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Early Islamic manufacture of crucible steel at Merv, Turkmenistan

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During the work of the International Merv Project (described in the 1997/98 issue of *Archaeology International*) evidence was unexpectedly unearthed of a sophisticated method of making steel that was practised there over 1000 years ago. Investigation of the archaeometallurgical remains from Merv has now revealed how the process worked and how the medieval steelmakers conserved and recycled the raw materials they used.

This a tale of archaeological detection, a tale of how a scatter of broken fragments of pottery eventually provided evidence of a steelmaking technique that was practised in Central Asia nearly a thousand years before it was discovered in the West. Archaeology still has much to teach us about technology, even at the beginning of the twenty-first century, but success in unravelling the technological processes that the archaeological remains represent depends on the collaboration of many specialists with different skills and areas of expertise.

The Merv oasis, in southeastern Turkmenistan, lies athwart the trade routes on the ancient "Silk Road" between China and the Mediterranean. It occupies part of the alluvial delta of the Murghab River which flows north into the Kara Kum desert from the mountains of Afghanistan to the south. Upstream, the valley of the Murghab was followed by a major trade route to India. Merv thus had access to imported materials and to imported ideas. In addition to its historical interest as a great staging post and urban centre, Merv has special archaeological appeal because the successive cities that flourished there from *c.* 500 BC are located next to rather than on top of each other and can therefore be more easily surveyed and excavated.[1]

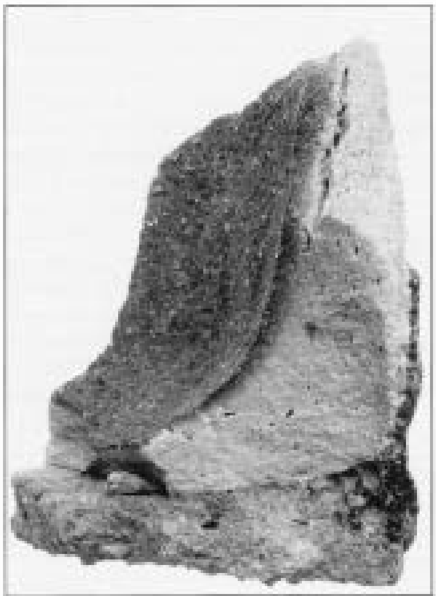

Figure 1 *A crucible fragment from Gyaur Kala, Merv, showing a cross section through the lower wall and the supporting pad below.*

The earliest city at Merv, known as Erk Kala, is thought to have been founded in the Achaemenian period about 500 BC. It was succeeded by the Hellenistic city of Gyaur Kala, founded by Antiochus I who reigned from 281 to 261 BC. Gyaur Kala continued in use for over 1500 years, but towards the end of this time much of it became an industrial area when occupation shifted west to what became the large medieval city of Sultan Kala. It was at Gyaur Kala that evidence of steelmaking was discovered. In part of the site now identified as an industrial area there was a dense surface scatter of broken ceramic fragments (pottery sherds) of unusual appearance. These remains are from crucibles and provide evidence of a sophisticated process of making fine steel in them, a process that could yield the very special steel used for manufacturing the so-called Damascus swords, famed for their appearance and their mechanical properties. The evidence for steelmaking is believed to date, by reference to associated coins, to the late ninth to early tenth centuries AD. Following discovery of the crucible fragments, samples of them and of other material that later proved to be parts of furnace walls were brought to the Institute in London for conservation and analysis.[2]

The crucibles

Archaeological conservation is not limited to examination of the external appearance of the objects under scrutiny, but aims to obtain and conserve as much information as possible about them. Close examination of the samples from Merv revealed two vital facts. First, most of the sherds were fragments of a single type of vessel, despite the fact that some sherds were thick and white and others thin and black. Remains of previously molten glassy slag found within them showed that the vessels were crucibles. Second, by sectioning some of the sherds it was found that tiny, almost microscopic, spherical droplets of metal (called prills) were trapped in the green glassy ring or fin around the insides of the crucibles. Thus it was established that most of the sherds, of which hundreds of similar examples were found on site, were parts of a single type of metallurgical crucible. Moreover it was a type that had not previously been discovered. Several metallurgists who visited the Institute were interested to see these curious crucibles, and Ian Freestone of the British Museum's Department of Scientific Research was the first to suggest that they might have been used to make steel.[3]

Study of the fragments has allowed us to reconstruct the shape and structure of the crucibles (Figs 1 and 2). Each stood on a pad of coarse clay and had thick white lower walls merging into thin grey upper walls. Despite the thick lower walls, some of the crucible bases were very thin, and some crucibles also show mutual distortion of the crucible base and the supporting pad. The crucibles were 18–20 cm high with a rim diameter of about 8 cm. They had thin lids joined to the rim by a thin coil of clay. The lids had a central hole with a raised rim. The outsides of the crucibles were covered with a thick black glassy deposit that looked as though it had flowed down the crucible walls over the pad and attached the pad to adjacent fragments of broken ceramic. The insides of the crucibles had a thin layer of greenish glassy slag on the lower walls, a horizontal fin of green glassy slag around the top of the thin layer of slag, and rust-coloured small nodules adhering to the upper walls, plentiful just above the green glassy fin but becoming sparse higher up the walls and on the undersides of the lids.

From close examination of all these features we can deduce several aspects of the manufacture and use of the crucibles. They are likely to have been made on a potter's wheel, and the contact features of the base with the pad suggest that both were probably in a plastic state when joined. The peripheral clay join around the lids suggests that the crucibles were filled and covered before being fired. The black glaze that appears to have flowed down the outsides is probably the result of the reaction of fuel ash with the clay of the crucible, and the broken pieces of crucible around the pads would have prevented the black glaze attaching the crucible firmly to the furnace floor as it solidified.

Further observation and analysis of the insides of the crucibles suggested that the green glassy fin was shaped when, in liquid form, it had floated on the periphery of the convex upper surface of a denser liquid such as a molten metal. The metallic prills trapped in the green glassy fin were analyzed by optical and electron microscopy and, with one exception, were found to consist of high-carbon steel. This also threw light on the small rust-coloured nodules found on the interior walls, some of which contained remnants of steel. Both

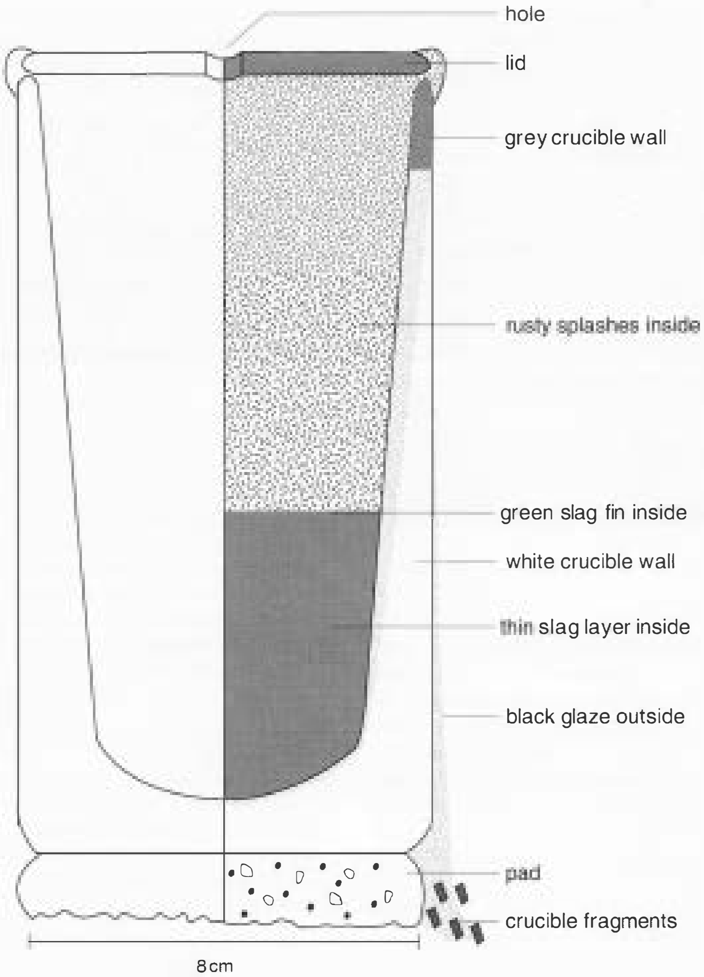

Figure 2 *A schematic reconstructed cross section through one of the steelmaking crucibles found at Gyaur Kala, Merv.*

the prills in the green glassy fin and the rust-coloured nodules could thus have originated from splashes of molten metal.

The crucibles were made of a remarkably refractory type of ceramic (one that can withstand high temperatures without collapse). In laboratory tests the lids did not sag until a temperature of about 1500°C was reached. Pure iron does not melt until around 1500°C, but the melting point falls progressively with increasing carbon content to a minimum of around 1150°C in iron containing about 4.3 per cent carbon.[4] The splashes of iron could not have arisen from normal boiling of a liquid cast iron as the necessary temperatures could not have been reached, but splashes could occur as a result of what is called a carbon boil: a phenomenon that resembles boiling but actually arises from the reaction of oxygen with carbon in molten cast iron or high-carbon steel, which produces bubbles of gaseous carbon oxides.

Analysis of the prills has shown one to have a cast-iron structure and composition and others to consist of high-carbon steel. This implies that molten cast iron was present at one stage in the process and molten high-carbon steel at another. A text by the twelfth-century Islamic author al-Biruni[5] refers to the melting together of two sorts of iron to make a product that sometimes proved suitable for making hard-edged tools (probably a high-carbon steel) and sometimes for making the blades of Damascus swords with their characteristic shimmering surface patterns.

The combined archaeological and literary evidence suggests a working hypothesis that the crucibles were used to make steel by melting cast iron (with its high carbon content) together with a source of low-carbon iron (such as wrought iron, scrap iron or iron ore) to produce a molten steel of intermediate carbon content. Recent research by Verhoven and others[6] has shown that trace impurities (present in some sources of iron and not in others) influence whether the Damascus pattern will emerge during forging and heat treatment, and hence whether the product of a given crucible can be used to make a Damascus sword, or whether it will only produce plain steel objects. This fits with al-Biruni's statement that human effort could not influence the chance outcome of whether or not the steel product would be suitable for making Damascus swords. Unfortunately, the sources of the iron used in the steelmaking process at Merv remain as yet unknown.

The furnaces

Excavation of the area where the crucible fragments were found revealed several circular features that were interpreted as being the lower parts of furnace walls, as suggested by the reddening of the soil in their vicinity and the extensive vitrification of the inside of the walls. The furnaces had an internal diameter at ground level of around 80 cm and were found to have a single air supply that emerged through the centre of the floor from an underground pipe (Fig. 3). They had an exit flue at ground level through a breach in the furnace wall. We know that the central pipe was the air inlet and the exit flue was the outlet for hot gas because around the exit flue there is extensive vitrification and reddening whereas around the air inlet there are no indications of exposure to very high temperatures. The evidence thus suggests a central floor-level air inlet and a ground-level exit flue. Had the furnaces been open-topped there would not have been the great transfer of heat through the exit flue: the hot combustion gases would have escaped primarily through the top by convection. We must therefore conclude that the top of the furnace was closed. These are the only ancient metallurgical furnaces known to us that were designed in this way.

The archaeological evidence for the furnace design appears to tie in perfectly with the evidence of reducing and oxidizing conditions shown in the colour of the crucible walls and with the presence of the supporting pads and the scattered crucible fragments between them. The furnace had a deep fuel bed of charcoal fed with air supplied from below (Fig. 3). The refractory mass of broken crucible fragments facilitated both the distribution of air around the lower part of the fuel bed and the removal of the crucibles. The pad raised the lower part of the crucible and its contents into the hottest part of the furnace where the atmosphere was oxidizing, making the crucible walls white because any carbon would be burnt to gaseous carbon oxides. Higher in the fuel bed, where the oxygen had been used up and the atmosphere was reducing, deposits of carbon caused the crucible walls to be grey.

Conservation of raw materials

It is perhaps surprising that few of the raw materials needed for the crucible-steel process appear to have been available locally. In the Merv oasis there was limited fuel, no refractory clay and no iron ore. Investigation of possible sources of raw material is under way and it may be that suitable iron-ore deposits and fuel were available farther south up the Murghab Valley. Adaptation to the limited availability of the raw materials can be seen in many aspects of the metallurgical process.

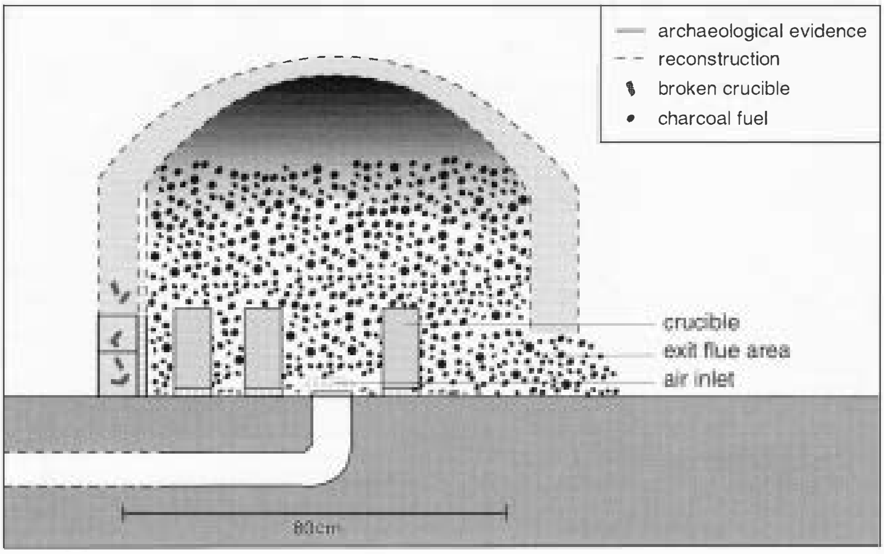

Figure 3 *A schematic reconstructed cross section through one of the crucible-steel furnaces found at Gyaur Kala, Merv.*

One aspect of this adaptation is the efficient use of fuel. As noted above, the crucibles appear to have been placed in the Merv furnaces in an unfired state. This would have necessitated a more controlled initial rise of temperature but would have used far less fuel than if the crucible had been fired separately before use. The combustible gases from the top of the fuel bed were swept down into the oxidizing zone and would have burned around the crucible bases. It is salutary to note that the efficient use of the combustible gases emitted from the top of a fuel bed was still a matter of national concern in Britain in the middle of the twentieth century.[7]

The clay available in the Merv oasis melts at relatively low temperatures, and crucibles made of local clay would not have been usable because they would have melted and collapsed before the steel was formed. Even the furnaces could not have been built using such clay on its own. The crucibles are made of an imported refractory clay, the source of which has yet to be discovered. Efficient use of this clay is illustrated by the use of a refractory filler, probably made by crushing used and broken crucibles, to reduce the amount of fresh clay needed to make more crucibles. A further indication of economy in the use of the clay is that the crucibles have thick lower walls where the furnace temperature is highest and the greatest strength is needed to withstand the weight of the molten metal ingot, but a thin base where the pad provides the physical support, and thin upper walls and lids where strength is again less important.

Economy in the use of the imported refractory clay was also ensured by the efficient recycling regime practised by the Merv steelmakers. The crucibles had to be broken to extract the steel ingots. Many of the crucibles were also further broken up and the different size ranges of sherd used for different purposes. The larger fragments were incorporated into bricks used to build the furnace and incorporated in the furnace linings and re-linings. The bricks and linings were made primarily of local clay so the crucible fragments would have been important in giving them sufficient structural rigidity to withstand high temperatures, particularly in the case of the linings.

Finer fragments of broken crucible were scattered between the crucible pads to promote distribution of the air from the central inlet around the base of the fuel bed and to facilitate removal of the crucible. (The black glaze runs over the fragments rather than onto the floor and the necks of solidified glaze between the fragments are easy to break.) Still finer fragments were incorporated in the pads themselves, and the finest-grade fragments of crushed crucible were mixed with new refractory clay and used as temper in making the crucibles and lids for the next cycle of steel production. The use of the crushed refractory temper could increase the wet strength of the new crucibles, facilitate drying without mishap by reducing shrinkage and helping water to escape, and improve the capacity of the crucibles to retain their structural integrity at high temperatures. In these ways the need for new raw clay was reduced. The absence of refractory clay in the Merv oasis led to the development of recycling methods that were wholly integrated into the process of steel production. This seems sophisticated even by late twentieth-century industrial standards, and is an example of the sustainable use of raw materials that made good economic sense.

It is satisfying to have discovered how steel was made at medieval Merv, but humbling to realize that this technology was known there over a thousand years before it was understood in the West. Thanks to archaeology, third-millennium industry may yet learn something from its first-millennium counterparts.

Notes

1. Dr Georgina Herrmann of the Institute of Archaeology, UCL, is director of the International Merv Project which has been conducting surveys and excavations at Merv since 1992; see her article "A Central Asian city on the Silk Road: ancient and medieval Merv" which appeared in the first issue of *Archaeology International* (1997/98, 32–6).
2. Dr John Merkel, an archaeometallurgist from the Institute of Archaeology working with Dr Herrmann at Merv, initiated the research on crucible-steel production by bringing the samples to London and interesting us in their further study. Ann Feuerbach is now studying the crucibles as part of her doctoral research on crucible steel in Central Asia. We wish to thank Dr Herrmann and other members of the International Merv Project for allowing us free access to the crucible material for the purposes of study, and Dr Merkel for first bringing the crucibles to our attention. We are also grateful to other colleagues for their interest and helpful comments.
3. The term "steel" is used to describe iron containing some carbon, usually 0.1–2.0% carbon.
4. Iron containing 2–4 per cent carbon is called cast iron because its suitability for casting is enhanced by a melting point much lower than that of pure iron or steel.
5. H. M. Said, *Al-Buruni's book on mineralogy* (Islamabad: Pakistan Hijra Council, 1989); see also A. Y. Al-Hassan & D. R. Hill, *Islamic technology: an illustrated guide* (Cambridge: Cambridge University Press, 1986).
6. J. D. Verhoven & D. T. Peterson, "What is Damascus steel?", *Materials Characterization* **29**, 335–41, 1992.
7. See for example *The efficient use of fuel* (London: His Majesty's Stationery Office, 1944).