New evidence for early crucible steel

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Abstract

This paper reports the discovery and examination of an early example of crucible steel in the collections of the British Museum. This is a Sasanian sword, dated to the 6th-7th century AD. The sword is considered in relation to other new discoveries in the early history of crucible steel, suggesting, as a material, it may have been much more widely used and at an earlier date than previously supposed.

Introduction

In 1986 Bennet Bronson wrote a seminal article on crucible steel in which he drew together much of the available literary evidence and a number of points were established:

> That within the two basic methods of making crucible steel — *in situ* carburization and co-fusion — there was a very wide range of reported procedures.
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> That only part of the production was destined to be forged into the famed damascus blades with their distinctive watered patterns; most of the steel was simply good homogeneous carbon steel.
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> That although crucible steel has always been perceived as a quintessential product of southern India, in fact production was widely disseminated throughout the Middle East and Central Asia as well as India; however crucible steel from India certainly was widely traded.
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> That none of the early, mainly classical, references to crucible steel, when investigated, made any specific reference to crucible steel at all, and that really there was no reliable evidence before the mid first millennium AD.

The veracity of the first three points has been amply reinforced by discoveries made since publication, which confirms the importance of the paper in establishing a more balanced understanding of the true nature of crucible steel and its production and distribution. However, on the fourth point, although Bronson is correct that the specific early sources he cited almost certainly do not refer to crucible steel, he had overlooked some ancient surviving crucible steel from archaeological excavations already reported and a detailed early description of its manufacture. These together with other evidence published more recently show that crucible steel was certainly in production and quite widely known during the early centuries of our era (Craddock 1998). Many of the early sources mention Persia, and recent excavations both at Merv in Turkmenistan (Herrmann *et al* 1996, 1997) and Achsiket in Uzbekistan (Papachristou and Swertschkow 1993) have uncovered remains of crucible steel production dating from the Early Islamic period, specifically dating from the 9th century and later.

With these discoveries in mind a search was undertaken for possible earlier examples of crucible steel amongst the collections of the British Museum, concentrating on blades. General scarcity and time's decay has meant that few survive, and even fewer still retain sound metal for metallographic examination. The initial search has concentrated on Sasanian metalwork, specifically two swords that were not totally corroded. These were a single edged blade (WA 135056/1968-10-12, 22) and a double-edged sword (WA 135747) (Fig 1) that could be removed from its silver scabbard (WA 135739), both from the Dailaman region of north-western Iran and dated on reliable iconographic and comparative archaeological grounds to the 6th-9th centuries AD.

Examination and Results

Wedge-shaped samples were removed from the blades by sawing in from the cutting edge to the mid-rib in an area of sound metal (determined by radiography and a magnet). The sampled areas were refilled with resin and the swords re-displayed within the Ancient Iran gallery of the British Museum. The wedges were mounted in cold setting resin, ground and polished before being examined in the unetched condition by optical microscopy. After etching with nital (2% solution of nitric acid in ethanol) the sections were re-examined. The scanning electron microscope (SEM) with energy dispersive X-ray analysis (EDXA) was also used to examine and analyse the samples. A Vickers diamond pyramid microhardness tester

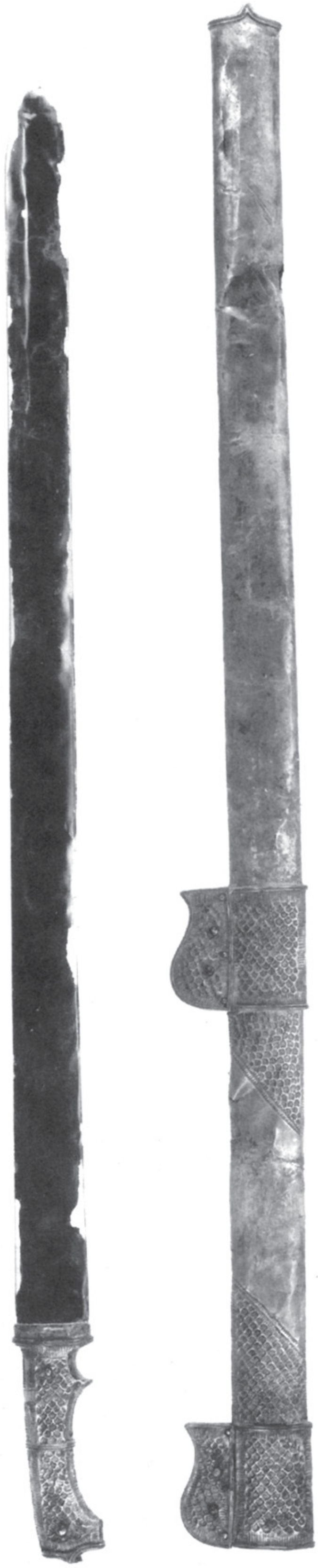

Fig 1: Sasanian sword and silver scabbard (British Museum WA 135747, scabbard WA 135739); scabbard is 933mm long.

was used to determine their microhardness.

Analysis of inclusions
Analysis was carried out using pure element, oxide and simple mineral standards, at 15kV using a JEOL 840 scanning electron microscope with Oxford instruments energy dispersive analysis and a Link germanium detector with Isis processing. The samples were flat and polished. Typically, the detection limits are 0.2% (Mn, Ti), 0.3% (S, K, Ca) and 0.4% (Al, Si). The inclusions were arbitrarily selected for analysis. All are rounded in shape, featureless and very small (*eg* 25μm). The results are semi-quantitative and should be treated with caution. As Table 1 shows, the composition was not uniform, especially with regard to aluminium, silicon, calcium and titanium, while potassium was either low or absent. Phosphorus, manganese and arsenic were not detected. Any elements present in the iron body metal were below detection limits. The purity of the metal and the small quantity of slag inclusions indicate an efficient steelmaking process.

The inclusions in the single edged sword were much more numerous, variable in shape, size and appearance. They were also analysed, but as this sword will be published more extensively elsewhere, a table of analysis is not given here. Generally, however, it may be said that the silicon, aluminium, potassium and titanium contents are higher than in the double edged blade. Manganese was also present in some inclusions, while phosphorus was present in just under half of these analyses. Clearly, the number of inclusions indicates that the metal of this sword is not as 'clean' as that of the double edged blade, and the steelmaking process was less efficient.

The double-edged sword with a silver scabbard
When the blade was cut to provide the sample, the wedge-shaped sample broke into a number of fragments (Fig 2). The central section is sound metal and a careful

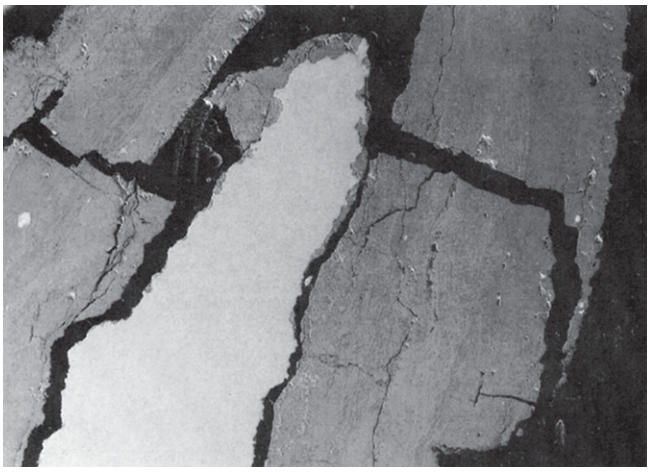

Fig 2: Sword sample, showing sound metal core and fragmented corroded surfaces (x 5).

Table 1: Semi-quantitative analysis of elements present in inclusions in sword WA 135747

Inclusion	wt% element							
	Al	Si	S	Cl	K	Ca	Ti	Ni
1	3	6	-	-	0.2	2	10	-
2	1	3	0.1	-	-	2	9	0.3
3	12	20	0.3	-	3	10	1	-
4	6	8	-	0.1	1	4	1	-
5	12	-	0	1	1	5	3	-
6	7	10	0.2	-	1	6	1	-
7	15	35	-	-	2	30	3	-

Iron, carbon, nitrogen and oxygen are omitted.
Phosphorus, manganese and arsenic are below the detection limit of 0.2 ± 0.2%

examination of the fragments suggested that the original blade may have consisted of three layers, of which only the central one remains uncorroded. The metal contains small rounded inclusions, fairly evenly dispersed. The analytical results (Table 1) show the inclusions do not contain manganese or phosphorus, indicating that they are not slag. Generally the silicon content of the inclusions is low in comparison with those in the single-edged blade.

Etching revealed a mottled macrostructure, with slightly elongated light and dark etching areas. The shape and distribution of these areas indicated that the original macrostructure was dendritic (Fig 3). Viewed at a high magnification, the microstructure could be seen to consist of a very fine dark-etching matrix of pearlite with agglomerations of rounded globules of cementite (Fig 4). This was confirmed by etching with boiling alkaline sodium picrate, which preferentially darkens cementite. The structure is that of a steel which was formed in the liquid state and has been subsequently worked; it is concluded that the sword (WA 135747) was fabricated from crucible steel. The hardness values of 400 VPN are consistent with the structure and indicate that the metal was not fully hardened. The pearlitic matrix is extremely fine and irresolvable in parts of the section indicating that the final cooling process had been rapid.

The presence of uncorroded carbides in the corroded metal of the outer segments immediately adjacent to the core suggests that these segments were probably made from steel similar to the core metal (Fig 5). Because the surfaces and cutting edges have corroded so that neither metal nor

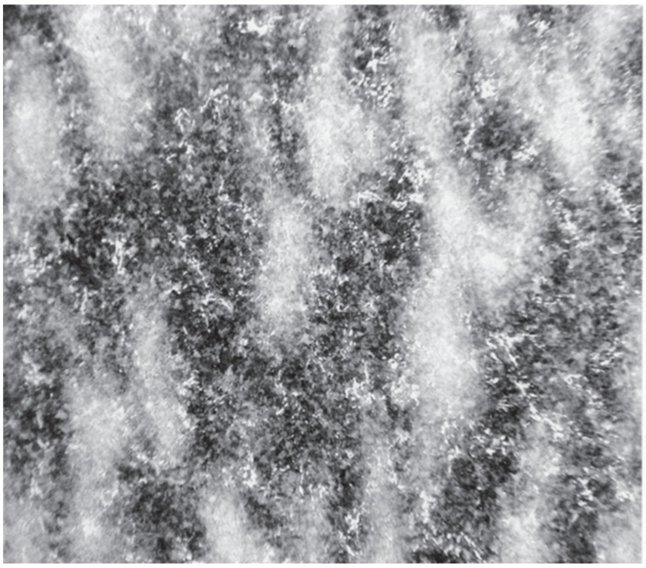

Fig 3: Sword sample etched with nital, showing mottled structure (x 100).

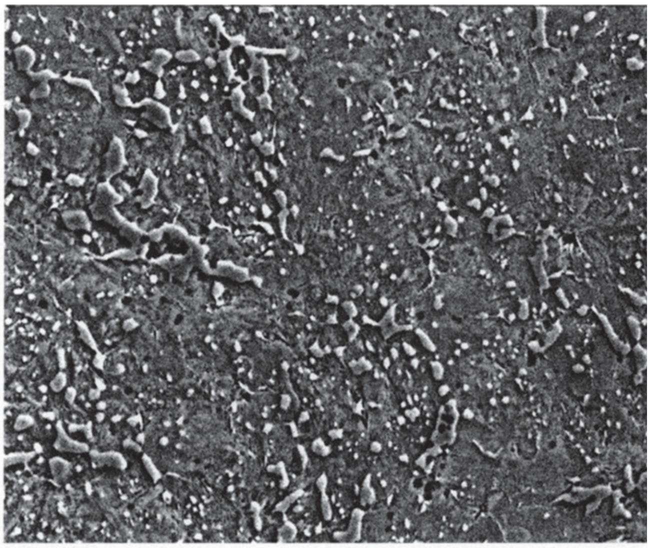

Fig 4: Sword sample etched with nital, near cutting edge, showing agglomerated iron carbide globules in an irresolvable pearlite matrix (x 500).

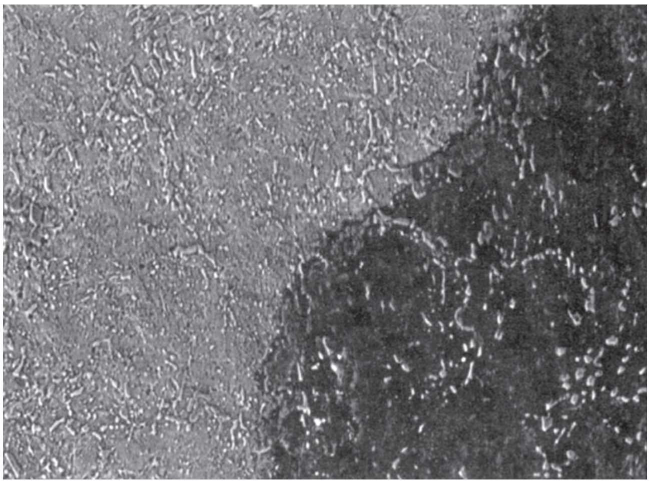

Fig 5: Sword sample etched with nital, showing the agglomerations of iron carbides continuing into the corroded surface layer (x 200).

signs of the original morphology preserved in the corrosion product (relict structure) remains, it is impossible to be certain of the original structure and hardness of these areas.

The dendritic macrostructure is typical of a metal which has solidified from the molten state and can be seen in ingots of crucible steel. Forging cycles have distorted the structure perceptibly but have not homogenised it to any extent. The proeutectic cementite has agglomerated into globules within the pearlitic matrix as a result of the working processes. However, there is no indication of the cementite globules segregating into the layered structure which characterises damascus-type steel patterned blades and has been described and discussed by many writers including Verhoeven *et al* (1987, 1992, 1993, 1994, 1996). On a finished damascus blade, polishing the tiny undulations in the surface reveals different layers unevenly; the light and dark bands are visible on the polished surfaces of the finished blade as patterns. The finished surface of this blade would not have been patterned as there is no evidence that the cementite distribution was layered, which is necessary for making patterns.

Discussion

Early history of crucible steel

Currently the earliest evidence for crucible steel are the pieces excavated by Marshall (1951) from the ancient city of Taxila, near Rawalpindi, now in Pakistan, and dating from about 2000 years ago. They were examined by the eminent metallurgist Sir Robert Hadfield (in Marshall 1951 II, 535). Of the ten samples of iron examined three, namely two swords and an adze, had high carbon contents (1.3-1.7% C). Hadfield was in no doubt of their significance, remarking 'Evidently the Indians of this locality and at this period quite deliberately made high carbon steel'. He also noted that although the other pieces examined 'contained the usual amount of non-metallic inclusions, but the high carbon specimens, are however, comparatively clean'. Marshall (1951, 535-7) was in no doubt that these pieces were of crucible steel, and Hadfield's description could apply to the double edged sword examined by us. Although it is unfortunately not possible to make a direct comparison with the analyses of the Taxila material, or other analyses summarised by Bronson (1986, Table 3) as the methods of analysis are very different, it is important to note that neither the Taxila pieces nor the sword identified here had the specialised structure of patterned damascus blades.

The first certain reference to crucible steel is the detailed description by the Alexandrian alchemist Zosimos in the 3rd century AD (Berthelot 1888, II V.v, 347-8, III V.v, 332). In the latter reference it states (in translation from the French):

> 'The Tempering of Indian Iron
>
> 1. Take soft iron four pounds, broken into small pieces, then take the skins of the fruits of the palm tree [or more likely the *myrobalans,* fruit of the *terminalia*], called *elileg* in the lands of the Arabs, fifteen parts by weight, and four parts by weight of *belileg,* similarly cleaned from the interior, that is to say just the bark, as well as *ambileg,* similarly cleaned, and of glassmaker's magnesia two parts. Grind all together, not too finely, and mix in four pounds of iron. Then place in a crucible and make level the place for the crucibles in front of the bellows, because if you do not take this precaution, to avoid that this [crucible] is not displaced you will find difficulties in the melting operation. Then put on the charcoal and blow the fire until the iron becomes molten and the components [mentioned above] become united with it. Note that the four pounds of iron need one hundred pounds of charcoal.
> 2. Note that if the iron is not very soft it does not need the magnesia, but only all the other ingredients, because the magnesia renders it dry to a great degree and makes it brittle. But if it is soft it needs only it alone as has already been said, because this accomplishes everything.
> 3. Such is the premier and royal operation, which is practised today and by means of which they make marvellous swords. It was discovered by the Indians and exploited by the Persians, and it is from them that they are coming.'

This succinct account of the production of crucible steel by the direct carburization method and its use and distribution was to be broadly true for the next 1,500 years. It is clear from its use elsewhere in the alchemic literature that glassmaker's magnesia meant either iron or manganese oxides. Note again that there is no mention here of damascus patterns on the blades. The properties of a sword made from a homogeneous high carbon steel free from slag stringers would have been quite marvellous in themselves, especially to the warriors either using or encountering such a sword in combat.

Sasanian iron and steel

It is possible to learn more of the trade between India and the west from references in the Babylonian Talmud, compiled between the 3rd and 5th centuries AD when a sizeable Jewish population lived in central Mesopotamia, close to the political and economic heart of the Sasanian Empire. In the 3rd century tractate Avodah Zarah 16/a, Rav Adah the son of Ahava stated that it was forbidden to sell iron to other nations because they would fashion it into weapons (Bodenheimer and Rothenberg 1996). This was later overturned by Rav Ashi (died *c*427 AD) on the grounds that now they sold even *Hinduan* [Indian] iron to the Persians because they protected the Jews. The significance here is that *Hinduan* was used in succeeding centuries by Islamic authors as synonymous with crucible steel. The restriction on trade is mirrored by 4th and 6th century classical authors (Libanius and Procopius) who refer to a corresponding Roman ban on the export of high-grade iron ore to Persia which was said to have lacked its own iron ore resources (Dodgeon and Lieu 1991, 157, 382). One possible scenario is Jewish trade in crucible steel between India and Persia. An alternative hypothesis is that Jews formed part of a wider commercial network linking Mesopotamia, Iran and India via the Persian Gulf. A growing number of archaeological finds along the Gulf littoral, and as far east as Sri Lanka, of Sasanian pottery, glassware, coins, seals and bullae certainly indicate Gulf trade during this period, confirming an earlier hypothesis advanced by Whitehouse and Williamson (1973); how this trade was organised or who was primarily responsible remains uncertain in the absence of relevant historical sources. The probable Mesopotamian point of entry for imported Indian goods would have been Ubulla, at the head of the Persian Gulf and close to the later port of Basra; Ubulla was referred to by Early Islamic authors as 'the opening for [or gateway to] India' (Friedmann 1992, 15-16). Indians also formed a minority population within the Sasanian state, judging by occasional historical references to Indian gypsies, musicians and elephant-handlers (Morony 1984, 271-72).

Sasanian trade and foreign relations appear to have been carefully regulated. There is no surviving historical evidence for the widespread import of Far Eastern or Roman/Byzantine goods into the Sasanian Empire, or vice versa; indeed, surface surveys in northern Mesopotamia suggest that the markedly different distributions of Sasanian and Roman finds correspond closely to the political limits of the respective Empires (Simpson 1996). This places the talmudic reference within a somewhat clearer political perspective. Sasanian craftsmen and traders worked within a well-organised, Persian-dominated society that maintained cautious, at times belligerent, relations with its neighbours. Despite talmudic prohibitions on the intermingling of Jews and non-Jews, political and economic realities dictated changes to minority religious orthodoxies. Jews were occasionally conscripted to serve within the Sasanian army, and Jewish communities within frontier zones were billeted with [non-Jewish] troops (Morony 1984, 317). The Babylonian Talmud therefore provides a glimpse into events within the heart of the Sasanian Empire but the economic significance of this community should not be over-estimated.

Middle Persian (Pahlavi) sources refer to a variety of terms for artisans, including iron and steel-workers (Tafazzoli 1974). These distinguish between 'ironsmith', literally 'one who works in steel' (*pōlāwad-paykar*), 'one who casts or moulds iron' (*āhen-paykar*), 'swordsmith', literally 'one who makes small ironware' (*čēlangar*) and 'blacksmith', literally 'one who makes large ironware' (*āhengar*). There are further tell-tale Middle Persian references to steel and Indian steel (Tafazzoli 1993/4), including 'daggers [of] hard steel', a 'knife made of steel', 'Indian swords' (*šamšēr i hindūg*), 'sword made of steel' (*šamšēr i polāwaden*) and '12,000 Indian adorned swords made of steel' (*šamšēr i polāwaden i wirastag i hindūg*). 'Steel swords', 'thin-bladed Indian swords', iron spearheads, javelins and arrowheads, 'polished armour of iron', iron caltrops, bits, chains and needles are also mentioned in Classical, Aramaic, Armenian and Islamic sources (Dodgeon and Lieu 1991, 209, 312; Friedmann 1992, 121, 140, 148; Montgomery 1913, 121-26; Newman 1932, 126; Whitby and Whitby 1997, 45, 50-51, 53, 70, 84, 98, 104, 111). Furthermore, Ferdowsi's Shah-Nameh, a 10th century compilation of stories largely dealing with Sasanian Iran, includes sporadic references to 'fine-tempered scimitars', 'Indian scimitars' and steel arrowheads (Levy 1985, 252, 259, 327, 396, 410). This range of references hints at a complex underlying pattern of production and import of iron and steel but, in the absence of technological analyses of Sasanian ironwork, these literary allusions have remained unconfirmed. The present analysis now proves that crucible steel was indeed used within Sasanian Iran.

Swords (Middle Persian *šafšēr* or *šamšēr* were regarded as visible status symbols within Iran during this period. The Sasanian court included the king's 'sword-bearer' (Lukonin 1986, 710-11), and swords feature together with belts, bracelets and coats as personal booty that was prized by Arab fighters (Friedmann 1992, 140). Sasanian kings and nobles were regularly depicted wearing a long sword on the left thigh with a matching dagger on the opposite side. Two principal methods of sword suspension were employed, namely using a bridge-mount or scabbard slide, or from pairs of D-, P- or R-shaped mounts which allowed the sword to be slung at a more convenient angle. The latter method was widely diffused from Central Asia to Iran, eastern Europe and the Far East, and is thought to mark the transition towards the use of lighter cavalry sabres with a single edge that later replaced the older heavier double-edged blades (Bálint 1978). This method of sword suspension is depicted on a single Late Sasanian rock relief at Taq-i Bustan in western Iran that shows king Khusrau II (591-628 AD).

About a dozen Late Sasanian two-edged swords set in approximately one metre long decorated silver or gilded scabbards with two-point suspension mounts survive in public collections (Overlaet 1982, 195-201; Overlaet *et al* 1993, 177-9). These include three examples within the British Museum, of which WA 135747 is one. All are believed to derive from cemeteries discovered in the mountainous forested region of Dailaman, in north-western Iran. The similarity between the scabbards suggest that they may have been the product of a single Iranian workshop tradition that was also responsible for manufacturing daggers and helmets. These were likewise decorated with overlapping feather patterns that may represent the mythical bird Varagna, an incarnation of the Zoroastrian god of victory Verethragna (Ghirshman 1963, 310). However, although these swords have attracted wide discussion no technical analyses of the blades themselves appear to have been undertaken (cf Ghirshman 1963, Nickel 1973, Overlaet 1982, 1989).

Crucible steel production in Central Asia and Sri Lanka

The new discovery of a Sasanian crucible steel sword blade changes our understanding of the origins and diffusion of this technology. Further discoveries of slightly later, Early Islamic, crucible steel help refine Bronson's (1986) original hypothesis. Recent excavations have found evidence for the early production of crucible steel in Central Asia, at Achsiket (Eski Achsy) in the middle Fergana Basin of Uzbekistan, dating to the 9th-14th centuries AD (Papachristou and Swertschow 1993) and at Merv, now in Turkmenistan, dating to between the 9th and 10th centuries AD (Herrmann *et al* 1995, 1996). At both sites the principal evidence are the scatters of large quantities of crucible sherds and at Merv, the excavated remains of furnaces. The composition of the crucible sherds is interesting as they contain very little iron, but large quantities of alumina (of the order of 30%), and with the silica this created a refractory with a very high melting point; indeed these are probably the very first true industrial refractories.

The newly discovered remains of an early Sri Lankan crucible steel smelting site to the north east of the Central Highlands, east of the Knuckles mountains, which is approximately contemporary with the activities at Merv, was recently reported by Juleff (1997, 3); this apparently has crucibles of similar ceramic fabric to those used at Mawal Gana in the Central Highlands in the recent past (Craddock 1995, 279-80). The refractory body of these crucibles is very different, a ferruginous clay, copiously tempered with rice husk. In the intensely reducing conditions of the crucible furnace the iron oxides were reduced to metallic iron, thereby creating a refractory body *in situ* (Freestone and Tite 1986).

Varieties of crucible steel

Zosimos described the Indian process as being one of *in situ* carburization and the majority of the processes described in the south of India and in Sri Lanka in the 19th century also seem to have been *in situ* carburization using a variety of woody plants (Bronson 1986). The process was also reported by Massalski at Bokhara in the mid 19th century (Wulff 1966, 8-9; Massalski 1841).

The alternative process of co-fusion, where cast and wrought iron were melted together in the appropriate quantities needed to produce a steel with the required intermediate carbon content, also seems to have a wide distribution and long history. In India co-fusion seems to have been the process used at Konasamudrum and other sites of the old state of Hyderabad, now the Niziambad district of the state of Andhra Pradesh, but it was also used in the south of India in Tamil Nadu, for there is a report of the operation of a blast furnace, to produce grey (?) cast iron, specifically for the co-fusion process (Craddock 1995, 282).

The antiquity of the co-fusion process in Islamic lands is presently uncertain, but the Islamic authors of the 12th-13th century seem to describe both *in situ* carburization (al-Tars̄usī) (Cahen 1947/8, 106-7) and co-fusion processes (al Birūnī) (Allan 1979, 75). This situation is mirrored to some extent by the recently excavated sites and the last records of the process in Central Asia in the 19th century. At Achsiket the excavators believed the process to be one of *in situ* carburization, whilst at Merv the process is believed to have been co-fusion. In the early 19th century the Russian Anossoff (1841) observed the co-fusion process, using white cast iron, in operation at Bokhara, but twenty years later his brother officer Massalski recorded the *in situ* carburization process in the same city (Wulff 1966, 8-9).

The use of the co-fusion process from early times in both Central Asia and apparently in India means that cast iron must also have been in regular production, but as yet almost nothing is known about its production at these early dates outside of China.

Much research has been conducted into the nature and preparation of the steel of the damascus-patterned blades (Figiel 1991). Bronson's (1986) survey suggested that the steel intended for the production of the damascus blades was a very specialised variety of crucible steel, and more specifically its preparation seems to have involved the very slow cooling of the molten ingot to allow the distinctive structure of cementite globules to develop at the grain boundaries. Exhaustive examination and replication experiments by Verhoeven and his co-workers (Verhoeven *et al* 1987, 1992, 1993, 1996) has shown that the composition of the iron used is also important, and that the layered structure is developed as the metal is forged to make the sword.

Because of the prestige of the damascus-patterned blades there has always been a tendency to believe that this was all that crucible steel was used for, and that it was a highly sophisticated, very specialised material that was remote from everyday requirements and usages. In fact none of the early pieces that have been identified so far have the distinctive damascus structure, and none of the earliest references to crucible steel mention patterns (see above). Not until the Early Islamic period are the two varieties of crucible steel mentioned. For example the Persian author al-Birūnī gave a confused account of the co-fusion process of making crucible steel in the 12th century AD, writing that:

> 'Either the *narm-ahan* [wrought iron] and its water [cast iron ?] melt equally in the crucible and unite so that one cannot distinguish the one from the other, in which case it is good for files and the like ... Or alternatively, the melting qualities of what is in the crucible vary, so that the two do not mix completely but on the contrary are separate in their parts from one another, and each part of their two colours is seen individually. This is called damask (*firind*).' (Translation taken from Allan 1979, 75)

Of course, in reality, both varieties were fully molten, but in the second the segregated cementite structure had been allowed to form from the melt, giving the damascus pattern which al-Birūnī mistook, not unnaturally, for incomplete melting.

Reports from many of the Indian production centres in the 19th century, such as those from the Chitradurga region of Mysore, now part of the state of Karnataka, make no mention of damascus blades, but rather of chisels (at Ghattihosahalli) or of sitar strings (at Channapatna). Crucible steel was in everyday use, and probably from a very early date, for a whole range of applications where a good quality steel was necessary. Clearly the material had a much wider technical and economic significance than that of the damascus-patterned blades alone. (Craddock 1998, Anantharamu *et al* forthcoming).

It is not possible to say by which process the crucible steel of the Sasanian sword examined here was made, yet its discovery amongst surviving Sasanian weaponry is important. Together with the other early survivals from Taxila, the re-evaluated documentary evidence and the newly discovered evidence of early crucible steel production sites, it is further demonstration of and evidence for the production and uses of crucible steel in the first millennium AD.

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