgical debris near the village of Mel-siruvalur about 5km from the Kanankadu hillock. However, investigations of some of the debris collected and presented here, indicate that it is instead related to crucible steel processes; which is nevertheless of significance to the history of metallurgy in the area.

The village of Mel-siruvalur comprises a cluster of two or three houses in this very sparsely populated arid region. Evidence of metallurgical activity came from a mound just behind the village of about 25m x 8-9m wide and up to 5m high (Fig. 2) and from some trenches near the houses. However the villagers had no memory of recently undertaken metallurgical activity. Occupation of the area in antiquity is indicated by pottery sherds collected adjacent to an old canal, about 1/2km away from the mound. Floating slag debris and crucible fragments were also found all around the canal site. Among the sherds were many large rim fragments, about 3cm thick, belonging to huge storage jars about 60cm in diameter. These had no slip, and were found to be tempered with rice hulls. C. S. Patil (pers. comm.) of the Mysore Archaeological Survey has pointed out their resemblance to megalithic storage jars of red ware without slip. The megalithic occupation in Tamil Nadu starts around the fifth-fourth century BC and continues to around the fifth century AD. Megalithic dolmens have been found in Thiruvannamalai and Tirukoilur taluks adjacent to Kallakurichi taluk, in South Arcot district. Also among the finds were pottery sherds of painted ware with a red slip, decorated with a chain or hatched design, which were identified by C.

S. Patil as being of the late medieval period (c. sixteenth century AD). Several hollow conical terracotta jars about 70cm long of indeterminate function were also found stacked along the walls of the canal. Without more detailed survey and investigations, the possibility of these pottery assemblages being related to the metallurgical activity cannot be confirmed.



**Figure 2** Mound near Mel-siruvalur village, South Arcot district, Tamil Nadu.



**Figure 3** Lid fragment of broken wootz crucible.

### **Description of archaeo-metallurgical debris at Mel-siruvalur**

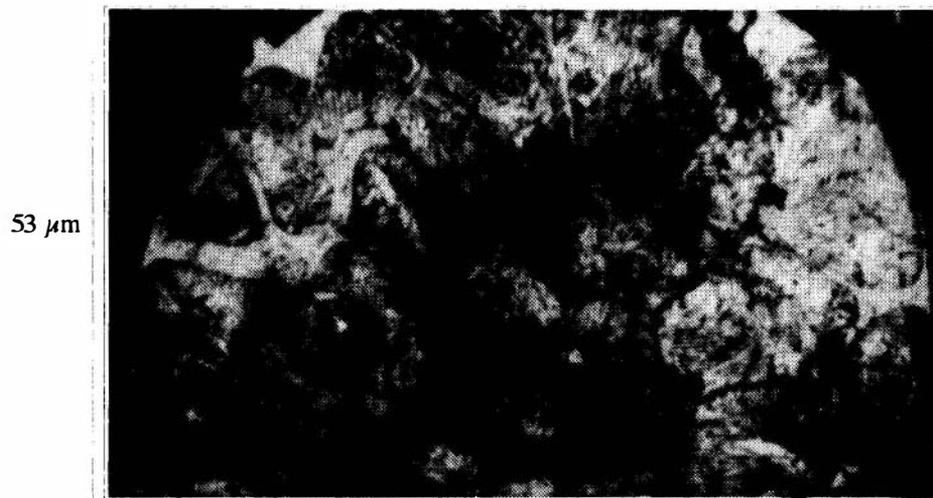
Numerous crucible fragments were found at the Mel-siruvalur mound together with fragments of glassy slag, charge and debris. When re-constructed the fragments of crucibles showed typical features of the aubergine-shaped closed crucibles used for wootz steel production known from other sites in South India such as Gatihosahalli and Konasamudram. Thick covering lids of a diameter of about 7cm, which would have sealed the refractory vessel during firing with the iron charge, were found. Pieces with interior glazed surfaces and distinctive 'fins' of glassy slag that would have formed the middle portion of the crucibles were also located. Several curved bases of the crucibles, about 0.8-1.5cm thick were among the finds. The dimensions of the various fragments indicated that the ingots were of a diameter of c. 2.5cm. Some of the crucible bases appear to have remnants of the rusty charge attached to them. The exterior surface of the crucibles was covered with thick black ash glaze.

About 70m away from the mound were a set of two trenches inter-connected in a pinch and swell shape of about 10m long. One of these was clearly the furnace area, as it contained several tapering tuyeres fragments (with an inner diameter c. 1.5cm, and varying from 0.8-2cm thick), along with furnace remnants, consolidated mud and slag. The other trench contained only blocks of slag 20cm high and 20cm in diameter with a flow texture; indicating that it had been used to tap out slag from the main furnace.

### **Analytical results and discussion**

A mounted section of a lid of a crucible (Fig. 3) was examined microscopically and tiny iron prills of a diameter less than  $100\mu\text{m}$  were found along the glassy edge of the lid. Analyses of the prills using Electron Probe Microanalysis (EPMA) confirmed that they are steel prills (Table 1). The prills were embedded in the outer crucible lining of the lid probably due to splashing of molten liquid due to overflow at high temperatures. Similar prills have previously been found embedded in Deccan wootz crucibles (Scott 1991: 35).

The etched microstructure (Fig. 4) of the largest prill (Prill 1), of a diameter of c.  $80\mu\text{m}$ , has a lamellar eutectoid structure of fine pearlite inside original hexagonal grains of austenite. This suggests that it derives from a very good quality hypereutectoid high-carbon (>0.8 per cent) steel. The prill had a hardness of around 400 VPN which is within that for normalised steel of c. 1 per cent carbon (Scott 1991: 82). The presence of much smaller amounts of a lightly-etched network of cementite (iron carbide) between grains near the boundaries, and as occasional needles in the pearlite was also noted. Scanning Electron Microscopy with Energy Dispersive Spectroscopy (SEM-EDS) suggested that this lightly-etched cementite contained some phosphorus impurities, i.e. consisted of cementite-phosphide. Iron phosphide tends to form a ternary eutectic of steatite along with pearlite (Avner 1988: 439) and its presence may indicate a slightly higher carbon content of about 1 per cent. Prill 2 and four tinier prills



**Figure 4** Prill from lid of crucible showing pearlitic structure in prior austenite grains interspersed with some cementite.

inspected microscopically had a similar pearlitic structure, with the presence of the interdendritic continuous lightly-etched network of cementite around the pearlitic eutectoid in varying degrees.

It is interesting that the micro-structures of the prills etched in nital, of darkly-etched pearlite surrounded by lightly-etched cementite, are somewhat reminiscent of the macro-structures associated with the beautiful patterns formed on Damascus swords. These patterns are thought to consist of well formed lamellar darkly-etched high carbon pearlitic steel interwoven with a network of lightly-etched iron carbide or cementite; formed by the forging of a high carbon iron ingot followed by etching (Smith 1960: 16; Tylecote 1962: 295).

<u>Sr. No.</u>	<u>Fe (wt%)</u>	<u>Cu (wt%)</u>	<u>As (wt%)</u>	<u>S (wt%)</u>	<u>Total (wt%)</u>
Prill 1	97.615	0.038	0.023	0.565	98.241
Prill 2	102.385	0.075	-----	0.251	102.385

**Table 1** Analysis of prills in a section of a crucible from Mel-siruvalur

Analysed by EPMA on a polished and carbon-coated cross-section using JOEL Superprobe JXA-8600 at 20 KV with ZAF correction, within instrumental accuracy of 1% over 100%. Trace silicon and phosphorus were also noted especially in Prill 2 but have not been analysed by EPMA; however these elements were shown to be less than 1% using SEM with EDAX analysis (HITACHI S-570 with link AN-1000).

As has been reported in previous analyses of wootz-making crucibles in South India (Lowe 1990: 237-50), the fabric of the Mel-siruvalur vessel consists of a porous glassy matrix with distinctive cooked rice hull relics (Fig. 5) dispersed in the matrix along with sand or quartz grains. The inclusion of rice hulls in the refractory material is a distinctive feature of the manufacture of Deccani wootz crucibles (Lowe 1990; Voysey 1832: 246). Lowe postulates that these were added for their high silica and carbon content, making the crucible a particularly effective re-inforced composite refractory material; both to withstand very high temperatures over a very long firing cycle and to maintain a highly reducing environment to enable carburisation of the iron charge.

Qualitative analysis of a few samples of the slag collected from the second trench by SEM-EDS showed that the major constituents were iron and silicon, suggesting that these may be fayalite (iron silicate) type iron slags. Hence it appears that the iron charge was being smelted by the bloomer process in the trenches. The iron bloom produced here may have formed part of the charge to produce high carbon iron by the wootz crucible process in the area where the mound with the crucibles was found. Further investigations are needed to verify which of the crucible steel processes was followed here: the carburisation of a bloom, i.e. the Mysore or Tamil Nadu processes, or the fusion of cast iron with a bloom, i.e. the Deccani process. The crucible fragments found on the mound appear to be from fired crucibles which had been broken to retrieve the finished ingots.



**Figure 5** Rice hull relic in glassy matrix of fired refractory.

## Conclusions

The preliminary investigations reported here indicate that crucible steel production was carried out, in the pre-industrial era, at a hitherto unreported site at Mel-siruvalur, South Arcot district, Tamil Nadu. Analytical investigations indicate that closed crucible fragments were fired to a high degree of vitrification with the charge, to produce a high carbon steel. Use was made of refractory reinforced with rice hulls in the manufacture of the crucible as observed in the Deccani process of wootz steel production. Further archaeo-metallurgical investigations and surveys are required to determine the extent of metallurgical activity and the antiquity of the site.

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