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The Making of Roman Lead Ingots. Their Casting by Experiment and the Archaeological Evidence

Norbert Hanel and Ingo Pfeffer

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Roman lead ingots with inscriptions, casting moulds made of clay-sand and wood, chaîne opératoire, archaeological experiments

Abstract

Casting experiments in Brilon-Hoppecke (North Rhine-Westfalia, Germany) in 2011 and 2012 as well as in 2015 aimed to reconstruct the production of Roman lead ingots with the help of archaeological experiments on the one hand; on the other hand, traces of the moulding process on the Roman lead ingots themselves and the epigraphic evidence were examined to provide further information on the production process. The results of this research, suggest that most of the lead ingots were very likely cast in clay sand moulds which almost completely disintegrated after the ingots had been removed. In a few cases, wood could be verified as the material for the moulds. Finally, all known artefacts associated with the casting of lead ingots have been critically examined and reinterpreted.

Introduction

Lead ingots are an important link in the production chain (chaîne opératoire). They are also a crucial artefact group within archaeometallurgical studies for tracing the ore to the final metal product (Hauptmann, 2007, pp.115-116, Fig.1; 2008, pp.125-126, Fig.2.22; Domergue, 2008, pp.143-163, esp. p.157, Fig.100; Stöllner, 2003, pp.417-420, Fig.1; 2014, pp.134-135, Tab.7.1). Lead ingots are known from Late Bronze Age; here we want to concentrate on specimens used during the Roman period (Rothenhöfer and Hanel, 2013, pp.273-274). They are the means of transport of the metal from the mining regions – distributed throughout the Imperium Romanum – to the processing workshops or consumers. The majority of Roman lead ingots were provided with numerous epigraphic elements, such as cartouche inscriptions, stamps and chisel inscriptions as well as graffiti. Against the background of archaeological find contexts, these ingots provide outstanding possibilities for answering questions about the origin, dating of the metal, etc.; they also make an important contribution to the evaluation of further aspects of trade and economic history within the Roman Empire (Domergue, 1998; Bigagli, 2002; Hanel, 2011, p.119-120; Rothenhöfer and Hanel, 2013, pp.275-277; Domergue and Rico, 2014; Rico and Domergue, 2016). Independently of the data obtained by archaeological-epigraphic means, new insights regarding the origin of the lead ingots are emerging through the use of lead isotope analysis (Gale and Stos-Gale, 2000; Bode, 2006, esp. pp.37-41; Hauptmann, 2008, pp.137-139; 2020, pp.335-336, 491-492).

State of research

In the archaeological literature dealing with lead in general and Roman lead ingots as trade and transport goods in particular, the question of how the ingots were made has not played any significant role to date; at most, only brief statements or marginal comments have been made on the subject – usually without further justification – and these have not been discussed further. There are also no surviving reports in the ancient literature that describe the casting progress (Meier, 1995, pp.218-219). In his encyclopaedic *Naturalis historia*, Pliny the Elder dealt with lead and its use (e.g. in medicine), some lead mines, lead smelters and the topic of the cupellation process in books 33 and 34; however, he does not explicitly discuss ingot casting itself. Very few archaeological objects have come to light from the mining regions of the Roman Empire that can be connected with ingot casting. These are discussed below (pp. 24-25). Because the written source

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Figure 1. 1-2. Two lead tablets with inscriptions from the Coto Fortuna mine (Mazarrón); 3. Lead tablet from the Cabeza del Moro (Mazarrón) with retrograde, recessed inscription SOC. Graphics: J.A. Antolinos Marín and B. Díaz Ariño (2012, p.42, Fig.3.1-3).

Figure 2. Lead tablet from the Cabeza del Moro (Mazarrón) with a retrograde, recessed inscription MONT ARGENT. Photo: N. Hanel.

Figure 3. Lead tablet from the Coto Fortuna mine (Mazarrón) with recessed and mirror-inverted inscription SOCIET. Photo: N. Hanel.

material is too insufficient to reconstruct the underlying processes, the focus of this article is on the interpretation of the ancient ingots and the casting experiments carried out in order to come closer to the reconstruction of Roman casting techniques and its moulds.

Until now, only a few finds have been recovered from two mining regions of the Roman Empire, which researchers interpret as fragments of cartouche inscriptions on lead ingots or as templates for their production. There are a total of five lead tablets of different size with inscriptions. Firstly, two pieces from the Roman mining area of Mazarrón (Province Murcia) will be discussed. The first lead tablet (Figures 1. 3 and 2) was found in 1847 in an ancient slag heap at the Cabeza del Moro, northwest of the city centre of Mazarrón (Dubois, 1901, p.214, no.13; Antolinos, 2003, p.5B, with Fig. center left; Domergue, 2005b, p.188-189, cat. no. 67; Ramallo Asensio, 2006, pp.69-70, with Fig.; Antolinos Marín and Díaz Ariño, 2012, p.32, 42, Fig.3). It is now kept at Museo arqueológico de Murcia (inv.no. 0/39). The long, rectangular, slightly truncated pyramid-shaped lead tablet measures approximately 11 x 2.3 x 1.2 cm. The approximately 1.5 cm long letters MONT•ARGENT with the two ligatures NT are recessed. The 10 letters are inverted and retrogradely etched into the lead background.

The second, also slightly truncated, pyramid-shaped lead fragment came to light as a chance find in the 1980s in a slag heap in the Roman mining zone near Coto Fortuna, approximately 8 km west of Mazarrón (Domergue, 2005a, p.188, cat. no. 66; Ramallo Asensio, 2006, p.69; Antolinos Marín and Díaz Ariño, 2012, p.32, 42, Fig.3.2). It still measures 7.8 x 2.5 x 0.6 cm. The 1.5 cm high letters are invertedly recessed. They are: SOCIET (Figures 1. 2 and 3).

Another chance find from the beginning of the 21st century, and once again from the Coto Fortuna mining zone, is the third, poorly preserved, slightly truncated, pyramid-shaped lead fragment (Figure 1. 3) (Antolinos Marín and Díaz Ariño, 2012, p.32, p.42, Fig.3.1). It has the following dimensions: 6.4 x 2.5 – 3.5 x 2 cm. Only the 3 letters SOC[---] are visible. The letter height is 1.5 cm. Both of the last-mentioned tablets are privately owned.

Researchers soon established a connection with the lead ingot production of the *Societas argent(ifodinarum) mont(is vel montium) Ilucro(nensis vel -nensium) Galena* (Antolinos Marín and Díaz Ariño, 2012, pp.33-35; Antolinos Marín, Díaz Ariño and Guillén Riquelme, 2013, pp.95-97). So far, 29 lead ingots with different spellings are known from this societas, which are spread over five sites in the Western Mediterranean. In the following we are going to examine in more detail which ingots from this society the three inscribed tablets belong. According to current knowledge, the form of the 1st lead tablet only matches the 2nd cartouche form, which were used for the five ingots from the Coto Fortuna (Cabezo del Castillo) mine (Corpus of Roman lead ingots = CRLI 1932–1936), only one of which is preserved today in the Louvre Museum. The dimensions, shape and writing style of the middle cartouche in question match each other quite well, although there are slight differences which show that there is no exact match between the lead ingot and the cartouche. Of course, we only know part of the Societas' production output, so a direct allocation could be possible in case of new ingot finds. It should also be not-

Figure 4. Two fragmented lead tablets from the Mendip Hills (Somerset) with framed imperial inscriptions. Photos: N. Hanel.

ed that there is a short distance of around 8 km between the proven production center of Coto Fortuna and the area where the tablet was found, around 8 km further east. Therefore, several Societas production sites were assumed in what is now Mazarrón (Antolinos Marín and Díaz Ariño, 2012, p.33)

The 2nd lead tablet generally stands for the beginning of the cartouche inscription *Societ(atis)*: If this word alone was used for a cartridge, only the above-mentioned lead ingots from Coto Fortuna (Mazarrón) can be considered. On a closer inspection, however, an identical impression cannot be seen in this case either: For example, the letter O in the cartouche inscription on the lead ingot is larger than the O on the lead tablet.

The poor state of preservation of the third lead tablet, with only three letters, makes it difficult to associate it with the lead ingots.

In addition to the three tablets from the Roman mining region around Mazarrón in Hispania citerior, two lead tablets from the British mining area of the Mendip Hills (Somerset) were also discussed in the production of the cartouche inscriptions (Figures 4, a and b). Here, however, a direct connection with the casting of lead ingots was recently ruled out (Hanel, 2022, esp. p.424).

As suspected by various sources (Domergue, 2005a, p.188-189; Ramallo Asensio, 2006, p.69; Antolinos Marín and Díaz Ariño, 2012, p.32-33), the small lead tablets were obviously used to carry cartouches with inscriptions which should be placed on the tops of the ingots: the size, shape and style of writing undoubtedly tells of this. However, the letters on the tablets would have to be raised in order to create raised letters in the cartouches on the tops of the lead ingots by carving them into the clay mould. It must therefore remain unclear how the tablets ultimately fit into the work processes involved in the production of ingots.

The following section lists and critically examines previous considerations in the specialist literature that address questions about the material of the moulds and mention different materials.

Moulds made of a clay/loam/sand mixture

Most researchers have argued in favour of casting moulds made of clay/loam into which the liquid metal was poured and solidified into ingots. Ronald Frank Tylecote (1986, p.68, 88) made particularly detailed comments: „The pigs themselves have been cast in clay moulds, a wooden pattern being used to form the mould. The inscriptions were carved on panels attached to the wooden patterns so that they appear on the pig in relief (see, ibid. Fig. 21) The inscriptions were mainly confined to the smaller bottom surface (as cast) of the pig, and usually appear in a sunken panel, although in some cases the letters are not empanelled but are merely raised proud of the surface. Some pigs have inscriptions on the sides and ends which are merely stamped, or are in relief and not in panels.“ So far, however, no clay remains associated with ingot production have been discovered in the numerous known lead mines or smelting sites that were operated in Roman times.

Stone moulds

Just like clay moulds, no casting moulds made of stone have been found to date (Gowland, 1901, p.388; García Romero, 2002, p.680; Arboledas Martínez, 2010, p.108; Cordella, 1869/2016, p.116). Given the durability of the material, one would expect such a legacy in ancient mining regions. In particular, two finds from different Roman mining areas have dominated the discussion about stone casting moulds. These are a mould for gold ingots from Austria (Piccottini, 1994; Piccottini, Schroll, Spindler 2003) and a mould for small lead ingots from Spain (Sandars, 1905, pp.311-332). The possible production of small ingots or weaving weights made of lead in

a)

b)

Figure 5. Cuboid lead ingot of main type C from the shipwreck of Comacchio (prov. Ferrara), (a) with remnants of wood splints (arrows) from the wooden casting mould in the ingot surface, (b) traces of the wood grain and axe marks from processing of the wooden casting mould on the narrow side (width at the bottom 15 cm) of the ingot. Photos: N. Hanel.

various regions of the Roman Empire and Germania in stone moulds will not be discussed further, as only the recasting of large ingots was investigated experimentally and it differs from the casting of small ingots.

In 1993 two marble moulds for metal ingots were found in the Roman mountain settlement at Magdalensberg (Carinthia, Austria). They bear the remains of an inscription that identifies Emperor Caius Caesar (Caligula) as the owner. Based on adhering gold particles, Gernot Piccottini linked these moulds to the production of gold ingots from Noric mines (Piccottini, 1994, pp.467-477, Figs.1-4; Piccottini, Schroll and Spindler, 2003; Domergue, 2008, p.83, Figs.32 a-b). Recently, Alfred Pichler and Paul Gleirscher have expressed doubts that gold ingots were cast in the two moulds, due to the poor heat resistance of marble; instead, they assume that lead ingots were cast (e.g. Pichler and Gleirscher, 2011, p.60; Gleirscher, 2015, p.375). Heimo Dolenz immediately contradicted this interpretation with good reasons (Dolenz, 2015, p.385, Fig.5; also, Gostenčnik, 2016, pp.30-31, Fig.15 right).

Metal moulds

To date, there are no known examples of metal moulds (e.g. iron, copper alloy, etc.) for Roman lead ingot production. They are only rarely considered a possibility (Drescher, 1976, p.60).

Wooden moulds

Wood was also considered as a material for the ingot moulds.

The fact that wooden moulds were used to produce ingots, at least in rare cases, is undoubtedly proven by traces on a few lead ingots, particularly from the mining areas of the northern Aegean, which were found in the Comacchio (Prov. Ferrara, Italy) shipwreck near Ravenna (Domergue, 1987; Berti, 1990; Bode, Hanel and Rothenhöfer, 2021). Some ingots from the lead cargo provide concrete evidence for this assumption in form of splinters or negative wood impressions.

Small remnants of wood splinters were found on the tops and narrow sides of the ingots, where they stuck to the rough surface during casting and have been preserved to this day. Specifically, it is an ingot of type B 5: CRLI 91 and three ingots of type C 3: CRLI 133, 136, 137. The negative impact marks of an axe are particularly noticeable on the narrow sides of the ingot CRLI 137 (Figures 5, a and b).

Multiple use and filling of the moulds

In addition to the question of the material of the moulds, there is discussion as to whether the molten lead was introduced into the mould in the course of one or several casting processes.

While John Armstrong Smythe and Helmuth Schneider argue in favour of continuous casting without giving further reasons (Smythe, 1939/1940, p.139; Domergue 1966, p.70; Schneider, 1992, pp.80-81), George Clement Whittick (1961, pp.106-111) dealt more intensively with the casting of lead ingots. From his observations in a modern foundry, he came also to the conclusion that Roman lead ingots were made with an uninterrupted supply of lead and that no casting ladles were used.

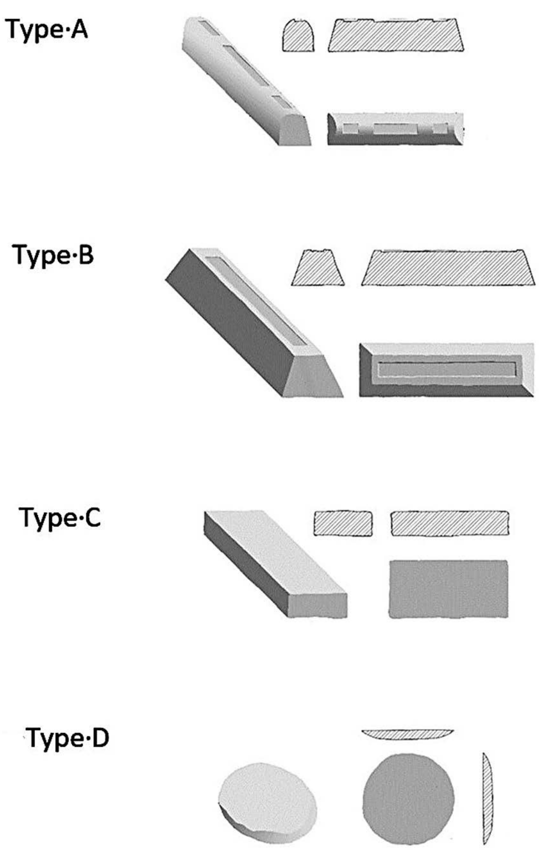


Figure 6. The main types A – D of Roman lead ingots. A: Semicylindrical ingots with rounded top side, B: truncated and elongated pyramidal ingots, C: cuboid in shape, D: plano-convex ingot (sometimes irregular). Graphic: G. Michel/N. Hanel.

Typology of Roman lead ingots

This article can only provide a general overview of the variety of lead ingots and their forms in Roman times. The period of interest spans from the late Republic (1st half of the 1st century BC) to late antiquity (5th century AD). During this long period of ingot utilisation, various forms of ingots were used as a means of transporting the heavy metal. These can be divided into four main types; a current typology was created as part of the work on the corpus of Roman lead ingots (CRLI 2024).

Main type A: elongated semi-cylindrical
Main type B: elongated truncated pyramid-shaped
Main type C: almost cuboidal
Main type D: roundish to oval, flat to spherical segmental.

These four main types can in turn be subdivided into different variants. For the archaeological experiments described below, ingots of the main types A and C were recast, because there are finds from these types in Westfalia (Figure 6). The names given to the sides of the ingots in the following are based on the designations already presented by Claude Domergue in 1991, using the example of the semi-cylindrical ingots (type A 1) (Colls, Domergue and Guerrero Ayuso, 1986, p.40 Fig.3 A; Bernard and Domergue, 1991, p.95, Fig.16A.), and which are adopted here with slight modifications (Figure 7).

1. Top of the ingot: if present, this is defined by the so-called primary epigraphic inscriptions. The primary epigraphic elements are inscriptions that had already been applied to the mould before casting; the letters or occasionally signs (symbols, ornaments) are

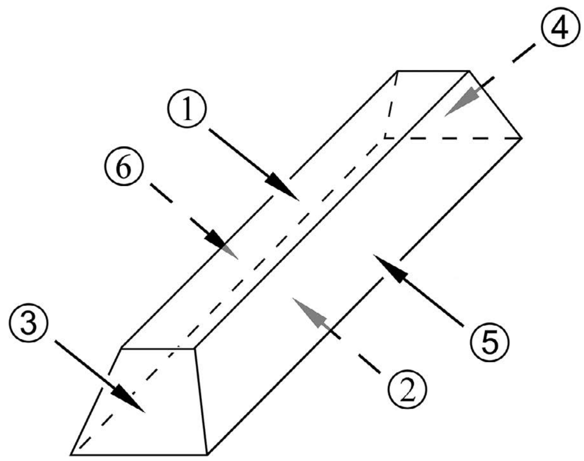


Figure 7. Names of the sides of Roman lead ingots (after casting). 1: top/face, 2: bottom, 3: left narrow side, 4: right narrow side, 5: front, 6: back. Graphic: G. Michel/N. Hanel.

raised. The side, facing upwards during casting, cannot have any primary epigraphic elements (Hanel, et al., 2013, p.215, Fig.4). If there are no primary inscriptions, the top is determined by the fact that it is the side corresponding to the bottom of the mould.
2. Underside of the ingot: this is located on the side of the ingot opposite the top. As this is the side the molten lead is poured on during the casting process, no primary inscriptions can appear on this side.
3. Left narrow side: this is defined by the reading direction of the primary inscriptions on the top side.
4. Right narrow side: this is defined by the reading direction of the primary inscriptions on the top side.
5. Front side: this is located below the top side and the side facing the reader of the inscription.
6. Back: this is opposite the front and below the top.

Problem and potential

Although our casting experiments were carried out without financial support and were therefore subject to certain limitations, we have shown what possibilities are conceivable for lead ingot casting. For these reasons, impurities and the temperature of the lead during casting were not documented in our tests and therefore cannot be included in the results.

We are aware that many casting variations were used in the countless Roman foundries, not all of which we were able to take into account in our experiments.

However, the experiments have shown us that we are on the right track with our basic idea and that we have been able to model basic ancient casting techniques. For the reasons mentioned, some questions must of course remain unanswered, which will have to be investigated in the future.

The casting experiments

As part of the Deutsche Forschungsgemeinschaft-project the Deutsches Archäologisches Institut, Kommission für Alte Geschichte und Epigraphik, Munich (Peter Rothenhöfer), the Deutsches Bergbau-Museum Bochum (Andreas Hauptmann, Michael Bode) and the Universität zu Köln, Archäologisches Institut, Archäologie der Römischen Provinzen (Norbert Hanel), a small team (Reinhard Köhne, Ingo Pfeffer, Alice Beele, Reinhard Köhne [†], Norbert Zeumer) was established to investigate, by way of casting experiments, the question of what materials were used in the production of lead ingots.

Experimental archaeology can contribute important insights into the course of ancient production processes (e.g. Timberlake, 2007). However, only by the close integration of scientific and archaeological-historical methods is it possible to achieve significant gains in knowledge.

In the period between 2010/11 and 2015 a total of four casting trials were carried out in order to investigate the production steps of Roman lead ingots. In the further course of the project the question of how many lead ingots can be obtained from one casting mould was also addressed.

Archaeological experiments to investigate the above questions have rarely been carried out to date, or only to limited extent. The first and, as far as we know, only attempt was observed by George Clement Whittick in the 1930s; however, the casting experiments were not published until well after the Second World War (Whittick, 1961, p.105, note 10). It should be noted that the casting in a large-scale lead producing plant were not carried out in a clay-sand mould but in a large cast-iron basin (Whittick, 1961, p.111). However, he did not deal with, or only briefly touched on, some aspects of the production of lead ingots that are discussed here: e.g. the question of moulds with cartouche inscriptions or the multiple use of ancient moulds. The following question played a major role in the experiments of the time: was the molten lead poured into the mould in one or several batches, and what conclusions can be drawn from the casting lines that were observed on Roman lead ingots as early as in the 18th century (e.g. Watson, 1782, pp.267-268; further literature in Whittick, 1961, p.105, notes 2-6). Experiments at the time showed that pouring the lead into the mould without interruption could also cause lines to form on the sides of the lead ingots (Whittick,

Figure 8. Pouring the liquid lead into the clay mould, using a metal four-pronged casting ladle. Photo: N. Hanel.

1961, p.108). However, this presupposes the provision of a large quantity of molten lead for the complete casting of an ingot. Nevertheless, such a supply has not yet been proven for the Roman period (see p. 36 below).

For the time being it remains unclear how liquid lead was filled into the moulds in ancient times, as no archaeological finds have been documented in this regard. With our experiments, a large metal vessel containing sufficient liquid lead was available, which was transported from the blast furnace to the casting area via an overhead crane; a four-pronged, long, rectangular cast ladle was used to transfer the clay into the moulds (Figure 8). Temperature analyses of the lead were not carried out during the experiments.

Essentially two casting processes are possible: casting in expendable or in permanent moulds. For lost mould casting, clay is the only possible moulding material. It can be assumed that respective local clay and sand deposits in the vicinity of the smelting site were utilised in Roman times.

Modern moulding sand can be mixed with various binders, such as oil or water. However, moulding sand mixed with oil was unknown in antiquity, and pure moulding sand contains too much residual water, so that a strong reaction with the liquid lead is to be expected (courtesy of Frank Willer, Bonn). On the other hand, moulds made of wood, fired clay, stone and iron could theoretically be used several times.

We therefore decided to use one wooden, several clay moulds and a ceramic mould for the casting experiments in permanent moulds. The results of the experiment series are presented below.

Models of lead ingots based on ancient models were needed to make the clay moulds, so a model was machine-made from beech wood. It measures 45 x 10 x 11 cm and thus corresponds to semi-cylindrical ingots that were used in the Roman Empire from the late Republican period and are known, for example, from ore districts in Spain (Domergue, 1990, p.253 (type I); Hanel, 2011, p.119; Rothenhöfer and Hanel, 2013, p.276, Fig.3). The ingot model with the inscription cartouche “PLVMBVM MMXI” was milled out of the solid wood (Figure 9).

Two moulds (Figure 10) made of unfired clay were available for the first experiment, thanks to Reinhard Köhne (†) and Dipl. Ing. Norbert Zeumer. Fine sandy to silty loess loam from the middle terrace of the river Ruhr near Meschede-Enste (Hochsauerlandkreis) was used for the mould, which was put into a wooden box. As the mould had to withstand a long transport, it was built very solidly. Historically It could have been smaller on site. No experiments were made with cleaning the clay. This would have required many trials with different

Figure 9. Wooden model for lead ingots with rounded face. The model was marked with the cartouche inscription PLVMBVM MMXI. Photo: R. Köhne.

Figure 10. Clay mould 2 with cartouche inscription: PLVMBVM MMXI. Photo: R. Köhne.

additives. As the clay stuck to the wooden model in the preliminary experiment, the models were rubbed with olive oil so that they could be removed without damaging the green mould. In metallurgy, the casting mould is referred to as a ‘green (unfired) sand mould’ in case of casting in a lost mould (Brunhuber, 1976, p.314). Minor damage to the rammed earth of the mould walls could be repaired with a brush and a thin mixture of loess clay and water after the models had been removed. After six weeks of drying in the covered outdoor area in late summer weather, the two moulds were cast with lead at a temperature of approximately 450° C, using a metal casting ladle with four pouring openings (Figure 11). The liquid raw lead required for this was provided from the smelting furnace of the Metallhütte Hoppecke GmbH & Co. KG. With a four-pronged ladle it was taken out of a large metal vessel and filled in several stages into the mould. As the mould clay still contained some water, the lead began to boil at the contact surfaces: ‘Boiling’ here refers to the contact reaction between the liquid lead and the water content in the clay mould, which is noticeable by the formation of bubbles from the evaporating water (Brunhuber, 1976, p.400). Because of the strong reaction with the water, it was necessary to wait a few minutes before pouring in the next layer, as otherwise, the contact reaction would have been too strong and too

Figure 11. Pouring the molten lead into the clay mould, using a four-pronged casting ladle. In the background there is the metal vessel for removing the lead. Photo: N. Hanel.

Figure 12. Finished lead casting into the clay mould - with bumps and small voids on the later underside of the ingot. Photo: I. Pfeffer.

much lead would have splashed out. The drop-shaped pieces of waste that solidified next to the mould have the typical shape of processing residues found in lead-processing workshops of Roman times (Duvauchelle, 1999, p.136, pp.141-142, cat. no.50-88; Pfeffer, 2012, pp.92-93, Fig.187).

The experiments showed that it is possible to cast ingots with and without inscription cartouches in air-dried clay moulds. However, due to the water content in the moulds, the liquid lead can only be poured in very slowly, as contact with the water content in the moulds makes the lead solidify. The surface of the finished ingots was very rough and cavities and unevenness were visible, especially on the underside (= top side during casting): various casting defects, such as blowholes, were detected. The term 'shrinkage cavity' is another technical term from metallurgy and casting technology and refers to cavities formed during the solidification of cast objects (Figure 12).

The individual casting layers were clearly recognisable, and the inscription was legible but poorly formed (Figures 13, a and b). The removal of the metal ingot was unproblematic, as the clay mould detached and disintegrated even at low pressure, leaving hardly any characteristic mould parts behind (Figures 14, a and b).

Figure 13. a. Top of the modern lead ingot with cartouche inscription. Traces of the cracked and repaired mould in the right half of the photograph; b. Front of the lead ingot with horizontal casting lines. Photos: N. Hanel.

For the second casting experiment, the moulds were dried in an oven. Loess clay from Meschede-Enste was used again. This time, however, the clay was cleaned of impurities by using a hand sieve with a mesh size of 4 mm. By adding 15 % water, a high binding activity could be achieved and the clay could be easily prepared

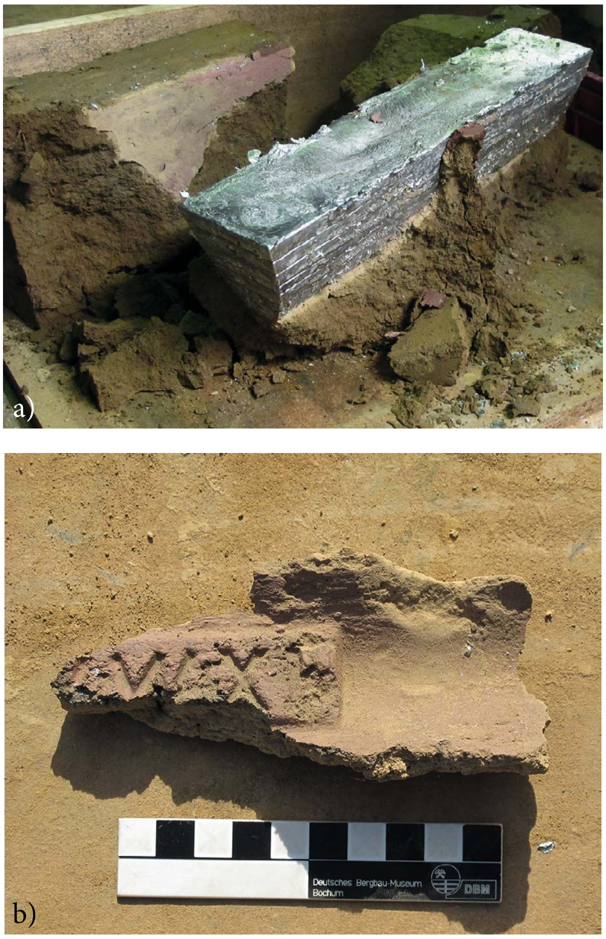


Figure 14. a. Removal of the cooled lead ingot from the clay mould; b. Rest of the cartouche inscription after the ingot casting. Photos: N. Hanel.

with a cement mixer. The laboratory measurement at the Honsel sand laboratory showed a water content of 14.2 %. A steel frame measuring 65 x 35 x 17 cm was filled with the finished moulding material, and the two ingot models already made for the first experiment were reused. Once again, we rubbed the models with olive oil to make them easier to remove, so that the negative print of the inscription retained a flawless typeface. The finished mould was sprayed with water to improve its transportability to the drying oven. Drying took place at 140° C. To prevent the mould from cracking during drying, the temperature was slowly increased until the desired 140° C was reached after three hours. The mould then remained in the oven at a constant temperature for a further three hours. Once the drying process was complete, the shrinkage cracks were smeared with loess clay while the mould was still warm.

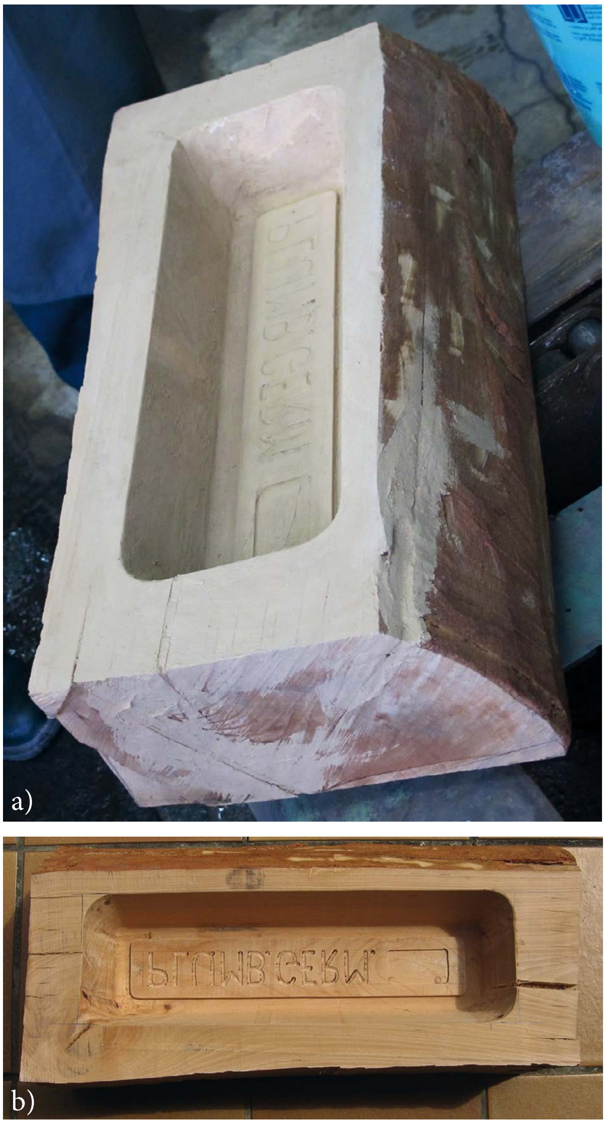
Two pieces of woven burlap were worked into the mould without the inscription cartouche during the stamping process in order to clarify how a fictitious repair to the mould would show on the final product. The linen remained in the mould during casting and was only lightly smoothed with a loess clay slurry (Figure 15).

The casting experiment went smoothly. The lead, heated to approximately 450° C, was poured into the preheated mould with a casting ladle. Despite drying in an oven, however, the lead boiled again and pouring could only be carried out slowly, however somewhat faster than during the first experiment. Numerous small casting residues also accumulated around the casting form. The double mould again disintegrated completely when the two ingots were removed. The surface of the lead ingots was somewhat smoother than those from the first casting experiment, but again it showed shrinkage cavities and was uneven. The inscription was legible but not clearly defined. The casting layers were again clearly recognisable. The fabric imprint was clearly visible on the area with the applied burlap (Figure 16), meaning that the fabric imprints on the original ingots most probably originated from repairs to the moulds (see below p. 36). The casting process took approximately one hour per ingot and was therefore only slightly faster than the first attempt.

Because Roman lead ingots with impressions of wood grain and even remains of splinters are known (see below p. 26), the third experiment was to be carried out in a reusable wooden mould. With this experiment, the cuboid ingots (type C) were used as a model (Figures 17, a and b). No Roman ingots cast in wooden moulds ever

Figure 15. Clay mould for double ingot casting. Scraps of tissue inserted into the upper ingot. Photo: R. Köhne.

Figure 16. Modern lead ingot with an impression of the tissue remains (top left) and casting lines. Photo: R. Köhne.



Figures 17. Wooden mould for the casting of a cuboid ingot (main type C) with a large cartouche inscription PLUMB. GERM. Photos: N. Hanel and R. Köhne.

Figure 18. Modern lead ingot with cartouche inscription from a wooden model. Photo: I. Pfeffer.

had a primary cartouche inscription, only secondary inscriptions as stamps, chisel inscriptions and graffiti. A beech log was used as the blank. As manual processing would have been too time-consuming, the hollow mould was milled out by machine. As the wood was fresh, it had to be sufficiently dried beforehand: this process was carried out at a professional drying plant.

Although the few Roman lead ingots with wooden impressions have not yet been found to have a cast (cartouche) inscription, an attempt was made to produce an inscription cartouche. However, the company carrying out the work was unable to mill the desired inscription "PLUMP-GERM" into the wooden block, so the mould maker produced the inscription separately in a 6 mm thick wooden panel and glued and nailed it into the mould. This process was not agreed with us, but it shows that it was certainly impossible to carve an inscription cartouche into a wooden mould even in antiquity.

To protect the wood, the mould was filled with a loess-loam slurry (a mixture of water and loess-loam). The thin slurry was air-dried. These are used to protect the mould surface and to improve the release of the cooled casting from the mould, as an insulating layer of gas forms during the casting process. During the casting experiment, as with the other experiments, the liquid lead was poured into the mould at a temperature of approximately 450° C, using a casting ladle with a capacity of approximately 7 kg. No oxide skin could form between the individual casting cycles, as the lead boiled very strongly and mixed with the layer below. After filling very slowly, a crack formed at the bottom of the mould, from which about a third of the lead dripped out during the solidification process. The wood smoked slightly after filling but did not start to burn. The solidification of the block began after approximately 12 minutes, and after a further 25 minutes the surface had solidified. To speed up the entire solidification process, the outer wall of the wooden mould was cooled with a fine water jet, and after approximately 45 minutes the ingot could be separated by tilting the mould. The ingot had a casting weight of 21.4 kg (Figure 18).

After removing the ingot, the inscribed cartouche had become detached and liquid lead had penetrated between the base mould and the inscription plate. Parts of the wooden title block were stuck to the ingot and had to be removed with a chisel. Another casting without a title block would have been possible after repairing the crack in the mould. The charring of the surface was only very slight and had a layer thickness of about 1 mm.

The experiment shows that multiple casting in wooden moulds is possible. However, the wooden mould must be very well dried during casting, as otherwise the lead reacts strongly with the water and a lot of lead splashes out. The surface of the finished ingot was very rough and showed blowholes and severe unevenness on the underside. The inscription was legible but poorly formed.

Figure 19. Modern ceramic casting mould of a lead ingot type A with inscription PLUMB GERM. Photo: R. Köhne.

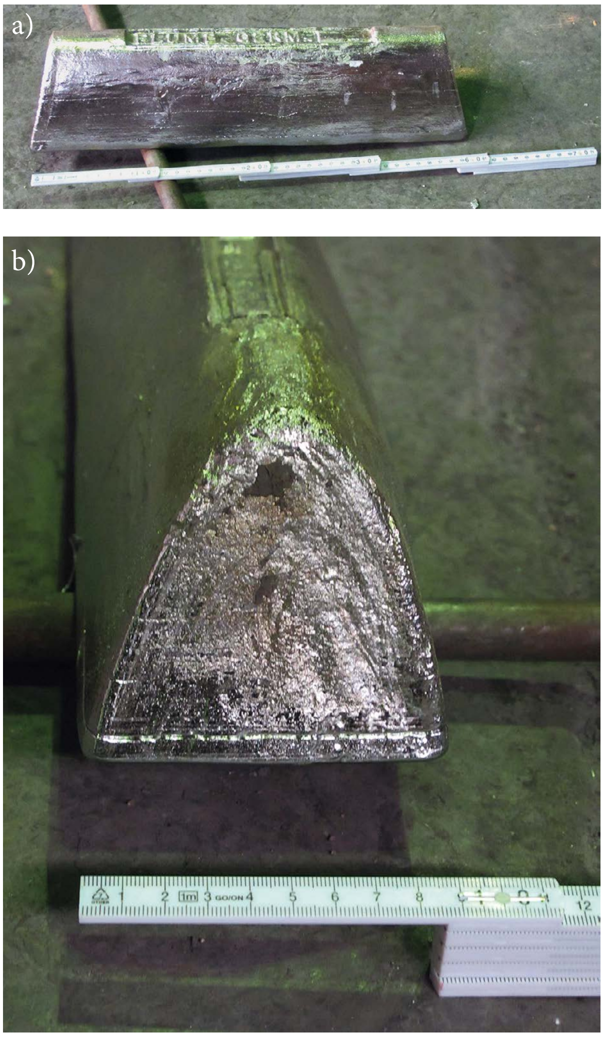


Figure 20. Modern lead ingots from the ceramic casting mould (a) with interrupted fillings, b. in the course of one casting process. Photos: N. Hanel.

There were no casting lines, due to the crack in the mould and the lead that had run out in places, as well as the heavy boiling. Overall, this casting attempt took the most time, around two hours, as wood insulates very well, so that the lead solidified only slowly and no casting lines could develop.

We had the opportunity to have a modern ceramic mould made for our experiments by the Klett pottery in Fredelsloh, City of Moringen (Landkreis Nordheim). The wooden model of a semi-cylindrical lead ingot (type A 1) served as a model for the clay mould. We chose the inscription "PLUMB GERM" for the mould (Figure 19). The mould was made of clay found near the pottery and tempered with 20 % quartz sand from the range of hills called Solling. This corresponds to the amount of temper used by the potter for vessels based on medieval models. A different firing temperature, as is known for medieval cast iron crucibles, could not be used in order not to jeopardise the firing of the other modern commercial ceramic vessels in the firing chamber (Zientek and Rehren, 2009, pp.179-180). After air-drying for a few days, the mould was fired in a replica of a medieval kiln. The firing temperature was approximately 1000 °C. The kiln journey – charging the kiln, bricking up the kiln, heating up the kiln, firing, cooling and opening the kiln chamber – took 15 days. During firing, fine cracks appeared on the narrow side of the mould, which widened in the course of the casting process. According to Mr Johannes Klett-Drechsel, the owner of a ceramics manufactory, the cracks in the mould were probably due to the mould having been air-dried for too short a period of time and could have been avoided with sufficient preparation time. The fine cracks in the clay mould next to the inscription and on the narrow side were smeared with clay paste in the foundry on the day of the casting experiment. The lead was then poured into the mould in several portions at a casting temperature of 400 to 420 °C, using a casting ladle. The filling could be done quickly in the course of one casting process, as there were no reactions with the mould. After 22 minutes, the ingot had solidified and was tipped out of the mould. Three ingots were cast in quick succession. There was no discernible change in the surface/shape of the ingots. After casting the third ingot, the cracks on the mould that had previously been smeared with clay paste were visible again. Despite these cracks, the ceramic mould could have been used for further castings.

The surface of the three freshly cast ingots was very smooth, with only a few blowholes and irregularities on the underside of the ingots. The first ingot was cast in several stages with pauses between each pour (similar to the manner used in the previous experiments), with pauses in between, and the casting lines were clearly visible on the final product (Figure 20, a). With the two subsequently cast ingots, the lead was poured in the course of one casting process, and the lines were only pronounced at the corners where the lead cooled fastest (Figure 20, b). Only the last casting layer was poured a little later, so that it appeared as a fine oxide line. The ingots were about 40.5 x 10.5 x 9.8 cm in size at the base and weighed about 28 kg, which corresponds approximately to a Roman ingot of this type.

Pouring into a ceramic mould was extremely simple: the lead did not boil in the mould and the molten lead could be poured in with the ladle without any waiting pauses in between. Depending on how quickly the ladle was refilled, the individual pouring lines were clearly visible, partially visible or not visible at all, and the ingots had a very smooth surface, so that pouring into the clay mould achieved the best result. The labelling was flawless and did not lose its quality even after the third casting.

Discussion of the results of the casting experiments on ingot casting in Roman times

The multiple casting experiments that we successfully carried out to produce lead ingots in reconstructed "Roman" moulds have yielded new findings, although some questions remain unanswered. The experiments and comparisons with Roman ingots have shown that the majority of Roman lead ingots were presumably produced in lost clay sand moulds. In rare cases, wood was also used; there is no evidence to date for metal, ceramic or stone moulds, and these findings are consistent with the observations from the CRLI project. In principle, however, the use of metal, ceramic or stone moulds cannot be ruled out, as casting in these moulds was also possible in antiquity. The fact that moulds were made of a mixture of clay and sand or of wood explains the lack of any traces of such moulds in the numerous known Roman mining regions. Moulds made of fired pottery are also conceivable; however, such remains, just like everyday pottery, have not been reported so far in the ancient mining regions.

a)

b)

Figure 21. Two Roman lead ingots from Wade Street, Bristol, with identical casting defects in the centre of the cartouche. Photos: CRLI.

Figure 22. Modern ingot with a shrinkage cavity on the underside. Photo: N. Hanel.

Lead ingots with identical casting defects prove that damage was already present on the wooden model and that this was transferred to the ingots via the clay sand mould. This is particularly noticeable with two pieces from Bristol, from the banks of the River Frome; the casting defect (Figures 21, a and b) is visible in the centre of the cartouche inscription (CIL VII 1210 (2 x); Gowland, 1901, p.399, Tab.58, 15, RIB II 1, 2404. 17-18; Tylecote, 1962, Tab.33, 18-19; Elkington, 1976, p.195; Tylecote, 1986, Tab.38, 18-19, CRLI 2455-2456).

In future experiments, the question of the number of lead mould casts from an ingot model should be investigated in more detail than was possible in our experiments.

Previous assumptions, which vary only slightly, assume up to five ingot casts from one clay mould. Claude Domergue assumed that nine to ten lead ingots could be cast from a stock of 275/300 kg of lead (Domergue, 1966, pp.70-72). However, our tests show that the air-dried clay-sand mould completely disintegrates after the first casting and only the ingot model, probably a wooden model, could be used several times, the defects of the model were transferred to the casting mould and passed on to the final product.

When using ceramic moulds, casting could be carried out in the course of one casting process; if casting lines still appear, this is for other reasons. In addition, the experiments made clear that the formation of casting lines depends solely on the speed at which the individual layers are poured. Due to the reaction with any water present in the mould, unfired clay moulds can generally only be filled slowly, which inevitably results in casting lines. However, when casting into the wooden mould, the lead boiled so much that no casting lines appeared.

The Roman lead ingots also exhibit defects that allow conclusions to be drawn about the labour processes involved in casting and are consistent with our casting experiments.

In our experiments, we observed shrinkage, particularly on the underside of the bars (Figure 22, also Figure 14, a). These elongated depressions are often found on the original ingots. However, so-called 'closed' blowholes inside the lead ingots (Brunhuber, 1976, p.158,

Figure 23. Roman lead ingot (a) from the northwest coast of Sardinia; (b) modernly divided with closed blowhole. Photos: N. Hanel.

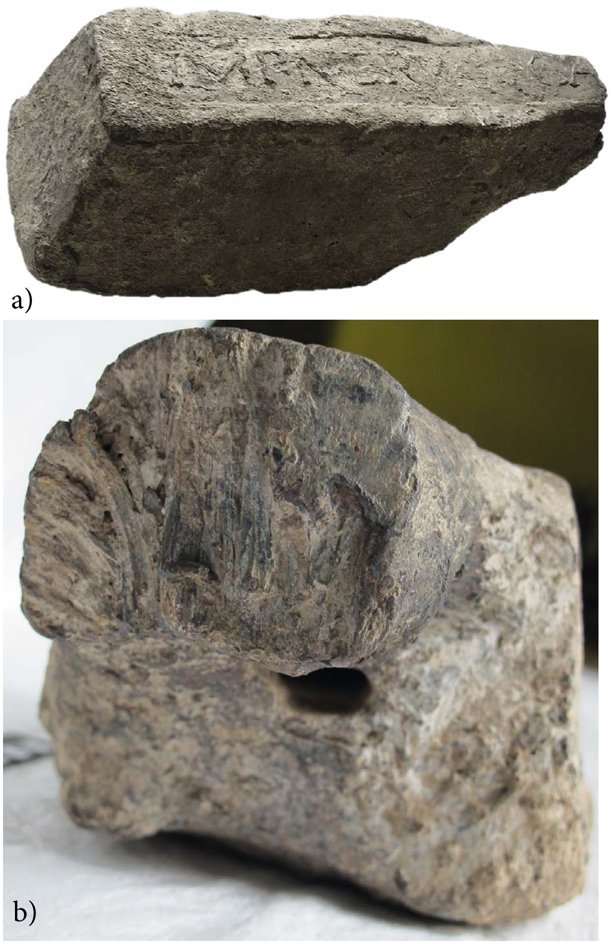


Figure 24. Roman lead ingot fragment (a) from Rutupiae/Richborough (Kent) with cartouche inscription of Emperor Nerva; (b) closed blowhole in the middle (width of the ingot at the bottom 15.7 cm). Photos: N. Hanel.

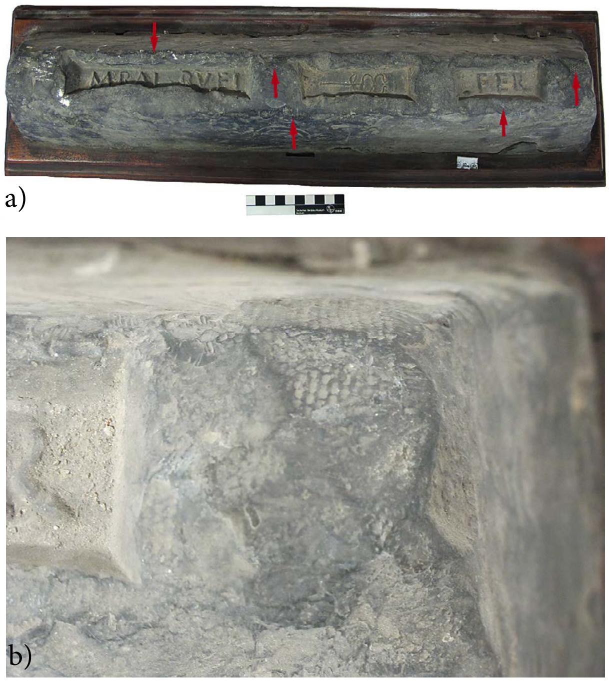


Figure 25. Roman lead ingot from Cartagena (a) by entrepreneur M. Raius Rufus with impressions of tissue (arrows), (b) detail with tissue impressions on the top right. Photos: CRLI; N. Hanel.

Figure 26. Tissue print on the top of a Severan lead ingot from Aléria (Corsica). Photo: M. Bode.

pp.473-475) are also occasionally found in Roman lead ingots. This is the case with the specimen of C. Utius (CRLI 1209), found in northwest Sardinia; modern cutting made the blowhole in the center of the ingot visible (Figures 23, a and b). Another example is the fragment of an ingot (CRLI 2420) with the cartouche inscription of Emperor Nerva, found in the Roman settlement of Rutupiae (Richborough, Kent) (Figures 24, a and b).

Our experiments also clarified why with some lead ingots (e.g. CRLI 1875, found in Cartagena, Murcia; CRLI 1216, found in Aleria, Corsica) there are clear material impressions on parts of the ingot surface (Figures 25, a and b; 26) (Weisgerber, et al., 2007, p.152, Fig.8). Apparently, moulds were patched with scraps of fabric and clay and, as our experiments showed, the fabric was imprinted on the billet. The remaining material, which was covered by a clay slurry, does not burn when the lead is poured, but rather seals the underlying crack in the mould and creates the material impression.

Apart from the reasons for casting defects mentioned above, other causes may have played a role in casting defects: e.g. the temperature of the raw lead or mould, the speed of pouring, defects in the mould (impurities etc.), contamination and gases in the raw lead.

In our opinion, there are three possibilities conceivable in ancient times:

1. Some researchers assume that lead was passed directly from the melting furnace, via a channel, into the ingot casting moulds in one go. However, this had the disadvantage that control of the casting material from the smelting furnaces was hardly possible or only with difficulty.
2. Another possibility is to provide liquid lead in large crucibles that have been heated for casting. The problem here is that a sufficient amount of liquid lead must have been available, especially for larger ingots. There must therefore have been large melting tanks from which the molten lead was scooped out with the help of crucibles or ladles and poured into the casting mould. So far, only relatively small crucibles are known from Roman finds; for a large crucible fragment in Augst the filling volume can be calculated to approximately 830 cm^3, i.e. 7.5 kg of non-ferrous metal. The procedure described here is very likely, as it explains the casting lines that could be detected in our experiments.

   To fill in the liquid lead, specially shaped crucible tongs were required – depending on the size of the crucible (Brunhuber, 1976, p.764, with Fig.; Levy, et al., 2008, p.76, Fig.50, with modern, oversized crucible tongs). Evidence of special crucible tongs in Roman times is e.g. known from Augst (Mutz, 1976, pp.28-30, Figs.23-23a). Indirect evidence of such tongs are impressions of the tong tips in the slagged outer layers (*lutum*) of crucibles for non-ferrous metal casting (Furger, 2018, pp.50-52, Fig.14). Possibly with larger crucibles, two pieces of green wood, could be used by two people at each end; trapping the crucible in the middle so replacing the tongs.
3. According to William Gowland, iron pouring ladles were used as filling tools. Accordingly, the lead would have been heated in such iron casting ladles until it became liquid and was then poured directly into the moulds without having to rely on crucibles. To date, such finds from Roman mines and smelting sites have not been made or published. Due to their value, one must assume that these tools were carefully looked after and loss was largely avoided.

Conclusions

Our casting experiments were able to clarify some open questions about the casting process, but others could only be partially answered. There are no significant differences between the lead ingots produced in our tests and the original Roman ingots. Our casting experiments have shown how Roman lead ingots could have been produced. It should also be borne in mind that in the various mines in the Roman Empire, in addition to different ingot shapes, the lead casters used different manufacturing processes; this applies in particular to the heavier lead ingots, which can weigh up to 300 kg (see above: CRLI). We had to use transportable moulds for the casting tests. In Roman mining operations, however, stationary and therefore more stable moulds may have been used. It remains to be hoped that our results can be substantiated by further casting experiments or that original remains of casting moulds will be found in the numerous Roman mining regions that shed light on the manufacturing technology of these lead ingots.

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Abbreviations

CIL = Corpus Inscriptionum Latinarum
CRLI = The Corpus of Roman Lead Ingots (P. Rothenhöfer, M. Bode, N. Hanel, in press)
RIB II 1 = The Roman Inscriptions of Britain

Sources

https://www.giessereilexikon.com/en

References

Agricola, G., 1556/1994. *De re metallica libri XII. Vom Berg- und Hüttenwesen*. Basel - Reprint München: Deutscher Taschenbuch Verlag.

Anguilano, L., 2012. *The Roman lead silver smelting at Rio Tinto. The case study of Corta Lago.* Ph. D. University College London. [online] Available at: < https://discovery.ucl.ac.uk/id/eprint/1348305/ > [Accessed 8 September 2023].

Antolinos, J.A., 2003. La zone minière de Mazarrón. In: A. Orejas, ed. 2003. *Atlas historique des zones minères d'Europe II*. Luxembourg. pp.1, A-7 B.

Antolinos Marín, J.A. and Díaz Ariño, B., 2012. La societas argentifodinarum Ilucronensium y la explotación de las minas romanas de Carthago Noua. *Chiron*, 42, pp.25-43.

Antolinos Marín, J.A, Díaz Ariño, B. and Guillén Riquelme, C., 2013. Minería romana en Carthago Nova: el Coto Fortuna (Murcia) y los precintos de plomo de la Societas Argentifodinarum Ilucronensium. *Journal of Roman Archaeology*, 26, pp.88-121.

Arboledas Martínez, L., 2010. *Minería y metalurgia romana en el sur de la Península Ibérica. Sierra Morena oriental. BAR, International Series*, 2121. Oxford: Archaeopress.

Bachmann, H.G., 1977. Bleiglätte-Fund aus der Nordeifel. *Bonner Jahrbücher*, 177, pp.617-622.

Bernard, H., and Domergue, C., 1991. Les lingots de plomb de l'épave romaine Sud Perduto 2, (Bouches de Bonifacio, Corse*). Bulletin de la Société des Sciences Historique et Naturelles de la Corse*, 659, pp.41-95.

Berti, F. ed., 1990. *Fortuna maris. La nave romana di Comacchio*. Comacchio, Palazzo Bellini, 28 aprile - 31 dicembre 1990. Bologna: Nuova Alfa Ed.

Bigagli, C., 2002. Il commercio del piombo ispanico lungo le rotte attestate nel bacino occidentale del Mediterraneo. *Empúries*, 53, pp.155-194.

Blázquez, J.M., 1978. *Historia económica de la Hispania Romana*. Madrid: Ed. Cristiandad.

Bode, M., 2006. Neues aus dem Alte Rom mit Hilfe der Archäometallurgie. In: R. Köhne, W. Reininghaus and Th. Stöllner, eds. 2006. *Bergbau im Sauerland. Westfälischer Bergbau in der Römerzeit und im Frühmittelalter. Schriften der Historischen Kommission für Westfalen,* 20. Münster: Verlag des Westfälischen Heimatbundes. pp.32-44.

Bode, M., Hanel, N. and Rothenhöfer, P. 2021. Roman lead ingots from Macedonia – The Augustan shipwreck of Comacchio (prov. Ferrara, Italy) and the reinterpretation of its lead ingots' provenance deduced from lead isotope analysis. *Archaeological and Anthropological Sciences*, 13(163), pp.1-13.

Brown, H.G., 2011. *A Study of Lead Ingot Cargoes from Ancient Mediterranean Shipwrecks*. Master Thesis 2011, Texas A&M University. [online] Available at: < https://www.academia.edu/1017259/A_Study_of_Lead_Ingot_Cargoes_from_Ancient_Mediterranean_Shipwrecks > [Accessed 9 April 2017].

Brunhuber, E. ed. 1976. *Gießerei-Lexikon*. Berlin: Schiele & Schön.

Elkington, H.D.H., 1976. The Mendip Lead Industry. In: K. Branigan and P.J. Fowler, eds. 1976. *The Roman West Country. Classical Culture and Celtic Society.* Newton Abbot, London, Vancouver: David & Charles. pp.183-197.

Colls, D., Domergue, C. and Guerrero Ayuso, V., 1986. Les lingots de plomb de l'épave romaine Cabrera 5 (Île de Cabrera, Baléares). *Archaeonautica*, 6, pp.31-80.

Cordella, A., 1869/2016. *Le Laurium.* Marseille: Cayer. Reprint Delhi: Facsimile Publishers.

Davies, O., 1935/1979. *Roman Mines in Europe*. Oxford/New York: Oxford University Press/Arno Press.

Dolenz, H., 2015. Die Goldbarrengießerei in der Stadt auf dem Magdalensberg – Einblicke in einen kaiserlich römischen Hightec-Betrieb. In: Th. Stöllner and K. Oeggl, eds. 2015. *Bergauf Bergab. 10000 Jahre Bergbau in den Ostalpen. Wissenschaftlicher Beiband Ausstellung Bochum 2015–2016, Bregenz 2016. Veröffentlichungen aus dem Deutschen Bergbau-Museum Bochum*, 207. Bochum: Deutsches Bergbau-Museum Bochum, Rahden/Westfalen: Verlag Marie Leidorf. pp.383-388.

Domergue, C., 1966. Les lingots de plomb romaines du Musée Archéologique de Carthagène et du Musée Naval de Madrid. *Archivo Español de Arqueología*, 39, pp.41-72.

Domergue, C., 1987. Les lingots de plomb de l'épave romaine de Valle Ponti (Comacchio). *Epigraphica*, 49, pp.109-175.

Domergue, C., 1990. *Les mines de la Péninsule Ibérique dans l'antiquité romaine*. Collection l'École française de Rome, no. 127. Paris - Rome: Boccard, L'Erma di Bretschneider.

Domergue, C., 1998. A view of Baetica's external commerce in the 1st c. A.D. based on its trade in metals. In: S. Keay, ed. 1998. *The Archaeology of Early Roman Baetica. Journal of*

Roman Archaeology Supplement Serie, 29. Portsmouth/ Rhode Island: Roman Society. pp.201-215.

Domergue, C., 2005a. Matriz para sellar cartella en lingote de plomo. In: *Bocamina: Patrimonio minero de la Región de Murcia*. Exhibition catalogue Murcia 2005. Murcia: Biovisual. p.188, no.66.

Domergue, C., 2005b. Matriz para sellar cartella en lingote de plomo. In: *Bocamina: Patrimonio minero de la Región de Murcia.* Exhibition catalogue Murcia 2005. Murcia: Biovisual. pp.188-189, no.67.

Domergue, C., 2008. *Les Mines Antiques. La production des métaux aux époques grecque et romaine*. Paris: Éditions A. et J. Picard.

Domergue, C., and Rico, Ch., 2014. Les itinéraires du commerce du cuivre et du plomb hispaniques à l'époque romaine dans le monde méditerranéen. In: *La Corse et le monde méditerranéen des origines au moyen-âge: Échanges et Circuits Commerciaux. Actes coll. Bastia 21.-22.11.2013. Bulletin de la Société des Sciences Historiques et naturelles de la Corse,* 746-747. Bastia: Société des Sciences Historiques & Naturelles de la Corse. pp.35-168.

Domergue, C., Quarati, P., Nesta, A. and Trincherini, P.R., 2012. Retour sur les lingots de plomb de Comacchio (Ferrara, Italie) en passant par l'archéométrie et l'épigraphie. In: A. Orejas and Ch. Rico, eds. 2012. *Minería y Metalurgia Antiguas. Visiones y revisiones, Homenaje a Claude Domergue. Collection de la Casa de Velázquez,* 128. Madrid: Casa de Velázquez, pp.81-103.

Drescher, H., 1976. *Reallexikon der Germanischen Altertumskunde*[2] 2, pp.60-70, s. v. Barren.

Dubois, Ch., 1901. Inscriptions latines d'Espagne. *Bulletin Hispanique* 3(3), pp.209-225.

Duvauchelle, A., 1999. Un atelier de métallurgie du plomb du Bas-Empire à Avenches/En Selley, investigations 1997. *Bulletin de l'Association Pro Aventico,* 41, pp.133-146.

Eiseman C.J. and Ridgway, B.S., 1987. *The Porticello Shipwreck: A Mediterranean Merchant Vessel of 415-385 BC*. College Station: Texas A&M University Press.

Furger, A.F., 2018. *Antike Schmelztiegel. Archäologie und Archäometrie der Funde aus Augusta Raurica. Beiträge zur Technologiegeschichte*, 1. Basel, Frankfurt a. Main: Librum Publishers & Editors.

Gale, N.H. and Stos-Gale, Z.A., 2000. Lead isotope analyses applied to provenance studies. In: E. Ciliberto and G. Spoto, eds. 2000. *Modern analytical methods in art and Archaeology*. *Chemical Analysis,* 155. New York: John Wiley & Sons. pp.503-584.

García Romero, J., 2002. *El papel de minería y metallurgia en Córdoba*. Ph. D. Universidad de Córdoba 2000. [online] Available at: < https://helvia.uco.es/bitstream/handle/10396/244/13078938.pdf?sequence=1&isAllowed=y > [Accessed 8 December 2023].

García-Bellido, M.P., 1997. Lingotto con bollo del produttore-proprietario. In: J. Arce, S. Ensoli and E. La Rocca, eds. 1997. *Hispania Romana. Da tierra di conquista a provincia dell'Impero.* Roma, Palazzo delle Esposizioni, 22 settembre - 23 novembre 1997. Mailand: Electa. p.348.

Gleirscher, P., 2015. Keltisch-römischer Edelmetallbergbau in den Hohen Tauern? In: Th. Stöllner and K. Oeggl, eds. 2015. *Bergauf Bergab. 10000 Jahre Bergbau in den Ostalpen. Wissenschaftlicher Beiband Ausstellung Bochum 2015–2016, Bregenz 2016. Veröffentlichungen aus dem Deutschen Bergbau-Museum Bochum*, 207. Rahden/ Westfalen: Verlag Marie Leidorf. pp.373-376.

Gostenčnik, K., 2016. Eisen - Bronze - Gold. Zum Metallhandwerk in der römischen Stadt „Alt-Virunum" auf dem Magdalensberg. *Carinthia,* I(206), pp.11-35.

Gowland, W., 1901. The Early Metallurgy of Silver and Lead. *Archaeologia*, 57, pp.359-422.

Hanel, N., 2011. Auf der Spur des Bleis. Das Corpus römischer Bleibarren (CMPR). *Kölner und Bonner Archaeologica*, 1, pp.119-123.

Hanel, N., 2022. Bleitafeln aus Charterhouse-on-Mendip (Somerset/GB) mit Inschriften aus der Samtherrschaft der Kaiser Marcus Aurelius und Lucius Verus – Neubewertung und Neudatierung. *Archäologisches Korrespondenzblatt*, 52, pp.421-427.

Hanel, N., Pfeffer, I., Köhne, R. and Zeumer, N., 2013. Zur Herstellung römischer Bleibarren: ihr Nachguss im archäologischen Experiment. In: *Archäologie in Westfalen-Lippe 2012*, pp.213-216.

Hauptmann, A., 2007. Alten Berg- und Hüttenleuten auf die Finger geschaut: Zur Entschlüsselung berg- und hüttenmännischer Techniken. In: G.A. Wagner, ed. 2007. *Einführung in die Archäometrie*. Berlin: Springer Verlag. pp.117-137.

Hauptmann, A., 2008. Vom Erz zum Metall - naturwissenschaftliche Untersuchungen innerhalb der Metallurgiekette. In: A. Hauptmann and V. Pingel, eds. 2008. *Archäometrie. Methoden und Anwendungsbeispiele naturwissenschaftlicher Verfahren in der Archäologie. Veröffentlichungen aus dem Deutschen Bergbau-Museum Bochum*, 56. Stuttgart: Schweizerbart. pp.125-140.

Hauptmann, A., 2020. *Archaeometallurgy – Materials Science Aspects*. Cham: Springer Nature.

Köhne, R., 2010. Römisch-germanische Bleiwirtschaft in Westfalen. In: Geographische Kommission für Westfalen, ed. 2010. *Westfalen regional*, 2. Münster. S.126-127.

Levy, Th.E., Levy, A.M, Radhakrishna Sthapathy, D., Srikanda Sthapathy, D. and Swaminatha Sthapathy, D., 2008. *Masters of Fire. Hereditary Bronze Casters of South India. Veröffentlichungen aus dem Deutschen Bergbau-Museum Bochum*, 162. Bochum: Deutschen Bergbau-Museum Bochum.

Meier, St.W., 1995. *Blei in der Antike. Bergbau, Verhüttung, Fernhandel*. Ph. D. Universität Zürich. Zug: BS Building Services AG Landis & Gyr.

Mühlethaler, B., 1978. *Reallexikon der Germanischen Altertumskunde*[2]*. Band 3.* Berlin, pp.72-75, s. v. Blei.

Mutz, A., 1976. *Römisches Schmiedehandwerk*. *Augster Museumshefte*, 1. Augst: Römermuseum.

Palmer, L.S. and Ashworth, H.W.W., 1958. Four Roman Pigs of Lead from the Mendips. *Proceedings Somersetshire Archaeological and Natural History*, 101, pp.52-88.

Pfeffer, I., 2012. *Das Blei der Germanen - Die Besiedlung der älteren römischen Kaiserzeit in Soest. Soester Beiträge zur*

Archäologie, 12. Soest: Westfälische Verlagsbuchhandlung Mocker & Jahn.

Piccottini, G., 1994. Gold und Kristall am Magdalensberg. *Germania*, 72, pp.467-477.

Piccottini, G., Schroll, E. and Spindler, P., 2003. Ein römerzeitlicher Bleibarren vom Magdalensberg. *Rudolfinum - Jahrbuch des Landesmuseums für Kärnten 2002*, pp.153-161.

Pichler, A., and Gleirscher, P., 2011. Zum Goldreichtum der »norischen Taurisker«. Lagerstätten versus antike Quellen. *Archäologisches Korrespondenzblatt*, 41, pp.51-63.

Projektgruppe Plinius, eds., 1989. *Plinius der Ältere über Blei und Zinn. Naturalis Historia 34,156-178 und 33, 94 und 106-108.* Werkhefte der Universität Tübingen, Reihe A, Naturwissenschaften, 10. Tübingen: Attempto Verlag.

Ramallo Asensio, S.F., 2006. Mazarrón en el contexto de la romanización del sureste de la Península Ibérica. In: J.M. López Ballesta, ed. 2006. *Carlantum. Jornadas del Estudio sobre Mazarrón. Actas III Jornadas*. Mazarrón: Gráficas Álamo, S.L. pp.11-164.

Rebiscoul, A., 2004. Solaize. Rues du Pilon et du Repos, Clos des Eparviers. In: Direction Regionale des Affaires Culturelles Rôhne-Alpes, ed. 2002. *Bilan Scientifique de la Région Rhône-Alpes 2002*. pp.185-188.

Rico, Ch. and Domergue, C., 2016. El comercio de los metales en el Mediterráneo occidental en la época romana a través de los hallazgos subacuático. Estado actual de la investigación. In: *Actas del V° Congreso Internacional de Arqueología Subacuática (IKUWA 5), Cartagena 2014*. Cartagena: Ministerio de Educación, Cultura y Deporte. pp.590-609.

Rothenhöfer, P., 2004. Das Blei der Germanen. Bemerkungen zu einer neuen Fundgattung und zur Aufnahme der Bleiproduktion durch Germanen während der älteren Kaiserzeit in Westfalen. *Archäologisches Korrespondenzblatt*, 34, pp.423-434.

Rothenhöfer, P., 2007. Iam et plumbum excoquere docuimus? – Zum Phänomen der germanischen Bleiproduktion im nördlichen Sauerland während der römischen Kaiserzeit. In: W. Melzer and T. Capelle, eds. 2007. *Bleibergbau und Bleiverarbeitung während der römischen Kaiserzeit im rechtsrheinischen Barbaricum. Soester Beiträge zur Archäologie*, 8. Soest: Westfälische Verlagsbuchhandlung Mocker & Jahn. pp.47-55.

Rothenhöfer, P., and Hanel, N., 2013. The Romans and Their Lead - Tracing Innovations in the Production, Distribution, and Secondary Processing of an Ancient Metal. In: St. Burmeister, S. Hansen, M. Kunst and N. Müller-Scheeßel, eds. 2013. *Metal Matters. Innovative Technologies and Social Change in Prehistory and Antiquity. Forschungscluster 2, Innovationen: technisch, sozial. Menschen - Kulturen - Traditionen*, 12. Rahden/Westfalen: Verlag Marie Leidorf. pp.273-282.

Sandars, H., 1905. The Linares bas-reliefs and roman mining operations in Baetica. *Archaelogia*, 59, pp.311-332.

Schneider, G., and Zimmer, G., 1984. Technische Keramik aus antiken Bronzegußwerkstätten in Olympia und Athen. *Berliner Beiträge zur Archäometrie*, 9, pp.17-60.

Schneider, H., 1992. *Einführung in die antike Technikgeschichte.* Darmstadt: Wissenschaftliche Buchgesellschaft.

Smythe, J.A., 1939-1940. Roman Pigs of Lead from Brough. *Transactions of the Newcomen Society*, 29, p.139-145.

Stöllner, Th., 2003. Mining and Economy - A Discussion of Spatial Organisations and Structures of Early Raw Material Exploitation. In: Th. Stöllner, G. Körlin, G. Steffens and J. Cierny, eds. 2003. *Man and Mining. Studies in honour of Gerd Weisgerber. Der Anschnitt, Beiheft*, 16. Bochum: Deutsches Bergbau-Museum Bochum. pp.415-446.

Stöllner, Th., 2014. Methods of Mining Archaeology (Montanarchäologie). In: B.W. Roberts and Ch.P. Thornton, eds. 2014. *Archaeometallurgy in Global Perspective. Methods and Syntheses*. New York: Springer. pp.133-159.

Timberlake, S., 2007. The use of experimental archaeology/archaeometallurgy for the understanding and reconstruction of Early Bronze age mining and smelting technologies. In: S. La Niece, D. Hook and P. Craddock, eds. 2007. *Metals and Mines. Studies in Archaeometallurgy. Selected papers from the conference Metallurgy: A Touchstone for Cross-cultural Interaction, held at the British Museum 28-30 April 2005 to celebrate the career of Paul Craddock during his 40 years at the British Museum*. London: Archetype Publications Ltd. pp.27-36.

Tsuna, M., 1983. *Kodō zuroku. Illustrated Book on the Smelting of Copper*: *ca. 1801*. Norwalk [Conn.]: Burndy Library.

Tylecote, R.F., 1962. *Metallurgy in Archaeology. A Prehistory of Metallurgy in the British Isles*. London: Edward Arnold publishers Ltd.

Tylecote, R.F., 1979. *A history of metallurgy*[2]. London: Metals Soc.

Tylecote, R.F., 1986. *The Prehistory of Metallurgy in the British Isles*. London: The Institute of Metals.

Tylecote, R.F., 1987. *The early history of metallurgy in Europe*. London, New York: Longman.

von Petrikovits, H., 1956. Neue Forschungen zur römerzeitlichen Besiedlung der Nordeifel. *Germania*, 34, pp.99-125.

Watson, R., 1782. *Chemical Essays, volume III*. Cambridge: J. Archdeacon printer.

Weisgerber, G., Craddock, P.T., Meeks, N., Baumer, U. and Koller, J., 2007. Roman brass and lead ingots from the western Mediterranean. In: S. La Niece, D. Hook and P. Craddock, eds. 2007. *Metals and Mines. Studies in Archaeometallurgy. Selected papers from the conference Metallurgy: A Touchstone for Cross-cultural Interaction, held at the British Museum 28-30 April 2005 to celebrate the career of Paul Craddock during his 40 years at the British Museum*. London: Archetype Publications Ltd. pp.148-158.

Whittick, G.C., 1961. The Casting Technique of Romano-British Lead Ingots. *Journal Roman Studies*, 51, pp.105-111.

Zeiler, M., and Baales, M., 2021. Sauerländer Blei für Rom. In: J. Ricken, ed. 2021. *Archäologie in Soest und anderswo. Festschrift für Walter Melzer. Soester Beiträge zur Archäologie*, 17. Soest: Westfälische Verlagsbuchhandlung Mocker & Jahn. pp.69-81.

Zientek, C. and Rehren, T., 2009. Analyse ausgewählter Schmelztiegel und Schlacken. In: D. Lammers, ed. 2009, *Das karolingisch-ottonische Buntmetallhandwerker-Quartier auf dem Plettenberg in Soest. Soester Beiträge zur Archäologie*, 10. Soest: Westfälische Verlagsbuchhandlung Mocker & Jahn. pp.179-180.

Authors

Norbert Hanel (Corresponding author)
Ruhr-Universität Bochum
Institut für Archäologische Wissenschaften
Am Bergbaumuseum 31
44791 Bochum, Germany
Tel.: 0049/(0)234/32-25217
Norbert.Hanel@rub.de

Ingo Pfeffer
LWL-Archäologie für Westfalen
Außenstelle Münster
An den Speichern 7
48157 Münster, Germany
Tel.: 0251 591-8912
ingo.pfeffer@lwl.org