Evidence of Circular Economy in Roman Northern Italy: Bronze Casting Technology

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Received date 12 Oct 2016; Revised date 18 Nov 2016; Accepted date 19 Dec 2016

Abstract

In several recent excavations carried out in Northern Italy, archaeologists have encountered the remains of metalworkers' workshops where, in the Roman imperial period, large bronze objects were cast. The significance of these finds is considerable as, although the high levels of craftsmanship achieved by Roman bronze workers in the region are undisputed, little is still known regarding the layout of the workshops and the technologies used.

The present research, still in its early stage, deals with the metalworking evidence from two bronze working sites located in Vimercate (Milan) and Verona, where remarkably well-preserved evidence was found, for instance, large casting pits, moulds and metalworking debris.

A thorough review of the archaeological stratigraphy was carried out, in order to trace back the working processes and, where possible, the structure of the workshops. Moreover, archaeometric analyses were performed on both refractories and metal residues, aiming at reconstructing technological aspects. Analyses of slags, in particular, are meaningful because they help to retrace technical choices and patterns.

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KEYWORDS: archaeology, Roman, bronze, copper, tin, lead, silver, recycling, refining, casting, workshops, economy

INTRODUCTION

In recent excavations carried out in Northern Italy, archaeologists have encountered the remains of metalworkers workshops where, during the Roman imperial age (1st-3rd century AD), various copper-based objects were cast. The significance of these finds is considerable as, although the high levels of craftsmanship achieved by Roman bronze workers in the region are undisputed, little is still known regarding the layout of the workshops and the technologies used.

The present research, still in its early stage, deals with the metalworking evidence coming from two bronze working sites located in Vimercate (Milan) and Verona, where remarkably well-preserved evidence have been found, for instance, large casting pits and moulds for the production of bronze objects, for which only a few parallels are known so far (1)(2). A review of the archaeological stratigraphy was carried out, in order to trace back the working processes and, where possible, the structure of the workshops. Moreover, archaeometric analyses were performed on both refractories and metal residues, aiming at reconstructing technological aspects.

MATERIALS AND METHODS

In Vimercate, a small town some 20 kms east of Milan, archaeologists have discovered, alongside a late-roman necropolis and the remains of a graveled road, part of a

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metalworking workshop, devoted to copper and copper alloys, which had been in use for at least 70 years (3).

In the first half of the 3rd century AD (*period 1*) the layout of the workshop was very essential: the working spaces were defined by fences and wooden partitions; the main productive structure encountered was a large casting pit, almost 2 meters wide, found backfilled with metalworking debris. Further away from the proper workshop were located other utilitarian facilities, such as a well and a cistern, silos for storing raw materials and other pits of unknown function. The width of the area and the large size of the casting pit suggest a large-scale production. Bronze working evidence such as bronze spillages and fragments of furnace walls and tuyeres have been found in the area (Fig. 1).

Later on (late 3rd-early 4th century AD: *period 2*), the workshop was completely reshaped: the casting pit was disused, and the wooden partitions replaced by cobblestone walls. Copper alloys continued to be dealt with in the new working space, smaller than the previous one: its focus was the furnace, the remains of which were found in the excavations. In the open area east of the workshop a new, smaller casting pit was identified (Fig. 2).

Amongst the metalworking-related finds belonging to both phases there are furnace wall- and tuyère fragments, crucible slags, bronze spillages and one fragment of a casting mould, too small to allow any hypothesis as to the objects made (Tab. 1).

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A further recent archaeological excavation, carried out in Verona in 2013-2014, discovered an extensive metalworking site. The archaeological remains were discontinuous, because the area is in the cellar of a 17th century building, crossed by several partitioning walls. A stretch of the Late-Republican walls was found in the main room: adjoining them was a large workshop, with several structural remains and scattered metalworking debris.

It became immediately clear that the workshop, dating to the early Imperial period, was devoted to copper alloys' working: once again, the area was characterised by several large metalworking hearths, at least one casting pit (160x120cm, 140 cm in depth) with scorched walls and bottoms, and treading layers rich in charcoal and scorched clay. The structures concentrated in two areas: twelve hearths, arranged in neat rows, occupied the main room of the cellar (*area C*) (Fig. 3), and a few more, roughly of the same size and shape, were clustered a few meters away (*area A*).

Here as well, the interpretative hypothesis is that this was a large-scale bronze casting workshop.

Several samples of metalworking slags and refractory ceramics have been analysed in order to proof/disproof such hypothesis and to have an insight in the technologies involved (Tab. 2).

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Several archaeometrical analyses were performed on ceramics, slags and metal samples from the two study areas. The initial hypothesis was that the workshops were devoted to the casting of large bronzes, yet the analyses unveiled more complex situations.

Nineteen samples (12 from Vimercate and 7 from Verona) have undergone chemical and mineralogical analyses using X-Ray Diffraction (XRD), X-Ray Fluorescence (XRF) and Scanning Electron Microscope with Energy Dispersive Spectrometer (SEM-EDS).

Two small fractions of the samples were cut for the observation using the above-mentioned techniques. The tuyeres and wall fragments were sectioned, allowing the glazed surface to be saved for SEM observations while the section without vetrification was used for X-ray analyses. The choice was made to recognize the original clay material by using XRD, and assess the ore/metals reaction with the ceramic glazed surface by SEM.

The slag samples were cut and prepared for the two techniques with no distinction between the fragments. The metals were prepared only for SEM analysis.

The samples for XRD and XRF were pulverised by using a Laarmann LMLW 320/2 stainless steel mill until they reached a talc-like texture. The samples for the SEM were mounted in Epoxy resin and then polished using silicon carbide papers until the 2500 mesh and consequently using 6, 1 and ¼ microns diamond paste to obtain a mirror-like surface. They were then carbon coated for electron microscopy observation.

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The XRD used is a Bruker D8 advanced equipped with copper tube and Lynxeye position sensitive detector. The samples were scanned between 5 and 100 2theta with an increment of 0.02 degrees step and a speed of 0.1 seconds per step.

The XRF used is an Oxford Instrument 2000 with ISIS system equipped with silver X-ray tube operating at a tube voltage of 25kV, a collimating aperture of 4.5mm, and a deadtime of 45%. The XRF was only used for qualitative bulk analysis in order to ascertain the similarities between samples at trace elements level.

The Scanning Electron Microscope used is a Zeiss Supra V35 Field Emission Gun SEM equipped with Octane Super EDAX energy dispersive spectrometer with increased sensitivity for light elements.

RESULTS AND DISCUSSION

A. Vimercate

The ceramic samples belong to different kind of artefacts.

#72 is a coarse, heavily vitrified ceramic of unclear function: it might be a fragment of furnace wall, or, less likely, of a crucible.

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#217 is part of a mould: it is made of fine-grained ceramic, light orange in colour, with a greyish internal surface. Unfortunately, it retains no recognisable shape.

#234 and **#248** are fragments of large tubular elements, made of coarse ceramic highly vitrified on one end, with traces of oxidised metal, which were probably tuyeres.

#240 is part of a furnace wall, with a coarse matrix, vitrified on one side.

The ceramic compositions are extremely consistent: all samples have a high silica – high iron – low (hardly any) calcium content. The XRD analysis revealed the constant presence of quartz, minerals of the mica group such as muscovite and partially de-hydrated glauconite, and calcium and aluminium silicate such as albite.

This is consistent with the composition of local ceramics, as the available raw materials are indeed iron-rich clays, micaceous and poor in calcium. The high percentage of quartz, on the other hand, is most likely intentional: a technological choice purposely made in order to achieve a suitable, highly refractory material. It is worth noticing that there are no significant differences in composition between samples belonging to the two different phases of the workshop's life, meaning that the technological knowledge involved remained the same.

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Several metal residues were also analysed, in particular, the metal droplets and residues trapped in the vitrified phase of furnace walls and tuyere fragments, and a metallic object of unclear nature.

The metal samples revealed some unexpected features. Namely, none of them contained proper bronze: the metal remains are, in fact, mostly pure copper, iron-rich copper, or leaded copper, sometimes with traces of other metals. When tin was detected, it was always in the form of non-alloyed tin oxide crystals.

In detail:

#234 and **248** are both fragments of tuyeres, their ceramic fraction is explained above. Their metallic fractions present very similar features, both from the macro- and microscopic point of view.

In both cases, the SEM detected droplets of pure copper (or almost pure, as in a few cases it contains traces of iron) and leaded copper trapped in the vitrified matrix. In the leaded copper (with a lead ratio of about 13%), the lead prills always contain a certain (variable) amount of Sb/As (up to 13% Sb and 10% As approx.). In only one instance, a small amount (5%) of silver was also detected in the metallic lead.

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In both cases the vitrified slag features a dispersion of microdroplets or dendrites of pure copper, lead, and tin oxide crystals indicating the co-presence of the three metals in the system (Fig. 4).

The presence of arsenic and antimony is most probably an indicator of the initial mineralization of the copper: tennantite and tethraedrite deposits are testified in the areas of Roman age mines close to Vimercate, such as the Val Brembana (BG) and the Val Malenco (SO), and cupriferous arsenopyrite was mined in the Val Seriana. Lead and tin were probably being added to copper to create the ternary alloy, most common in Roman times.

The evidence provided by the metal residues suggests that they might be the results of recycling of scrap leaded bronze, which was being mixed with tin to form a new alloy. In fact, being the tuyere the area of maximum oxidation within the furnace, the presence of oxidised tin oxide crystals in hopper form can indicate the existence of oxidised tin, or re-crystallised cassiterite. The presence of copper/lead prills can be the result either of an alloying process of the two metals with tin (in metal or mineral form), or the re-melting of pre-existing leaded bronze, by which the tin "burns away" due to the oxidising atmosphere and re-crystallizes in tin oxides. The traces of antimony and arsenic in lead is surely linked to the role of collector played by lead within metallurgical processes, and can result from the use of "impure" copper, deriving from the above-mentioned mineralisation (as would be the case with iron, which, instead of being collected by lead, is removed in the silicatic phase).

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XRF analyses of sample #248 detected also a small amount of zinc, thus suggesting that brass (or most likely gunmetal) was also being worked here. Zn and a heavily corroded lead were also detected by XRF in furnace wall #240, and in mould #217. This seems to corroborate the hypothesis that in this workshop copper alloys of variable composition were being recycled.

Several other samples present a more complex composition, thus providing a further insight into the metalworking processes carried out in the site, which were not restricted to alloying and casting.

#116/1 is a highly porous, shapeless slag, reddish with patches of green oxidation. It features a glassy matrix mainly of lead silicate (both as amorphous vitreous material and as barysilite) (Tab. 3) containing small amounts of Ca, K, Fe, Al and Cu, with quartz grains (Fig. 5).

Embedded in the matrix are prills of various composition:

- Slightly oxidised lead (containing P and, in places, traces of Cu),
- Small droplets of leaded copper containing traces of S, Sb, As, Fe and Sn. The lead contains traces of Sb, As, Sn, Cl, Fe, P, and Ag (Tab. 4). Tiny particles of silver are also present in segregation in the copper. Coalescence of lead, due to segregation from the leaded copper prill, because of the high temperature treatment, is visible. Different stages of lead segregation are observed in the sample: one heavily corroded copper

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droplet with intergranular lead still in place, and one droplet of nearly pure copper in which lead is almost entirely concentrated at the edge.

#152 has the same macroscopic appearance and a very similar composition (Fig. 6). A few metal prills are embedded in a glassy matrix mainly made of lead silicate, containing >3% of Fe and Ca, approx. 2% of Al and P and traces (<1%) of Zn, Mg, Ti, K, and Cu. The metal remains are of copper, lead and tin, in various combinations:

- prills of almost pure copper containing very small amounts (<1%) of lead
- crystals of cassiterite and droplets of metallic tin. Their coexistence seems to suggest that cassiterite in hopper form derives from the oxidation of metallic tin
- large droplets of lead
- prills of very high-tin, high-lead bronze (28-33% Sn, 17% Pb), also containing silver particles: the silver content is 1% approx. (Tab. 5).
- small- and medium-sized prills of leaded bronze (mainly positioned at the edges of the lead droplets) featuring extremely high tin (36-31%) and low lead (1.5-0.5%) ratios (probably because most of the lead has already segregated from the bronze, as shown by the abundance of pure lead in the sample) (Tab. 6).

The composition of the alloy is peculiar and deserves further reflection. The tin ratio is very high, even when considering the extreme variability of Roman age alloys: establishing an "average" tin content for Roman bronzes is impossible, but high-tin bronzes usually did not exceed 20% (4).

Such a large amount of tin might be due to the addition of new metal to a re-melted bronze, to compensate for the loss due to selective oxidation, following a well-known practice in the recycling of bronze (5). The contemporary presence of both tin oxide

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crystals and tin seems to support this hypothesis. Lead is also present in large amount: this is not surprising, as high-lead alloys are common in Roman age.

The traces of silver detected in the two samples described above are an interesting feature, as further evidence of silver refining was identified at the site (see below, sample #165). In this perspective, the large amount of Pb present in the slags leads to the hypothesis that the Pb (either already existing in the alloy, or added on purpose) was being used to attempt a recovery of silver by means of cupellation. Indeed, if the original alloy contained 17% of Pb, it could easily have been used as a silver collector.

#165 METAL RESIDUE

The metal composition for this sample is similar to that of #134 and 148: it is a leaded copper, with a 1.25% lead ratio (Fig. 7). The copper is pure, whereas the lead droplets invariably contain low amounts of arsenic and antimony. No tin was detected in spot and area analyses, but traces of it exist in the surface corrosion layer, and show in the map of the metal. Moreover, the microstructure of the metal is characterised by large equiaxed grains, typically indicators of slow cooling, and shows no evidence of cold working or deformation, suggesting that this could be a casting or a spillage of metal, which underwent some sort of heat treatment, and not part of an artefact (Fig. 8).

Interestingly, on the surface of this sample there is a bright-red, glassy inclusion: the SEM analyses revealed it to be a vitrified slag rich in lead oxide, with a few copper droplets trapped within (Tab. 7). The copper droplets contain several microscopic silver

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prills (Fig. 9). The silver rate is very low, averaging 1%, nonetheless it probably confirms the suggested hypothesis that silver refining was carried out here. Silver traces, associated with copper and lead, have been detected in other samples, and this indicates that bronze artefacts containing low amounts of silver (either debased silver coins, or silvered objects) were recycled at the site.

The most common method for recovering precious elements (mainly silver) from base metals was the addition of large quantities of lead to the molten alloy. During slow cooling, lead and copper separate, and the silver, previously alloyed with copper, dissolves in the lead. In the second step, oxygen is added to the molten mass, thus causing Cu2PbO2 to form, while silver remains unaffected by oxidation and can be recovered by cupellation (6). The earliest written account of this process – widely used in the Renaissance - is given by Theophilus in the 12th century AD (7), but archaeological evidence shows that it was already in use as early as the Late Iron Age (5), and quite common in the Roman period (8)(9).

A third group of samples presents yet different features, suggesting that other metallurgical processes were being performed in the site.

#116/2 is a completely vitrified slag, with a dark grey, dull surface and low porosity. It features a glassy matrix with a high (ca.11%) Al content, also containing Fe, Ca, K, Mg and traces (<1%) of Na, Cr, and Ti (Tab. 8). Embedded in this matrix are a few quartz grains and several elongated crystals of fosterite (Mg2SiO4). The only metal recorded is

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iron, in the shape of metal prills (with some impurities: mainly P, a low amount of Ni, traces of S), and of large dendrites of wüstite, containing approx. 6% each of Mg, Al, and Cr.

#162 is a completely vitrified ceramic residue (most likely a fragment of furnace wall), with a dark-reddish, glossy surface. The glassy matrix is made of aluminium silicate with traces of Na, Mg, K, Ca, and Fe, containing quartz grains and a few heavily corroded iron prills with Ti (Tab. 8).

#72: the vitrified portion of the ceramic fabric (Tab. 8) contains several metal remains. Beside the fayalite dendrites in the slag, several metallic residues are present (Fig. 10). The SEM analyses observed that the metals trapped in the fabric are not the results of a "straightforward" casting process, as expected, but something more complex. Several almost pure copper droplets were detected, all of them containing a small amount (2% ca.) of iron. A few large iron prills are present as well; no lead is present in the sample, whereas minimal amounts of tin, usually in the form of newly formed cassiterite crystals, were found. None of the tin is alloyed with copper, but it is always associated with iron droplets. Moreover, small areas with concentrations of gold, copper and (in lower amount) silver were detected within one of the iron droplets.

#72/1 is a highly porous, shapeless slag, reddish with patches of green oxidation, very similar to #116/1. The XRF analysis indicated that its main chemical component is iron, followed by Mn, Ca and Si.

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What kind of process do these samples account for?

Given that no smelting slags, or any kind of evidence related to a smelting process have been found on site, we should probably think of an intermediate step between copper smelting and bronze working. The lack of lead and the scarcity of tin also suggest that these might not be residues of the alloying process. Besides, we know that pure copper was hardly ever used in Roman times (but for coins). Therefore, the only likely possibility is that these are the residues of impure copper refining: the quite high iron rate in the copper can very well be related to the smelting of sulphides such as chalcopyrite (which at the time was mined in areas not far from Vimercate, such as Valsassina, Val Seriana and Valtellina).

Other features pointing towards the refining process are the existence of cuprite crystals, which typically need slightly oxidising conditions to form, and are therefore considered a marker of refining slags (10). Also, the iron droplets trapped in the vitrified matrix, in some cases alongside traces of sulphur, are consistent with impure copper refining: they can indeed be the results of successful purification (11)(12). Iron appears in the sample as olivine and wüstite, as revealed by XRD: both phases are typically results of heat treatment of the metal and oxidising conditions in the presence of silicatic phase (i.e. quartz for slagging purposes).

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As for the gold traces in the iron, we might refer them to the original ore (which could have been auriferous chalcopyrite?).

An alternative hypothesis can be that these remains result from the re-melting of a different source of copper and leaded copper. In this regard, some Roman building brackets from the Adrian Athenaeum in Rome, analysed by Anguilano, represent an interesting parallel. They feature a copper or copper/lead composition with a large number of lead sulphide inclusions (Tab. 9).

The analysis of the brackets also show localised antimony, arsenic and silver, which seem similar to some of the remains found here at the site of Vimercate (Fig. 11).

The analyses of the brackets seem to suggest the possibility that this kind of materials were re-melted and cleansed of impurities (i.e. iron sulphides), to obtain a copper or copper/lead base alloy for further alloying/working. Wether the amount of silver present was economically viable to require cupellation needs further investigation.

Finally, #**217** is a fragment of a bronze casting mould: only a minimal, nonetheless meaningful amount of metal residues was detected in the sample. Microscopic copper prills, alongside with minimal traces of silver and oxidised iron are trapped in an inclusion of vitrified lead silicate. These features might once again result from a cupellation process.

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Moreover, the XRF analysis detected low amounts of zinc and arsenic. The metal cast in this mould was therefore most probably brass or leaded brass. The shape of the mould is impossible to recognise, but it was surely used in the production of small objects

Taking into account all evidence discussed so far, the metalworking site of Vimercate appears as a specialised complex, dedicated to metal treatment, in which different technologies coexisted. The structures, as well as the casting mould, show that casting, probably of ternary and quaternary alloys (leaded bronze and leaded gunmetal), was performed alongside copper refining (maybe aimed also at recovering silver) and bronze alloying. Local bronze workers were most likely using both freshly smelted copper (as suggested by the often identified inclusions of Fe, As and Sb) and recycled scrap metal (indicated by the traces of Zn in a few samples).

B. Verona

Also in this case, the ceramic samples belong to different kinds of artefacts.

#230, **233c** and **257** are partially vitrified coarse-grained ceramics – most likely furnace walls, none of which contains metallic remains, but only metal oxides in the vitrified matrix.

#211, on the other hand, shows a fine-grained, light orange matrix, with no heat alteration: it is most likely a fragment of a mould for casting bronze objects.

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The fabric composition of three out of four samples, quite rich in calcium, is once again consistent with the local raw materials. The XRD analyses showed typically local minerals, such as calcite and dolomite. It should be noted that their high Ca content hinders the refractory properties of the fabric: on the other hand, the constant presence of quartz grains, probably voluntarily added as temper, indicates an attempt at improving them.

The analyses of similar refractories from Verona carried out in the past came up with analogous results (13), suggesting that this was the common practice at the time.

We also observed that sample **#211**, i.e. the only casting mould we analysed, presents a slightly different petrological composition. In particular, the XRD analysis revealed the presence of two minerals, Montmorillonite and Illite, which do not occur in the other ceramic samples. The SEM analysis shows a very low iron content and the existence of quartz grains in the ceramic matrix. These elements all concur in suggesting an identification of the raw material as the so-called Terra Bianca di Vicenza, a light-coloured clay well known in ancient times, whose main quarries were near Isola Vicentina, only approximately 40 kms far from Verona and conveniently connected with it through the Via Postumia, the main Roman road (14). This is a finer and, even if rich in calcium, more refractory clay than that used for two of the furnace walls, indicating that the artisans were aware of the qualities of raw materials, and carefully selected them according to the purpose. The mould needs to remain intact during casting, therefore a

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material that would not fracture, when in contact with high temperature liquid metal, was selected for this purpose.

Furnace wall sample **#233C** presents some interesting feature as well. First of all, the calcium content is much lower than in the other samples, suggesting a different provenance of the clay. Moreover, the SEM analysis observed the existence of Ti-Fe oxide crystals interspersed in the ceramic fabric: they might be recognised as ilmenite, a mineral quite usual in an area not too far from Verona (Colli Euganei). Titanium was also detected in the fabric, throughout the sample. The fabric contains grains of quartz and zirconia, probably added as temper. All these elements suggest that this furnace had been built with carefully selected materials, in order to make it highly efficient and reduce the hazards. Was it because it was used for a different, more complex or more expensive process?

None of the samples discussed so far contained any metallic residue: on the other hand, the XRF analyses were able to detect traces of metal within the ceramic fabric. All samples (both furnace walls and mould) contained some copper and zinc: the mould #211 also had traces of lead and arsenic, whereas one of the furnace wall fragments (#233C) also contained some tin. These traces are too scant to attempt a definition of the alloys cast here, but they surely indicate that several different copper alloys were being made/worked in the same place, as it usually happened in Roman times.

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As for the proper metal remains, three copper alloy slags were analysed to define which metallurgical activities were performed at the site.

One of them comes from the main casting area (*Area C*), and two from the nearby *Area A*, so that it was also possible to compare them and try to understand whether the two zones were devoted to different processes.

#233, A rather complex slag, with a high metal content, was found in a treading layer next to the hearths of *Area C*. It is mostly formed of pure / slightly oxidised copper, interspersed with areas of low-tin (3% average) bronze, pure lead, and leaded copper (Fig. 12). No unalloyed tin was detected.

Several more elements were identified in the sample. First of all, it features a very high chlorine content: it is mostly concentrated in the corroded areas, but also in the bronze and copper droplets (Tab. 10). It is most likely a result of the corrosion process, due to the environment ("bronze disease").

Molybdenum is often present in traces throughout the sample: it was detected both in the lead and in the corroded areas. No significant deposits of molybdenite (MoS_2) are known in the mining areas exploited in Roman times near Verona. Small quantities of molybdenite can be often found in association with galena and chalcopyrite and, according to some sources (15) , in antiquity it was sometimes mistaken for galena and smelted in the attempt to produce lead.

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The overall impression is that this slag results from the alloying process, this time involving the re-melting of bronze together with pure copper and freshly smelted, still rather impure lead.

Sample **#345,** found near the smaller cluster of firing structures called *Area A*, features a glassy matrix containing several droplets of pure copper and crystals of tin oxide. Elsewhere in the slag, there are larger residues of leaded low-tin bronze (approx. 4% Sn content) and of copper with a high sulphur content (20%) (Fig. 13). The surface corrosion layer also contains tin crystals. This slag, containing droplets of unalloyed metals together with remains of the final ternary alloy, is likely to be (once again) a residue of the alloying process. Alternatively, it can result from the recycling of bronze with the addition of copper sulphide ore. The sulphur is instrumental in avoiding excessive oxidation. It is worth noticing that this slag largely differs from the one previously discussed, as if two different working practices were involved. They also come from two different area of the excavation that, although contemporary, could have been part of two separated workshops.

Sample **#396**, also coming from *Area A*, seems to be a casting slag: in a vitrified matrix are trapped several droplets of heavily corroded leaded bronze (Fig. 14).

The best-preserved metal residues show an average alloy composition of approx. 84% Cu, 11% Sn, 5% Pb. (Tab. 11). In one instance, the copper contains a 2% Zinc. Traces of

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zinc have been detected elsewhere in the site: their erratic occurrence suggests that it is probably unintentional, perhaps due to the recycling of scrap brass/gunmetal.

This composition is significantly different from that of the bronze residues found at Vimercate. A similar alloy, with a relatively high tin and low lead content, was observed in a few other archaeological bronzes from Verona (a finger of a statue at the Archaeological Museum and some production debris from the Seminario Vescovile) (16) and a fragment (foot) of statue from Cividate Camuno (17).

CONCLUSIONS

The comparison between the two sites allows us a few interesting considerations.

The two workshops were devoted to the production of similar artefacts, i.e. large cast bronzes, yet the processes involved were not exactly the same, as far as the material evidence goes.

The metalworking evidence from Vimercate presents significant similarities with Verona, but also a few different and significant features.

Large bronze artifacts were cast on site, and alloying was performed to create the most suitable bronze. Nonetheless, it appears that recycling played here a relevant role: most significantly, besides re-melting scrap metal to obtain bronze for casting, they were also

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attempting to recover small quantities of silver contained in copper alloys, by using a complex yet fairly effective technology. (Fig. 15)

The main reason for this lies probably in the chronology of the workshop. Metalworking seems to have started in this site in the 3rd century: in this period, the Empire underwent a most serious political and economic crisis, the effects of which are clearly perceivable. Interestingly, at this time the supply of precious metals decreased dramatically, due to the exhaustion of the most exploited mines, and the disruption of the trade routes caused by political uncertainty. Therefore, the government begun to issue debased silver coins, with the silver content dropping from 73,5% at the end of the 2nd century to 46% under Caracalla (211-217), down to 2,5% under Aurelian (post 275 AD) (18). The effort put into silver recovery becomes more significant in this perspective.

On the other hand, in Verona we find a well-organized industry, in which alloying and casting were performed. The metalworkers appear to be highly skilled and well aware of the properties of raw materials. They were successfully balancing cost- and technical-effectiveness, as in the case of the clays used for the refractory ceramics. Regarding the metals, it seems that the artisans were mostly creating their own alloys, sometimes from freshly smelted metals, and sometimes mixing recycled scrap metal and new, scarcely refined copper (or copper sulphide ore?). (Fig. 16)

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This fits very well within the picture of early imperial age production: in this period, the accessibility of raw materials, the road network connecting most regions of the Empire, and the overall wealth allowed highly specialized craftsmanship to thrive.

ACKNOWLEDGEMENTS

This research was possible thanks to the cooperation of:

- Brunel University London, Experimental Technology Centre, where all the archaeometrical analyses were performed
- Università Cattolica del Sacro Cuore, Milan
- Soprintendenza Archeologia della Lombardia
- Soprintendenza Archeologia del Veneto

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Table 1. List of samples from Vimercate with the analyses performed

SAMPLE	PERIOD	MATERIAL	OBJECT	SEM	XRF	XRD
MI VIM 72	2	Ceramic	Furnace wall(?)	x		
MI VIM 72/1	2	Ceramic	Slag		X	X
MI VIM 116/1	2	Ceramic+metal	Slag	X	X	X
MI- VIM 116/2	2	Ceramic	Slag	X	X	X
MI VIM 152	2	Ceramic+metal	Slag	X	X	X
MI VIM 162	2	Ceramic	Furnace wall(?)	X	X	X
MI VIM 165	1	Metal	Spillage?	x		
MI VIM 165/1	1	metal	Spillage		X	X
MI VIM 217	2	Ceramic	Mould	x	X	X
MI VIM 234	1	Ceramic + metal	Tuyere?	x		
MI VIM 240	1	Ceramic	Furnace wall		X	X
MI VIM 248	1	Ceramic + metal	Tuyere?	X	X	X

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Table 2. List of samples from Verona and analyses performed

SAMPLE	AREA	MATERIAL	OBJECT	SEM	XRF	XRD
VR 211	C	Ceramic	Mould	X	X	X
VR 230	C	Ceramic	Furnace wall		X	X
VR 233	C	Metal	Bronze slag	X		
VR 233c	C	Ceramic	Furnace wall	X		
VR 257	C	Ceramic	Furnace wall		X	X
VR 345	A	Metal	Bronze slag	X		
VR 396	A	Metal	Bronze slag	X		

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Table 3. #116-1 Vitrified matrix (Processing option: All elements analysed (Normalised)

All results in Weight%)

Element			
O K	30.21	19.09	24.59
MgK	1.90	0	0
AlK	3.85	2.18	2.60
SiK	18.31	25.90	35.40
P K	0.72	0	0
PbM	13.80	42.43	33.87
K K	1.38	1.13	1.73
CaK	6.94	0.98	0.72
MnK	0.28	0	0
FeK	1.08	1.59	1.10
CuK	21.55	6.70	0

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Table 4. #116/1 Leaded bronze (Processing option: All elements analysed (Normalised)

All results in Weight%)

Elemen		
O K	2.54	1.07
AsL	2.05	0.03
PbM	20.60	24.76
SnL	2.74	0
FeK	0.39	0
CuK	71.69	67.81
S K	0	4.02
SbL	0	2.31

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Table 5. #152 bronze (high-Sn / high Pb) (Processing option: All elements analysed (Normalised) All results in Weight%)

Elemen					
O K	9.21	6.17	10.55	6.17	18.02
SiK	1.74	1.77	2.77	1.77	2.65
P K	3.15	3.71	4.14	3.71	4.15
PbM	16.91	16.83	18.45	16.83	17.43
AgL	0	0	0	0	1.10
SnL	32.93	32.85	30.93	32.85	28.40
FeK	0	0.37	0.46	0.37	0.39
CuK	36.07	38.30	32.70	38.30	27.86

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Table 6. #152 bronze (high-Sn / low Pb) (Processing option: All elements analysed (Normalised) All results in Weight%)

Element			
O K	0.57	0.49	0
PbM	1.09	1.51	0.40
SnL	36.05	35.91	31.12
FeK	0.16	0.16	0
NiK	0.36	0	0
CuK	61.77	61.78	68.48
SiK	0	0.15	0
P K	0	0	0

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Table 7. #165 slag (Processing option: All elements analysed (Normalised) All results in Weight%)

Element	Weight
O K	65.83
AlK	1.83
SiK	2.90
S K	0.10
PbM	7.63
ClK	1.67
AgL	1.00
SnL	0.53
CuK	18.51

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Table 8. #116/2, 162, 72/1 vitrified matrix (Processing option: All elements analysed (Normalised) All results in Weight%)

	116/2	116/2	162	162	72	72
O K	38.95	39.51	40.50	36.92	37.09	36.16
NaK	0.23	0.44	0.14	0.28	1.33	0
MgK	11.15	3.76	1.13	1.06	0.93	3.46
AlK	9.25	10.79	23.01	18.30	5.76	4.78
SiK	33.18	34.69	26.75	31.12	23.43	23.38
K K	2.14	2.88	2.97	2.77	2.32	1.48
CaK	0.85	2.38	1.21	1.28	3.69	1.92
TiK	0.24	0.31	0	0.21	0.36	0
FeK	4.01	4.97	4.30	7.92	23.76	26.27
P K	0	0.25	0	0.15	0.39	0.33
CuK	0	0	0	0	0.93	1.77
MnK	0	0	0	0	0	0.45

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Table 9. a Brackets from Adrian's Athenaeum, bracket-hook (Processing option: All elements analysed (Normalised) All results in Weight%)

	O	Si	P	S	Cl	Ca	Fe	Cu	As	Sb	Pb
general composition								100			
black inclusion				20.84			2.39	76.8			
white inclusion	1.88							54.5			43.6
white inclusion								94.4			5.6
white inclusion								32.3			67.7
white inclusion								25.6			74.4
black inclusion				20.34			1.83	77.8			
black inclusion				13.04			0.78	86.2			
Spectrum 9	23.37				11.3			65.3			
Spectrum 10	42.06	15.9	1.39			0.97		39.7			
Spectrum 11	41.82	1.43						52.4		1.7	2.69
Spectrum 12	13.5							86.5			
Spectrum 13								100			
Spectrum 14	40.66	9.37	0.59			0.85		41.2		2.42	4.93
Spectrum 15	13.49			3.2	0.76			72.7	0	1.42	8.4
Spectrum 16	14.66							81		1.56	2.77
Spectrum 17	34.23	4.5	0.87		0.74	0.69	0.72	38.2	2.3	4.34	13.4
Spectrum 18	13.79				0.55			83.7			1.94
Spectrum 19	13.3							86.7			

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Max.		42.1	15.9	1.39	20.8	11.3	0.97	2.39	100	2.3	4.34
Min.		0	0	0	0	0	0	0	25.64	0	0

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Table 9b. Bracket (short fragment) (Processing option: All elements analysed (Normalised) All results in Weight%)

	O	Si	P	S	Cl	Ca	Mn	Fe	Cu	Ag
general composition									100	
black inclusion				19.62					80.38	
black inclusion				18.75					81.25	
very black incl.	12.08		5.51				8.44	10.36	63.61	
Spectrum 5				1.54					98.46	
Spectrum 6	10.41	6.07			0.56				82.96	
Spectrum 7	10.21	0.99							88.8	
Spectrum 8	13.3								86.7	
Spectrum 9	37.74	15.55	0.79		1.59	1.13			43.25	
Spectrum 10	27.81				16.8				55.41	
Spectrum 11									100	

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Spectrum 12	15.99	1.9							78.54	3.57
Spectrum 13	13.17	0.93		4.25					77.11	4.54
Spectrum 14	13.34				0.95				72.62	13.09
Max.	37.74	15.55	5.51	19.6	16.8	1.13	8.44	10.4	100	13.1
Min.	0	0	0	0	0	0	0	0	43.24	0

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Table 10. #233 metal prills (Processing option: All elements analysed (Normalised) All results in Weight%)

Element			
MoL	2.80	0	0
ClK	21.32	1.78	0
SnL	4.12	2.34	3.41
CuK	71.75	95.88	96.59

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Table 11. #396 Metal prill (Processing option: All elements analysed (Normalised) All results in Weight%)

Element		
PbM	4.49	5.31
ClK	3.02	0
SnL	10.22	11.04
CuK	82.27	83.65

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Figure 1.

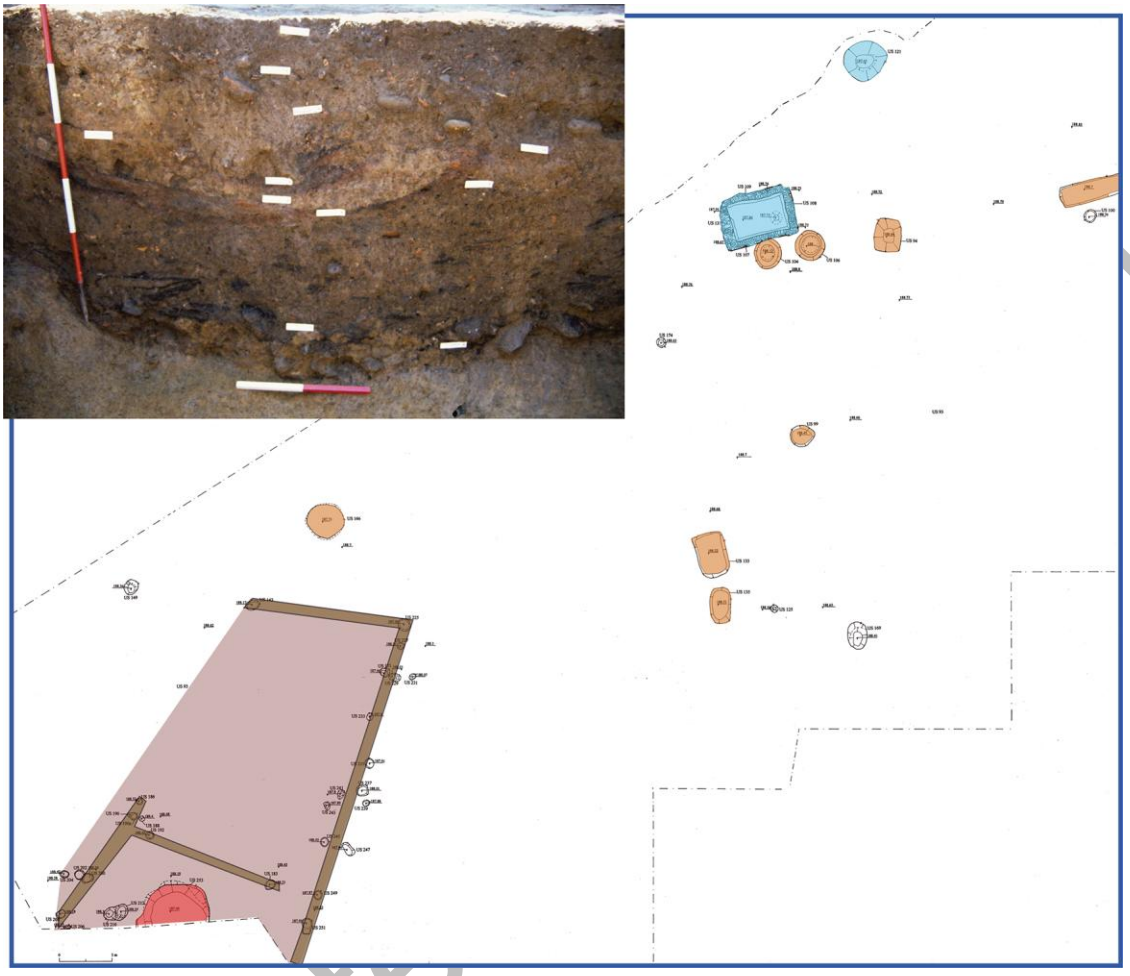

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Figure 2.

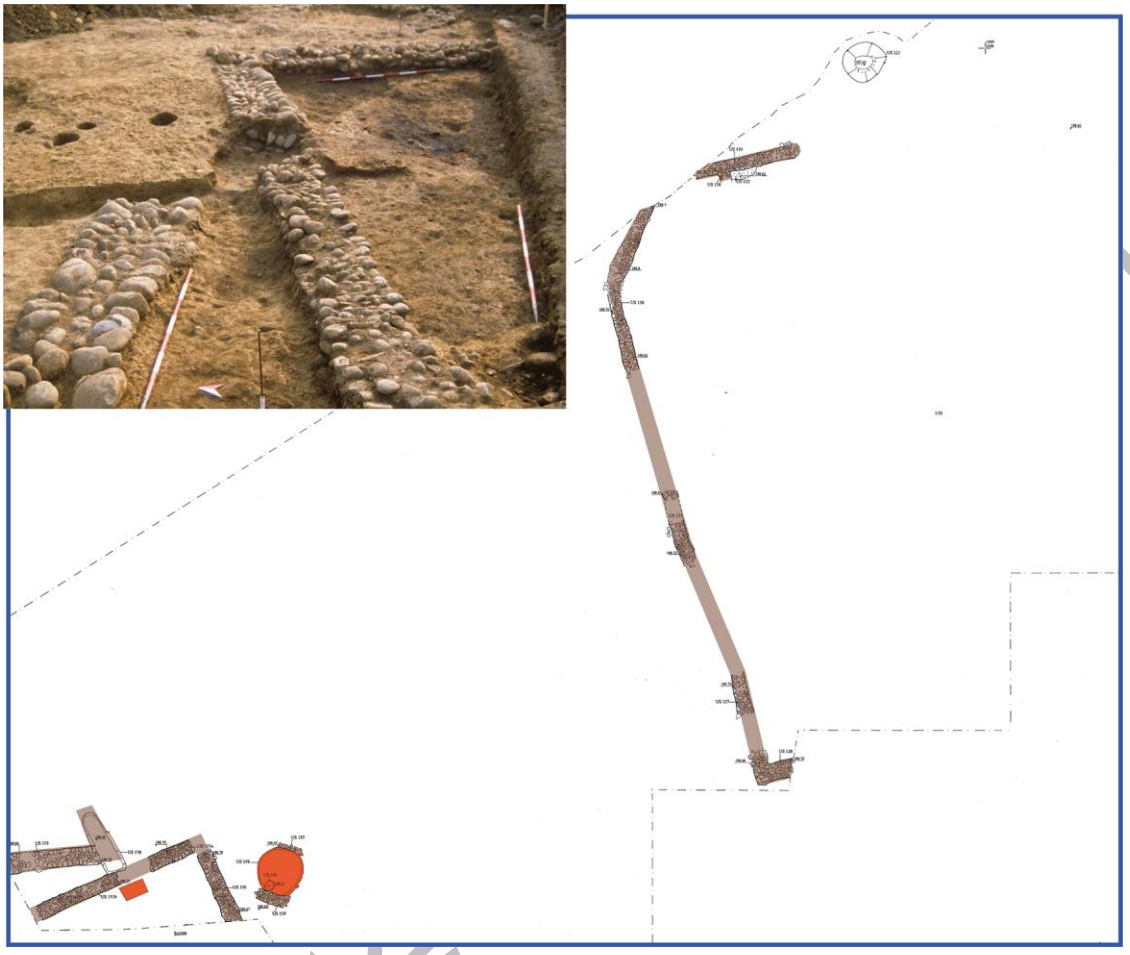

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Figure 3.

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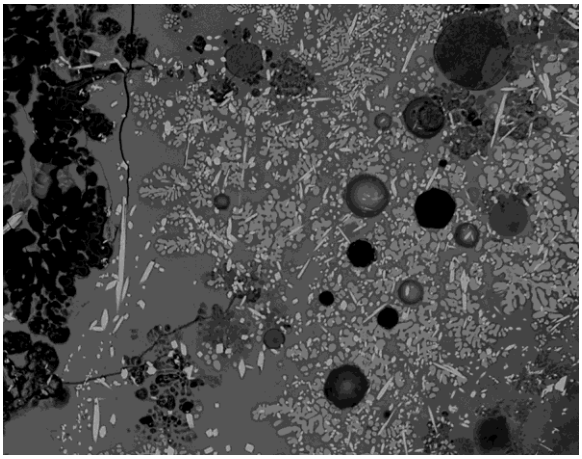
Figure 4.



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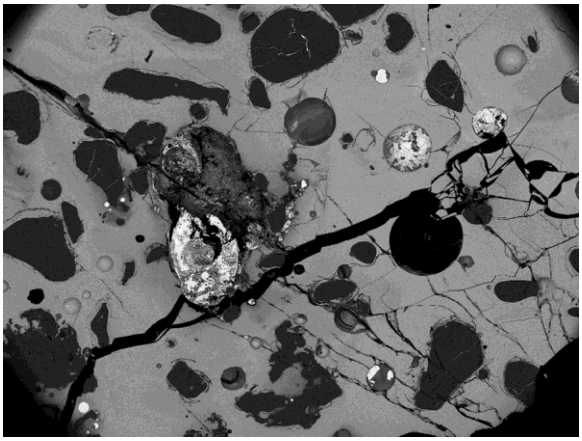

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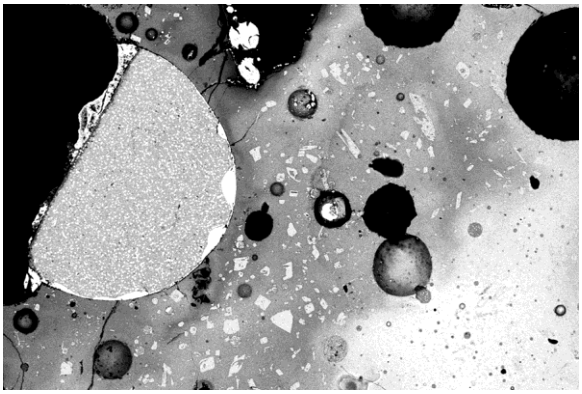

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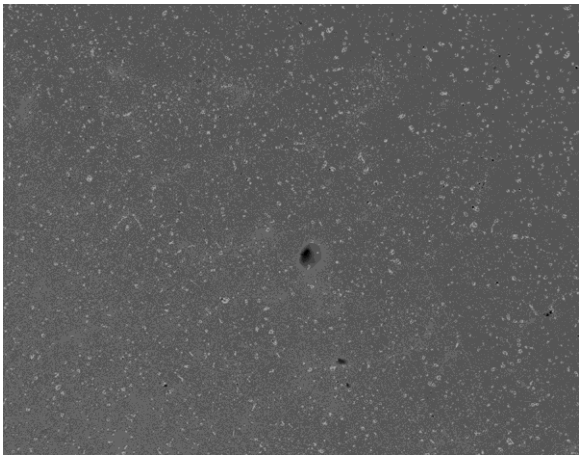

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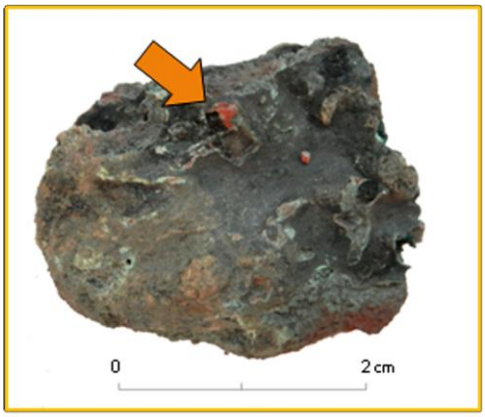

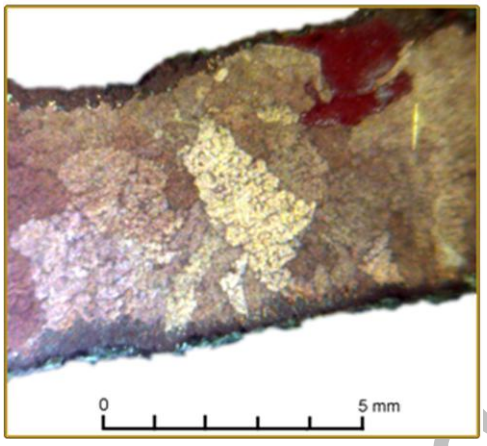

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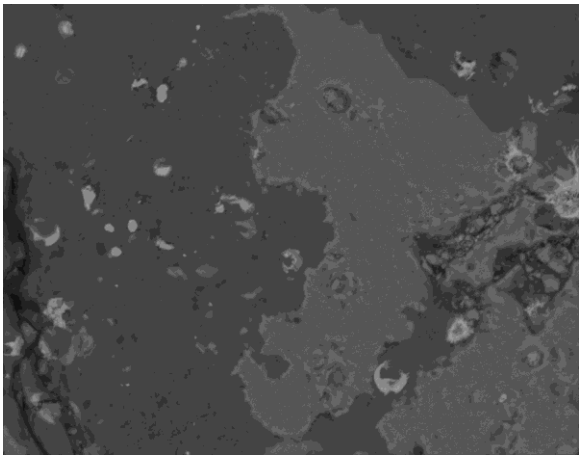

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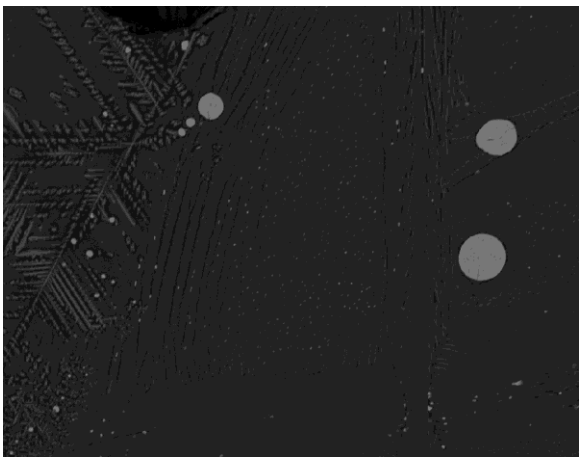

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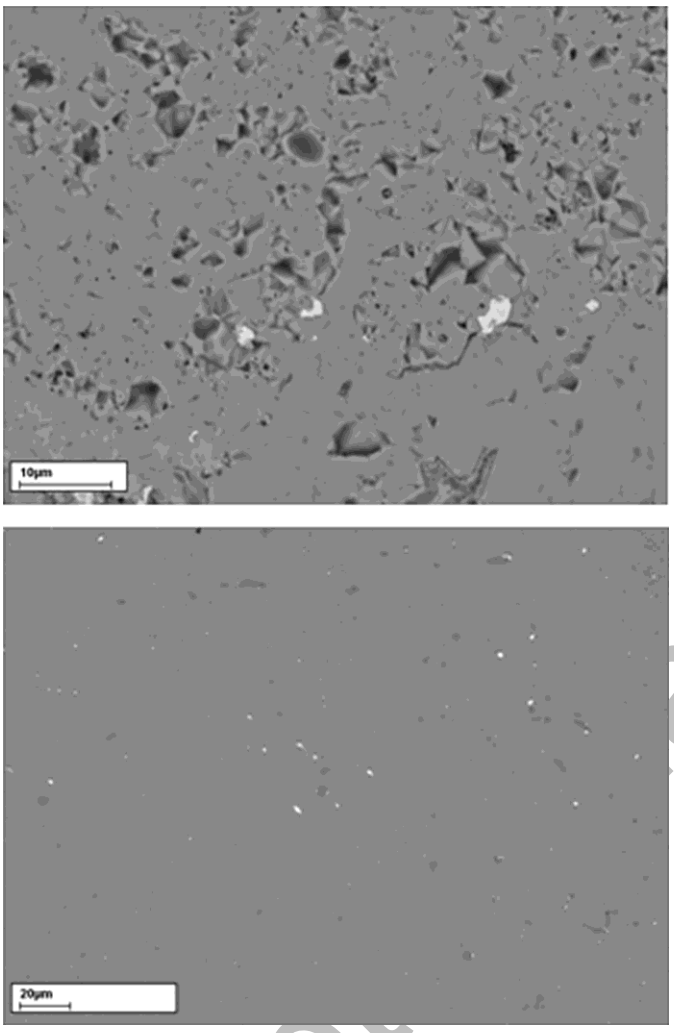

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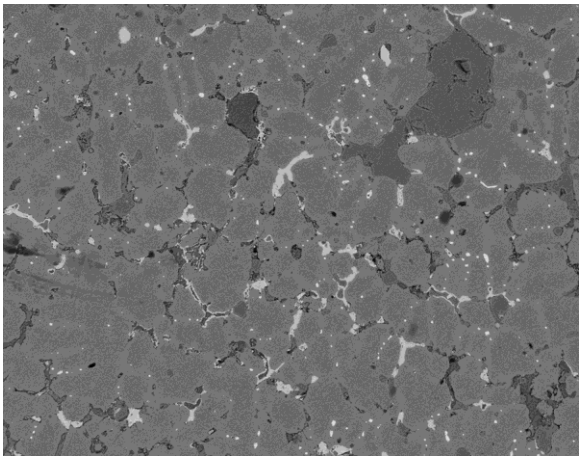

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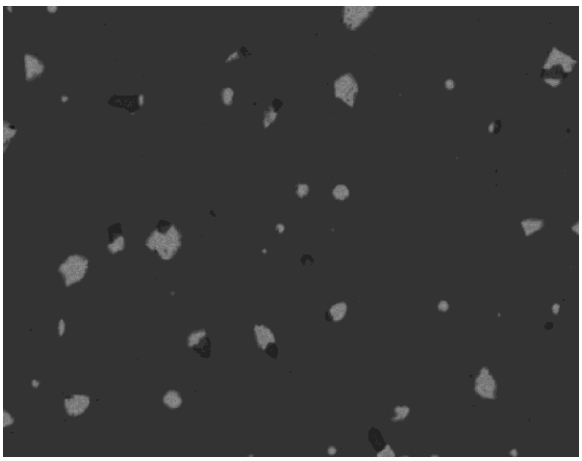

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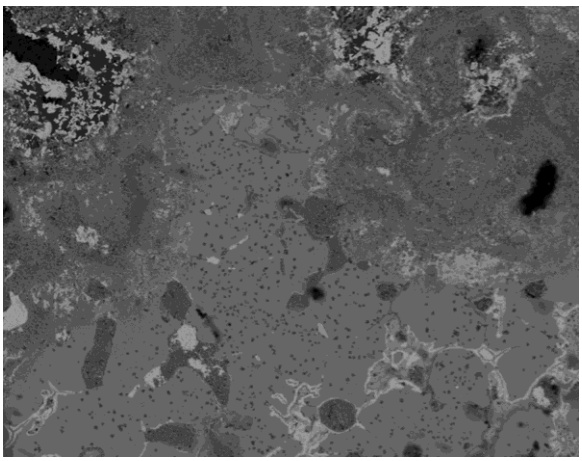

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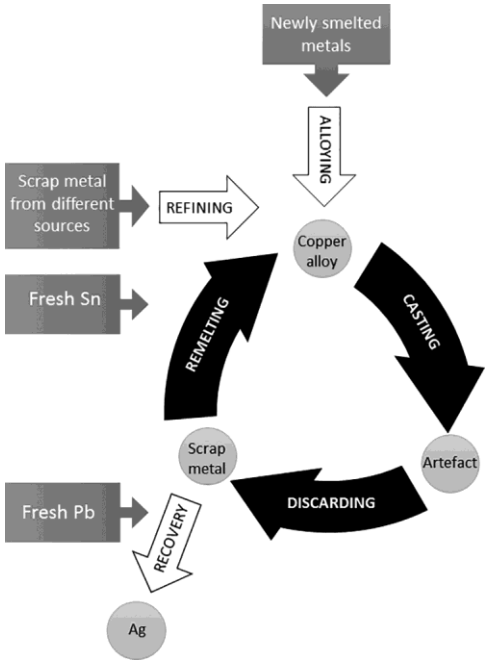

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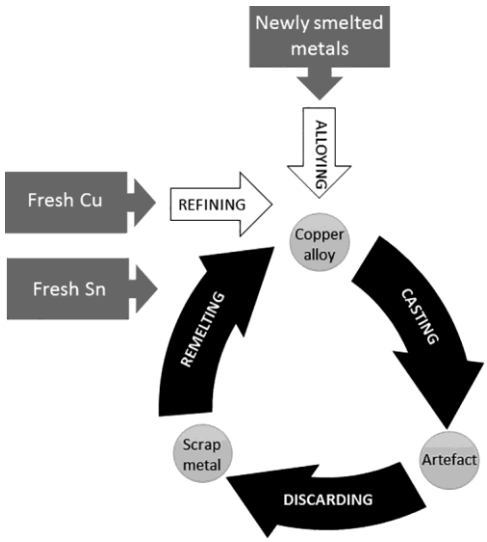
Figure 16.



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