Crucible steelmaking in Sri Lanka

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Abstract

Early Arab literature, travellers' accounts and ethnographic studies point to Sri Lanka as a traditional source of high-quality steel, which would have found a ready market as a raw material for the manufacture of tools and weapons, including the so-called Damascus swords. The present work concerns the analysis of a find of Sri Lankan crucible steel collected from the village of Mawalgaha, the site where Coomaraswamy, in 1904, witnessed and described the process by which crucible steel was traditionally manufactured. Also studied were a collection of blacksmiths tools, along with several iron blooms which are believed to be melting-stock for crucible steelmaking. The morphology and microstructure of the high-carbon steel ingots are consistent with products expected of the local crucible steelmaking process, and also explain the processing requirements for the material. Similarities between the blooms and the ingots support the suggestion that the blooms are indeed raw materials for the crucible steelmaking process. The smithing tools were found not to have been made from crucible steel. The recent find of a mid-to-late first millennium AD crucible steelmaking site shows that the industry has a long history in Sri Lanka, but the ultimate use for the crucible steel which was produced remains unclear. One possible interpretation of the evidence available to date is that crucible steelmaking may never have been a major industry in Sri Lanka, and that the island's reputation for high-quality steel arose from the wind-powered smelting technology which has also been shown to be capable of producing high-carbon steel.

Introduction

Sri Lanka was known for its steel at least as long ago as the ninth century AD when it was referred to by the Islamic writer al-Kindi, who ranked Serendib- (*ie* Sri Lankan-) made swords among the most important in use in the Arab world. In addition, al-Kindi named four areas (Yemen, Khorasan and Fars in Iran, and Mansura in Pakistan) where swords were made using steel imported from Sri Lanka (Bronson 1986, Allen 1979). Sri Lanka thus shares with South India a reputation as a producer of high-quality steel, and, for both, this has generally been taken to mean crucible steel (frequently referred to as 'wootz', *ie* cast ingots of high-carbon crucible steel) which is often assumed to be the traditional raw material for the production of so-called Damascus swords. Recent fieldwork in Sri Lanka (Juleff 1997, and see further description below) has revealed evidence of crucible steelmaking as early as the mid-first millennium AD, which may well be the origin of the steel referred to by al-Kindi, although the early writings do not specifically state that high-quality steel was produced by the crucible process. In fact much of the new archaeological and archaeometallurgical evidence points to the possibility that high-quality high-carbon steel was being made in Sri Lanka at that time by a direct smelting process involving wind powered furnaces (Juleff 1996; 1998).

Nevertheless, it is certain that a millennium later, during the nineteenth century, crucible steel was being produced in Sri Lanka. This is attested by the eyewitness reports of W C Ondaatje and Ananda K Coomaraswamy. Ondaatje, in the Ceylon Almanack of 1854, describes the 'Kandyan Mode of Manufacturing Steel', which at that time was apparently in decline, constituting only a 'little inland trade' and that the steel was 'now made only in Saffragam and Kandepalle in the District of Badulla'. Saffragam is the modern province of Sabaragamuwa, and the Samanalawewa survey area (Fig 1) straddles the border between Sabaragamuwa and the neighbouring province of Uva (Ouvah). However, Ondaatje stated that steelmaking had at one time been a flourishing industry under native rule, and gave a description of the technique as follows:

> 'It consists of introducing a small bar of good iron into a clay mould of a tubular form which they call "covey" with pieces of dried wood of the *Cassia auriculata* (*Ranwara* of the Singhalese). The open end of the tube is afterwards closed with clay, and it is placed in a charcoal fire for two hours, by which process carbon is supplied to the iron, which is thus converted to steel. The proportions for making steel of the best qualities are as follows; 7 parts iron to 3 of dried wood. They also use the wood of the *Toddelia aculeata,* the *Kudu Meris* of the Singhalese in which case the proportions are 3 of iron to 1 of wood. This wood, however, produces an inferior steel, but by increasing the iron to 5 parts a better kind may be obtained. This kind of steel is not generally manufactured, as it is brittle and unmalleable.'

Ondaatje also described how two blacksmiths from the Uva District annually supplied the King's stores with 24 small bars of steel, which are called *wane karal* (elongated seed-pods of steel). He claimed that steel had been manufactured at 'Deheigolla and Iwalla in Wellasse, Irewandumpalla in Kandepalle [in Uva province]', and that it was then still made at 'Horaguna Hanahappawaela Kammala and Kosgama Kammala, belonging to Kandepalle, also at Mahawalgaha in Saffragam district.'

The other eyewitness account of the making of crucible steel in Sri Lanka, dating from 50 years later, is that of Coomaraswamy. In the 1903 and 1904 Annual Administration Reports of the Mineralogical Survey, of which he was then Chief Mineralogist, Coomaraswamy described seeing and photographing, in the Balangoda district, both iron being smelted by the bloomery process and steel being made by the crucible process. The same account appears in a paper in the *Ceylon Geographer* (1961), but is most widely accessible from Coomaraswamy's book *Medieval Sinhalese Art* (1907-8, 1956) which includes sketches and photographs. With regard to the steelmaking, Coomaraswamy's description reads:

> 'The manufacture of steel, even as a service rent, is quite extinct; but two very old men at Alutnuvara still keep up the tradition, and are able to demonstrate the process when required; with these men a knowledge of the process will be gone, so that a record of their methods is of much value. The steelmakers are smiths *(navandanno),* thus of much higher caste than the *yamannu* from whom they buy the iron required. The process of steel making is more delicate than that above described [bloomery iron smelting in 'village furnaces']. The [steelmaking] furnace . . . is smaller, and at the ground level, instead of being raised three feet above the ground; it is a semicircular hearth filled with charcoal, into which air is conducted from the bellows, which are identical with those of the iron furnace. The hearth is defined by a low clay wall, rising about six inches above the ground. The steel is made in clay crucibles, each about 8 inches long, two inches in diameter, and a quarter of an inch in thickness. Into the crucible is put a piece of iron, with some chips of *ranavara (Cassia auriculata);* in the proportion of 12-1/2 oz. iron to 5 oz. wood, in the case examined. The crucible is covered with a lid, having small holes pierced for the escape of gas; six crucibles thus prepared are embedded in the charcoal, and a fire started. Very soon the gases burn off and while this goes on the blowing is stopped. Then the blast is kept up continuously, while the tubes are turned about and more charcoal added, the great object being to keep up a constant and even distribution of heat. When the steel is likely to be ready, a hole is opened in the front part of the hearth, so that the blast goes right through the furnace, and the tubes are lifted up one by one in long iron tongs and shaken to see if the steel is quite liquid. Any which are not quite ready are returned to the furnace for a time. The others are laid down to cool and subsequently broken open and the bar of steel removed. The steel is highly crystalline and used for the best cutting tools. The bars which weigh from 12 to 15 oz., are worth from 75 cents to a rupee each.
> A specimen of steel has been analysed at the Imperial Institute, with the following results: Iron 99.77%, Manganese 0.07%, Silicon 0.07%, Sulphur 0.07%, Phosphorus 0.02%, Carbon (combined) 1.97%.'

Coomaraswamy's writings make clear that he was well aware of the importance of crucible steel and familiar with at least some of the early reports (*eg* those of V S Sambhasiva Iyer [1898-99] on the industry in Mysore). Furthermore his account has an air of credibility, as noted by Bronson (1986) who described Coomaraswamy's work as 'among the best documented and most credible of all descriptions of wootz making …' and his photographs of both iron smelting and steelmaking provide convincing corroboration of his descriptions. Unfortunately, as pointed out by Bronson, there remains the question of whether the steel produced for Coomaraswamy by the two old men was representative of the product of the traditional steelmakers, bearing in mind that at the time of the demonstration the indigenous industry was no longer in existence. For this reason it would be of great interest to examine the steel products of these demonstrations. Hadfield (1912) mentions that the crucibles and the steel ingots prepared for Coomaraswamy were at that time in the Colombo museum, and material which sounds comparable was referred to by Cooray (1967) as being 'on view in the Museum of the Geological Survey Department.' Searches of these two institutions by one of us (GJ) were unsuccessful in locating this material[1].

The reports of crucible steelmaking as a traditional Sri Lankan technology were very much in mind when the Samanalawewa Archaeological Survey (SAS) commenced its work (Fig 1) in 1988. This survey was carried out to assess the impact of the construction of a hydroelectric power dam. The area has a strong iron-smelting and iron-working tradition, although smelting, in small bellows-driven shaft furnaces which were the basis of a technology termed 'village smelting' by the SAS, died out early this century (Juleff 1998). One of the aims of the SAS was to identify, in the field, evidence for smelting as well as iron- and steel-working and to correlate this with the eyewitness accounts and with local oral traditions. In fact, traditional manufacturing of agricultural implements remains active throughout the Samanalawewa area in specialist blacksmithing villages such as that at Hatanpola, which is situated less than a kilometre from the temple village

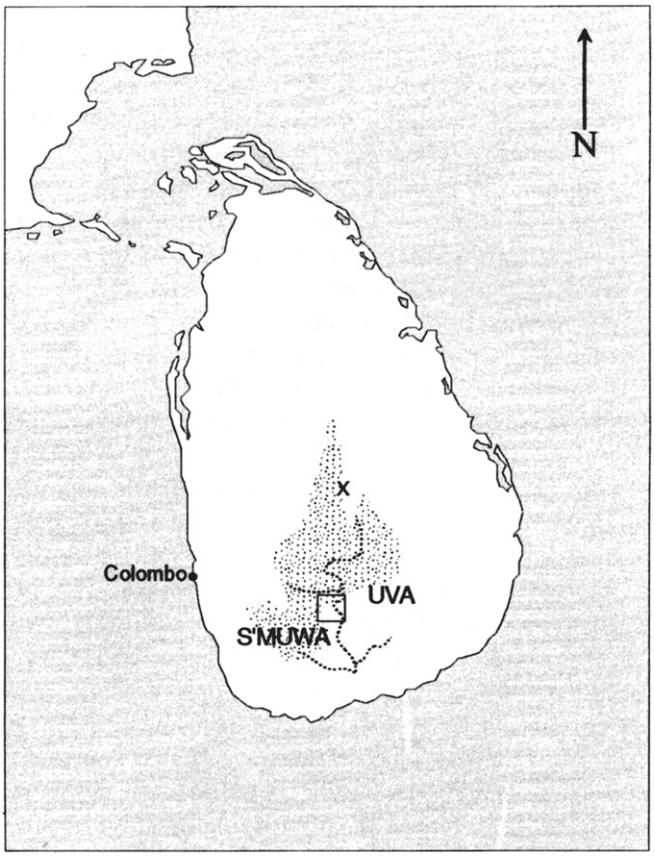


Figure 1: Map of Sri Lanka showing area of the Samanalawewa Archaeological Survey (box) and the Knuckles site (X) to the north of the highlands (shaded area). Portions of the provincial boundaries of the provinces of Sabaragamuwa (to the west) and Uva (to the east) are also shown; their common boundary passes through the survey area.

of Alutnuvara (referred to by Coomaraswamy). The complex ethnographic and archaeometallurgical records of Samanawalewa have been exhaustively investigated and are described in detail elsewhere (Juleff 1998).

During a visit by the SAS to the blacksmiths' village of Hatanpola, one of the smiths, H A Elias, recognized the description of a crucible and, with his guidance, a site comprising predominantly crucible fragments was located in the village of Mawalgaha, about two and a half kilometres from Alutnuvara (this is both Ondaatje's Mahawalgaha and the location of the crucible steelmaking demonstration witnessed by Coomaraswamy). Elias reported that his father had made use of the old broken crucibles to melt brass for decorative inlay work on the knives which he forged. The site is located in a village garden overlooking the paddy fields in the centre of the village. Crucible fragments are visible in a 1.5m high earthen bank over a distance of 16m. The surface layer of this bank, some 0.3m deep, consists of plano-convex or convex-convex slag cakes, which appear to be furnace bottoms from an iron smelting operation believed to be unrelated to the crucible steelmaking process. The crucible fragments are densely packed in a matrix of soil and charcoal in a layer which directly underlies this surface layer. The shapes of the crucible fragments conform well with the descriptions reported by Ondaatje and Coomaraswamy, with a wide range of size and completeness represented, from small base or wall fragments to almost entire crucibles (Fig 2). Crucible lids, with small pierced holes, again conforming with the written descriptions, are also present in the deposit. Although the external surfaces of the crucibles are covered with a glassy slag, no separate fragments of slag were found in the crucible-bearing layer of the deposit.

In addition to its having been specifically mentioned by Ondaatje, Mawalgaha is recorded as a steelmakers' village in the records of the local temple (Alutnuvara Devale) in 1870. The village was owned by the temple and the steelmakers (the *wane achariya* - a sub-caste of the blacksmith's caste) paid service rent for their land (Juleff 1998).

About 25m from this site, in another village garden in Mawalgaha, a surface scatter of smaller crucible fragments was also located, along with tuyere fragments and small

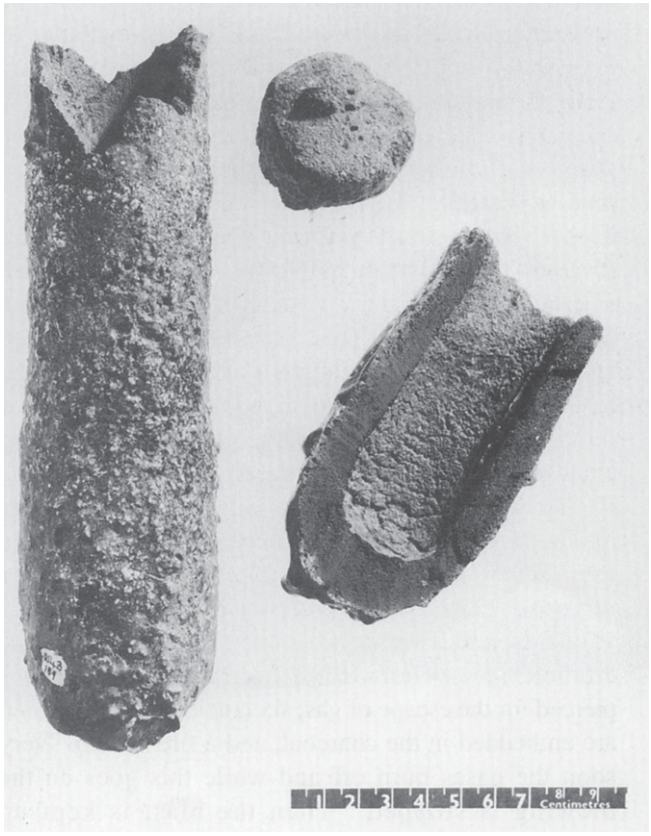


Figure 2: A partial crucible with a fractured end, a crucible fragment sectioned longitudinally and a crucible lid. The sectioned crucible is 10.5cm long.

green and blue glassy slag lumps. The three other locations mentioned by Ondaatje were also surveyed for evidence of crucible steelmaking; Irewandumpalla, at Koslanda, Horaguna Hanahappawaela at Horaguna and the Kosgama Kammala at Kosgama, all in Uva province and the last barely five miles from Mawalgaha. No evidence was found at the first two, but at Kosgama an extremely disperse scatter of very small fragments of crucibles was located in cultivated paddy fields known as *Kammala-arawa* (blacksmith's place).

Although no other evidence for crucible steelmaking was located during the survey of the Samanalawewa area, a more recent reconnaissance survey in the Knuckles range to the north of the Central Highlands of Sri Lanka (Fig 1) has identified a single crucible steelmaking site. This comprises a deposit containing used crucible fragments, abundant pottery sherds and plano-convex cakes of slag. A brief evaluation excavation established the contemporaneity of the crucible fragments and the mid to late first millennium AD pottery, and also retrieved charcoal which has now given three radiocarbon dates (Beta 101297-9) between the 6th and the 10th centuries (Juleff 1997). Interestingly, the crucibles in this case, while being thin-walled like those from Mawalgaha and having the same fabric, appear to be pear-shaped, or light-bulb shaped, rather than tubular.

The fabric of the Mawalgaha crucibles is a uniform black colour, being made from a mixture of rice husk and clay, with dimensions as described by Coomaraswamy and quoted above. The external walls of the crucibles are covered with a layer of green, blue or black glassy slag which appears to have flowed along the surface parallel with the long axis of the tubular crucible (*ie* downwards with the crucible in the upright position in the furnace) and collected in thick viscous lumps around the base. The interiors of the crucibles are also lined with a thin layer of glassy slag, with the position of the top surface of the liquid steel being marked by a circumferential slag 'fin'. In addition a longitudinal slag fin is present, running at right angles to the first; this marks the level of the liquid steel surface when the crucible was laid on its side to cool. This evidence corroborates Coomaraswamy's account as quoted above, and demonstrates that the ingot would have had a long thin shape, very like the *wane karal* (steel seed pod) of its customary name. Such a shape would have been more convenient as a starting material for forging a blade or a cutting tool edge than would the discoidal cast ingots associated with Indian crucible steel.

Thus, the archaeological evidence is consistent with the descriptions of Ondaatje and Coomaraswamy and the SAS has been successful in locating sites mentioned by them. In addition, the interviews with villagers carried out during and subsequent to the SAS were also successful in providing information and evidence with respect to crucible steelmaking (Juleff 1998). At Mawalgaha, contact was made with W A Siyadoris (WA denotes *wane achariyage* – of the steelmakers' family or clan), a man of some 49 years of age, whose father had been a blacksmith and whose grandfather had been both a blacksmith and a steelmaker. According to Siyadoris, when his father (or grandfather) had wanted iron, he had arranged for smelters to come to Mawalgaha and smelt iron in his garden. He then made steel from this iron using the crucible process. Siyadoris did not know his grandfather and had never seen steel being made, but had heard the stories from his father. When shown Coomaraswamy's photographs of crucible steelmaking (Coomaraswamy 1956: Plate LIII), he expressed the opinion that the man in one photograph might be his grandfather. He had been told that his grandfather had made steel for a government commissioner who had come to the village and that photographs, which he believes are now in the Kandy and Colombo museums, were taken at that time[2].

Siyadoris had in his possession a box containing blacksmith tools, iron fragments and ferrous scrap, which had belonged to his father and which he kindly donated to the SAS. Amongst the contents of the box were two ingot fragments shaped exactly as would be expected for products of the crucible steelmaking process described by Ondaatje and Coomaraswamy. The box also contained a bloom fragment. This material is of major technological importance in view of the real possibility that Siyadoris' grandfather was one of the two old men who had demonstrated crucible steelmaking for Coomaraswamy. In addition to the analysis of the blooms and steel ingots, as raw materials and products, respectively, of the crucible steelmaking process, also of interest is the analysis of the tools, which could have been fabricated from crucible steel ingots (recall Coomaraswamy's comment that the crucible steel was used 'for the best cutting tools'). Smiths traditionally manufacture most of the tools they need; however it is equally possible that the steel ingots were made only as payment of service rent to the temples, and that the tools were made from imported steel.

The ingots, tools and bloom from the box were subjected to chemical and metallurgical analysis, as were several other bloom fragments obtained from iron-smelting villages in the vicinity of Mawalgaha and were thus also potential raw materials for crucible steelmaking. The remainder of this report concerns the analysis of this body of material.

Analysis

The analysis of this material was carried out mainly in the Department of Scientific Research, British Museum,

London, with minor supplementary work at the University of Alberta. Samples were cut from each object with geometries as described individually below. In most cases a jeweller's saw was adequate for cutting the samples from the objects but the high hardnesses of several of the tools necessitated the use of a low-speed circular diamond saw with a water soluble oil coolant/lubricant. Samples were mounted in polymer mounts and were prepared for metallographic analysis using standard techniques. Examination of the samples was carried out using optical and electron metallography. Samples were first examined in the optical microscope in the unetched condition in order to obtain metallographic information on the non-metallic inclusions. Chemical elemental characterization of the matrix and the inclusions was performed using energy dispersive X-ray analysis in the scanning electron microscope (SEM-EDX). The samples were then etched using 2% nital (nitric acid in alcohol) and re-examined for characterization of the matrix microstructures. Ingot and bloom samples were also examined after etching with Stead's reagent (Verhoeven and Jones 1987:162), which reveals the solidification structure by differential attack of regions with different contents of impurities. Microhardness measurements were carried out using a diamond indenter and a load of 100gf. In some cases X-ray fluorescence (XRF) determinations of the bulk elemental compositions were also performed.

Analysis of two crucible steel ingot fragments

The two ingot fragments from Siyadoris' box, referred to here as Ingot A and Ingot B, were examined. Each of these was about 40mm long (Fig 3) and appeared to be a fragment of a bar, the cross-section of which was approximately plano-convex with rounded corners, the maximum width being about 30mm, and maximum depth about 13mm. The shape and size of the ingots were

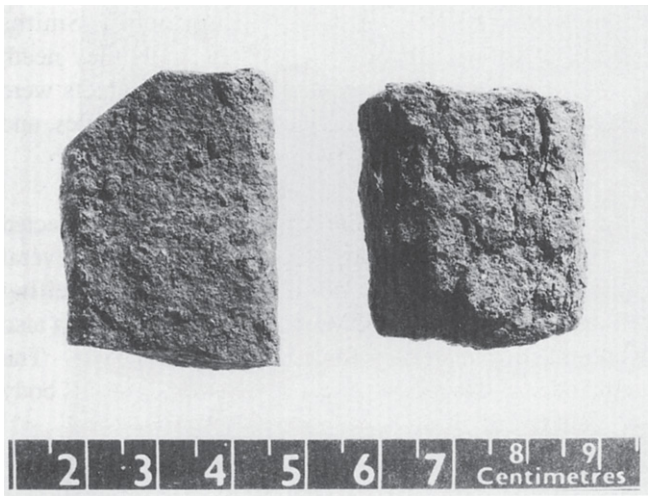


Figure 3: The two ingot fragments from Siyadoris' box. The angled corner of one ingot shows the location where sampling was carried out.

Figure 4: The two ingot fragments from Siyadoris' box, one lying in a sectioned crucible fragment.

consistent with their having solidified in a cylindrical (tubular) crucible lying with its long axis horizontal, i.e. on its side rather than on end. Thus, the approximately planar surface of the ingot was the top surface during solidification, while the convex surface solidified in contact with the inside of the crucible. The shapes and dimensions of both ingots were such that they fit well into the crucibles collected at Mawalgaha (Fig 4), crucibles which in turn correspond well with Coomaraswamy's description.

From each ingot, a sample was cut so as to include half of its cross section. Bulk XRF analyses of both samples and SEM-EDX analyses of their metallic matrices detected no metallic elements other than iron, with the possible presence of silicon at about the detection limit of the SEM-EDX (of the order of 0.1%).

Examination of the unetched samples showed that extensive porosity was present, some of it spherical and some with the complex shapes characteristic of interdendritic solidification shrinkage cavities (Fig 5). Non-metallic inclusions, containing sulphur and phosphorus as described below, were also present in geometries suggestive of interdendritic formation. These observations are consistent with a cast structure, and the response of the microstructure to Stead's reagent

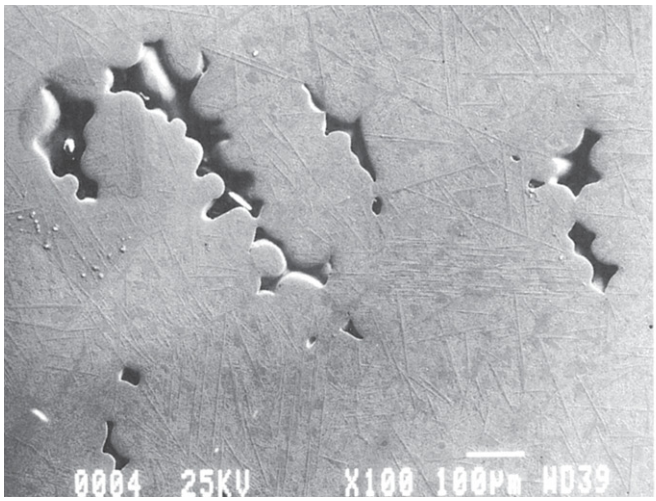


Figure 5: Ingot B showing interdendritic shrinkage porosity. Nital etch. Scanning electron micrograph. Magnification 75x.

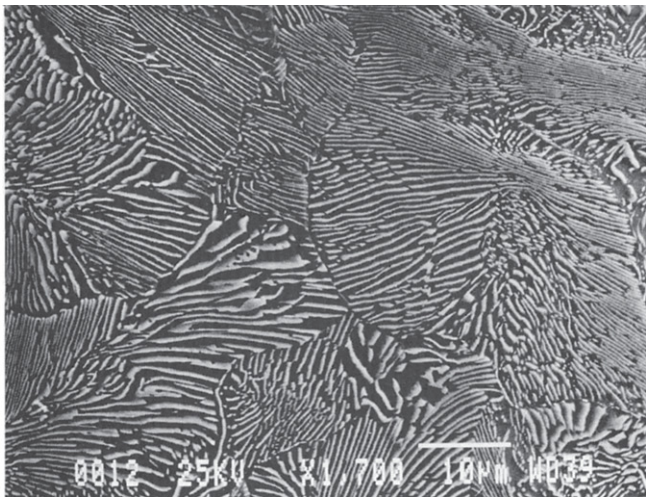


Figure 7: Ingot A showing pearlitic microstructure. SEM micrograph. Nital etch. Magnification 1250x.

Figure 6: Ingot A showing dendritic solidification pattern. Stead's reagent. Optical micrograph. Magnification 5.5x.

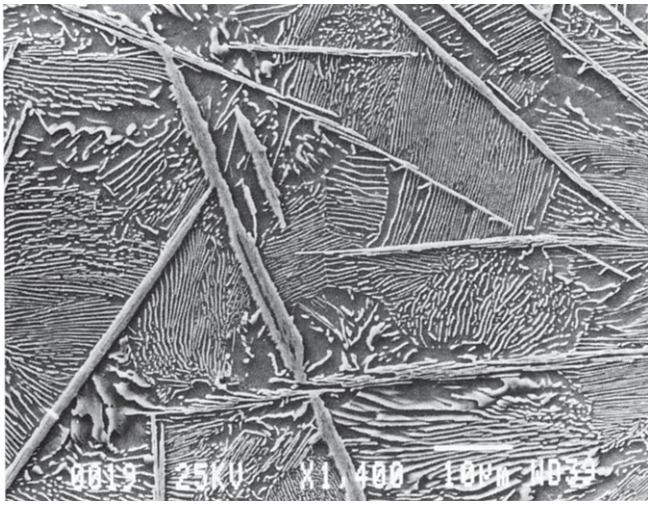


Figure 8: Ingot A hypereutectoid region, Widmanstatten cementite in pearlite. SEM micrograph. Nital etch. Magnification 1050x.

confirmed this unequivocally: both ingot fragments were found to be completely dendritic (Fig 6), and therefore in the as-cast condition. It is generally believed that interdendritically segregated phosphorus causes the strong response to Stead's reagent; however in the present case electrochemical reactions between the matrix and the various interdendritic phases may also have been involved.

The surface of ingot B was covered by an oxide layer approximately 4mm thick, about four times as thick as that on Ingot A. Despite this, however, the microstructures of both ingots were free of penetrating corrosion products other than occasional millimetre-size oxide inclusions in a region near the outer surface of Ingot A.

The nital etch, which brings out the basic microstructure of the steel without emphasizing the solidification structure, revealed that the microstructures of both fragments were those of high-carbon steel which had been cooled moderately slowly after solidification. Both ranged from eutectoid to hypereutectoid, consisting largely of pearlite (Fig 7) along with pro-eutectoid cementite which displayed several different morphologies. Ingot A contained several regions in which this pro-eutectoid cementite was present mainly as fine Widmanstatten plates within the prior austenite grains (Fig 8), although the austenite grain boundaries frequently contained thin films of cementite as well. Ingot B had a significantly higher carbon content, with thicker Widmanstatten plates of pro-

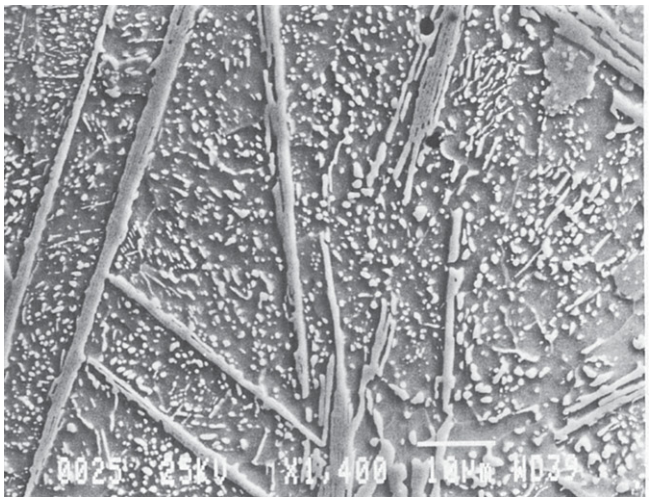


Figure 9: Ingot B, Widmanstatten cementite in degenerate pearlite. Nital etch. SEM micrograph. Magnification 1050x.

Figure 11: Ingot A. Interdendritic steadite particles with Widmanstatten cementite in pearlite matrix. Nital etch. SEM micrograph. Magnification 1050x.

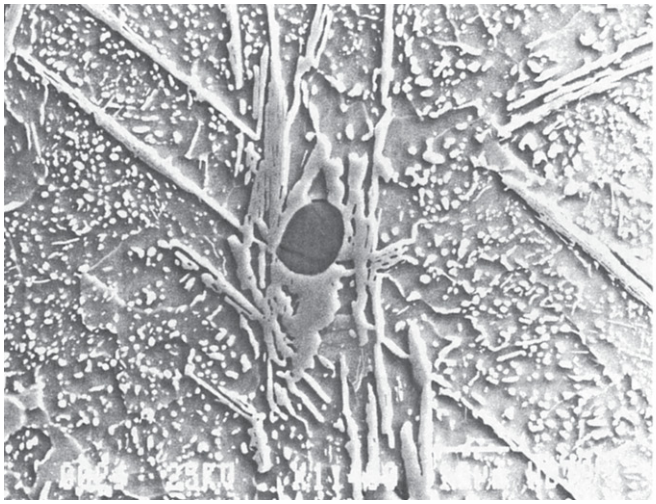


Figure 10: Ingot B. Iron sulphide particle within assemblage of cementite laths in degenerate pearlite matrix. Nital etch. SEM micrograph. Magnification 1050x.

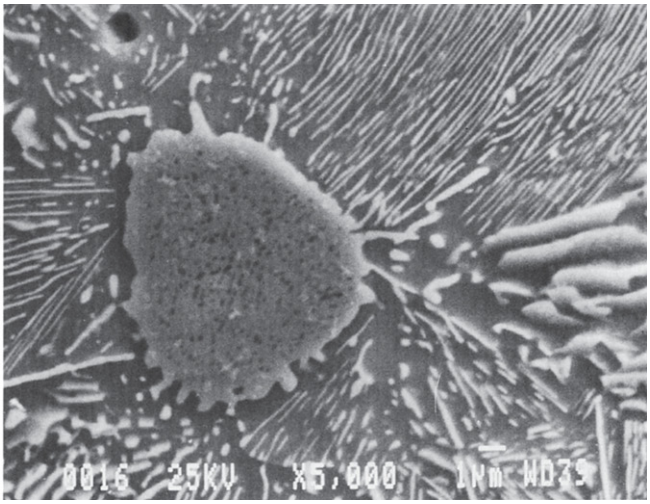


Figure 12: Ingot A. Steadite particle with cementite rim in pearlite matrix. Nital etch. SEM micrograph. Magnification 3700x.

eutectoid cementite; in addition, its pearlite was much more degenerate (Fig 9) than that of Ingot A. The carbon contents of both ingots were heterogeneous; for example, one area of Ingot B had a very high carbon content with coarse blocky cementite plates similar to those shown in Figure 16. The austenite grains of both ingots were very large, in the order of several hundred micrometres in diameter.

The average microhardness within the pearlitic regions of Ingot A was found to be 348 HV_{100} while that of the degenerate pearlite of Ingot B was 258 HV_{100}. It is expected that degenerate pearlite should have a lower hardness, and these numbers are quite reasonable for the microstructures observed, bearing in mind that they are not bulk macrohardnesses, but rather the microhardnesses of the pearlite constituents alone.

Three types of non-metallic inclusion were observed in the microstructures. These inclusions and the porosity tend to occur both separately and together in various combinations and all were present to similar extents in interdendritic locations in both ingot fragments. The first type of inclusion consisted of particles of iron sulphide, smoothly shaped, often ovoidal, and fairly bright in the optical microscope (Fig 10). SEM-EDX analysis showed that these consist predominantly of iron and sulphur with much smaller amounts (<5% total) of manganese and

titanium, as well as, in some cases, phosphorus and traces of chromium and vanadium. Surrounding many of these iron sulphide particles were regions which etched more strongly by nital than either the sulphides or the matrix and these regions were somewhat enhanced in phosphorus content compared with the matrix. With Stead's reagent, and in some cases with nital also, these phosphorus-enhanced regions showed a distinctly lamellar microstructure.

The second and most abundant type of non-metallic inclusion was steadite, the phosphorus-bearing eutectic constituent. Steadite inclusions were found alone in the interdendritic regions (Fig 11), often within a rim of cementite (Fig 12), as well as in association with iron sulphides (Fig 13), or with both iron sulphide and cementite (Fig 14). The association with cementite is normal (see, *eg* Verhoeven and Pendray, 1992), steadite often being in fact a ternary eutectic of iron phosphide, cementite and austenite or ferrite. EM-EDX analysis showed that the steadite contained about 9.0% phosphorus, as compared with the expected binary austenite-iron phosphide eutectic at 10% P and the ternary austenite-cementite-iron phosphide eutectic at 6.8% P.

The third inclusion type present in the microstructure consisted of small globular particles, 1-10 micrometres in diameter, which appeared dark both optically and in the SEM (one is visible near the top of Fig 9). Analysis showed them to be single-phase particles of calcium-aluminium silicate slag, which possibly contain iron as well as minor amounts of potassium and magnesium.

Discussion of the ingot fragments

The two ingot fragments are readily interpretable from their microstructures as high-carbon steels with somewhat variable carbon contents and considerable amounts of sulphides and phosphorus-rich inclusions as well as small silicate slag particles. They are clearly cast structures, entirely consistent with the ingot product expected from a crucible steel process. The sulphur- and phosphorus-bearing constituents, which have the lowest melting points in the system (the ternary steadite eutectic melts at about 950°C) were observed at interdendritic locations, where the last remaining liquid is pushed by the growing austenite grains during solidification. The volume contraction which accompanies solidification is manifest as shrinkage porosity in the last remaining liquid areas, hence this porosity is also interdendritic.

The presence of slag particles in the steel is at first sight somewhat surprising. One of the prime advantages of crucible steel is that, while it is in the liquid state, the slag particles are able to float to the surface where they can be skimmed off, rather than being trapped within the steel. However, although slag inclusions were present in these ingots, their abundance was low by comparison with steel

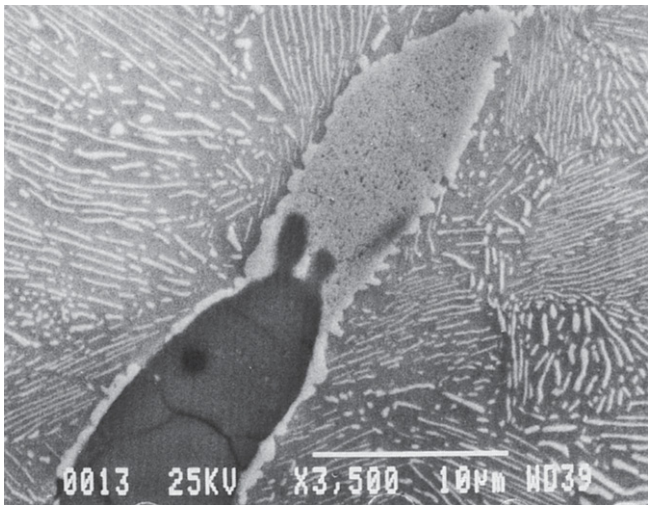


Figure 13: Ingot A. Iron sulphide particle (dark) with cementite rim and associated steadite particle. Nital etch. SEM micrograph. Magnification 2600x.

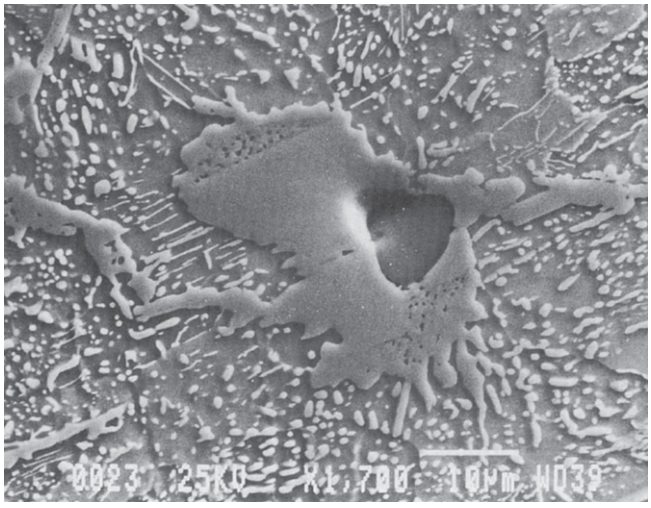


Figure 14: Ingot B. Iron sulphide particle within cementite-steadite aggregate in pearlite matrix. Nital etch. SEM micrograph. Magnification 1250x.

made by other pre-Bessemer steelmaking processes and furthermore they were small and equiaxed, minimizing their detrimental effects on the mechanical properties of the steel. Similar small equiaxed slag particles have been observed in 19th century industrial crucible steels presumed to have been made in England by the Huntsman process (M L Wayman, unpublished work in progress).

The presence of the steadite, with its low melting temperatures, would render the steel hot-short and hence difficult to forge unless it was given an annealing treatment sufficient to permit the steadite to dissolve into the surrounding matrix. Alternatively, Verhoeven and Pendray (1992b) have shown that material such as this can be

readily forged if it is first given a surface decarburizing treatment so that the hot-short steel is encased in an envelope of low-carbon ductile material. That the hot-shortness is associated with steadite is shown by the observation of Verhoeven *et al* (1995) that limiting the phosphorus content to levels of 0.02-0.03% removes the hot-shortness.

Microstructures similar to these have been reported by Verhoeven and co-workers (Verhoeven and Jones 1987; Verhoeven and Pendray 1992a; Verhoeven and Pendray 1992b) in synthetic crucible steel alloys containing 1.7% carbon and 0.1% phosphorus. In the present case it is not possible to make precise estimates of carbon content from the microstructure. However, since Widmanstatten cementite is not expected below 1.1% carbon (Samuels 1980:308) and since substantial amounts of Widmanstatten cementite were observed in some regions, the maximum carbon content present must appreciably exceed 1%.

The cementite morphology observed in the exceptionally high-carbon region of Ingot B is worthy of comment. The appearance of these coarse, blocky cementite plates, which were always associated with steadite, suggests their direct formation from the liquid during solidification (*ie* pro-eutectic cementite). However, experiments on this type of steel by Verhoeven and Pendray (1992b) have provided strong evidence that this blocky cementite can form by solid-state precipitation in the presence of interdendritic liquid rich in phosphorus (and sulphur). This explanation is consistent with the present observations, both in Ingot B and in several of the bloom fragments discussed below.

The differences between the microstructures of the two ingot fragments may be at least partially related to the differences in their carbon contents, degenerate pearlite being associated with higher carbon contents (the hypereutectoid regions of Ingot A also show a higher degree of pearlite degeneracy than do the eutectoid regions, as shown by comparing Figures 8 and 9). The lack of spheroidization of the pro-eutectoid Widmanstatten cementite laths shows that the granular nature of the cementite in Ingot B was the result of degenerate pearlite formation, rather than being lamellar pearlite which had spheroidized. The different carbon contents of Ingots A and B, along with the different thickness of their surface corrosion layers argue, albeit not strongly, that these two ingot fragments are from two separate ingots rather than being portions of the same original ingot. The similarity of their dimensions and overall appearance leave no doubt however that they are products of the same process.

Analysis of six iron blooms and a fragment of possible crucible charge

The objects described in this section are blooms, that is highly heterogeneous agglomerations of metal and slag, with extensive amounts of porosity and non-metallic inclusions including oxide particles. Many blooms from India and Sri Lanka were traditionally axe-cut in a radial direction toward their centres, so that the bloom quality could be assessed. For example, the relative amounts of metal and slag in a bloom would have been of interest to a crucible steelmaker wishing to use it as feed-stock.

Six blooms were analysed. These were Bloom 1 from the box of material donated by Siyadoris; Bloom 2, a surface find in the village of Mawalgaha; Bloom 3 from a traditional iron smelting village near Mawalgaha, Bloom 4 from the Ekneliyagoda Walawwa (manor house) at Kuruwita, some 35km from Samanalawewa. The remaining two blooms, 5 and 6, are unprovenanced. All had been axe-cut. Also analysed was a rough metal fragment found wedged in the mouth of a broken crucible in the Mawalgaha deposit. It is possible that this represents a fragment of bloom destined for charging into a crucible. In all cases the microstructures were found to consist of highly heterogeneous mixtures of metallic and non-metallic constituents and porosity, as expected in blooms.

The metallic components of the blooms consisted of iron containing highly heterogeneous carbon contents. Blooms 1, 2 and 3 were mainly ferrite (less than about 0.1%C) but with areas of higher carbon content, ranging from 0.2%C (Bloom 2) to 0.8%C (Bloom 1). The low-carbon areas consisted of ferrite containing less than 0.1% carbon, with small amounts of cementite as grain boundary precipitates and in some cases as small amounts of pearlite on the ferrite grain boundaries (Fig. 15). Bloom 3 exhibited a region which was martensitic. Most of Bloom 4 contained between 0.2 and 0.5%C, having a microstructure of pearlite along with pro-eutectoid ferrite in the form of intragranular Widmanstatten plates. Local regions were ferritic with less than 0.1%C and other regions contained higher carbon levels. One area, near an edge of the sample, contained numerous blocky laths of cementite (Fig 16), as in the high-carbon region of Ingot B discussed above; this region was estimated to contain at least 4%C locally. Blooms 5 and 6 range from less than 0.1 to about 0.8%C.

The microhardnesses of the microstructural constituents were in accord with their carbon contents, with the low-carbon ferrite in the range 107 to 125 HV_{100}, and the pearlite between 184 and 277 HV_{100}. The region of martensite in Bloom 3 exhibited a variable hardness as high as 572 $HV_{100.}$

No metallic elements other than iron were detected in the matrix of any of the blooms at levels above the detection limit of the analytical system employed (*c* 0.1%).

The non-metallic constituents included silicate slag, oxide

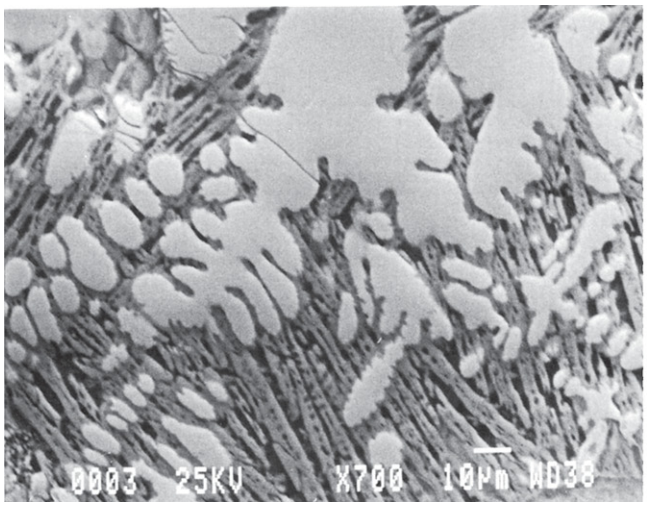


Figure 15: Bloom 1. Light wustite dendrites and fayalite laths in dark glassy matrix. Nital etch. SEM micrograph. Magnification 520x.

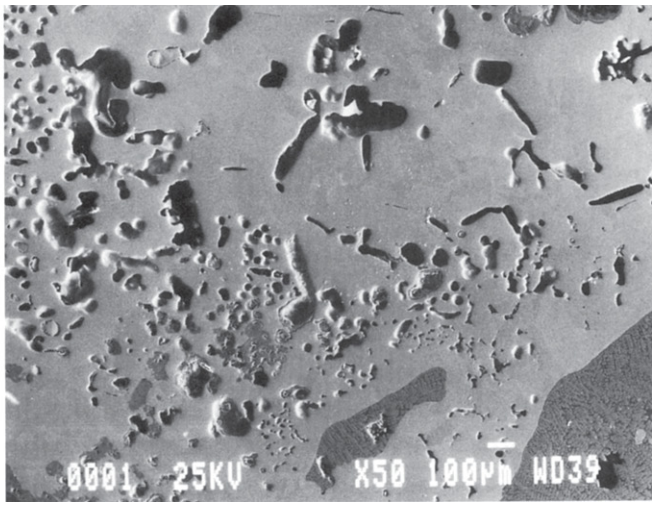


Figure 17: Bloom 3. Multi-phase slag inclusions and porosity, some of it in networks, in a matrix of very low-carbon ferrite. Unetched. SEM micrograph. Magnification 35x.

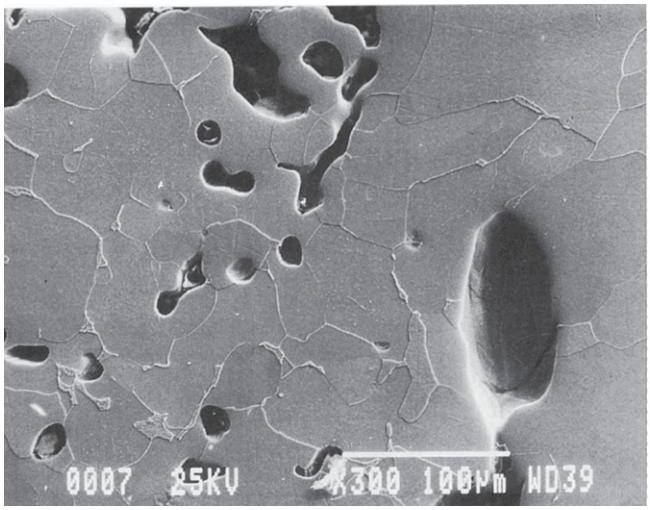


Figure 16: Bloom 2. Ferrite grains and porosity with pearlite on the ferrite grain boundaries. Nital etch. SEM micrograph. Magnification 220x.

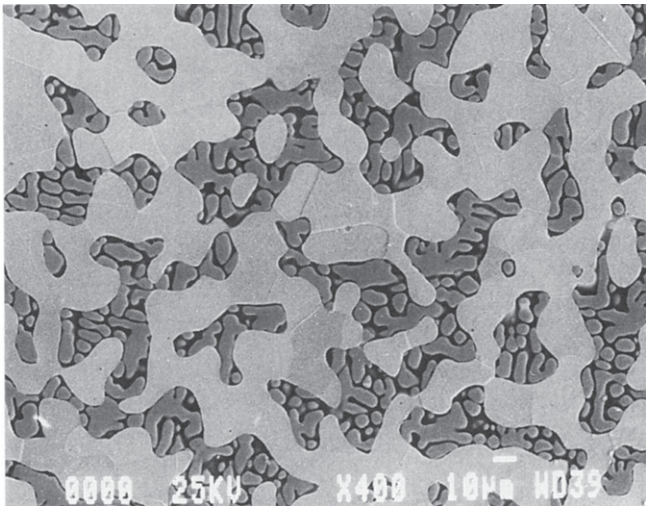


Figure 18: Bloom 3. Dispersed mixture of slag and ferrite. Nital etch. SEM micrograph. Magnification 300x.

particles, sulphide particles and steadite. Several types of porosity were also present. In Blooms 1, 2 and 3 some of the silicate slag inclusions were found to be two-phase mixtures of wustite in a glassy silicate matrix; in other parts of these blooms fayalite was also present in the inclusions (Fig 17). One region of Bloom 3 exhibited, in one region, an intimate mixture of highly dispersed slag particles in the ferrite matrix (Fig 18). In Blooms 4, 5 and 6 the slag inclusions were single-phase calcium-aluminium silicate inclusions, most often spherical, which contained iron as well as trace amounts of manganese and phosphorus.

Blooms 3, 4, 5 and 6 also contained iron sulphide particles which were globular and smooth, sometimes having an internal shrinkage void that appeared dark in the SEM. Some of these sulphide particles contained trace amounts of manganese and possibly phosphorus and many were located within pro-eutectoid ferrite grains, especially in the high-carbon regions. These sulphides were often surrounded by phosphorus-enhanced regions which etched more rapidly than the ferrite, and in some cases there appeared to be cementite at the interface between this region and the sulphide (Fig 19). In the optical microscope these phosphorus-enhanced regions appeared distinctly blueish, compared with the yellowish FeS particles. Furthermore, as in the ingots, these regions sometimes displayed a lamellar structure of fine parallel lines (Fig 20).

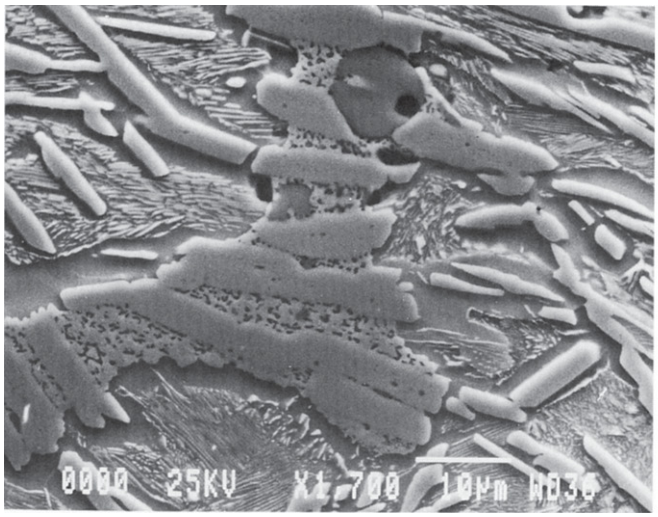


Figure 19: Bloom 4. Sulphides with steadite between coarse blocky cementite laths in the abnormally high-carbon region. Nital etch. SEM micrograph. Magnification 1250x.

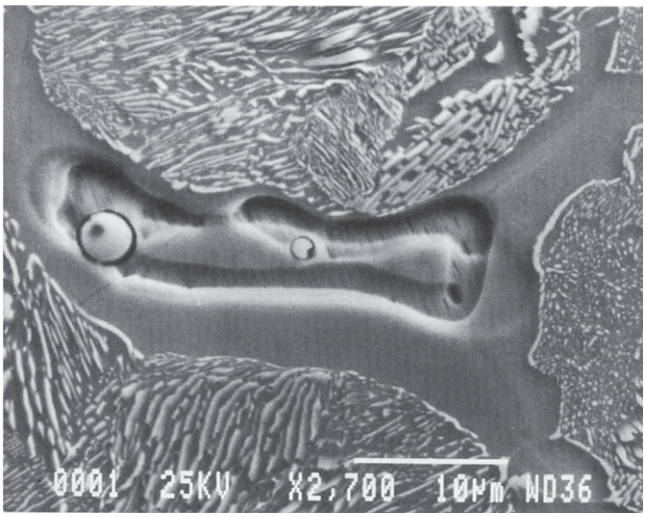


Figure 21: Bloom 4. Iron sulphide inclusions with associated phosphorus-enriched region displaying fine parallel linear structure. Nital etch. SEM micrograph. Magnification 2000x.

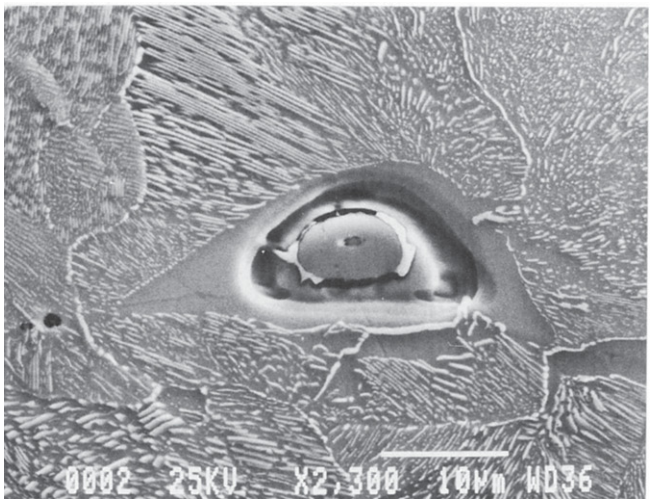


Figure 20: Bloom 4. Iron sulphide inclusion within deeply etched phosphorus-enriched region, with cementite at interface. These exist within a ferrite grain in a pearlite matrix. Nital etch. SEM micrograph. Magnification 1700x.

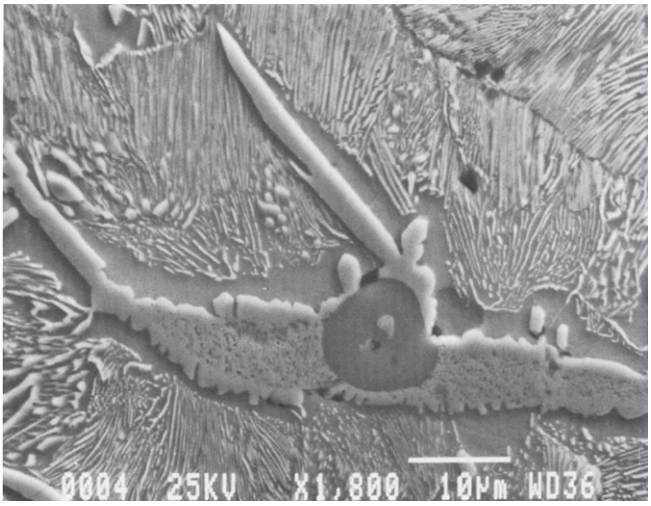


Figure 22: Bloom 4. Iron sulphide inclusion associated with steadite inclusion with cementite rim. Nital etch. SEM micrograph. Magnification 1350x.

Oxide particles were present in several blooms. A large unreduced ore particle had become incorporated into Bloom 1 while in other blooms the presence of chlorine in oxide particles indicated that they were corrosion products.

Steadite was present, both independently and in association with the sulphide particles in Blooms 4, 5 and 6 (Fig 21). Steadite was also present between the blocky cementite laths in the abnormally high-carbon area (Fig 16) of Bloom 4; the appearance of these constituents was very similar to that of the abnormally high-carbon region of Ingot B.

Extensive porosity was also present. This included porosity arising from shrinkage during solidification and cooling, gas porosity, and porosity due to incomplete consolidation. Shrinkage and gas porosity were often associated with slag, oxide and sulphide inclusions. In several cases, porosity occurred in the form of voids located on networks which outlined the original iron fragments in the process of consolidation as the bloom formed (Fig 22).

The response of the blooms to etching with Stead's reagent was markedly variable. Here Blooms 1 and 2 revealed no evidence which would suggest that any melting had

occurred within the areas examined. Definite local variations in response to etching did however suggest heterogeneity of phosphorus content, and small phosphide particles were detected on grain boundaries in the high-carbon region of Bloom 1. Stead's reagent revealed in some areas of Bloom 3 a dark-light blotchy effect within which definite dendrites could not be identified. However, the distribution of porosity and non-metallic inclusions, including iron sulphides, confirmed that this was a solidification structure which had been partially homogenized by subsequent thermal treatment. In other words melting and re-solidification had occurred in some localized areas of this bloom during the smelting process. The response of Bloom 4 to Stead's reagent showed that all but a few small areas of the sample had undergone melting, with a dendritic pattern clearly visible (Fig 23) and porosity and sulphides in the interdendritic regions. There was also some evidence, in the form of distortions of the etch pattern, for local deformation of the structure after solidification. In much of Bloom 6 and in one region of Bloom 5, Stead's reagent revealed clear evidence for melting and subsequent dendritic solidification; these occurred in the areas of highest carbon content and hence lowest melting temperature. Within these melted regions interdendritic porosity, iron sulphides and steadite were observed. Phosphorus enhancement around the iron sulphide particles, as in Bloom 4 and the ingot fragments, was also observed. In those regions of Blooms 5 and 6 where melting had not occurred, the characteristics of the porosity were markedly different, being extensive, heterogeneously distributed and with a broad size range up to quite large voids. Some voids appeared to lie along networks, probably as a result of incomplete agglomeration of individual metallic particles in the bloom.

The fragment of possible crucible charge which was also analysed was found to be similar to Bloom 1. Thus its microstructure displayed porosity, extensive amounts of wustite-fayalite-glass slag, and some oxide in addition to a metallic component. The metal phase contained a wide range of carbon content (up to about the eutectoid composition). Etching with Stead's reagent provided no indication that any melting had occurred.

Discussion of the blooms

In most respects the objects described in this section are typical blooms, containing a metallic iron phase, slag inclusions and porosity. The amounts of slag and porosity revealed wide variations in the degree of consolidation, suggesting that some blooms may be in the as-smelted condition, with others having been smithed to varying extents. These variations may also reflect the locations from where the samples were taken within particular blooms. The metallic matrices consist of iron with highly variable carbon contents, hence the microstructures range widely, even within a single sample. The metallic

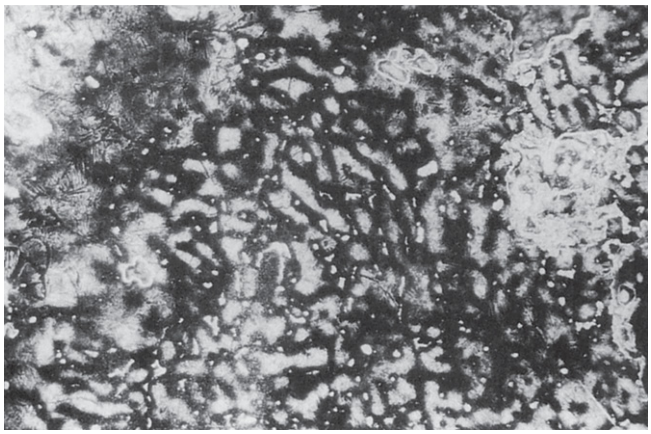


Figure 23: Bloom 4. Dendritic pattern showing solidification structure. Stead's reagent. Optical micrograph. Magnification 65x.

microstructures observed thus include ferrite with or without grain boundary cementite, ferrite-pearlite mixtures, pearlite with or without grain boundary or intragranular Widmanstatten cementite, and, in one case, martensite (resulting from the final rapid cooling of the bloom after its production or smithing). As in the case of one of the ingots, a localized region in one sample, Bloom 4, contained so much carbon that it could be described as a white cast iron. The phosphorus contents were also highly variable. The slag inclusions are typical of bloomery iron, consisting of wustite dendrites in a glassy matrix which in some cases also contained laths of fayalite. Manganese was not present at detectable levels in the metallic matrix of any of the blooms, however it was present, in small amounts, in some of the slag inclusions.

In addition to these normal characteristics, however, some of the blooms display clear evidence for the occurrence of melting, in the form of the strong dendritic contrast revealed by etching with Stead's reagent. This etching contrast is believed to result from interdendritic phosphorus segregation during solidification. Present in the interdendritic spaces were slag inclusions and porosity, caused by solidification shrinkage and/or gas evolution, as well as phosphorus and sulphur enrichment in the form of steadite and iron sulphide inclusions. The slag inclusions in these melted regions were small, single-phase silicate particles, while the interdendritic arrays of porosity were in contrast to the networks of pores seen in unmelted regions which appear to be gaps between individual iron particles arrested in an incomplete state of coalescence into a fully consolidated bloom. The melting generally appears to occur in regions of the bloom which were highest in carbon, consistent with the lower melting temperature of higher carbon alloys.

The occurrence of melting is not normally associated with bloomery iron, which forms by reactions which occur at

temperatures well below the melting point of iron. However, melting is known to occur in some bloomery smelting processes such as the Japanese Tatara furnace as well as some West African bloomery furnaces (Tylecote 1992; David *et al* 1989). Furthermore, fragments of cast iron are not infrequently found in association with Roman bloomery furnaces (Tylecote 1992), in contexts which suggest that they have been discarded. The occurrence of local regions within the furnace where the combination of high temperature and strongly reducing conditions occurs is undoubtedly sufficient to give this effect. In blooms to be used as feed-stock for a crucible steelmaking process the occurrence of locally melted regions would not be in any way detrimental.

It is significant that there are strong similarities between the ingot fragments and the regions of the blooms which have undergone melting. Notable among these similarities are the types of sulphide and phosphide inclusions and the overall appearances of the microstructures. There is no reason to doubt that blooms such as these could have served as the raw material feedstock for the crucible smelting process, which yielded a homogeneous and high carbon content.

Analysis of smithing tools from the collection in the tool box belonging to the grandfather of W A Siyadoris

Available for analysis were 15 objects from the Siyadoris tool box: 3 chisels, 1 wedge, 3 files, 1 knife blade, 1 punch, and 6 bars of indeterminate function; these are shown in Figure 24. Some of the unidentifiable pieces may have been partially fabricated objects or single-use tools made for a particular operation. One of the files had been partially re-worked to form a gouge or engraving tool. The wedge and several of the chisels had clearly been used, as they all had outwardly-splayed shank ends caused by repeated hammering. Of the 15 tools, 12 were selected for metallographic examination (three of the indeterminate bars were not examined). The objective was to determine whether the tools might have been made using steel produced in the local crucible steelmaking process; the high quality of the crucible steel produced, its high carbon content and low inclusion density, would have made it an excellent raw material from which to manufacture tools such as these.

Chisels and Wedge

One of the three chisels, Chisel 1 (Fig 24a), was sectioned at both the cutting edge (longitudinal section) and along the shank (transverse section), about 60mm from the cutting edge. The microstructure at the cutting edge was found to be untempered martensite, with a hardness of 1130 HV_{100}, while the shank was a high-carbon steel with a carbon content of about 0.7% and a fine pearlite microstructure. The martensitic tip region contained brittle microcracks, part of the tip having been lost by fracture. The non-metallic inclusions, mainly manganese sulphide particles and silicates, were similar in the two sections, as was the bulk manganese content of approximately 0.7%; this and the high carbon content in the shank suggest that the chisel had been made from a single piece of steel rather than having had a cutting edge forge-welded in place.

The two other chisels, 2 and 3 (Fig 24c) were found to be similar to Chisel 1. Chisel 2 was sampled only in the vicinity of the tip (longitudinal section). Close to the tip the microstructure consisted of untempered martensite (1160 HV_{100}) with microcracking, and again part of the tip had been lost to a fracture. In this case the microstructure could be seen to vary within a few millimetres of the tip, changing progressively to a pearlite-ferrite mixture with the pearlite near the tip being very fine, with a carbon content of approximately 0.6%. The bulk manganese content was 0.3%

The tip of Chisel 3 had been completely broken off and thus only the shank was sampled (in transverse section). Here the microstructure was found to be a mixture of pearlite and pro-eutectoid ferrite (230 HV_{100}), with an estimated carbon content of 0.5% and a manganese content of 0.5%.

All three chisels contained manganese sulphide inclusions, as well as a lesser abundance of single-phase iron silicates.

The wedge (Fig 24a) was also sampled from the tip longitudinally for a distance of about 15mm toward the splayed end. At the tip the microstructure was found to consist of tempered martensite with a hardness of 460 HV_{100}. Farther from the tip the microstructure changed to a ferrite-pearlite mixture with the amount of ferrite increasing and the pearlite becoming progressively less fine with increasing distance from the tip. The carbon content 15mm from the tip was estimated to be about 0.6% and the manganese content about 0.6%.

Thus, all four of these objects have microstructures which are appropriate for their presumed functions. For a chisel or wedge, the optimum situation is to have high hardness at the cutting edge, hence a martensite with at least a light temper. In the case of a wedge, where the ability to cut is not a requirement, less hardness and more toughness are desirable, hence a more heavily tempered martensitic tip would be appropriate. Since the hard cutting edges are brittle, they must be backed by material with high toughness behind the cutting edges and in the shank; this toughness is most readily provided by a ferrite-pearlite mixture. There are several types of heat treatment which can be used to achieve this composite microstructure after forming the object to its final shape. The most logical is to place the tool in a forge fire so that only the tip region

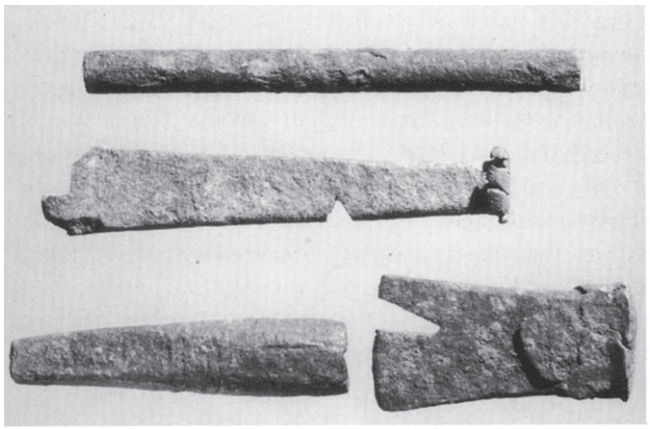
becomes austenitized, and then quenching the tool so that only the tip becomes martensite, while the shank retains its original (*eg* ferrite-pearlite) microstructure relatively unchanged. Depending on the heating and quenching conditions it is possible to obtain an intermediate region where the steel has been austenitized and air cooled, giving a fine pearlite or ferrite-pearlite microstructure. Furthermore, by limiting the amount of time that the tool is left in the quench bath, the martensite formed may 'auto-temper' as a result of being reheated as the heat flows from the shank into the tip after removal from the quench bath. This may well have been the case for the wedge described above. In an alternative type of microstructural control, the carbon content of chisels and wedges can be increased in the tip region by carburization as a component of the heat treatment. This higher carbon region is then capable of forming martensite under less severe quenching conditions, and furthermore the higher carbon martensite has a higher hardness in comparison with lower carbon martensite. The carbon contents of the shanks of several of the chisels were low enough for their tips to have benefited from carburization before being quenched and tempered.

Files

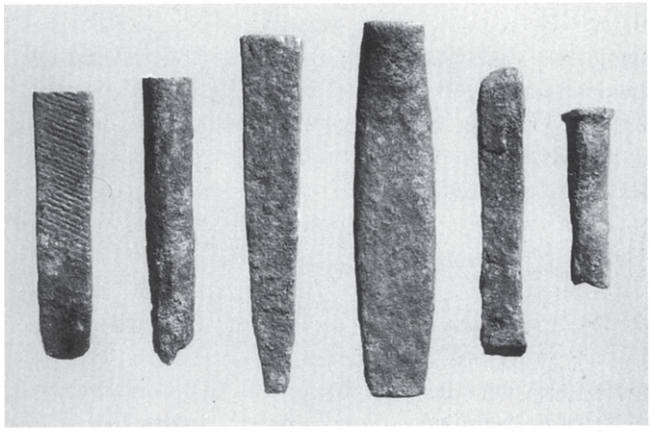
Three objects were identified as files, based on their overall shapes and the presence of arrays of grooves on their surfaces. Two were half-round files and the third had a rectangular cross-section, modified at one end. Their microstructures were sampled in transverse section.

The microstructure of the first file, File 1 (Fig 24a), comprised spheroidized carbides in a martensitic matrix with a microhardness of 1200 HV_{100}. Many of the carbides lay along the prior austenite grain boundaries while others were within prior austenite grains. Manganese sulphide inclusions were present throughout the microstructure, relatively equiaxed in this transverse section, and the manganese content was found to be approximately 0.2%. The microstructure was homogeneous in the region examined. This appeared to be a hypereutectoid steel, with a microstructure such as would normally be possessed by a good quality functional file.

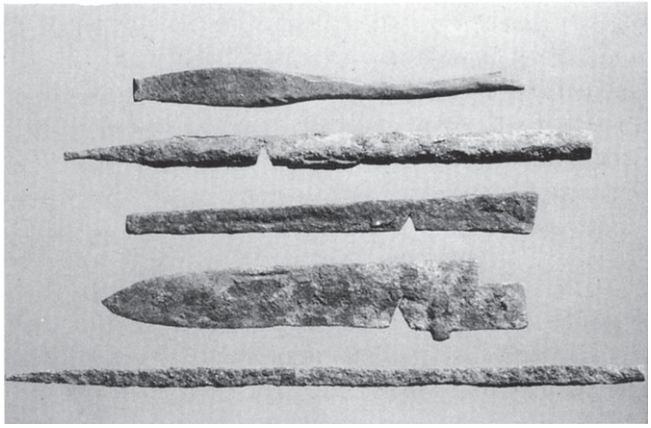
The second of the files (Fig 24c) was found to have a microstructure consisting primarily of plate martensite with significant amounts of retained austenite and microhardnesses ranging from 870 to 1023 HV_{100}. In the centre of the section, significant amounts of pearlite nodules were present, as was a thin layer of transformation product outlining the prior austenite grain boundaries. The amount of retained austenite also varied considerably from region to region. These effects reflect the existence of general carbon heterogeneity superimposed on heat treatment effects. However, the fact that the martensite was entirely of the plate type shows that the carbon content could not be much below 1%, as would be reasonable for



(a) top: File 1, centre: Chisel 1, bottom left: Bar 3, bottom right: wedge. The length of the top object is 110mm. The notches show the locations of metallographic sampling.



(b) left to right: File 3, Bar 2, punch. The other tools shown were not studied. The length of the file on the far left is 40mm.



(c) from top to bottom: Chisel 2, File 2, Chisel 3, knife blade, Bar 1. The length of the top object is 120mm. The notches show the locations of metallographic sampling.

Figure 24: Tools from the Siyadoris box. Sampling notches are visible in many of the tools.

a file. The manganese content of the matrix was found to be approximately 0.2%, and non-metallic inclusions, predominantly manganese sulphides but also some single-phase slag particles, were present. This is a functional file, although, in the section examined, its microstructure reveals that it is not of as high a quality as File 1. This is demonstrated by the absence of primary carbide particles and by the presence of pearlite in the microstructure, indicative of low or heterogeneous carbon content and/or slack quenching. The consequence of this is a lower hardness and poorer, though probably adequate performance.

File 3 (Fig 24b) had been modified at one end to enable it to be used as a gouge or engraving tool. Microstructural examination showed it to be somewhat heterogeneous, some regions being fully pearlitic, but most also containing pro-eutectoid cementite, precipitated both on the austenite grain boundaries and intragranularly as Widmanstatten plates. The microhardness was 397 HV_{100}, and the bulk manganese content about 0.3%. As with the other tools, manganese sulphide and silicate slag inclusions were present. This then was a hypereutectoid steel with carbon content in the correct range to have produced a good file, given proper heat treatment. However, its present microstructure is not optimum for a file, and it is suggested that the process of modifying the file to turn it into a different tool has involved heat treatments that have completely changed the microstructure, which was probably originally similar to that of file 1 described above. However, because the metallographic sample was taken from the shank, the possibility remains that at the cutting edge a quench-and-temper heat treatment may have given it a martensitic microstructure and hence more appropriate properties for use as a gouge or engraving tool.

Punch (Fig 24b)
This was a small bar, with a square cross section, tapering from 7.5 x 7.5mm at one end (flared asymmetrically by hammering to 9 x 9mm) down to 3 x 3mm at the tip, which appears to have been lost through fracture. Its identification as a punch was suggested by its tapering shape and flared end.

The microstructure (transverse section) of this bar showed it to consist of degenerate pearlite with pro-eutectoid cementite along prior austenite grain boundaries and as Widmanstatten plates within prior austenite grains. The microhardness was 334 HV_{100}. The carbon content was estimated to be above 1%, and the manganese content about 0.2%. The non-metallic inclusions present were primarily manganese sulphide particles with some silicate slag particles also present. This is an appropriate material for a punch, and the microstructure examined is as would be expected of the material far from the working end of the tool; for optimum performance as a punch the working end (now removed by fracture) would have had a tempered martensite microstructure.

Knife blade with integral tang (Fig 24c)
The microstructure (transverse section) of the cutting edge of this blade was martensitic, with a mixture of plate and lath martensite suggesting a carbon content in the range 0.6-1.0%. The microhardness was 662 HV_{100} near the tip and 632 HV_{100} about 10 mm from the tip, indicating that the blade had not been carburized but had been tempered (or allowed to auto-temper) after quenching. SEM-EDX showed the manganese content of the matrix to be about 0.4%, with a high density of elongated manganese sulphide inclusions as well as some iron silicate inclusions. The carbon content and heat treatment of this material have resulted in a microstructure, and microhardness, which are entirely appropriate for the blade of a functional knife.

Three bars
Of the three bars of unidentifiable function, Bar 1 (Fig 24c) and Bar 2 (Fig 24b) were found to be similar in microstructure, although Bar 1 was long (200mm) with a thin square cross-section (6 x 6mm), while Bar 2 was more compact (40mm long with a 6-7mm diameter). Metallographic examination (transverse sections) revealed both to be low-carbon steels. Bar 1 contained about 0.15% carbon, with equiaxed ferrite grains and colonies of degenerate pearlite and a microhardness of 196 HV_{100}. Bar 2 contained less than 0.1% carbon, occurring as carbides on the ferrite grain boundaries, with microhardness ranging between 160 and 220 HV_{100}. The bulk manganese contents in Bars 1 and 2 were about 0.6% and 0.3% respectively, with manganese sulphide and silicate inclusions. Bar 2 also contained a large, forked oxide-filled lamination, which had been closed during forging. The mechanical properties of both these bars would have been inadequate for them to have served as tools, unless they represent shanks which originally possessed carburized and heat-treated working ends.

In contrast, Bar 3 (Fig 24a) had a microstructure characterized by large amounts of single-phase and two-phase non-metallic inclusions in a low-carbon ferritic matrix (Fig 25). The ferrite grains were equiaxed, with a wide range of grain sizes; a few intergranular cementite particles were present, suggesting a carbon content less than 0.1%. The microhardness could not be determined with accuracy because of interference by the non-metallic inclusions; the value obtained, 163 HV_{100} was thus probably higher than the true value. Low phosphorus levels were detected, while the manganese content of the material was below the detection limit (approx 0.1%). Some of the inclusions were single-phase slag particles of calcium-iron silicate containing high levels of phosphorus; others were two-phase mixtures of silicate

with iron oxide. No manganese sulphide particles were observed, but small phosphorus-rich particles were present. Although this object had the general appearance of a punch, its mechanical properties would be poor for any application involving appreciable mechanical stress. The microstructure, however, suggests the possibility that this was actually a piece of bloomery iron which had been roughly forged to reduce it to the required shape and size to fit into a typical tubular steelmaking crucible, as described above, for the production of crucible steel.

Discussion of the tools

Despite their association with the iron blooms and the crucible steel ingot fragment in the steelmaker's tool box, none of these tools appears to have been made from crucible steel. With the exception of Bar 3, which will be considered separately below, all the tools examined contain detectable concentrations of manganese, in the range 0.2 to 0.7% in the metallic matrix, as well as manganese sulphide inclusions in their microstructures. The detection of trace amounts of chromium and copper and possibly nickel in many of these objects may also be significant. These characteristics are not in accord with those of the crucible steel ingots, which have undetectable manganese, and have sulphur present as iron sulphides; furthermore, the ingots exhibited the characteristic presence of steadite. Hence, these blacksmiths tools must have been made from steel produced by a process other than the traditional crucible steelmaking, *ie* from imported steel. In addition, the presence of the manganese suggests that the steels date from the 19th or 20th centuries, *ie* after Josiah Heath's 1839 patent for the use of manganese-bearing additives in steelmaking.

Bar 3 differs from the other tools in that it did not contain manganese but it did contain multi-phase silicate inclusions typical of bloomery slag. In fact, this object, except for one roughly squared end, had none of the characteristics of a tool and its size corresponds approximately with the internal dimensions of the crucibles used in the local crucible steelmaking industry. This object could therefore be a processed bloom ready to be used as raw material for crucible steelmaking.

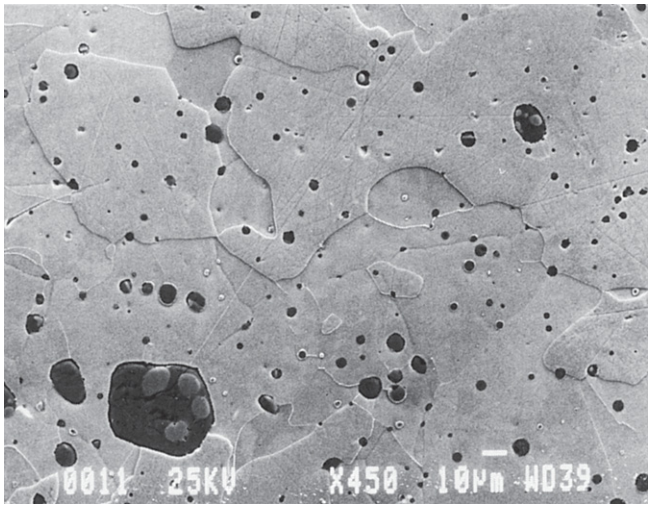


Figure 25: Bar 3. Ferrite with scattered cementite particles as well as single- and two-phase slag inclusions. Nital etch. SEM micrograph. Magnification 350x. (British Museum).

Conclusions

The analysis reported here has illuminated the contents of the box of material that belonged to the last traditional crucible steelmaker known to have operated in Sri Lanka. The two ingots from the box can be classified as high-quality steel in that they have high carbon contents and were relatively clean of slag inclusions. They do, however, contain iron sulphides and steadite, as well as having low manganese contents (*ie* the steel was made without manganese additions), and high phosphorus contents. These characteristics are entirely as might be expected from the crucible steelmaking process as reported by Ondaatje and by Coomaraswamy.

The iron blooms analysed are also as expected for iron smelted by traditional village smelting furnaces. Notable was their highly variable carbon content, the presence of extensive amounts of slag and porosity, and evidence for localised melting in high-carbon regions. The smithing tools from the toolbox were not made of crucible steel, although one of them may be a portion of bloom prepared as feedstock for conversion to steel in the crucible process.

It is worth reiterating the comments of Ondaatje and Coomaraswamy in their eyewitness accounts, that the traditional crucible steel industry was dying (1854) and dead (1903) respectively, and repeating our suggestion that crucible steel ingots were in fact produced as service rent to the local temple, rather than as raw materials for further industrial processing. In fact, it may well be that crucible steelmaking was never a major industry in Sri Lanka, that the island's reputation for high-quality steel, as reported in the 9th century by al-Kindi, arose from the extensive and prolific wind-powered smelting technology which has also been shown to be capable of producing high-carbon steel (Juleff 1996). However, it is important to note that the radiocarbon-dated site in the Knuckles does now indicate that crucible steel was being made at that time, albeit on an apparently very limited scale. This model implies that, unlike India, where crucible steel was a viable economic product, the making of crucible steel in Sri Lanka was a restricted caste/ceremonial activity, with steel being made perhaps annually to fulfil a feudal service, and the ultimate fate of the ingots was to be forgotten in temple stores. The absence to date of more and larger crucible steelmaking sites in Sri Lanka supports this interpretation and the comments of Bronson, who suggested that the

technology observed by Ondaatje and Coomaraswamy may have been 'a relict and perhaps degenerate process'. It is fascinating to see the industry in this light, while at the same time the microstructures of its products show that it was clearly capable of producing high-quality material which was not at all 'degenerate'.

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Notes

1. Since this work was carried out, it has been brought to our attention that the Science Museum in London is in possession of a complete steel ingot, a used crucible and a used crucible lid which reputedly derive from this demonstration. This group is part of the Percy collection, and is numbered 1908-187; it is not included in the 1892 Percy collection catalogue. Preliminary examination of this material, carried out by courtesy of the curator Dr S Mossman, shows that at least the ingot and crucible are indeed consistent with material expected from the Coomaraswamy demonstration.

2. A set of photographs similar to those published in Coomaraswamy's *Medieval Singhalese Art* is on permanent display in the Kandy Museum.

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