Offprint from
J. Mei and Th. Rehren (eds), Metallurgy and Civilisation: Eurasia and Beyond
Archetype, London 2009. ISBN 1234 5678 9 1011

South Indian Iron Age iron and high carbon steel: with reference to Kadebakele and comparative insights from Mel-siruvalur

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ABSTRACT This paper is based on studies of the use and modes of production of high carbon iron alloys in relation to surface finds from Iron Age and early historic sites in southern India, in particular the site of Kadebakele where recent excavations have revealed finds of iron and steel, some of which according to preliminary studies, seem to be of a higher carbon content. Preliminary comparative studies are also made on surface finds of crucibles related to high carbon steel production at Mel-siruvalur.[1]

Introduction

The iron and steel artefacts uncovered from the site of Kadebakele, Karnataka in southern India span the early phases of occupation radiocarbon dated from 800 to 400 BC. This site has been excavated by a collaborative team from the Karnataka Department of Archaeology, the University of Michigan, and the University of Chicago. The site was occupied from at least the early 1st millennium BC until the early centuries AD. Radiocarbon dates from the Iron Age period span from *c*.800 to 400 BC and it is thought that iron/steel artefacts from these levels may rank among the very early well-dated examples of higher carbon steels.[2]

Steel and south India

High carbon iron alloys are known to have been produced in Asia (e.g. *wootz*, the traditional Indian crucible steel (Smith 1960: 14–24, Bronson 1986) and Chinese cast iron (Tylecote 1976: 85)) before they were widely used in Europe. Classical Mediterranean accounts make several references to the reputation of Indian iron and steel (Bronson 1986: 18). From the 17th century onwards European travellers have described the production of steel ingots by carburising iron, or melting constituents in crucibles in parts of south India e.g. Golconda/Nizamabad (Voysey 1832), Mysore (Buchanan-Hamilton 1807) and Salem (Buchanan-Hamilton 1807; Wood 1893) in the present-day states of Andhra Pradesh, Karnataka and Tamil Nadu respectively. Coomaraswamy (1956) has also described crucible steel processes in the Kandyan region of Sri Lanka. *Wootz* is thought to be a European corruption of the south Indian Telegu/Kannada word for steel, *ukku*. *Ukku* may derive from the related Tamil word *uruku,* meaning to make molten. It could also be related to *ekku*, the old Tamil word for sharpness/sharp spear.[3]

According to Smith (1960: 14–16; 1981: 67, 72) Indian *wootz* ingots were used to forge oriental Damascus swords found to be of a high (1.5–2%) carbon content with a typical 'watered silk' pattern. Damascus blades, made in Khorasan and Isfahan in Persia from south Indian *wootz* from Golconda were thought to have been the finest weapons then made in Eurasia, reputed to cut even gauze handkerchiefs (Bronson 1986: 22–3, 1). The properties of south Indian steel, which became synonymous with Damascus steel, were investigated and debated during the 19th and 20th centuries by several European scientists, including Michael Faraday, with the aim of industrial production (Smith 1960: 25–9). A typical *wootz* ingot analysed in 1804 by Mushet (cited in Smith 1960: 22) had 1.3% carbon and a dendritic structure.

Recent investigations of crucibles from surface collections from the known sites of Konasamudram, Nizamabad district, near former Golconda (Voysey 1832; Lowe 1990) and Gatihosahalli in Karnataka (Freestone and Tite 1986; Rao 1989; Anatharamu *et al.* 1999) indicate the existence of specialised semi-industrial *wootz* production processes, many of which, though not precisely dated, may range at least over the later medieval period, i.e. 16th–20th century. While these investigations have thrown some light on the ceramic material of the crucibles, studies remain to be done on the nature of the final product and metallurgical process. During the course of field investigations on copper mining and smelting in south India the lead author of this paper came across a previously unrecorded archaeometallurgical site in Mel-siruvalur, South Arcot district, Tamil Nadu. Investigations showed it to be a site for producing *wootz* crucible steel by what appears to be a process of carburisation of low carbon wrought iron (Srinivasan 1994, 1998, 2007; Srinivasan and Griffiths 1997). The discovery of this production centre supports the idea that *wootz* steel production was relatively widespread in south India, and further extends the known horizons of this technology.

High carbon steels from India and crucible steel from southern India

Pliny's *Natural History* mentions the import of iron from the Seres, which could refer to the ancient southern Indian kingdom of the Cheras, while the *Periplus of the Erythraean Sea* unequivocally mentions the import of iron and steel from India (Schoff 1915; Bronson 1986: 18). Certainly trade between the ancient Cheras and the Roman world is supported by finds of late Roman coins (mid-4th century AD) along with Chera coins from the river bed in Karur, the ancient capital of the Sangam era, while trade with 'Yavanas', i.e. Ionians or Mediterranean people, is mentioned in Sangam literature (Srinivasan 1994). Investigations on the iron-rich Iron Age sites of Tamil Nadu and Malabar (mid-1st millennium BC to early centuries AD) could be revealing. These fall within the domain and period of the Sangam Chera dynasty which might tie in with Roman accounts of iron from the Seres, possibly referring to the Chera kingdom. Excavations at an Iron Age site at Kodumanal, Tamil Nadu (3rd century BC), close to Karur, the capital of the Chera kingdom of the Sangam era (3rd century BC to the 3rd century AD) has revealed furnaces stacked with vitrified crucibles that were found separate from abundant iron slag (Rajan 1990: 98). Investigations by Sasisekaran (2004: 45, pl. 23.2) indicated the presence of high carbon steel, with a structure of about 1% carbon, in a projectile edge from Kodumanal, while investigations on a crucible fragment from Kodumanal show that it was iron-rich, which does not rule out its possible use in crucible steel production (reported in Srinivasan and Griffiths 1997; Srinivasan 2007).

Past observers of the manufacture of *wootz* steel in India have commented on the process of carburising iron to steel in crucibles where a batch of closed crucibles with the low carbon iron charge was stacked in a large furnace and fired in a long 14–24 hour cycle at temperatures of not less than 1200 °C in a strongly reducing atmosphere (Percy 1860–80: 773–6). The known sites of crucible steel production in south India, i.e. at Konasamudram and Gatihosahalli, date from at least the late medieval period (16th century).

Mel-siruvalur: archaeometallurgical evidence for high carbon crucible steel processing

In November 1991, field investigations were carried out[4] on old copper workings in Mamandur, South Arcot district, about 40 km from the nearest town of Tiruvannamalai. While searching for evidence of copper smelting activity, metallurgical debris was found near the village of Mel-siruvalur about 5 km from Mamandur, which is shown to be related to crucible steel production. Evidence of metallurgical activity came from a mound (25 × 8–9 m wide and up to 5 m high) just behind the village and from some trenches near the houses. The villagers had no memory of this metallurgical activity. Occupation of the area in antiquity is indicated by pottery sherds collected adjacent to an old canal, about ½ km away from the mound. Slag debris and crucible fragments were also found all around the canal site. Among the sherds were many large rim fragments, about 3 cm thick, belonging to huge storage jars approximately 60 cm in diameter. These had no slip, and were found to be tempered with rice hulls. Their resemblance to Iron Age storage jars of red ware without slip has been pointed out.[5] The Iron Age occupation in Tamil Nadu, which began in the 1st millennium BC, continued until as late as the 5th century AD. Iron Age dolmens have been found in Thiruvannamalai and Tirukoilur taluks in South Arcot district. Sasisekaran (2002) also observed signs of Iron Age occupation at the site.

Numerous crucible fragments were found at the Mel-siruvalur mound together with fragments of glassy slag, charge and debris (Fig. 1). The reconstructed fragments of crucibles resembled the aubergine-shaped closed crucibles used for *wootz* steel production known from other sites in south India such as Gatihosahalli and Konasamudram, indicating that the crucibles had been broken to retrieve the ingots. Also found were thick covering lids of a diameter of about 7 cm, which would have sealed the refractory vessel during firing with the iron charge. The exterior surface of the crucibles was covered with a thick black ash glaze indicating that the crucibles were fired under highly reducing conditions. Flat vertical ridges seen on some crucibles suggest that the crucibles had been stacked together. The base of the lid was uneven and bore imprints of a fibrous pattern suggesting that the crucible could have been stuffed with leaves and grass to act as carbonaceous material for carburising the charge.

Several curved crucible bases, about 0.8–1.5 cm thick, were also found. A lining of glassy slag with a honeycomb pattern covered the area below the fin to the crucible base, which would have been occupied by molten charge and solid ingot. Some of the slag linings on the crucible bases had rusty remnants of the charge attached to them. The dimensions of the various fragments indicated that the ingots were of a diameter of *c*.2.5 cm. Rusty patches and globules could

Figure 1 Assemblage of steel-making crucible fragments from surface finds at Mel-siruvalur, Tamil Nadu.

Table 1 Mel-siruvalur crucible: EPMA (wt%) analysis of prills in a section of a lid fragment.

Constituent	Fe (wt%)	Cu (wt%)	As (wt%)	S (wt%)	Total
Prill1	97.615	0.038	0.023	0.565	98.241
Prill 2	102.385	0.075	–	0.251	102.385

Analysed by EPMA on a polished and carbon-coated cross-section using a JOEL Superprobe JXA-8600 at 20 kV with ZAF correction, within instrumental accuracy of 1% over 100% using probe diameter of 50 µm. Trace Si and P were noted but were not analysed by EPMA; however these elements were found to be less than or around 1% using SEM with EDAX analysis (HITACHI S-570 with link AN-1000). Note: the results are as analysed and not normalised to 100%.

Table 2 EPMA-WDS (wt%) analysis of constituents in glassy slag fin on interior of crucible.

Constituent	Fe	Al	Si	Ni	Cu	Ti	P	S	Ca	Total
Prill	82.28	0.18	3.25	1.74	0.27	0.09	9.95	0.12	1.35	99.38
Glassy slag	0.32	8.62	24.46	0.0	0.0	0.89	0.02	0.0	7.13	43.79

Analysed by EPMA on polished, carbon-coated cross-section using a JOEL Superprobe JXA-8600 at 20 kV with ZAF correction, within instrumental accuracy of 1% over 100% with probe diameter of 5 µm. Lighter elements such as O, C, N etc. were not monitored

be seen scattered on the ring of slag fin, above this fin, along the crucible walls and even below the lid, almost certainly caused by splashing of molten charge possibly due to a carbon boil reaction. All of the above suggests that the ingot solidified from a molten charge.

Analytical results and discussion

The blackish glaze on the exterior suggests that the crucibles were fired under highly reducing conditions at high temperatures with heavy attack by fuel ash. Sections for microscopy were taken from different fragments of crucibles representing the lid, the glassy fin and the crucible base. The latter had a thin layer of glassy slag with a honeycomb pattern with some remnant rusty charge. Examination of the cross-section indicated that the rusty layer formed from the remains of the molten charge was extremely thin, no more than 10 µm thick. When this rusted layer was sectioned, tiny uncorroded metallic prills were detected by optical microscopy, but by the time fine polishing of the specimen was complete they had fallen out of the loose rust matrix. These uncorroded metallic prills were found, better preserved, in the glassy slag fins and slag coating on the interior of the crucibles, and the exterior black glaze in the lid section. While the prills in the exterior glaze may be attributed to factors such as the contamination by particles of charge or iron filings, which would also have been carburised, or the splashing of molten metal, the prills that were found trapped within the glassy slag fin and lining of the interior of the crucible can be linked directly to the final composition of the molten charge. The prills were of a diameter of less than 100 µm, with most prills in the glassy slag on the interior of the crucible being no more than 10–20 µm. Analysis of the prills using electron probe microanalysis with wavelength-dispersive X-ray spectrometry (EPMA–WDS) or scanning electron microscopy with energy-dispersive X-ray analysis (SEM–EDS) confirmed that they are steel prills (Tables 1 and 2). Instrumental accuracy is expected to be 1% at 100% of analysed component by EPMA–WDS and about 8% at 25% by SEM–EDS.

The etched microstructure of the largest detectable prill had a lamellar structure of fine pearlite eutectoid (of equilibrium composition of 0.8% carbon) inside original hexagonal grains of austenite (Srinivasan 1994). This suggests that it derives from a very good quality hypereutectoid high carbon (>0.8%) steel. The prill had a hardness of around 400 VPN which is within the range for normalised steel of approximately 1% carbon (Scott 1991: 82), suggesting that the crucible had not been quenched. The presence of much smaller amounts of a light unetched network between grains near the boundaries and as occasional needles in the pearlite was also noted. SEM–EDS analysis suggested that this was mainly cementite (iron carbide) with some phosphorus impurities, i.e. cementite-phosphide. Iron phosphide tends to form a ternary eutectic of steadite along with pearlite (Avner 1988: 439) and its presence could indicate a slightly higher carbon content of about 1–1.2%. Smaller prills in the lid also had a similar microstructure.

The prills trapped in the glassy slag fin of 3–4 mm thick (Fig. 2) and in the 1 mm thick slag lining of the interior of the crucible best reflect the composition of the molten liquid from which the ingot solidified. These also have the same structure as described above: lamellar pearlite eutectoid inside hexagonal grains surrounded by an intergran-

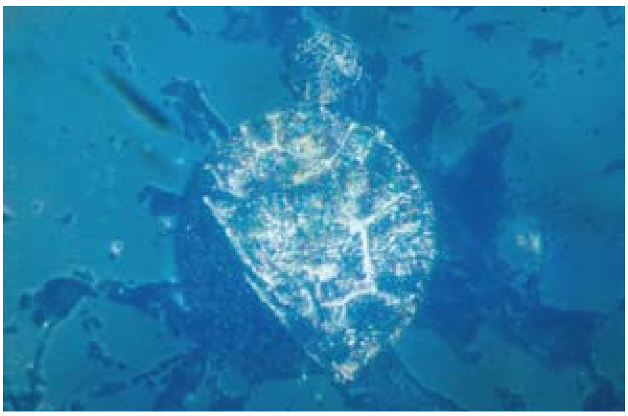

Figure 2 Mel-siruvalur crucible: high carbon steel prill (1.2% carbon) (50 *µ*m at original magnification 400×) showing pearlite surrounded by a cementite network.

ular network of cementite with some cementite needles. EPMA and SEM–EDS analyses also indicated the presence of phosphorus in the cementite network, strongly suggesting that the final product or solidified ingot was a high carbon steel of around or over 1% carbon. The microstructure of the prills compares well with that of a 1.2% carbon steel illustrated in Avner (1988: fig. 7.14). The impression of the honeycomb pattern in the slag lining and fin may also be related to the two-phase microstructure of the molten metal with the carbide network surrounding the polygonal grains of high temperature austenite which forms pearlite at lower temperatures.

Figure 3 Projectile points from Kadebakele. The iron projectile (middle) (acc. No. 337, Level 6, -21.6E-204 N) has radiocarbon dates of *c*.400–350 and 310–210 BC from charcoal associated with the specimen.

Iron and steel artefacts from the Iron Age site of Kadebakele

The south Indian site of Kadebakele is located on the northern bank of the Tungabhadra River in Koppal district of northern Karnataka, India. More than 60 hectares in area, occupation at the site spanned from the 1st millennium BC Iron Age period until the 1st millennium AD.

The Early Historic Landscapes of the Tungabhadra Corridor (EHLTC) research project seeks to examine settlement and economy throughout this sequence, through a program of excavation at Kadebakele and contemporary village sites and a regional survey in a 35 km^2 area surrounding Kadebakele. Excavations in 2003 and 2005 focused on the Iron Age sequence, in excavations of habitation and ritual mortuary areas in an area of the site referred to as the 'upper terrace' – a well-defended zone on top of an outcropping hill that rises some 110 m above the river flood plain.

Excavations were carried out in six areas of the upper terrace, which encompass some of the diverse activities that took place at the site. These include: residential areas characterised by the remains of houses and associated features (Block B, and Unit 52E/-86N); areas of waste deposition (Unit 94.84E/-16.93N, upper levels of -21.6E/-204N); areas of megalith construction (Block A, and lower levels of -21.6E/-204N); and a water storage feature (8E/-142N). With the exception of the test trench placed within the bed of the reservoir feature, all of the areas excavated produced metal artefacts. In this paper, we report on studies on some of the objects. Some speculation is also made about the typological and other similarities of the objects to those from other Iron Age finds, and the environmental and other considerations related to the finds of ferrous artefacts and modes or places of production etc.

One of the artefacts studied is a projectile point excavated at Kadebakele. Charcoal found in association with the iron projectile (Fig. 3, middle image; acc. No. 337, found in Level 6, -21.6E-204 N) had radiocarbon dates of *c*. 400–350 and 310–210 BC. A cross-sectional sample was taken from the cylindrical shaft of the projectile, which had a 9 mm outer diameter and a 3 mm diameter inner hole. The microstructure (Fig. 4) at lower magnification shows a network of ferrite grains with some pearlite along grain boundaries – the structure of low carburised iron or steel. The slag inclusions, which are elongated in an arc-like fashion,

Figure 4 Microstructure of a broken specimen from the circular shaft iron projectile (acc. no. 337) from Kadebakele (*c*.400 BCE).

suggest that it was heavily worked in that direction along the circumference. The hardness measurements were in the range of Hv (Vickers hardness) 165 (whereas for iron it is in the range of 65–75 Hv). This follows the parameters of mild steel that can be forged, which is borne out by the microstructure.

A small iron ring shown in Figure 5 (acc. no. 900, 22E-28 N, Level 7) was found above a plaster surface while charcoal from this level was radiocarbon dated to 800–440 BC. What is particularly interesting is that the microstructure of the ring (Fig. 6) consisted almost entirely of a pearlitic structure with a fine lamellar network suggesting a composition close to the eutectoid composition of 0.8% carbon. Given the secure dates of the layer from which it is excavated of 800–440 BC this could be one of the earliest known examples of pearlitic or higher carbon steel found anywhere in the world. The structure is not inconsistent with that found in the crucible fragment from Mel-siruvalur, which is confirmed to be from high carbon crucible steel production. The possibility that it may have solidified from the viscous if not molten state is suggested by the absence

Figure 5 Iron ring (acc. no. 900) from Kadebakele from the level radiocarbon dated to 800–440 BCE.

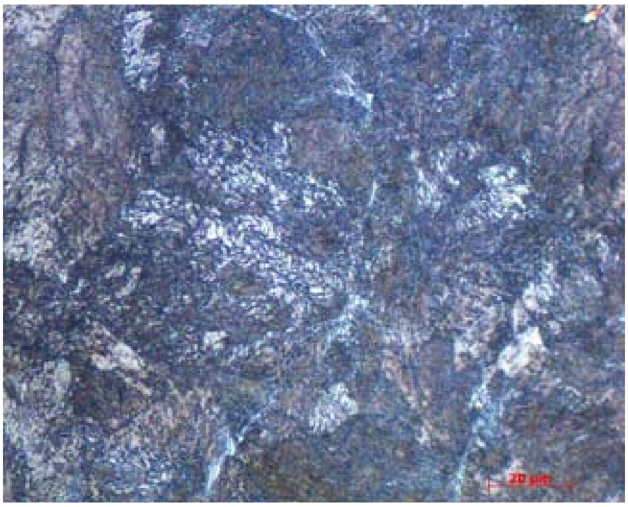

Figure 6 Photomicrograph of iron ring, acc. no. 900 (800–400 BCE) (original magnification 50×) showing pearlite with some cementite needles and some ferrite.

of any evidence of working, implying a possible link with the kind of crucible steel processes discussed in the context of southern India. However, further investigations are required to understand these aspects.

Conclusions

The investigations reported here indicate that at the Iron Age site of Kadebakele in Karnataka, there is preliminary evidence for the use of steel of a higher carbon content in a tiny ring and certainly forged mild steel in a projectile shaft, ranking among the earliest known higher carbon steels anywhere. Perhaps the finds at Kadebakele suggest some kind of precursors to the crucible steel process for high carbon steel, as seen clearly in evidence at the site of Mel-siruvalur. Although this latter site for crucible steel production, first identified by Srinivasan (1994), has not yet been properly investigated or excavated from an archaeological point of view, it shows potential for possible megalithic evidence as commented elsewhere by Sasisekaran (2002).

Acknowledgements

The authors would like to thank Mr Padaikathan, Department of Metallurgy, Indian Institute of Science, Bangalore for assistance in the metallurgical studies on Kadebakele artefacts, R. Krishnamurthy of the *Dinamalar Daily* and Dr Purushottam, formerly of the Department of Mines and Geology, Madras for helping Sharada Srinivasan with the site visit to the Mel-siruvalur/Mamandur area in 1991. We also express our appreciation to the late N. Seeley, D. Griffiths, J. Merkel and K. Reeves of the Institute of Archaeology, London for support in the studies on the Mel-siruvalur crucibles. We also thank Thelma Lowe, Dr Parthasarthy of the Geological Survey of India-Madras Circle, Dr Radhakrishan, the late Dr C. V Seshadri and Professor Balasubramaniam for their interest and assistance.

Notes

1. First identified by Sharada Srinivasan.
2. The metallurgical studies were made in collaboration with the National Institute of Advanced Studies, Bangalore with Sharada Srinivasan as principal investigator.
3. John Marr, pers. comm.
4. By Sharada Srinivasan with the help of the State Department of Mines and Geology, Madras, and Geological Survey of India-Madras Circle.
5. By the late C.S. Patil (pers. comm.) of the Mysore Archaeological Survey.

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