REFRACTORIES WITH A PURPOSE II: CERAMICS FOR CASTING

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Introduction

This is the second paper on metallurgical refractories; the first appeared in the previous issue of *The Old Potter's Almanack* (18.2) and concentrated on the refractories concerned with extractive metallurgy, the smelting and refining of metals (Craddock 2013). This paper is concerned with the role of ceramics in the fabrication of metal artefacts by casting. As with the previous paper the present paper is written from the view point of the user, expounding some of the requirements of a metallurgical refractory ceramic and to some degree how these were met in antiquity. For more detailed petrological and mineralogical descriptions the reader is recommended to works such as those of Freestone and Tite (1986), Tite *et al.* (1985) and Reedy and Meyers (2007).

Until the recent past, with the exception of a few stone moulds, the early history of casting technology was largely derived from the examination of the surviving metal castings. Only from the mid-20th century did casting debris become regularly collected or even recognised for what it was on most archaeological excavations. It was to be later still that serious scientific examination of such material commenced and the properties of these early refractories began to be recognised (Bayley 1992a and b; Bayley and Rehren 2009; Schneider and Zimmer 1984; Reedy 1991).

Even at the most basic level careful study of the mould fragments can give useful information on the castings, sometimes even more than on the surviving metal artefacts. For example, on typically worn and corroded pieces it is often very difficult to determine how much of the decorative detail was on the original casting and how much was engraved or chased on afterwards. Examination of the mould surfaces of similar pieces can easily determine whether the detail was cast or worked subsequently.

There are no serious European or Middle Eastern descriptions of casting operations before the works of the renaissance craftsmen such as Cellini (Ashbee 1898) and Biringuccio (Smith and Gnudi 1942), although the *Silpasastras*, etc. of the Chola period in India compiled in the first millennium AD do provide some information (Ganapati Sthapati 2002; Levy *et al.* 2008). For the more remote past there is only pictorial evidence, such as the Egyptian examples depicting casting and other metalworking scenes, most famously those on the walls of the tomb of Rekh-Mi-Re (TT100) of the 18th Dynasty which can be surprisingly detailed and informative (Davies 1943).

Thus it should come as no surprise that there is often considerable doubt, contradiction, dissention and unsustainable assumptions concerning the early casting processes, both in general and on individual pieces.

What follows is a progression through the main casting processes, commencing quite naturally, with the transport of the molten metal from the furnace/hearth where it was melted to the mould. This will usually have been in crucibles, although even this is an assumption. Large castings such as the Athlit bronze ram from the prow of a Greek warship (Casson and Steffy 1991; Oron 2006) would have required almost a tonne of metal to cast. Most contemporary crucibles had a capacity of a kg at most, is it conceivable that approximately a thousand separate crucible pouring were made? Surely for such large castings the metal would have been channelled directly from the melting furnace (termed a *cupola furnace*) as argued by Hoffmann and Konstam (2002) for casting statuary bronzes.

At traditional foundries in present day Swamimalli, Tamil Nadu in southern India, the largest crucibles can hold 60 kg of metal and their furnaces can accommodate four (Levy *et al.* 2008, 70 and 93). Thus theoretically 240 kg could be cast at one time, but such large crucibles have never been found in antiquity and it is doubtful if the refractory ceramics then in use could have supported such a mass of molten metal. The first written description of channelling the metal directly from furnace to mould is given by the monk Theophilus around 1100 AD (Hawthorne and Smith 1963, 173-5).

There is an alternative which provides a neat solution to the problem of pouring the metal for small castings. This is to attach the crucible to the mould.

The method is well exemplified by the mirror makers of Aranamula in the Aleppy District of Kerala, southern India (Srinivasan and Glover 1995; Craddock and Hook 2007; Figures 1-3).

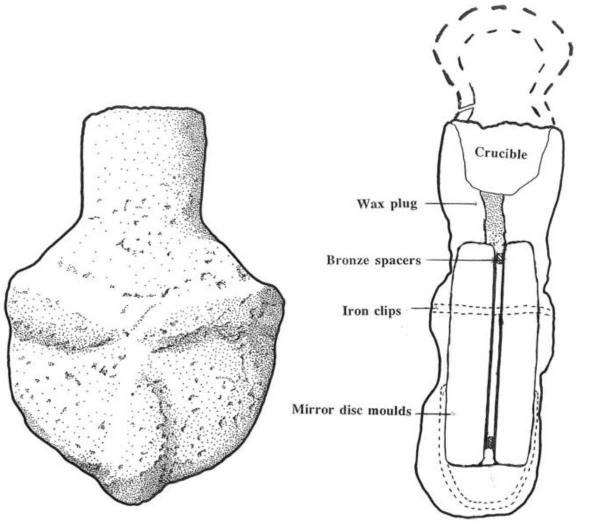

Figure 1. Diagram and section of mirror casting mould with the crucible at the top ready for pouring. The metal flows down into the space between the two clay discs held apart by fragments of old mirrors. The discs are clamped together and the whole encased in clay (from Srinivasan and Glover 1995, with modifications).

They use the process to cast the mirror discs, which are of the traditional silvery mirror metal, speculum (approximately two parts copper to one part of tin). After the mould has been assembled and the pieces of bronze placed in the cup at the top of the mould, the crucible is built around it. It is carefully moulded with stiff cotton cloth soaked in fine silt clay with cow dung, and over this further layers of fine clay with crushed and recycled refractory, sand, dung and vegetal tempers are added to form the walls of the crucible. The whole is then smoothed and luted with more clay to ensure a smooth continuous junction between crucible and mould (Figure 2), and a straw is inserted through the crucible wall from the interior to the outside to create a tiny channel through which, on firing, the expanding gases inside can escape. The unit is then placed in the hearth with the crucible now at the bottom. After about an hour, when it is judged that the mould has baked and the metal melted, the unit is removed (Figure 3), allowed to cool for a few minutes and then inverted, whereupon the metal flows down into the mould. After cooling, the mould is broken open and the cast mirror disc removed and the fragments of the crucible and outer mould discarded, some to be finely ground to act as a grog temper for another outer mould.

Figure 2. The finished mould and crucible firmly luted together with clay heavily tempered with rice husks, ready for firing (P.T. Craddock).

Figure 3. Removing the mould and crucible from the hearth after firing with the crucible beneath, after a short period to cool slightly the unit will be inverted allowing the molten bronze to flow down into the mould (P.T. Craddock).

The mirror makers of Kerala have been established for many centuries, but the history of the casting technique is unknown. It is practiced in many parts of the world, for example, the Obo of northern Nigeria use the technique and on this evidence Williams (1974, 178-88) believed not only that it had been the technique used to cast most West African copper alloy castings but that it was the prevalent technique used in antiquity everywhere and had been introduced into Africa by the Egyptians. This is unlikely but difficult to disprove. The technique is described in some Post Medieval European treatises on casting but as yet no direct archaeological evidence for its early use has been found. Most fragments would be indistinguishable from ordinary hemispherical crucible fragments. A fragment comprising the junction between the crucible and the cup at the top of the mould might be distinctive, but could be mistaken for a sprue cup (see below and Figure 15). This is a good example of a technique with an extensive recent literature and that is widely used by traditional metalworkers, but where we have little or no knowledge of its origins or how widely it was used in antiquity.

Crucibles

Early crucibles in Europe exhibit a wide range of shapes but before the Post Medieval period they tended to be small with capacities of no more than a few hundred grams of metal (Bayley and Rehren 2009; Tylecote 1976, 16-19; 1986, 96-102; 1987, 183). They were of two basic shapes, shallow open crucibles that were heated from above (Figure 4) and deep crucibles that were heated from the sides (Figure 5).

Figure 4. Shallow open crucible. Bronze Age, from El Agar, Spain (Copyright British Museum).

The former melt the metal rather quicker than the deep crucibles and usually only have evidence of strong heating on their inner, concave side (Figure 6). In the deep crucibles the heat has to penetrate right through the walls of the crucible to reach the metal inside and thus the evidence of strong heat is more even.

Figure 5. Deep crucible from Dariba, India. 3rd century BC Mauryan Period, with extensive vitrification all over where it had been heated from the sides and beneath. Note the small nipple on the base to raise the crucible from the floor of the hearth to ensure even heating (P.T. Craddock).

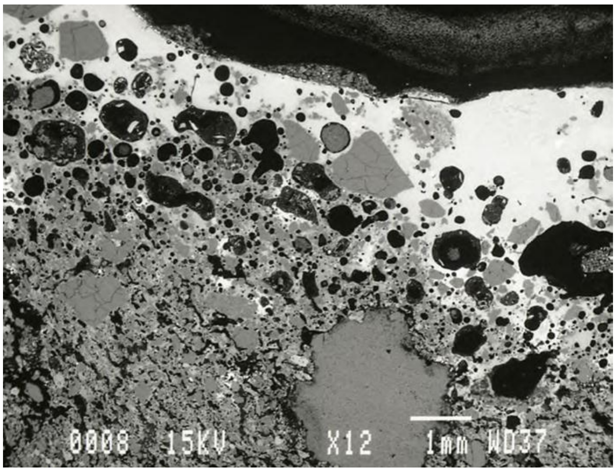

Figure 6. SEM image of a section of crucible for melting copper (white areas) from Dariba, India. 3rd century BC, Mauryan Period. It was heated from above with vitrification only on the inner concave surface. The penetration can indicate the duration of the heating and the degree of vitrification the maximum temperature attained (Copyright British Museum).

As noted in the previous article, the depth of penetration and degree of vitrification can provide an indication of duration and maximum temperature. Analysis of the inner surface should identify the metal being melted, but note that some metals, notably arsenic, zinc and lead are volatile and penetrative and could cause confusion. In the author's experience a fragmentary clay mould for casting a Celtic thistle brooch from Scotland and which had been vigorously cleaned after excavation, on analysis registered only zinc on the over-cleaned surface, even though the brooch cast was almost certainly of silver.

Early crucibles generally had rounded or pointed bottoms, which would sit more securely amongst the burning coals of the hearth. Also, the sharp angles between the flat bottom and the sides of a flat-bottomed crucible are a potential source of weakness especially in a vessel exposed to thermal shock. Flat bottomed crucibles only became common in the Post Medieval period suitable for sitting on an iron grid in the hearth.

Crucibles needed to be of a ceramic body that could withstand the high temperatures necessary to keep the metal molten whilst transferring it from the hearth to the mould, as well as being sufficiently robust and strong to enable them to be safely lifted from the melting hearth carrying the molten metal.

When compared to other refractories and the contemporary domestic ceramics, the clays used in early crucibles do tend to be rather more refractory with higher silica contents but less of the oxides of sodium, potassium, calcium, magnesium and iron, especially those found in urban centres where a greater selection of wares would have been available (Freestone and Tite 1986).

Some crucibles were made of fineware clays which were capable of withstanding high temperature, but were not necessarily physically strong or capable of withstanding a thermal shock or a steep thermal gradient, as Freestone and Tite found when examining Medieval crucibles from London. Thus in Late Saxon urban centres crucibles made of Stamford ware are found (Figure 7). These finewares happen to be refractory, so presumably it was found that Stamford wares possessed rather good refractory properties and crucibles were added to the list of wares produced, rather than any suggestion that the refractory body had been deliberately created to meet the demands of the metallurgists. Fine wares tended to be both thin and have poor resistance to thermal shock.

Figure 7. Typical bag-shaped crucible from Northampton, made as part of the range of Late Saxon Stamford ware. Stamford ware ceramics generally were found to be highly refractory, and so crucibles were added to the range of wares produced.

Some Roman crucibles of fineware clays were given jackets of much rougher clay (Figure 8; Bayley 1992b).

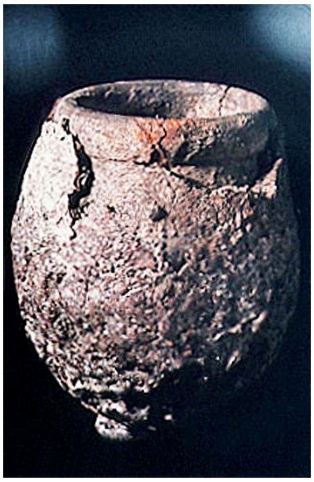

Figure 8. Roman fineware crucible with a clay jacket, from Carlisle. The fineware was highly refractory but without the rough clay jacket was not very strong and would also have dissipated heat rapidly on removing from the hearth (Bayley 1992b).

This combination had ideal properties, the outer clay jacket provided the physical and thermal robustness, as well as providing additional insulation, and the inner fineware was more resistant to high temperature and deformation. Bayley and Rehren's 2009 overview of European crucibles from prehistory to the Post Medieval period saw early crucibles as small, often shallow, relatively thick-bodied, of non-refractory clays often vegetal-tempered, progressing to taller, thinner more likely now to be tempered with quartz and using more refractory, lighter clays, that is those clays containing less iron-rich minerals.

Casting

Molten metal upon cooling solidifies and adopts the mirror image of the surface upon which it is in contact. Casting is thus an immediately obvious fabrication technique and must go back to the very inception of metallurgy; indeed the ability to take and retain a cast shape is one of the defining properties of metals.

Three methods of casting are likely to have been used in antiquity, sand casting, piece moulding and lost wax casting. The history of sand casting is most problematic as its material, loamy sand, leaves no permanent debris and sand castings themselves are not dissimilar to those created in a two-piece mould of clay (the Athlit ram mentioned above was originally published as a sand casting by Casson and Steffy [1991] but more recently has been published as a lost wax casting by Oron [2006]); it is still uncertain which method was employed. Sand casting could have a very long history, but is only attested with certainty from the last thousand years (La Niece 2003; forthcoming).

Piece moulding

Casting items in a two-piece mould is of great antiquity and ubiquity, the technique was used from the Bronze Age to the present day. Put very simply, a template of the artefact required or an existing example is pressed into fine soft clay, thereby creating half of the mould (Figure 9). More soft clay is then impressed onto the upper surface of the embedded template and lower mould. The contact surface of the latter will have been keyed in order that the two halves keep in register when they are reunited and a little dust, or latterly French chalk, will have been sprinkled onto the lower clay surface in order to stop the upper clay mould sticking to it when the two are pressed together. The two halves of the mould after drying are pulled apart and the template removed. A pouring channel is cut in the top of mould together with any venting channels that may be considered necessary on a larger casting. The two halves are then reunited, fired, the metal poured into the hot mould and allowed to cool. The mould is then broken and the casting extracted. As each mould could only be used just once, foundry sites can produce very considerable amounts of mould fragments.

Figure 9. Two-piece mould for casting a bronze spoon (below), from Castleford, Yorkshire (Bayley 1992b).

The moulding clay must have the ability to pick up and retain the detail of the modelling or of the template, but at the same time have sufficient physical and thermal strength to withstand contact with the molten metal. Although many metals must have been poured at temperatures high enough (*c.* 1100°C) to cause deformation due to vitrification, in practice this was not usually a problem because the metal had solidified before significant damage could occur. However heat deformation can occur during the firing of the mould sections such that they no longer join tightly, and for this reason piece moulding was not used in antiquity for large or complex castings, with the important exception of China.

There, ever larger and more complex piece mouldings were created from the second millennium BC (Figures 10a and b; Gettens 1969). Study of the ceramic bodies of these moulds has shown that they are largely composed of wind-blown sediments, known as loess that are remarkably resistant to warping on firing (Freestone *et al.* 1989). Several major casting sites have been excavated dating from the Bronze Age on, and have produced tens of thousands of mould and other refractory fragments, demonstrating that some extremely complex moulds were made (Li 1996). The exact way in which the decorative detail was produced is, predictably, vigorously debated (Nickel 2006, refuted by Bagley 2009).

Figure 10a, left. A simplified piece-mould assembly for casting a Chinese bronze vessel, in three outer sections and the inner core moulded around the template model of the vessel.
10b, right. Reconstruction of the piece mould blocks of loess (from Freestone et al. 1989).

Loess is very common over much of China and it frequently formed a component along with clay in the contemporary pottery, however the loess in the piece moulds had been carefully selected to include only the finest silt grade but omitting clay. It seems that the prevalence of loess through much of China strongly influenced the choice of casting method, as well as the range of shapes actually cast (Bagley 1987; Mei 2009).

Lost Wax Casting

Although this is seemingly the most sophisticated technique, it has been used since the inception of metallurgy from the Aegean through to northern India (Hunt 1980; Davey 2009), at least from the 5th millennium BC as exemplified by the castings from Mehrgarh in present day Pakistan, and somewhat later from Shahi-Tump also in Pakistan (Mille *et al.* 2004). Other very early examples from the Mediterranean world include the unused Early Bronze Age mould for casting an axe from Poliocohni on Lemnos (Figure 11; Branigan 1974, 82) and the extraordinary Chalcolithic hoard of hundreds of quite complex lost wax casting from Nahal Mishmar in Israel (see below).

The choice of casting method would seem to be as much cultural as technical. Thus in west Africa lost wax seems to have been the main method used since the inception of metallurgy (Williams 1974), even for such improbable items as wire, whereas in Western Europe the method only became common at the end of the Iron Age as exemplified by the major deposits of casting debris found in Britain at Gussage All Saints in Dorset (Wainright 1979; Foster 1980) and Grimsby (Foster 1995), and at the *oppidum* of Kelheim in Germany (Schäfer 2001; Schäfer and Scharff 2003).

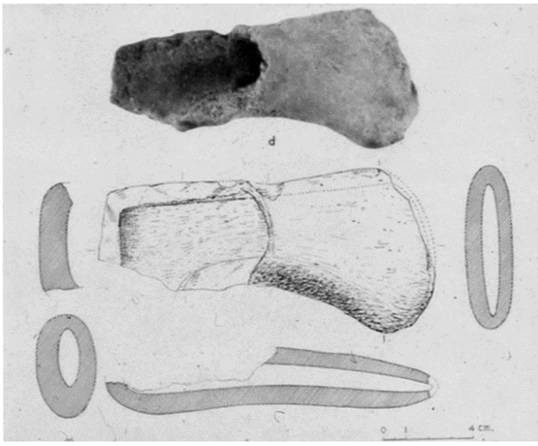

Figure 11. Unused Early Bronze Age lost wax mould for casting a small axe, from Poliocohni, on Lemnos (from Branigan 1974).

In China lost wax casting probably began in the first millennium BC but there is still heated debate over certain key pieces that are variously claimed to be lost wax or piece moulded (Strahan 2012; Zhou *et al.* 2009). These differences of preference continue to the present day, thus for example quite minor items that would be sand cast or welded together from forged components in Europe are routinely cast by the lost wax method in India (Figure 12).

Figure 12. Application of fine clay to the wax of what will be a brass smoothing iron. Kodumunda, Pattambi, in Kerala, 1994 (P.T. Craddock).

The lost wax method allowed complex and finely detailed shapes to be cast (Krishnan 1976; Reeves

1962; Mills and Gillespie 1969). To pick up the surface detail from the wax model a very fine clay was required for moulding, and for example, the bronze casters from Swamimalli, Tamil Nadu, use special clay collected from the river side (Levy *et al.* 2008, 60, 61). This is carefully sifted and ground with fillers such as charred coconut husk and cotton (cloth fibres and actual cloth feature quite frequently in the refractories associated with early casting operations generally). After mixing with water the resulting refractory has the consistency of a thin gruel or batter mixture and to cast an art bronze it would be carefully painted on, traditionally using a bird's feather in India. The layers would be very thin, for example, one of the early Indian texts on the casting of images stipulates that the first layer should be so thin as to be transparent with the wax clearly visible through it. Thus several layers have to be applied and dried (Figure 13).

Figure 13. The wax model of the lower part of a statuette with the first coating of fine clay in place. Patan, Nepal, 1987 (P.T. Craddock).

Even so these clays would not have the requisite physical and thermal strength, and thus it is necessary to add several outer layers of rougher, stronger clay, often collected from the paddy fields, to which is added vegetal material and crushed rock fragments as temper, the final layer being of very coarse clay (Figure 14).

Figure 14. Mould for casting a figure, with the outer layer of coarse clay in place. Swamimalli, Tamil Nadu, 1986 (P.T. Craddock).

All recent moulds of any size, be they from India or Europe, have also incorporated wire within the coarse clays for extra strength and resilience. Wire is not mentioned in any early source and wires or impressions of wires in the mould clay have never been reported from any of the early Greek foundries where large statues were cast (Heilmeyer *et al.* 1987; Schneider 1989a and b; Schneider and Zimmer 1984). Once again there is great uncertainty when or where a now standard practice originated.

The completed clay mould containing the wax model has to be dried and then carefully heated to melt and burn out all traces of wax before molten metal can be poured in. Once the molten metal has entered the mould it contracts and solidifies first of all against the walls and so the level of molten metal towards the centre and top falls quite appreciably, potentially ruining the casting. To counteract this it is common practice to have a small reservoir of molten metal above the main casting. Sometimes this is within the mould but often it is a separate cup, known as a *sprue* and these are quite common finds on foundry sites (Figure 15).

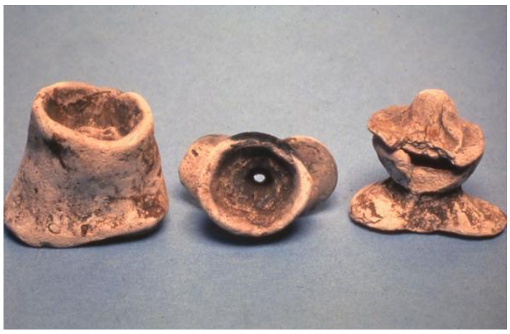

Figure 15. A selection of Romano-British sprue cups, which held a reserve of molten metal above the mould as the metal cooled and contracted (British Museum copyright).

Hollow Lost Wax Casting

The description given above covers the refractory requirements for a solid casting. However, if the casting was to be substantial, then solid metal becomes increasingly impractical. Not only are there considerations of the cost and weight of the metal, but more significantly the problem of shrinkage. As noted in the previous paragraph the metal will solidify first against the wall whilst the metal in the centre is still liquid and even when solid will still be contracting and thereby creating considerable strain, potentially causing distortion or cracking. The solution was to make a hollow casting achieved by having the wax model around a core of refractory material. From then on the method proceeds in the same manner as with solid lost wax casting.

Hollow lost wax casting goes back almost to the inception of the technique itself. Copper maceheads produced by the Middle Eastern Chalcolithic Ghassulian culture in the 4th millennium BC were cast around a solid core. Many hundreds of these were found as part of a spectacular hoard of lost wax castings at Nahal Mishmar in Israel (Bar-Adon 1980; Tadmor *et al.* 1995; Goren 2008). The cores of the maceheads were originally claimed to be ceramic, but with a decidedly odd analysis, that included 57% calcium carbonate, 10% anhydrite, 3.5% iron oxides, 7.5% alumina, 1.5% free carbon, but with only 8% of silica (Potaszkin and Bar-Avi 1980). Subsequently, Shalev *et al.* (1992) suggested this was actually a clayey chalk-limestone, as were the other mace head cores they examined from another Ghassulian site at Shiqmim, also in Israel.

Usually, however cores have been of ceramic. The core's sole requirement is to retain its shape during the casting process whilst the molten metal flows around it, supporting the solidifying metal and so defines the thickness and inner shape of the casting. In order for this to happen there are a number of important criteria that have to be met. Thus the core material, inside the metal has to have very specific properties, very different from those of the mould on the outside. During the actual pouring of the metal, even into a red hot mould there is likely to be some additional gas generation and expansion that can only be dealt with by absorption into the core (absorption into the mould would, of course, ruin the casting). Thus an open structure is necessary and was usually achieved in the past with large quantities of dung and vegetal material, often with quite macroscopic straws, now visible as voids. Sometimes a central spine of light wood or even twisted paper was inserted to act as a flue to remove the gases generated. The core also has to have the strength and rigidity to withstand local pressures and not to shrink whilst the metal is molten. However, after the initial solidification, the metal will continue to shrink which the core must accommodate in order to avoid serious stress and potential cracking in the casting. These two requirements are usually met by the addition of large quantities of crushed rocky filler, typically silica in one form or another which ensure surface rigidity during the few moments of solidification, but the voids created by the burnt out vegetal material enable the core to 'give' a little whilst the metal contracts.

Not only are the functions and materials of the core very different from those of the mould refractories, but their study is also very different. It is very rare for mould material still to be associated with the casting and thus the study of mould refractories is confined to material from foundry sites. In complete contrast core material was often incompletely removed from the casting, or in the case of an enclosed hollow casting, it is still present (Figure 16), and thus core refractories are usually directly associated with the casting, but not the foundry. This has led to a difference in the potential questions addressed to the material.

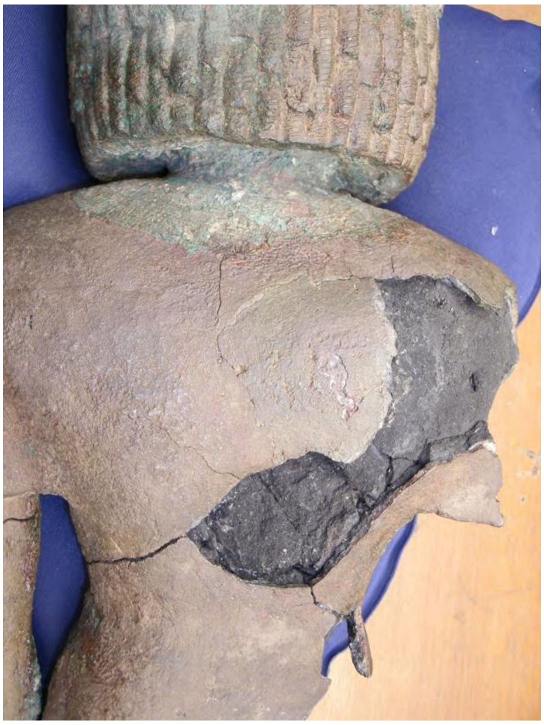

Figure 16. Badly damaged bronze torso of Egyptian statuette of an official (BM EA 22784), exposing the sandy clay core material inside (P.T. Craddock).

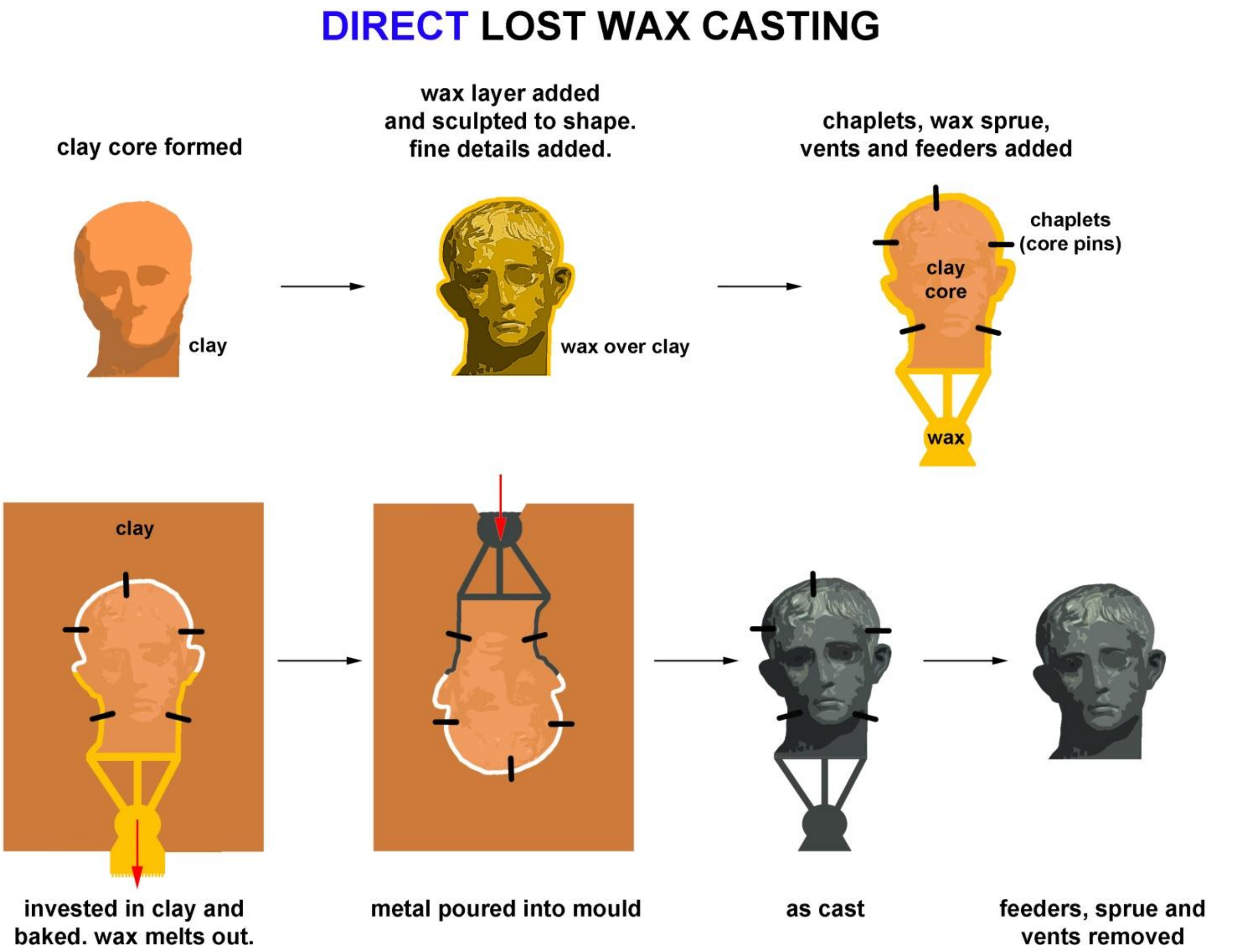

Figure 17. Stages in the direct hollow lost wax casting process (S. La Niece and A. Simpson; Copyright British Museum).

Examination of the mould fragments at a foundry can give information on the technology, as well as to what was cast, whereas the study of the core material from a casting can give further information on the casting technology, and in addition provide valuable insights into both the authenticity and also the possible provenance of the castings.

Technology

There are two processes by which a hollow lost wax mould may be produced, the direct and indirect processes. In the direct lost wax process the first task is to create the core of the approximate dimensions required but a little smaller (Figures 17 and 18; Krishnan 1976; Reeves 1962). The wax is applied to this in the required thickness. The core is held in place by thin slivers of metal driven through the wax into the core leaving the free ends to become embedded in the mould as shown in Figure 17. Thereafter the modelling of the wax, the moulding and casting proceeds as described in the lost wax casting section above.

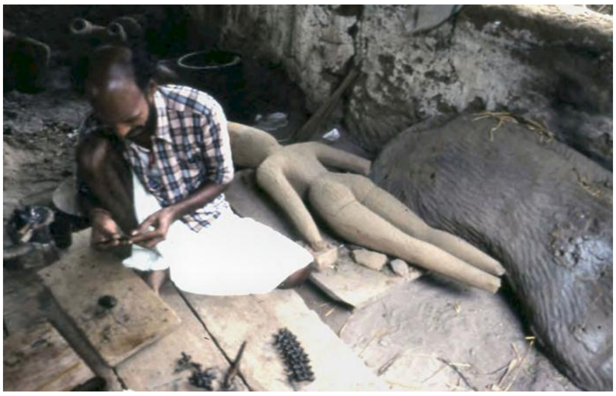

Figure 18. Large core for the direct lost wax casting of a life-size figure. Note a completed mould to the right. Swamimalli, Tamil Nadu, 1986 (P.T. Craddock).

In the indirect process the work to be cast is first modelled in any convenient material, or an existing

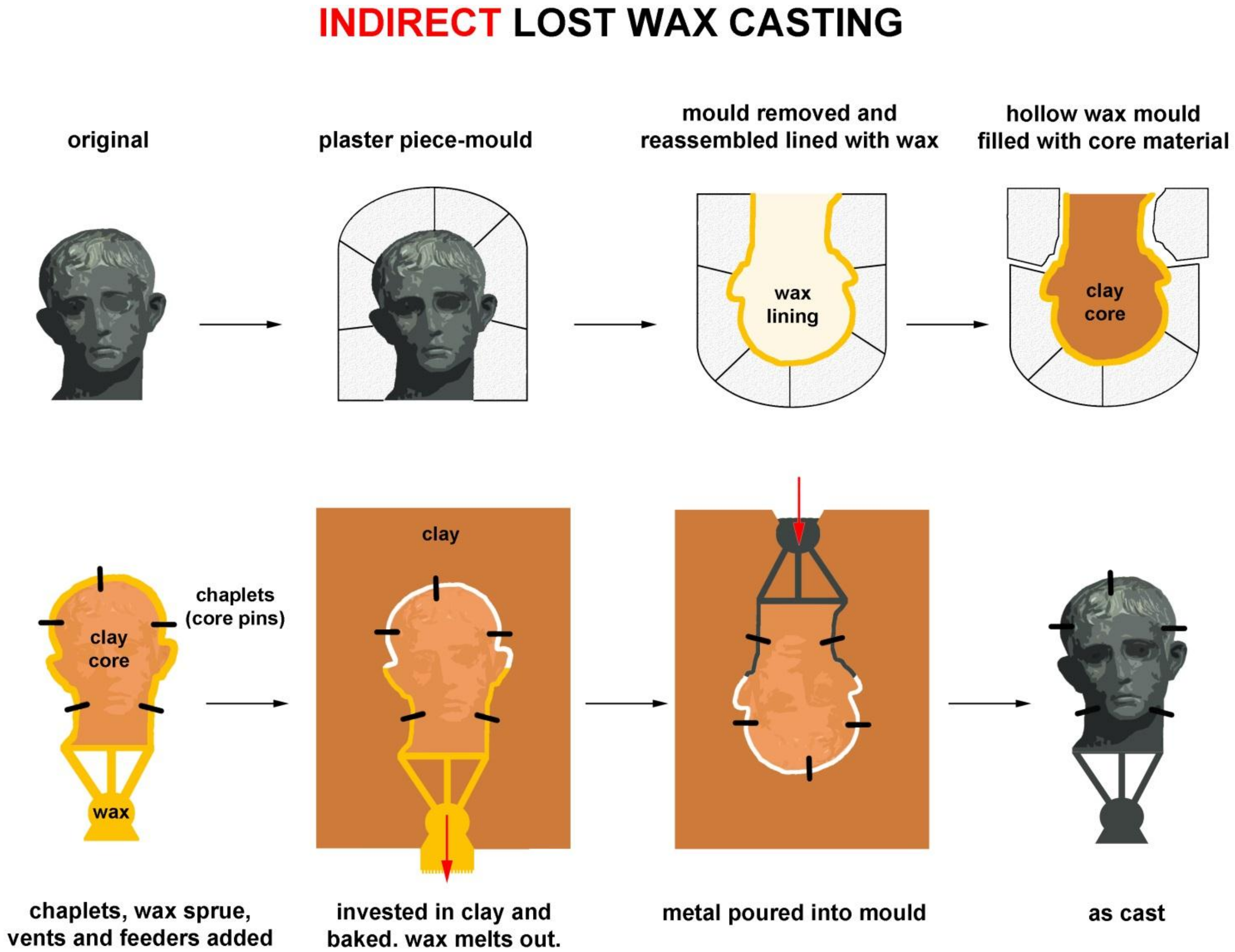

Figure 19. Stages in the indirect hollow lost wax casting process (S. La Niece and A. Simpson; Copyright British Museum).

artefact may be copied (Figure 19). This is covered with plaster of Paris in sections which after solidifying, are pulled away and the original art work removed to take no further part in the process. The plaster sections are reunited and form a negative mould. The wax is applied to the required thickness, forming the positive impression. There are several methods by which this may be achieved, Cellini recommended applying sheets of warm wax similar to sheets of pasta; in a complex mould this can be done by pouring in molten wax, swirling it around to cover all parts of the plaster mould, pouring out the excess and repeating the process, thus forming the hollow positive impression of the original art work in wax. The core is then inserted and the modelling and moulding etc., proceeds exactly as in the direct process.

The main difference between the direct and indirect processes lies in the core. In the direct process it forms the first phase of the operation to which the wax is added, but in the indirect process it is the core which is added to the inner surface of the wax. The latter presents no difficulties when the inside of the mould is fully exposed as with the head illustrated in Figure 20, but problems occur with filling restricted spaces with core material, such as the interstices of a limb for example, especially if an armature is already present.

Figure 20. Indirect lost wax casting. Two halves of a plaster of Paris negative mould that has been taken from the head that lies between them. Murlo, Tuscany, 1991 (P.T. Craddock).

The solution from Post Medieval time onwards has been to pour in a liquid core material based on plaster of Paris. Modern core materials typically contain one part plaster of Paris to three parts grog and this itself can be reused after firing and crushing with additional fresh plaster of Paris and grog (Mills and Gillespie 1969, 32-3). This has the consistency of a cream when poured into the mould to create the core.

The indirect hollow lost wax process developed from the early first millennium BC in Egypt and in the Sabatean kingdom of the Yemen (Mille *et al.* 2004; 2010; Mille 2012); this was adopted by the Greeks and Romans and has been the predominant casting technique for works of art from Post Medieval times onwards, at least in Europe and North America (Mills and Gillespie 1969). However, there is still considerable controversy concerning whether specific major castings of the classical period are direct or indirect castings. Thus for example the Riace bronzes are claimed as being indirect casting by Formigli (1999, 67-74) but Lombardi and Vidale (1998), arguing mainly from their study of the core material claim they are direct castings. Similarly, Frel (1982, 13) originally published the well-known Hellenistic statue known as the Getty Youth, now in the Getty Museum in Malibu as being a direct casting in one piece, but more recently Podany and Scott (2000) argue that it was made up of components that were indirect castings.

Thus it is evident that the nature of the core is potentially important to establishing the method by which the casting has been produced. If the core contains substantial calcium sulphate this suggests that the core was almost certainly added as a liquid and the piece is likely to have been cast by the indirect process. If the core was applied as a paste, then either process may have been used. So far core studies have failed to find evidence for liquid cores before the Post Medieval period.

However, the core material may still provide evidence for the use of the indirect method. As already stated the first stage is to create a plaster of Paris negative mould and in foundries where this process is taking place there will be quantities of plaster of Paris debris lying around. Studies of early core material show that they often contain a variety of material as fillers, including almost certainly, floor sweepings. Recent study of some large bronze Egyptian statuettes of the Third Intermediate Period, has revealed the presence of calcium sulphate (gypsum) in some of the cores, not as the major constituent, but as small fragments, showing that the material was around in the workshop (Spataro 2013). It might be argued that as many of the statuettes were subsequently coated in gesso (applied to support the gilding), this could be the source of the calcium sulphate. However, studies on these statuettes have shown that they are coated with the so-called Egyptian gesso which is formed of calcite, calcium carbonate. Thus the presence of calcium sulphate in the core is additional evidence for the indirect process, confirming the evidence previously obtained from the bronze casting itself. As noted above, it is interesting that no cores from antiquity have yet been found with sufficient calcium sulphate to suggest that liquid cores of plaster of Paris and fillers were used. Although ubiquitous now, it seems this was a Post Medieval European innovation. The absence of a pourable core material would have made it difficult to use the indirect technique on moulds where the interior spaces were not easily accessible to apply the core. Thus it is very possible that both direct and indirect methods were used, even on the same statue where it was made of separately cast components as was usual in Classical antiquity.

Authenticity

Thermoluminesence (TL) tests on core material have been used in a number of instances to date as well as to investigate the authenticity of suspect castings (Fleming 1979, 168-78; Stoneham 1990; Craddock 2009, 114-15). High profile cases include the 'Jüngling' of Magdalensberg (see below) and the reinstatement of the bronze horse in the Metropolitan Museum of Art, New York which had been wrongly condemned as a fake (Zimmerman *et al.* 1974; Lefferts *et al.* 1981; Craddock 2009, 160-67). The presence of anachronistic material can also be conclusive, as exemplified by the discovery of nylon fibres in the core of a supposedly Hellenistic portrait bust (Craddock 2009, 72).

The source of minerals in the core refractory can also provide important indicators as exemplified by the detailed study of the 'Jüngling' of Magdalensberg. Very briefly, a bronze statue of Mercury was found in the 16th century at Magdalensberg in Austria and achieved instant and lasting fame as the only complete life-size Roman bronze statue ever to be found north of the Alps. As such it held pride of place in the Kunsthistorische Museum in Vienna until quite recently. Then it began to be queried stylistically, and questions as to why it had no patina etc. led to a detailed scientific investigation (Gschwantler 1988; 'Jüngling' 1987/8, summarised in Craddock 2009, 167-72), on all aspects, and in which the core played an important role. TL established that the core had last been thoroughly hot approximately only 400 years ago (Vendl and Pilcher 1988; Erlach 1987/8), and analytical and petrological examination showed the core was very different from comparative genuine Roman core material from Italy (Sauer *et al.* 1987/8). In particular the temper was made up of mineral grains from rocks found only in the Alps, close to Magdalensberg and to Innsbruck where the statue was taken after its discovery. It is very likely that a major statue such as the Jüngling would have been cast at a major centre in Italy, not in the remote Alps, and thus it is unlikely that the present statue was cast in Classical antiquity. Other tests concurred with this conclusion. It is recorded that a copy of the statue was made after its discovery and sent to Spain, it now seems likely that it was the copy that stayed in Austria and original went to Spain, never to be seen again.

The vegetal material in the core can also provide vital information on an artefact's origins. This is well illustrated by the Olokun Head (Figure 21; Fagg and Underwood 1949; Craddock *et al.* 2013).

Figure 21. Olokun Head, NCMM 38.1.2. The first Ife head to be discovered, doubted and now rehabilitated (National Commission for Museums and Monuments, Nigeria).

This head, of leaded brass, was uncovered by the German traveller and collector, Leo Frobenius, on his travels through West Africa, at Ife, Nigeria in 1911 (Frobenius 1913, 98). The intrinsic dignity and naturalism of the head created an immediate sensation, with Frobenius opining that it must have been created by Greek craftsmen operating from beyond the Mediterranean world, that is, proof of the existence of Atlantis. He attempted to bring the head to Europe, but was prevented, and the head remained in Ife, its whereabouts uncertain. Some twenty five years later a major find of similar heads was made in Ife and re-awakened interest, but when the original head was shown to the British sculptor and ethnographer, Leon Underwood, in Nigeria, he declared it to be a copy. Subsequently the Ife heads, including the Olokun Head were sent to London for exhibition at the British Museum. Whilst there, the head was examined again by Underwood and his team and their claims that the piece was a crude sand-cast copy were duly published (Fagg and Underwood 1949). Their arguments, although expressed at great length, were not wholly convincing, and were indeed immediately challenged by A.A. Moss (1949) of the British Museum's own Research Laboratory. Thus when the Ife heads together with the Olokun Head were once again displayed at the British Museum in 2010 the opportunity was taken to examine the head in detail, which study concluded that the head was indeed genuine (Craddock *et al.* 2013).

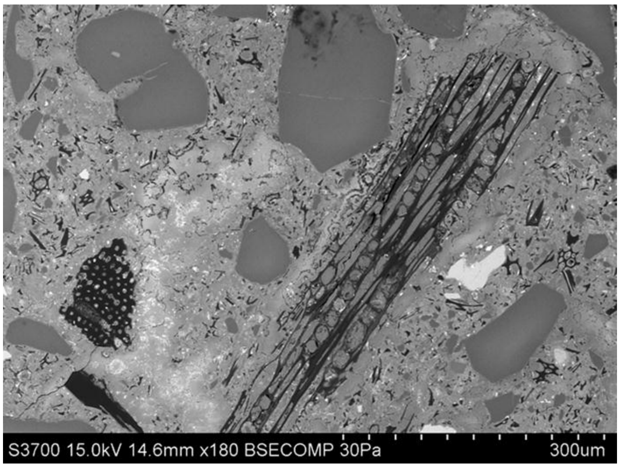

Figure 22. VP-SEM image of two charcoal fragments in the Olokun Head core sample. The fragments are typical of West African tropical species, demonstrating that the head is very likely to have been cast locally rather than in Europe as has been claimed (C.R. Cartwright; Copyright British Museum).

One of Fagg and Underwood's contentions was that

Frobenius had the copy made in Germany from the detailed photographs and measurements that he had taken of the original. The recent examination of the plant impressions in the core material showed that some belonged to taxa that only grew in tropical climates, certainly not Europe (Figure 22). Thus the main scenario for head being a modern copy was removed.

Provenance

Studies of the characteristic filler minerals in the core materials have been used to provenance the foundries where castings were made, including works from Greece and Rome (Schneider 1989b), China (Holmes and Harbottle 1991) and the Himalayas (Reedy 1991; 1997; Reedy and Meyers 2007). In particular Chandra Reedy's work has made the study of the core material an integral part of the technical and stylistic study and enabled many of the statuettes to be assigned by their characteristic core fillers to specific geographic regions, linking in with and complimenting the stylistic studies.

Conclusion

This concludes the second part of the review of the metallurgical refractories of antiquity. It is clear that the study of these ceramic materials both from the primary smelting and artefact production sites is fundamental to the understanding of the metallurgical processes. Similarly the study of the core material still entrapped within the castings also contains evidence on the early processes as well as information on authenticity and provenance of the artefacts concerned.

Some of the questions raised in these two papers demonstrate that there are still many uncertainties on the metallurgical process, questions that the continuing scientific examination of the refractories may well resolve.

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