Crucible Steel – Bright Steel

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ABSTRACT: This paper describes the examination of two ferrous Islamic mirrors. One is of very pure iron but the other would appear to be of crucible steel, confirming contemporary descriptions that mirrors were of steel. The methods by which the steel could have been produced and the mirror fabricated are discussed. Recent work has shown that crucible steel was used for a wider range of artefacts than previously appreciated and its use for mirrors reflects another property of the metal that was utilised. Crucible steel as a bright material was certainly appreciated in 18th century Europe, when one of the first uses of crucible steel was as the source material for the imitation diamonds known as 'brilliants' that featured so much in costume jewellery of the period.

Introduction

Crucible steel is popularly regarded as essentially a product of the European Industrial Revolution of the 18th and 19th centuries (Barraclough 1984a and 1984b), used for items such as the superior clock and watch springs of Benjamin Huntsman (Wayman 2000) and the cannon of Frederick Krupp (Manchester 1969). There is also some perception that the distinctively-patterned damascus blades from India and the Islamic world were made from a crucible steel known as *wootz* that originated in India (Bronson 1986).

Recent researches, variously embracing archaeological, documentary and metallographic studies, have together shown that the production and usage of crucible steel was much wider and from a much earlier date than had been previously realised (Allan and Gilmour 2000; Anantharamu *et al* 1999; Craddock 1998 and 2003). This paper reports on the examination of a 14th century Islamic mirror (Fig 1) which metallographic analysis has shown is likely to be of crucible steel. This has documented another and very different property of the metal that was understood and valued in previous ages, namely the ability to take and retain a brilliant reflecting surface.

Crucible Steel

Iron has been a metal in very common use for the last three millennia throughout the Old World, and for most of that period it was produced by the so-called bloomery process in the solid state. The high melting point of iron (*c* 1540°C) made it difficult to produce as a liquid. Smelting and working iron in the solid state, however, meant that impurities from the smelting process were trapped in the metal as slag stringers, causing weakness and failure. Furthermore both pure iron and wrought iron, with its slag stringers, have inferior strength properties when compared to bronze (Smith 1967). It is only when iron contains a small proportion of carbon (typically 0.2 to 0.8%), to become steel, that the hardness and tensile strength exceed those of bronze. If it was possible to liquefy the steel, much improved properties would be achieved as the slag floats to the surface and could be skimmed off. Also more carbon readily dissolves in the molten steel and is distributed far more evenly than when it was introduced at the surfaces in the solid state. The steel was melted in highly refractory crucibles requiring skilled control of the components and the conditions because if too much carbon enters the metal, cast iron would be formed, which has completely different properties to steel.

Figure 1: Back of the steel mirror, with calligraphic bands, the outer in gold, the inner in silver, stating the mirror belonged to a wife of an unnamed amir. Now in the British Museum (OA Reg 1960, 1-15, 1).

China pioneered the production of cast iron from at least the 9th century BC, and made some steel by the carefully controlled partial decarburization of cast iron (Craddock 2003). Despite the very advanced state of their ferrous metallurgy generally the Chinese never seem to have made liquid steel, but obtained supplies of crucible steel apparently from India (Gilmour 2000, 48–9), although Central Asia would have seemed a more likely source. There are also some rather interesting Arabic records of the import of Chinese iron, *hadid al-Sini*, specifically for making mirrors that are discussed further below.

There seem to have been three main methods by which liquid or crucible steel was made before the introduction of the Bessemer process in the mid 19th century ushered in the era of cheap steel, which changed steel-making, and the world, forever (Barraclough 1990):

- *In situ* carburization, in which wrought iron was melted in a crucible with a variety of carbonaceous materials, usually woody plants, to become steel.
- Co-fusion, in which cast iron, with about 3–4%C, and wrought iron, with little or no carbon, were melted together to give a steel with the required 0.5–1%C.

These two processes are both recorded in Central and South Asia (Bronson 1986; Craddock 1998 and see some of the medieval Islamic descriptions given below). Al-Hasain and Dunlop (1986, 253–5) claimed that the Chinese process of decarburizing cast iron to produce steel in the solid state was also used in the Islamic world, but the particular passage from Jabir al-Hayyan's *Book on Iron* could just as well be read as a description of the co-fusion process (Gilmour 2000, 57–61).

In post-medieval Europe another process developed:

- Steel was made in a solid-state process by packing bars of wrought iron in stone chests filled with charcoal dust, sealing them and then strongly heating for several days. The product, blister or cementation steel, was usually good, but it still contained some slag inclusions from the processes to produce the wrought iron and the carbon was often very unevenly distributed in the steel. Benjamin Huntsman in the 1740s began the process of melting the cementation steel in crucibles creating a pure homogenous product. This was the high quality crucible steel that established Sheffield's reputation as a steel-making centre for the next two centuries (Barraclough 1984a and 1984b; Craddock and Wayman 2000).

The Indian crucible steel industry has been known in Britain, and largely misunderstood, since the early 19th century (Bronson 1986; Craddock 1998), being perceived as an industry that was mainly post-medieval in date and whose main products were largely confined to the exotically-patterned *damascus* blades. The earliest surviving Damascus-patterned steels date from the 13th and 14th centuries AD, although Gilmour (2000, 54 note 63) believes that an extensively corroded early Islamic sword from Nishapur, in Iran, and now in the Metropolitan Museum, New York, may once have had the Damascus patterns.

Re-evaluation of the documentary sources and the metallographic examination of some steel artefacts have shown that crucible steel was being produced over two thousand years ago, and that by the 3rd century AD there was already a flourishing trade in the metal between South Asia and the Mediterranean (Allan 2000a, 113; Craddock 2003). The early Islamic technical authors such as al-Kindi, Jabir al-Hayyan, al-Biruni and al-Tarsusi, writing between the 8th and early 13th centuries AD (Gilmour 2000, 56–63) describe the production of

steel for swords in Iran and Central Asia in some detail, and recent archaeological fieldwork has identified several early Islamic production sites in Central Asia, notably at Merv in Turkmenistan (Feuerbach 2002; Feuerbach *et al* 2003) and at Achsiket in the Ferghana Valley of Uzbekisthan (Rehren and Papakhristu 2000) (Fig 2). At Merv, furnaces for the production of crucible steel have been excavated. They have been dated to between the 8th and 9th centuries AD, although the industry probably had its roots in the preceding Sasanian period if not earlier, as exemplified by the fine Sasanian sword of crucible steel now in the British Museum (Lang *et al* 1998) and the contemporary sword from Nishapur (see above). At Achsiket, the crucible steel making activities are dated to between the 9th and 12th centuries AD, and evidenced by heaps of crucible fragments. The steel-making crucibles from Merv and Achsiket are quite similar, both having been made from very refractory ceramics that contain approximately two parts of silica and one part of alumina. The ceramics contain very little of the other metal oxides, notably of iron or the alkali metals, such as sodium or potassium, which are found in ordinary clays and which cause the ceramic bodies made from them to progressively vitrify at temperatures above 1000˚C. The crucibles from Achsiket by contrast were still unvitrified at temperatures well in excess of 1500˚C in refiring experiments (Rehren and Papakhristu 2000).

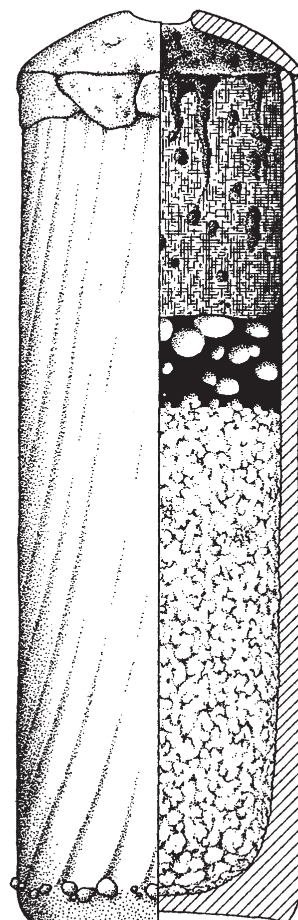

Figure 2: Section through a steel-making crucible, based on the fragments found at Achsiket, Uzbekistan. A vessel would typically have been about 250mm in height (from Rehren and Papakhristu 2000).

At both sites production terminated forever in the 1220s due to the Mongol invasions, and indeed the evidence for the continuation of crucible steel-making in Central Asia is somewhat equivocal. Later Iranian technical writers such as al-Khasani, writing in the late 13th century AD gave only a very imperfect description of the process, suggesting to Allan that al-Khasani had never actually witnessed the process (Allan 1979, vii and 71) and crucible steel was certainly being imported in quantity from South Asia at that time (Allan 2000a). However, much later, in the early 19th century Russians such as Anasov (1841) were able to record crucible steel making taking place in the Emirate of Bukhara and other centres in Central Asia (Wulff 1966, 8–9), suggesting continuity.

At the same time as these excavations have been taking place there have been important metallographic studies on surviving ferrous material from Central Asia and Iran. Feuerbach (2002, 233–50) has carried out metallographic examinations of blades, mainly of the first millennium AD, from sites in the Caucasus and across Central Asia to the Aral Sea. She found four or possibly five of the 39 blades she examined were likely to be of crucible steel, including blades dated to between the 3rd/4th and the 12th century AD. Allan and Gilmour's (2000) magisterial survey of ferrous metals from Iran includes the metallographic examination of a wide range of artefacts, other than blades, from the Tanavoli Collection, in the main dated to between the 15th and 19th centuries AD. Gilmour (2000, 506–7) noted that 'one of the most interesting overall results of the survey was that more than half of the artefacts examined were found to be made of an ultra high-carbon (hypereutectoid) steel. This would appear to be consistent with cast crucible steel ... (which) before now have hardly been recognised as having been used for objects apart from swords, daggers and some armour.' Both the layered water-patterned Damascus steel and plain steels were encountered.

Mirrors

The extended range of artefacts of crucible steel encountered by Allan and Gilmour, including strike-a-lights, scissors etc, made use of the material's hardness

and related ability to take an edge or resist penetration that was so necessary in the blades and armour previously examined. Their survey also included three steel mirrors (see below), two of which may have been of crucible steel (discussed below). These, together with the Islamic mirror from the British Museum, described here, shows that other properties were also valued, namely the ability to produce a good reflecting surface.

The mirror, OA Reg 1960, 1–15, 1, which once formed part of the Mutiaux collection, was acquired by the British Museum at auction in Paris in 1952 (Hayward Gallery 1976, cat. no. 228). The steel disc and the gold and silver inlays on the back are in near-perfect condition, but the handle that was once riveted to the disc is now missing. The front of the disc is quite plain, and the back is somewhat thickened and slightly bevelled at the edge, but is otherwise flat. The back has two concentric bands of calligraphic inlay, both of superb quality (Wiet 1958). The outer band is inlaid with gold and the inner band is inlaid with silver. The inscriptions state that the mirror was made for the wife of an amir, giving his titles but unfortunately not naming him, or where he was from. In the centre of the mirror is a blazon which Ward (1993, 107) has demonstrated represents a box or pencase, suggesting the amir was a court secretary. Stylistically the mirror is likely to have been made in Egypt in the 14th century AD.

Metallographic examination

The mirror was examined metallographically as part of an ongoing project on the scientific study of Islamic metalwork (Craddock et al 1998; La Niece 2003). Examination presented major problems as it was too large to fit within the chamber of the scanning electron microscope, and clearly cutting a standard metallographic section from such a well preserved and intact piece was out of the question. This rather limited the amount of metallography that could be carried out. However, the metal is only very lightly tarnished and in places the original filing of the edge had created some very flat surfaces that with a very minimal polishing to remove the superficial tarnish could serve as a taper section. It must be stressed at the outset that this means that the metallographic description is limited to the metal at the very edge.

The mirror was securely mounted in a wooden jig which exposed a short length of the edge, lightly polished with 1μm diamond paste and examined using an inverted stage optical microscope in both the unetched and etched condition. The unetched state revealed a number of small inclusions that were single phased and pale grey in colour. Some were lenticular in shape while others were more rod-shaped but all were elongated parallel to the face of the mirror. Corrosion had penetrated the surface at the edge of the polished area but it seems unlikely that the inclusions are corrosion products because the identifiable corrosion products are a darker grey and their shapes are more random. Similarly they did not have the appearance of slag inclusions; if the material is crucible steel then their presence is difficult to explain, possibly they formed during forging.

The surface was then etched using 2% nitric acid in ethanol which reveals the structure of the metal by preferentially attacking the grain boundaries (Fig 3). At low magnification a very fine structure was revealed but the detail could not be resolved. Very slight banding, resulting from a difference in the metal's response to the etch were discerned. The bands were irregular, but very generally seemed to run parallel to the surface of the mirror. Higher magnification showed that the structure was mainly spheroidized pearlite in a ferritic matrix. This suggested the iron contained just under the eutectoid composition, probably around 0.7–0.8% of carbon, and the composition seemed reasonably homogeneous. Some of the carbides had agglomerated to form slightly larger, more elongated shapes. Small areas of very fine lamellar pearlite could be distinguished and the structure also had some slightly more rapidly-etching areas that could not be resolved, but which may be very fine pearlite. Lighter-etching areas consisted of ferrite with some agglomerated carbides. A number of very small black dots were identified as being carbide precipitates. The overall microstructure of extremely fine spheroidized pearlite suggests that in the final stages of fabrication the worked metal was heated to above 727°C,

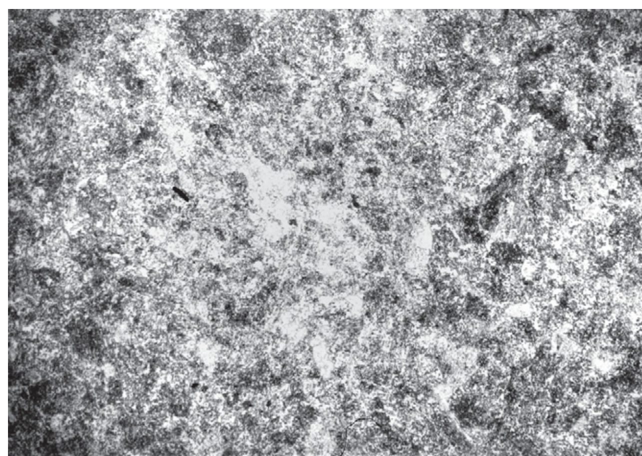

Figure 3: Micrograph of polished and etched taper section from the edge of mirror OA Reg 1960, 1-15, 1. Image is 144 micrometres across.

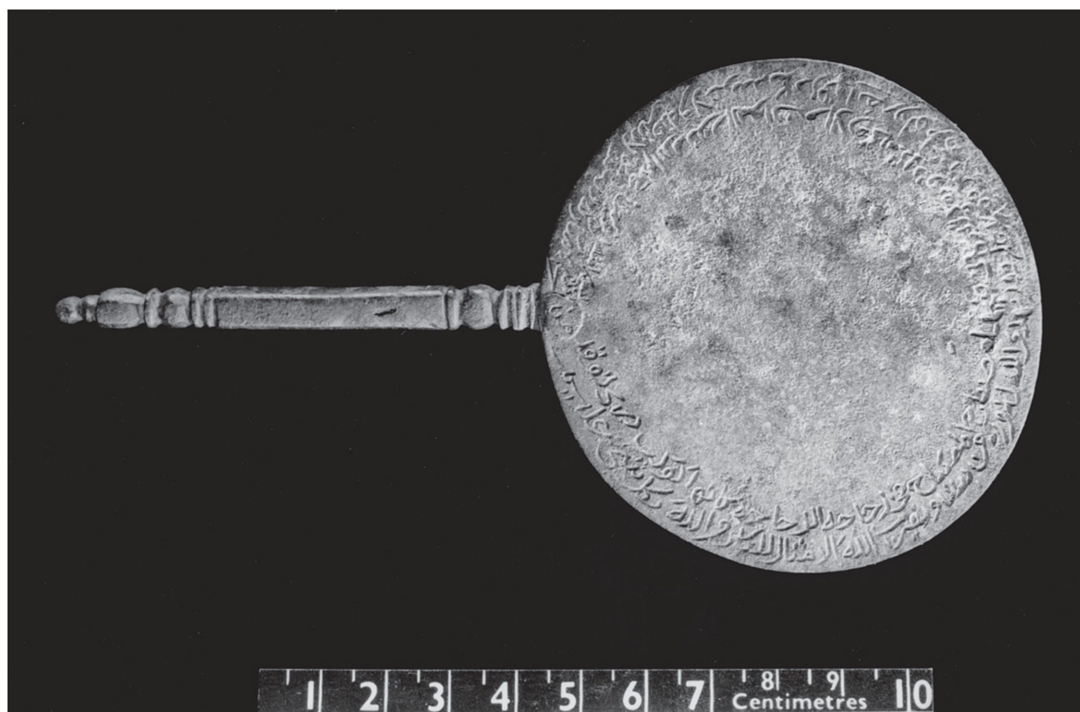

Figure 4: Small iron mirror with iron handle, and inscribed back. OA Reg 1866, 12–29, 80.

known as the A_1 (eutectoid) temperature, above which the austenite phase would have been present. It was then cooled to below that temperature, and the austenite transformed into pearlite and ferrite. The metal must have been held in the hearth for several hours to allow the observed spheroidization of the pearlite to take place, or alternatively hot worked just below the A_1 temperature, which causes the spheroidization to proceed much more rapidly, before being removed and allowed to cool in the air.

It was not possible to carry out hardness measurements, but the metal must have been fairly hard even though there was no evidence of heat treatment such as quenching. This would have involved cooling rapidly from above the A_1 temperature by plunging the metal into cold water so that the diffusion of carbon to form pearlite and ferrite was suppressed and the diffusionless transformation to martensite took place instead. Martensite is hard and brittle, which is probably why the mirrors were not quenched. Inevitably there is a real possibility of cracking during or immediately after the quenching or at least some distortion of the disc. With a full martensitic structure it would be too hard and brittle to hammer cold, and grinding would be very slow and probably unable to correct serious warping.

Other mirrors

Another ferrous Islamic mirror, OA Reg 1866, 12–29, 80, was examined for comparison (Fig 4). This mirror, which is likely to be 18th or 19th century, is much smaller and has a very thin disc and a thin iron handle held in place with a rivet. The mirror has an inscription running round the edge of the face taken from the ‘light’ verse of the Qur’an (suma 24, verse 35), implying that the mirror was a source of light or brightness. Once again the edge of the disc was selected and a small area clamped and polished to form a taper section, using 6μm and 1μm grade diamond paste abrasives. The section was examined in both the optical microscope and in the scanning electron microscope. In the unetched condition it showed just a single slag stringer, elongated parallel to the mirror surface, but in general the metal was very clean. After etching with nital, the section exhibited a ferritic structure with moderately variable grain sizes, the largest grains being about 0.1mm in their maximum dimension (Fig 5). There was a slight tendency for the grains to be elongated parallel to the mirror surface. Some subgrain boundaries could be seen, probably resulting from hot forging. Minute quantities of iron carbide were found in the grain boundaries, but in general this iron has a very low carbon content, and the application of Stead’s reagent failed to detect phosphorus.

The low carbon content and general lack of inclusions in this iron is surprising. If the microstructure on the edge is indeed representative of the structure as a whole, then the mirror would have been very prone to scrat-

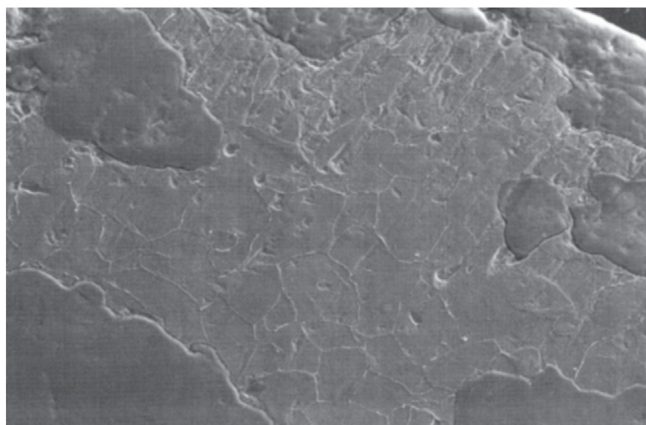

Figure 5: SEM micrograph of a polished and etched taper section from the edge of mirror OA Reg 1866, 12–29, 80, showing grain structure. Image 380 micrometres across.

ching, and being so thin, liable to bend. It is possible that decarburization of the surface took place during the hot forging, and that the body metal has more carbon it. Alternatively it could possibly be a decarburized crucible steel or, more likely, a very pure wrought iron, probably of European origin.

Three Islamic steel mirrors dated to the late 15th century were examined by Gilmour (2000, 488–9) as part of his metallographic survey of the Tanavoli Collection. All three were of steel and were estimated to contain between 0.6 and 0.8%C, but were not chemically analysed. From their structure, Gilmour concluded that they were probably air cooled after the final heating cycle. This is very similar to the structure of the British Museum's inlaid mirror. However, one of the mirrors had slag inclusions which led Gilmour to conclude that the iron had been made by the solid state bloomery process and carburized, and that the relatively low carbon contents of the other two suggested to him that they might be of carburized bloomery iron rather than crucible steel. He then qualified this conclusion as uncertain until more work had been carried out, as the slag inclusions could have come from the forging stage. However, this mirror and the British Museum's mirror, OA Reg 1966, 12–29, 60, discussed above, do seem to show that Islamic 'steel' mirrors can have a wide range of composition and structure.

Composition

The polished taper section surface of the British Museum's steel mirror, OA Reg 1960, 1-15, 1, was analysed by energy dispersive X-ray fluorescence using an open architecture instrument that allowed the mirror to be introduced directly into the beam. This showed that the iron contained about one percent of manganese, some of which may well have been in the observed inclusions as manganese dioxide, but the majority is likely to be manganese metal in solid solution in the iron.

The relatively high manganese content is interesting. Manganese oxides are not uncommon in iron ores, but are chemically much more stable than iron oxides. Thus in iron smelted by the traditional solid state processes the manganese is present as oxide inclusions in the slag stringers. Manganese oxides could only be reduced to metal that would then dissolve into the iron in significant amounts when the processes were hotter and more reducing. This is the case in blast furnace smelting and during the production of crucible steel.

It seems possible that manganese was being deliberately introduced into crucible steel from the inception of its production. Significantly, the earliest surviving account of the production of crucible steel, that of the Alexandrian alchemist, Zosimos, dated to the third century AD, specified the addition of *magnesia*, which is usually translated as manganese dioxide (Berthelot 1893, 332). Several of the ancient Islamic descriptions also list *magnesia* as one of the additions to be made to the crucible along with the iron, and the carbonaceous materials, although magnesia or manganese dioxide are apparently not mentioned in any of the 19th century European accounts of the South Asian (Bronson 1986, 37) or Central Asian processes (Wulff 1966, 8–9). Furthermore the few scientific investigations that have been carried out on the steel and the associated slags from southern India did not report significant manganese contents (Anantharamu *et al* 1999). Al-Tarusi, writing in the 12th century AD (Cahen 1947–48, 106, and Gilmour 2000, 63–4), for example, gives the following accounts (the [ ] are Gilmour's):

> 'if it [*narmahan*, soft iron] comes from the heads of old nails… 17*dirhems* of *myrobalan* from Kabul and the same quantity of *belleric*, should be cast upon it. The iron should be placed in a pot , which should be cleaned well with water and salt. The above mentioned should be mixed with it, and the whole placed in a crucible, which should be dusted with a *dirhem* and a half of crushed magnesia [probably manganese dioxide]. The foundry-fire should then be blown upon this until it melts and is collected as a cake [or egg]. This is over several days. Then allow this to cool and make a sword from it; this is a mortal poison [*ie* a deadly material].'

And:

> '3 *ratl* of *narmahan* [soft iron] and a half a *ratl* of *shaburqan* [hard iron]; place the whole in crucible and throw upon it 5 *dirhems* of magnesia [manganese

> dioxide] and a fistful of the husks of sour pomegranates. Blow upon the foundry fire to cause it to melt; and it turn into a ball [or ovoidal egg] shape; then remove it and make the sword.'

And:

> '1 part male magnesia [manganese dioxide], 1 of *sunbad* [coral], 1 of borax. Break up the whole then set it aside. Take a *mann* (about 300 *dirhem* or 600grams) of soft iron filings in the pure state, place them in a crucible, and pour over them two *uqiya* of the aforesaid mixture. Blow on the fire to cause it to melt and make it soft enough to take up a round shape in the crucible. Then take 1 part of [Syrian] rue (*peganum hamala*), 1 of gall nuts, 1 of acorns [or possibly almonds], 1 of aloes, together with a quantity of cantharides equal to all these. Make the whole into a powder, and of this mixture cast 2 *uqiya* on to the *mann* [the Indian equivalent is the maund; 1 *maund* = 2 *ratl*, OED] of iron, blow on the fire until what appears to be a rainbow rises out of the crucible. When it has reached this state, allow it to cool, then forge it to make whatever you want.'

And finally:

> 'Cultivated myrobalan, 20 *dirhem*; magnesia [manganese dioxide], 7 *dirhem*; scammony (a gummy resin), 5 *dirhem*. Reduce all to a powder. Cast this preparation onto 3 *ratl* of *shaburqan*, and blow the fire to make it melt in a crucible with a lid pierced with a hole so that one can see into it, and examine the iron until it is seen and felt with an iron [rod] to melt. Then remove it from the furnace, allow the crucible to cool with it, and make of it what you will.'

This documentary evidence is supported by the analyses of the slags from inside the crucibles (Fig 2) found at some medieval Islamic crucible steel smelting sites that are beginning to be investigated. These show manganese oxides to be a substantial component as exemplified by the slags from the *in situ* carburization process at Achsiket, which were found to contain around 15% of MnO (Rehren and Papakhristu 2000). The slags from the crucibles at Merv fell into two groups those with an average of about 2% and those with an average of about 12% MnO (Feuerbach 2002, 76–7, Table 4 and Appendix E). The latter manganese contents are far higher than those found in most ordinary iron smelting slags, but are typical of the slags from the processes for smelting the so-called 'natural' steels, which utilized manganese–rich iron ores (see below). In the crucible steel process where the iron feedstock was already smelted it suggests the manganese would have been made as a separate addition.

The fact that the addition of *magnesia* is mentioned in many accounts of the Islamic *in situ* carburization processes, and is found in the slags from the contemporary smelting sites, suggests that it performed a real and recognizable function. Of course, the Islamic smiths, as with the European iron masters until the mid 19th century, can have had no idea of the chemistry of these processes, just that the addition gave a better and more consistent product.

One function the manganese could perform was to stabilize the carbon contained in the iron. Most of the so-called 'natural steels', that is smelted bloomery iron with a high carbon content, such as the famed Roman *Noricum* steel were made from iron ores that were naturally rich in manganese (Barraclough 1984a, 164–70; Craddock and Wayman 2000, 18). Most of the slags produced in the bloomery process contained a great deal of the iron oxide, wustite. As the smelting process came to an end and the reducing conditions became less severe, but whilst the metal was still very hot, the carbon in the iron could react with the wustite, thereby reducing the iron's carbon content. If there was appreciable manganese in the ore then manganese dioxide would form preferentially to wustite, and this was much less liable to react with and decarburize the iron. It is suggested that this was what happened in the crucible steel process. During carburization some oxygen was present which would form the stable manganese dioxide in preference to iron oxide, and the manganese dioxide would not subsequently react with the carbon in the steel.

Another possible reason for the addition of manganese in the crucible steel process could have been to prevent the metal from being hot short (brittle during hot working or forging). This is caused by the occurrence of iron sulphide in the grain boundaries of the metal, even small amounts of which can cause severe embrittlement, as iron sulphide is molten at hot-working temperatures. The adverse effects of the sulphur can be ameliorated by the addition of manganese which removes the sulphur from the iron to form inclusions of manganese sulphide which have much higher melting temperatures and hence are relatively harmless. Some sulphur could have come from the iron ores, but by the early 19th century in Europe the majority would have come from the use of fossil fuels, coal and coke which are rich in sulphur. Small quantities of manganese began to be deliberately added to iron in Europe from the 1840s specifically to combat this problem. In 1839 Joseph Heath patented his 'carburet of manganese', which was a rather unpromising mixture of manganese metal, manganese oxides and various bituminous materials, of

which only the manganese metal actually did anything. The carburet was added to the molten iron as it lay in the ladle having just been run from the blast furnace (Barraclough 1984b, 59–61).

Thus, since the 1840s it has been usual practice to add small amounts of manganese to the molten iron and the resulting iron or mild steel typically contains between about 0.5 and 1% of the metal in solution. It is an interesting possibility that as the crucible steel was invariably hot-forged, manganese could have been added as a precaution in case the iron being used as the feedstock in the crucible contained any sulphur. If the iron feedstock had been smelted in the Islamic world, this sulphur would have come from the original iron ore as the smelting fuel would ordinarily have been charcoal, which contains little or no sulphur. If the co-fusion process was used, then there is a possibility that imported cast iron from China could have been used (see below), which in turn could well have been smelted with fossil fuel and thus contain sulphides (Craddock *et al* 2003; Wayman and Wang 2003). However, as noted above, the instructions to add *magnesia* do seem to be confined to the *in situ* carburization process.

Whatever the reason for its addition, it does seem possible that the incorporation of manganese into crucible steel in Asia was quite deliberate, and thus anticipated the European 'discovery' by at least 1500 years.

There are records that Chinese iron was apparently imported into the medieval Islamic world for the production of mirrors (Needham 1974, 238). Al- Razi, in his work on Metals and Salts (Ruska 1937, 85) compares the surface of Chinese iron, presumably cast iron, to that of mirrors:

> 'Regarding the metals, we do require their description, except for Chinese iron. This is like a mirror except it is even smoother, it is unknown.'

Just possibly cast iron was to be used as a feedstock in the cofusion process, as the evidence for Islamic production of cast iron is equivocal (Craddock 2003). However, none of the quite detailed medieval Islamic accounts of the additions to be made to the crucible mention Chinese iron, in fact elsewhere al-Razi (Ruska 1937, 139) describes crucible steel as melting *like* Chinese iron.

Needham (1974, 191) also drew attention to a special iron alloy containing 20% manganese, that was exported from China in the early 20th century. This was described as mirror metal by the European dealers. However, this was not because the alloy was intended for mirror production; mirror metal, or *spiegeleisen*, as it was also known, was the general name given in Europe to these high manganese cast iron alloys, produced by the smelting of special manganese-rich iron ores. Even so, it is interesting to speculate whether such alloys were exported in earlier times, although it does not seem that they could be the source of the manganese-rich steel used in the mirrors, as the early descriptions specify the addition of a manganese mineral, not a special Chinese iron.

Discussion

Ferrous mirrors seem to have been reasonably common in the medieval and post-medieval Islamic world until superceded by glass mirrors imported from Europe from the 17th century AD on (Allan 2000b, 463–70). They are usually described as being of steel by both the contemporary authorities and by present day art historians. These descriptions may well be correct, but they were and are made, apparently, without technical knowledge or scientific examination. Very likely the old distinction was being made between low status and rusty objects being described as iron and high status polished objects alone qualifying for the accolade of steel.

In fact crucible steel is a very good material for mirrors. It is hard and strong and as such will be resistant to both scratching and distortion by bending. It is also capable of taking a much better reflecting surface than other contemporary irons and steel because of the absence of inclusions. This property was recognized in the medieval Islamic world, reflected in statements such as that by al Beruni on the Damascus blades in his *Book on Mineralogy* (Said 1989), compiled in the 11th century that: 'People likeswords that have the essence of *farand* (the watered-pattern characteristic of the Damascus blades) with green colour glittering on it. Such sword has wrung considerable praise.' (*ibid*, 216), and '*Farand* in Khurasan is called *jawhar* (glitter); in fact the Khurasanians qualify it by calling it *jawhar al say* (the glitter of the sword.' (*ibid*, 217)

The French traveller, Bertrand de la Broquiere, who was in Damascus in the mid-15th century, made several interesting observations concerning steel and its surface treatment including the following: 'This polish is so highly finished that when anyone wants to arrange his turban, he uses his sword for a mirror' he also relates that 'They (the swords) are made in Damascus, and in the adjoining country, mirrors of steel that magnify objects like burning glasses.' (Ziadeh 1964, 46–7).

Steel mirrors never seem to have been made in Europe, even for astronomical purposes in reflecting telescopes. There is, for example, no mention of steel mirrors in Schweig's (1973) comprehensive technical history of mirror manufacture. Possibly this was due to the absence of crucible steel in Europe in the ages when metal mirrors were still being made.

However, the reflecting properties of crucible steel were recognized in post-medieval Europe, if not in mirrors then in costume jewellery. In fact, it is just possible that the first recorded production of crucible steel in Europe was for small decorative items in the early 18th century. This information is contained in the travel writings of a German nobleman, Zacharias Conrad von Uffenbach, who visited London in 1710 (Norman 1971; Quarrell and Mare 1934). He noted that:

> 'Herr Benedetti also showed us some articles made in steel by a clockmaker, Pingo (John Pingo Jr), in New Street. This is a most notable invention, for the steel can be cast so cleanly and well on account of its hardness, that it comes out quite pure out of the mould with the other side polished like a mirror.'

Clearly interested, he visited Pingo again with his brother:

> 'My brother intended to question him, but all in vain. He lets out this much—that, like the goldsmiths, he uses sand for casting his steel, but that he has to sprinkle a special powder in the forms so that all may come out cleanly. The metal or steel that he uses is nothing but old sword-blades which he melts down.'

They also saw

> 'a method of gilding steel with mercury so that it does not tarnish.'

The items were all castings, small plaques, heads and seals; the von Uffenbachs purchased a gilded seal of Cromwell. They were apparently sand castings, and the reference to 'the other side', suggests they had been cast in a single-valve mould. The special powder was probably some carbonaceous material added to prevent the molten steel from reoxidizing. In 1726 the antiquary John Byrom visited the premises of John Pingo 'the medal caster' and saw 'some of his castings' (Byrom 1854, 271), but although the Pingo family were the leading medal makers in 18th century London (Elmer 1998), no other references to this precocious cast steel are known, and none of the products have yet been recognized. However, it has been generally believed that Huntsman was not the first to make crucible steel, and Pingo's process, in as much as it can be reconstructed, melting old sword blades (which would have been made from cementation steel) sounds similar to the process that Huntsman was to adopt some 30 years later. Note, Pingo was apparently casting artefacts with his steel. This was highly unusual, crucible steel in Asia and in Europe was always forged to shape, even though the product is often referred to as cast steel in the contemporary accounts (see below). The first successful use of cast steel was for railway tyres in the 1850s that became for many years the most successful product of Krupp of Essen.

These accounts seem to have been generally ignored by the historians of steel, probably because Pingo's steel was not being used for the purposes that they would normally associate with crucible steel, such as cutlery and clock springs. In fact, the brilliant mirror-like appearance was to be one of the most valued properties of the new metal when it appeared again in the latter part of the 18th century, and Matthew Boulton, the great Birmingham entrepreneur and manufacturer, was an early customer for Benjamin Huntsman's steel, not just for rolls and dies, but also as the material for buttons and brilliants (Barraclough 1984b, 4–6).

In the European Renaissance there had been something of a revolution in jewellery fashions with precious stones being regularly cut and facetted for the first time (Scarsbrick 1994). This brought diamond, with its fire and brilliance, to the fore as the most valued gem. Inevitably it was copied and established a whole fashion in costume jewellery, both in flint glass, the so-called 'pastes', and also in steel (Fig 6). The cut steel 'brilliants' enjoyed rising popularity throughout Europe from the end of the 17th century (Becker1988, 44–50; Bury 1991, 702–7, Clifford 1971; Rawlings 1978 and Scarsbrick 1994, 240–4). Initially, English brilliants were thought inferior, as stated by Monsieur de Muralt in 1728 (Scarsbrick 1994, 240). All this was to change with the introduction of crucible steel as the feedstock, and from the 1770s English cut steel production flourished at major centres such as London and Birmingham as well as in smaller towns, of which Woodstock, just north of Oxford, is perhaps the best known (Becker 1988, 44–50).

The great advantage of crucible steel over ordinary cementation steel, used previously, was that the surfaces were not disfigured by slag inclusions and did not blister on heat treatment (the blisters were caused by the generation and escape of gas within the steel, brought about by the partial reduction of the iron oxide in the slag by the carbon to form iron metal and carbon monoxide). The differences were well appreciated, even if the causes were not fully understood. Thus in Rees *Cyclopædia*

Figure 6: The effects of bright crucible steel were certainly appreciated in the 18th century, the gentleman's cut-steel buttons and buckles dazzling his lady companion.

(Rees 1802–20, Vol 5, 159), under steel it states that:

> 'Blistered steel should not be used but for the commonest purposes, where great tenacity of polish is not an object. For all nice purposes, where great tenacity and soundness are necessary, shear-steel should be employed; and where a fine polish or great hardness is wanted, cast steel is indispensable.'

Little is known of the 18th century processes by which the buttons and brilliants were formed, the most detailed account seems to be that of Gill in 1830, by which time the craft production of brilliants had all but ceased. Writing in his *Technological Repository,* Vol 6 (reproduced in Rawlings 1978), Gill noted that for the manufacture of bright steel buttons:

> 'These steel beads and studs are formed either of well annealed sheet or hoop iron, or, which is better, of cast steel decarbonated (decarburized) and which is thereby reduced to the state of the softest and purest iron, and is entirely free from the defects of the ordinary iron, such as flaws, blisters *etc* which are often found in the articles made of common iron, after being case-hardened, but upon which, nevertheless much expensive work had been bestowed.'

The operation was to take the crucible steel feedstock and strongly heat it to remove the carbon that Huntsman's process had so carefully added, thereby reconstituting the original iron but with the slag stringers removed. The soft iron was then carefully shaped with the fly press or by hand filing to make the brilliants and buttons, with riveted or screw-threaded shanks (Fig 7). The completed items were then re-carburized by being packed by the thousand into iron trays containing bone dust etc and strongly heated. The shanks needed to remain soft and so they were shielded from the hot carbon with a dab of clay. After some hours the carburization of the surfaces was judged complete, and the items were plunged whilst still red-hot into cold water. This quenching gave the steel surface a very strong and hard martensite structure, but the absence of slag meant that there were no unsightly blisters, and the items would now have been complete but for a final cosmetic polish.

The use of decarburized steel seems to have continued on a minor scale for prestige art metalwork, as exemp-

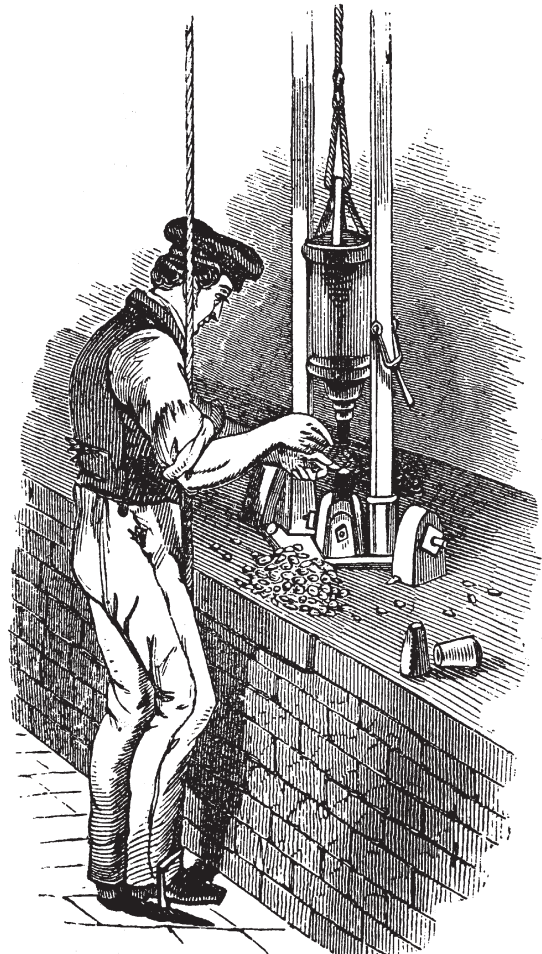

Figure 7: Stamping metal buttons in Birmingham using a simple drop press operated by the workman's foot.

lified by the Viking Punch Bowl designed by Paul Farnham, one of Louis Tiffany's silversmiths, for the 1893 Chicago exhibition (now in the Metropolitan Museum of Art, New York: 1969 (69.4)) (Loring 2001, 202–3). It was described in the exhibition catalogue as being made of decarburized steel, hammered to shape and inlaid with gold and silver.

The Islamic mirrors seem to have been made by hot-forging a billet of crucible steel to the relatively simple shape of the mirror disc and so there would have been no need to decarburize the metal beforehand, and the presence of the carbon uniformly throughout the body would have made the metal strong and resistant to bending, both desirable qualities in a mirror. After forging and annealing the steel was allowed to cool slowly, there was no attempt to quench the metal, probably to lessen the dangers of warping and cracking, which as explained above could have been difficult to rectify.

The true extent of the use of crucible steel in Asia through the ages is now becoming apparent. It also seems that through much of its 2000-year history, in Asia and latterly in Europe, crucible steel was valued both as a strong metal and as a bright metal.

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