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"The same ... ... but different": A juxtaposition of Roman and Medieval brass making in Central Europe

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European brass making relied for more than 1500 years on the cementation of zinc oxide with copper metal, conducted in crucibles as reaction vessels. Both archaeological and documentary evidence now allows us to distinguish two variants of this one process, namely a Roman method, conducted as a solid state reaction in neatly closed vessels, and a Medieval method, employing open vessels at higher temperatures, resulting in liquid brass of lower quality. The apparent differences and the time gap between the two variants raise doubts as to whether the Medieval process is a direct offspring of the Roman one. Alternatively, an independent, possibly eastern, origin of the later technique is to be considered. Furthermore, a paradigm shift in the understanding of the nature of matter becomes apparent. Ironically, the more 'modern' view of alloy handling is associated with the poorer process, both economically and ecologically, and probably yielded a lower quality of metal.

Keywords: Brass Making; Roman; Medieval; Zinc Oxide; Crucibles; Cementation.

Introduction

Brass is the most recent of the ancient metals and alloys. Its regular production started only in the first century BC, probably in the eastern part of the Roman empire. The early use of brass was limited to coinage and military implements, but soon brass merged into the metal stock in circulation (Caley 1964, Hook & Craddock 1996). Beginning in the 2nd century AD, the purity and quality of brass decreased, resulting in an ill-defined quaternary alloy of copper, tin, zinc and lead ('leaded gunmetal') for many everyday implements and castings. It appears that the production of fresh brass largely ceased even before the collapse of the Roman empire (Caley 1964, Dungworth 1997a, b:907). The Middle Ages saw a revival of brass making, and soon it became the dominant copper-based alloy of the Old World, except for more specialized objects such as bells, which remained high-tin bronze. The outstanding technological question is whether medieval brass making is or is not a direct continuation of the Roman tradition.

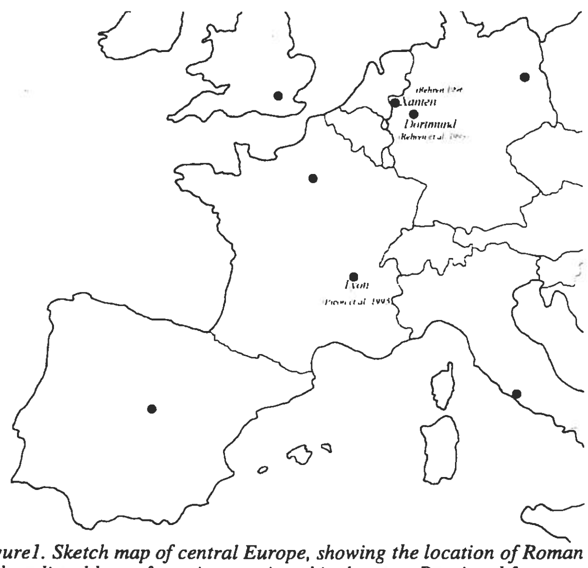

Figure1. Sketch map of central Europe, showing the location of Roman and medieval brass factories mentioned in the text. Reprinted from Haedeke, 1973. Reproduced by permission.

The same ...

It is generally accepted that during both periods brass was made by the cementation process, i.e., by the reaction of zinc ore, charcoal and copper metal in a crucible. Whilst the metallurgical outlines of this process are well studied, archaeological evidence for it was absent until less than twenty years ago. The investigation of recent finds from Roman (Picon *et al.* 1995, Rehren in press) and medieval settlements (Rehren *et al.* 1993, and unpublished results) now allows for the first time further differentiation between two variants of this process. The location of the sites discussed here are shown on the map in Figure 1.

Brass cementation

In brass cementation, zinc oxide is reduced to zinc metal by charcoal at a temperature of about 900 to 1,000 °C. At this temperature, zinc metal forms a vapour phase, which is absorbed easily by copper metal. The upper limit of zinc uptake in cementation brass is about 30 wt% Zn, with the precise limit being controlled by a range of factors, including temperature, pressure, atmosphere composition (Haedecke 1973), and other alloying elements present in the metal phase. It appears that the maximum zinc uptake occurs at temperatures around 900 to 950 °C, while higher temperatures result in lower upper limits of zinc concentrations in the alloy, with as little as 20 wt% at 1,200 °C (Fig. 2; Haedecke 1973:232). At lower temperatures the diffusion of zinc into the solid metal is slow and thus high zinc uptake is restricted to a thin surface layer. The lower uptake at high temperatures is due to the higher partial pressure of zinc vapour, which promotes the volatilization of the zinc from the solid phase. In consequence, brass cementation is ideally done at temperatures at or below 1,000 °C, with the recipient copper metal in a suitable form, e.g., thin sheet or foil with a large surface relative to the volume and with as little impurities like lead, tin or arsenic as possible. A full discussion of brass making kinetics is not attempted in this paper, although details of the process are still a matter of debate (e.g., Grothe 1973).

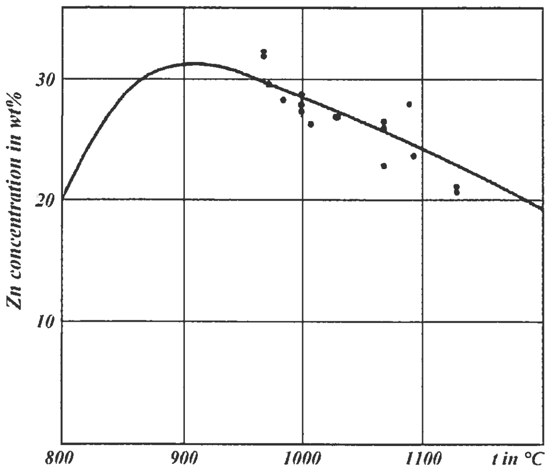

Figure 2. Experimental results (dots) and calculated equilibrium concentrations (vurved line) of zinc in brass. From Haedecked (1973: 232).

Brass cementation generally requires closed crucibles in order to keep the highly reactive and elusive zinc vapour in close contact with the copper metal, but away from any oxidizing agents. These constraints were only completely overcome long after the introduction of metallic zinc into brass making (Day 1990), when the crucible step was transferred to the distillation of zinc in retorts, i.e., crucibles providing a temperature gradient suitable to condense the metal vapour within the closed system.

Zinc oxide used in cementation can be either secondary zinc ores ('calamine'), i.e., zinc carbonates etc., transformed to zinc oxide by roasting (in the mid-13th century, Albertus Magnus reports that at Cologne and Paris they "*... convert copper into brass by means of the powder of a stone called calamina.*" Wyckoff 1967:224), or artificial zinc oxide obtained from a smelting process (again Albertus Magnus: "*Tutty, which is frequently used in the transmutation of metals, is an artificial, not a natural compound. It is made from the smoke that rises upwards and solidifies by adhering to hard bodies, where copper is being purified from the stones and tin which are in it. And a better kind is made by resubliming this.*" Wyckoff 1967:250). Literary evidence furthermore indicates the use (and therefore production) of large quantities of zinc oxide (*'tutia'*, *'spodos'*, etc.) as a pharmaceutical in the Roman empire, and Dioscorides explicitly mentions it condensing on iron rods put over smelting furnaces (Gunther 1934:234). Similar evidence exists for 'the East', i.e., Persia to India, from the early Middle Ages onwards (Allan 1979). Archaeological evidence for the production of such material is scarce (but cf. Hezarkhani-Zolgharian *et al.* 1994). Only recently, however, Eckstein *et al.* (1996) suggested a large-scale zinc oxide production in north west India from mixed, sulfidic lead-zinc ores, leaving behind a dense, lead-rich silicate slag.

Both types of zinc compounds, the natural calamine and the artificial *tutia*, are known to occur in different qualities, usually indicated by specifying their colour or origin. Impurities may contain earthy, non-reactive contaminants as well as metalliferous compounds, mainly lead oxides and sulfides. In particular lead enters the metal phase during the process (Maréchal 1938), probably more so if the alloy in forming is liquid rather than solid. Systematic studies of the behaviour and significance of these impurities, however, are lacking.

Brass working

Having made the brass, there are little characteristics in the further working of the alloy that distinguish it from the general contemporary copper-based metallurgy. Metal was melted in pear-shaped crucibles and cast, often with an addition of lead to increase fluidity and to lower the melting temperature. Sheet metal was being made, and both hammered and cut into shape. A range of surface decoration techniques were known, including the application of foil and leaves of gold and silver (Anhaeuser 1997), tinning, and artificial patination (La Niece & Craddock 1993). Non of these techniques seem specifically to be related to a certain alloy, although alloy preferences are known for particular types of objects.

Certainly, trade and recycling of copper and copper alloys were widely practised throughout the periods under consideration here. The extent to which recycling was done separately for different alloys, and whether there were any means to determine alloy composition except by colour, is still a matter of debate, though often based upon little factual evidence. Similarly, evidence for Roman or medieval brass trade is limited to a surprisingly small number of ingot finds (Bachmann & Jockenhövel 1974, Bollingberg 1995). Hence, there is again no sufficient base for an in-depth discussion of details of these aspects of archaeometallurgy, let alone for the discussion of differences between or characteristics of individual periods.

... but different

Within the general framework of brass cementation briefly given above, there are some parameters which vary to some extent. Reaction temperature, crucible design and raw materials employed are the most important ones, leading to different variants (and thus products?) of the same process. In order to reveal these differences, it is necessary to first characterize sufficiently the various processes. For the time being, this can be done only for two of the parameters, namely temperature and crucible design, while the exact nature and condition of the raw materials employed still remain enigmatic.

Roman brass making

"The metal is also got from a coppery stone called by a Greek name *cadmea*, a kind in high repute coming from overseas and also formerly found in Campania ... and it is also reported to have been recently found in the province of Germany. In Cyprus, where copper was first discovered, it is also obtained from another stone also, called *chalcitis*, copper ore; this was however afterwards of exceptionally low value when a better copper was found in other countries, and especially *aurichalcum*, which long maintained an outstanding quality and popularity, but which for a long time now has not been found, the ground being exhausted. The next in quality ... ... The highest reputation has now gone to the Marius copper, also called Cordova copper; next to the Livia variety this kind most readily absorbs *cadmea* and reproduces the excellence of *aurichalcum* in making sesterces and double-as pieces, the single as having to be content with its proper Cyprus copper. That is the extent of the high quality contained in natural copper (alloy)." (Pliny, translated by Rackham 1952:127-9)

This is the most detailed classical account of brass making, and certainly not a very precise one. It does show, however, that brass is considered a high quality variant of copper whose supply has been mainly depended on the availability of suitable ore. Only later, and after the exhaustion of that particular ore, the absorption of *cadmea* by copper was utilized to make brass. This report matches nicely the observation that brass was a rare, highly valued natural alloy during most of the first millennium BC, and only during the first century BC was made on a regular scale by a controlled process (Caley 1964, Pernicka 1990). Attention should be paid to the mention that certain variants of copper are more suitable for brass making than others.

Archaeological evidence for Roman brass production was first published by Bayley (1984, 1990), briefly describing closed, friable crucible fragments employed in a cementation process. More detailed studies of crucible remains, including chemical analyses of the ceramic and tentative process reconstructions, are given by Picon *et al.* (1995) and Rehren (in press). Common features of these crucibles are that they were mass-produced, though individually formed, sealed vessels, made from clay of no particular refractoriness, into closely similar size and shape at each findspot, but with huge variations among different sites. As far as can currently be said they were used at temperatures at or below 1,000°C, and their fabric contains only a few percent of zinc. The luted crucibles (Fig. 3) imply that they were charged and sealed while cold, while the conspicuous absence of any metal prills or slag remains within the vessels strongly indicate that cementation was done as a solid-vapour reaction, with no liquid metal/alloy or slag formation.

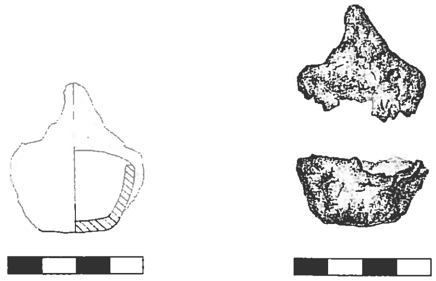

Figure 3. Roman brass making crucibles from Xanten, about 1st c. AD (n.b.: the lids and cups are made from the same clay). Drawing K. Engel.

Medieval brass making

"And when the crucibles are red-hot take some calamine, that has been ground up very fine with charcoal, and put it into each of the crucibles until they are about one-sixth full, then fill them up completely with the above-mentioned copper, and cover them with charcoal. ... Now, when the copper is completely melted, take a slender, long, bent iron rod with a wooden handle and stir carefully so that the calamine is alloyed with the copper. Then with long tongs raise each crucible slightly and move them a little from their position so that they may not stick to the hearth. Put calamine in them all again as before and fill them with copper and cover them with charcoal. When it is once more completely melted, stir again very carefully and remove one crucible with the tongs and pour out everything into furrows cut in the ground. Then put the crucible back in its place. Immediately take calamine as before and put it in, and on top as much of the copper that you have just cast as it can hold. When this is melted as before, stir it and add calamine again and fill it again with the copper you have just cast and allow it to melt. Do the same with each crucible. When it is all thoroughly melted and has been stirred for a very long time pour it out ... and keep it until you need it." (Theophilus, translated by Hawthorne & Smith 1963:143-4)

This medieval description of how to make brass comes much closer to the heart of an archaeometallurgist than the Roman equivalent. Together with the description of how to make the crucibles, the necessary furnaces and even how to refine the copper when making high-grade brass, all given in adjacent chapters of the treatise, there remain only a few uncertainties about the process.

Archaeological evidence for such brass making, however, was widely absent until quite recently. The first published investigation of medieval brass making crucibles is from Rehren *et al.* (1993). A voluminous waste deposit of crucible fragments (Fig. 4) from Dortmund, dating to the late first millennium AD, confirmed Theophilus' description in almost every detail, even adding further information. In the meantime, two more broadly contemporary brass making sites were identified in Westphalia, namely in Schwerte and Soest. In all these cases, cylindrical, template-formed crucibles were made from a highly refractory clay. Whilst the vessels from Dortmund and Schwerte are flat bottomed and of a height similar to their width, the Soest crucibles are plano-convex bottomed and appear, on average, much taller than wide. Most significantly, they are all open vessels, with the possible exception of Soest where matching clay disks were found, tentatively identified as loose crucible lids. The crucible fabric is now very rich in zinc oxide, and regularly contains inclusions of brass both within the fabric, and trapped in an internal slag layer.

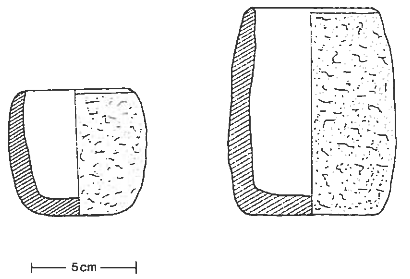

Figure 4. Medieval brass making crucibles from Dortmund, about 10th c. AD. Drawing N. Zieling. Reprinted from "Schlachen und Tiegel aus dem Adlertaun in Dortaund" in Moutanarchaologie in Europa 1993. Reproduced by permission of Jan Thorbecke Verlag Sigmaringen.

From the combination of literary and archaeological evidence, it is highly probable that the crucibles were charged only when hot, heated to a temperature well above the melting point of the resulting alloy, and operated in an 'open mode' except for a top cover of charcoal or possibly sometimes a protective lid. From this, a liquid-vapour reaction is inferred, based upon a kind of counter-current with rising zinc vapour and downward dripping molten metal.

Noteworthy, though still unexplained is the intimate association of the crucible fragments with dense, glassy lead silicate slag lumps in the archaeological record at Dortmund and Soest. However, there are only traces of similar slag within the crucibles, making it highly unlikely that this slag formed inside the vessels during the process.

Juxtaposition

Crucible fragments are regularly found in many urban archaeological sites. A common and probably diagnostic feature of the brass cementation vessels studied here is that they consist of small vessels of identical size and shape, found in large quantities within closely defined areas. This is interpreted as evidence for the use of these vessels in a standardized mass production process both in the Roman examples (Lyon and Xanten) and in the medieval ones (Dortmund, Schwerte and Soest). Significantly, the fabric of these crucibles always contains elevated levels of zinc oxide, absent in 'ordinary' melting vessels. Contemporary melting crucibles, in contrast, are typically individually formed vessels, found in much smaller quantities and/or spread over wider areas, representing occasional casting-on-demand in less specialized workshops.

The basic differences between the two brass cementation variants discussed here are firstly the lower temperature of the Roman process and secondly the use of open crucibles in the Middle Ages. These two parameters have wide-ranging implications for the actual conduct of the process. The use of a closed reaction vessel minimizes the loss of volatile zinc vapour, while a reaction below the melting point of brass ensures maximum exposure of potentially reactive metal surface and hence a maximum uptake of zinc. Thus, the zinc vapour has every chance of being absorbed by the metal, slowly but steadily. Since all the materials are contained in tightly closed vessels, loss of zinc vapour is restricted to the inevitable pressure release. Without evidence for appropriate openings in the crucibles, one can only speculate if this was achieved through the porosity of the extremely thin-walled ceramic (Rehren in press).

The medieval variant, in contrast, was conducted at a higher temperature and in open vessels. It relies on a kind of counter-current of zinc vapour rising from the bottom of the crucibles, and liquid copper alloy dripping downwards. To protect the zinc vapour from re-oxidation, and to hinder its escape, the vessels are covered either with a top layer of charcoal, as described by Theophilus, or with a loose lid as indicated by the Soest finds. As soon as all the metal has settled in a pool at the bottom of the vessel, and particularly after stirring, the incorporation of zinc into the alloy ceases even if the generation of zinc vapour continues. Eventually, the metal pool is poured out, the vessel recharged with fresh calamine/charcoal and the metal fed again into the crucible, until a satisfactory alloy quality is reached.

On a first glance, the medieval variant appears more sophisticated (and hence technologically more impressive) than the Roman one, using better quality ceramics, higher temperatures and experienced personnel. It employed crucibles of much higher refractoriness (Table 1 (at end)), able to withstand temperatures well above 1,000 °C while being attacked by zinc oxide, which is a strong flux, and craftsmen handling them with tongs for pouring and recharging. The Romans, in contrast, used mere clay for their crucibles, charged and luted them while cold. The firing of these vessels probably did not even demand any particular furnace constructions, but would have been possible in heating devices like those used in underfloor heating or thermal baths. The only disadvantage of the lower temperature lies in a relatively slow diffusion of zinc into the copper alloy. On the other hand, the higher temperature of the medieval process inevitably led to a lower upper limit of zinc content in the alloy (Haedecke 1973).

When comparing the economic aspect of the medieval variant with that of the Roman technique, the apparently 'high-tech' process falls badly behind. As a consequence of its higher temperature, iterative and open mode of operation, the medieval process required a much greater input of qualified labour to manipulate the red-hot crucibles, of thermal energy to reach the higher temperatures in the furnace and to maintain them over an extended period of time, and of costly raw materials for high quality crucible production and the zinc-rich charge feed than the Roman one.

Know-how transfer and the Nature of Things

Medieval technology and philosophy are deeply rooted in late Roman traditions (Gies & Gies 1994). The church, and in particular its monasteries, served as the major time tunnel, bridging the 'Dark Ages', thus providing the wealth of classical knowledge, often *via* Islamic intermediaries, to the Middle Ages. Theophilus (Hawthorne & Smith 1963) and Albertus Magnus (Wyckoff 1967) are amongst the most important authors in this process with regard to technical know-how and the medieval view of the Nature of Things. Does this hold true for the tradition of brass making technology as well?

Probably not. A fundamental problem in the tradition of classical technology lies in the lack of comprehensive technical literature. Apparently, the crafts were generally not considered worthy of being discussed in literature; with exceptions like Pliny only confirming this rule. Thus, the transmission of traditional technology was restricted to direct teaching and individual apprenticeship. In regard to brass making, we are faced with a particular problem, namely the strong possibility that this particular knowledge was already mostly lost before the collapse of the Roman empire in the west (Caley 1964, Craddock 1978, Dungworth 1997a, b). Therefore, the usual ways of know-how transfer probably did not work in this particular case.

Furthermore, the fundamental differences in crucible design and mode of operation make it unlikely that the

	SiO_2	Al_2O_3	FeO	MgO	CaO	Na_2O	K_2O	ZnO	Cu
Dortmund (2)	50.3	22.9	2.8	0.5	2.8	0.9	2.9	11.5	0.6
Soest (4)	62.5	16.1	2.5	0.4	0.9	0.4	1.5	8.2	1.5
Schwerte (3)	63.6	16.2	1.5	0.2	1.2	0.6	1.4	12.3	1.0
Xanten (4)	*75.7*	*11.0*	*3.8*	*1.3*	*1.3*	*1.7*	*2.8*	*1.6*	*0.1*

Table 1: ICP-OES data of the fabric of brass cementation crucibles from the Middle Ages (top three rows) and Roman (bottom row). Note the significantly higher alumina and lower alkali concentrations in the medieval samples, resulting in a higher refractoriness of the ceramic. The zinc oxide content of the Roman crucibles is much lower than in the medieval ones, indicating a better control of the process. Data are averages of multiple analysis (number of individuals from each site are given in brackets) in wt%, analysis W. Steger.

medieval variant is just a derivative of the Roman brass making technology. An independent origin is entirely possible. In view of a broad flow of know-how and materials into Europe from 'the East' during the Viking Period and the Middle Ages, a link to traditional Indian brass making appears not at all unlikely. Documentary indications for this are to be found in the mid-13th century work *Mineralia* by Albertus Magnus (Wyckoff 1967:250), when he refers to *tutia* from India, and half a century later, when Marco Polo reports the production of zinc oxide in Persia (Latham 1972).

Very recently, Eremin *et al.* (1998) presented data on late first millennium AD brass objects from Scotland, indicating that those finds which were identified as local on stylistic grounds were of a low-zinc brass, often with significant tin contents, whilst imported Scandinavian objects were of brass with a much higher in zinc and without indications of the recycling of tin bronze. In view of the known Viking contacts to Central Asia, this would also seem to support the proposed 'Eastern' origin of medieval brass making technology.

Another possible hint to an 'Eastern' origin of the medieval brass cementation technique lies in the frequent association of the Westphalian crucibles with large amounts of dense lumps of lead-silicate slags (Rehren *et al.* 1993 for Dortmund, unpublished data for Soest). These slags have their closest parallels in finds from north-west India (Table 2 (at end)). These are related to a tremendous underground mining of sulfidic zinc ore, and are tentatively interpreted as the remains of a smelting operation leading to the production of zinc oxide (Eckstein *et al.* 1996). Without more detailed information about the kind of raw materials used in brass making, however, one can only speculate whether or not these European slags are really zinc oxide slags.

Another fundamental difference between the Roman and the medieval variant lies in the approach to metals in general. The Romans accepted different qualities of copper as a natural phenomenon, while the medieval craftsmen actively controlled the quality of copper or scrap to adjust it to their needs. Pliny mentions that the good quality copper/*aureichalcos* of former times is now exhausted, and that certain kinds of copper are more suitable for brass making than others. Theophilus, in contrast, tells us in his next chapter how to refine copper for making better quality brass, suitable for gilding work. This reveals a shift from a passive, receptive understanding of nature to an actively manipulating one. Ironically, the inferior, wasteful

medieval technology comes together with a more modern, 'superior' philosophy, which in the long run eventually enabled significant progress beyond the Roman technology. In brass making, however, this was not achieved before the Modern Period. Even in 1546 Agricola (Fraustadt 1958:231-2) describes brass making in open crucibles which are only half-heartedly covered by lids, more than half a millennium later than the Westphalian finds, and cementation served as the major method of brass making well into the Industrial Period (Day 1990).

Acknowledgements
The title of this paper was inspired by Graham Philip's 1995 paper on MBA metalwork from Palestine and Egypt, and I am grateful that he allowed me to make use of this phrase in a similar manner.

	SiO_2	Al_2O_3	FeO	MgO	CaO	K_2O	PbO	ZnO	CuO
Dortmund (9)	32.8	3.8	4.1	0.6	3.3	2.2	44.9	3.2	1.8
Zawar (47)	43.0	6.2	12.1	4.6	13.1	1.9	6.9	11.0	0.1

Table 2: ICP-OES data of dense slag lumps from medieval Dortmund (top row) and Zawar in NW India (bottom row). Data from Rehren et al. (1993) and Eckstein et al. (1996), resp. Both sites are in intimate context with brass making (top) and zinc ore mining and smelting (bottom). Data are averages of multiple analysis (number of individuals from each site are given in brackets) in wt%.

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