EXARC JOURNAL 2021/1
19 Articles | Open Access

Reviewed Article:

Irish Copper Axe-Ingots Recovered in Brittany: Experimental Casting to Recreate Porous Material

Persistent Identifier: https://exarc.net/ark:/88735/10553

EXARC Journal Issue 2021/1 | **Publication Date:** 2021-02-25

Author(s): Aurélien Burlot [1]

[1] Department of Historical Studies, Gothenburg University, Box 200, 40530 Göteborg, Sweden.

The present study discusses the casting of copper axe-ingots in open, wet sand moulds, in an attempt to recreate porous artefacts that have been recovered in Brittany, France. The original axe-ingots are considered to be Irish copper metalwork from the Early Bonze Age. However, these artefacts are not finished objects and are poorly cast. This nevertheless appears to be deliberate because, as it has been argued (see Gandois et al., 2019; Burlot, 2019), they consisted of copper ingots designed to be re-melted and alloyed with tin to create bronze objects. These axe-ingots are porous, and present many imperfections, and some of them have perforations running through their entire thickness. The aim of the experiment is to recreate the porosity and some of the perforations present on those artefacts.

> "The skills of ancient Irish metallurgists cannot be questioned considering the quality of earlier and

Introduction

A series of copper axe-ingots (ingots shaped like axeheads) found in Brittany during the early 20th century, has a shape similar to that of the flat axeheads of the Killaha phase, which is when tin-bronze was first used in Ireland (circa 2150-2000/1900 BC). These artefacts (now termed Ploukilla axe-ingots) are not finished contemporary copper and bronze metalwork. The use of bivalve moulds notably for the production of halberds, demonstrates a high level of sophistication. It is therefore reasonable to suggest that the poor casting was deliberate, and the original shape itself may have been a recognisable symbol for Irish copper that was ultimately lost during the alloying process.

products and are considered as imported ingots, because they represent metal artefacts found in a region where evidence for prehistoric copper mining remains absent (Briard, 1965; Gandois et al., 2019; Burlot, 2019). Their Irish origin has been suggested considering their shape and an early compositional analysis also supports this suggestion (see Briard and Maréchal, 1958, p.422; Briard, 1965, p.59; Needham, 2000, p.180). More recent studies (including compositional analyses) of these objects confirm this (Gandois et al., 2019; Burlot, 2019). This is furthermore substantiated by the discovery of similar objects in Ireland, and namely a pair of axe-ingots from Lough Gur, Co. Limerick (ibid.; see also Harbison, 1969a, pp.22-24, plates 17-18 for examples of axe-ingot). The axe-ingots from Brittany, however, are not finished products as they are made of copper instead of bronze, and they have many casting defects such as cracks, perforations, pitting, vacuoles and depressions caused by gas exhausts during the casting process (Gandois et al., 2019; Burlot, 2019). This strongly suggests that their main purpose was to provide copper to some Early Bronze Age communities in Brittany, and that they were to be further transformed locally into tin-bronze artefacts (ibid.). Consequently, if the axe-ingots were indeed intentionally poorly cast, their production may have involved processes that differed from the conventional customs of copper/bronze-making. What is clear is that the artefacts were cast in univalve (open) moulds. This is demonstrated by their common plano-convex sections. Past experiments to recreate such pieces (in clay, stone, wood and green sand) have produced mixed results (Papillon, 1997; Gandois et al., 2019; Burlot, 2019; see below). It was previously suggested by two researchers (H. Gandois and myself; see Gandois et al. 2019, p.18) that the mould material may have been wet, but this was not experimented with for various reasons.

The experiment discussed here includes casting copper axe-ingots in homemade wet green sand, and the results are further detailed below. The aim here is to purposely recreate porous pieces but also to understand the specific casting process. This experiment is rather straight forward as it simply consists of casting copper into sand moulds. However, since the sand is wet, extra safety measures are essential. This would have also been an important factor for prehistoric metalworkers.

Background to the Experiment: the Ploukilla Axe-ingots in their Context

This particular series of axe-ingots consists of various finds from the north-western French region of Brittany, as well as three single finds with no recorded provenance. The latter were part of the personal collection of Paul du Châtellier, a well-known Breton archaeologist (Gandois et al., 2019; Burlot, 2019). No contextual information is known for any of those finds (ibid.). The provenanced finds include a hoard of three axe-ingots from Keranou, Ploudaniel (*département* of Finistère), a hoard of nine pieces from Plouhinec (also Finistère), a single find from Belz (*département* of Morbihan).

The artefacts are roughly shaped like flat axeheads, with a narrow butt, concave sides (sometimes asymmetrical), a broad cutting edge and a plano-convex section (See Figure 1). This particular shape is reminiscent of the axeheads of the Killaha phase. This phase situated at the beginning of the Early Bronze Age of Ireland, began sometime in the 22nd century BC and ended in 2000/1900 BC (See Figure 2) (O'Brien, 2004; Gandois et al., 2019; Burlot, 2019; see also Needham, 2017 for British contemporary axehead productions). This phase is characterised by the production of tin-bronze objects such as flat axeheads, daggers and halberds (Harbison, 1969a; 1969b; Burgess, 1974; 1979; O'Brien 2004; Burlot, 2019). It is worth mentioning, however, that the same types of object were already produced during the Irish Chalcolithic, which began circa 2500 BC (ibid.).

Where the axe-ingots from Brittany are concerned, only one does not have a similar shape to the rest. It is a small triangular axe-ingot with straight sides from the Plouhinec hoard (Finistère). Interestingly, out of all the material subjected to chemical analysis from this hoard, it was the only object that was deliberately alloyed with tin (3.96 %). The rest of the analysed material is made of copper (Gandois et al., 2019, table 3). This, of course, reinforces the suggestion that the stray finds from Brittany are from the Early Bronze Age. In addition, compositional analyses of the copper from some of these artefacts indicate that the metal was extracted from the Chalcolithic and Early Bronze Age mine at Ross Island, Co. Kerry in the south-west of Ireland. This area also included a work site associated with the processing of copper ore and the production of metal. This copper is rich in arsenic and has a distinctive impurity pattern (As>Sb>Ag) associated with the exploitation of fahlore mineralisation (tennantite) (Gandois et al., 2019; Burlot, 2019; see O'Brien, 2004 for details about the Ross Island mine).

Taking into account the origin of the metal (Ross Island, Co. Kerry) and its phase of production, it is possible to suggest a broad date of 2150-1900 BC for the exchange of the copper axe-ingots between Ireland and north-west France (Gandois et al., 2019; Burlot, 2019). The link is further supported by the recovery of similar objects in Ireland. Axe-ingots from the island are indeed recorded (see Harbison, 1969a, pp.22-24, plates 17-18), although none of these really look like the Breton artefacts. However, a pair of axe-ingots recovered from the Knockadoon peninsula at Lough Gur, Co. Limerick in 1987, shares striking similarities with the material from Brittany. In addition, metal analyses prove that one artefact is made of copper and the other is made of tin-bronze (Gandois et al., 2019, table 4; Burlot, 2019). Irish copper artefacts in Brittany are rare but this region has produced a substantial amount of Chalcolithic/Bronze Age material. Evidence for prehistoric copper mining in this area however remains elusive. It is widely suggested that copper from other regions of France and Europe (the Languedoc, the Massif Central, the Alps, Iberia for example) was imported, yet local exploitation cannot be entirely excluded (see Gandois et al., 2019; 2020; Burlot, 2019).

The axe-ingots recovered at Lough Gur are well-cast pieces, and except for some light surface pitting, they do not exhibit major casting defects (Gandois et al., 2019; Burlot, 2019). The same observation however, cannot be made for the axe-ingots from Brittany. The latter are porous, with substantial pitting. Some of the artefacts have complete perforations, as well as depressions, vacuoles and cracks (ibid.; see Figure 1). Some even have exhaust bubbles trapped in the metal core, as was demonstrated by X-radiography (ibid., figure 11). Post-cast work is very limited on the Ploukilla axe-ingots, except for light polishing on some surfaces, but hammering into shape or final polishing are not noticeable. Nevertheless, some of what would have been cutting edges have been hammered against the line, making those ends thick and squared (ibid.). This also supports the theory that the artefacts are indeed ingots rather than blanks. Blanks can be worked into shape (by forging for example) (Briard and Giot 1956). In order to become finished bronze artefacts, these objects have to be re-melted and alloyed with tin. Of course, during this process the distinctive Irish Killaha shape would have been lost. The intention to further process the metal may explain why these objects were so poorly cast (see Gandois et al., 2019; Burlot, 2019).

The skills of ancient Irish metallurgists cannot be questioned considering the quality of earlier and contemporary copper and bronze metalwork. The use of bivalve moulds notably for the production of halberds, demonstrates a high level of sophistication (O'Flaherty, 1995). It is therefore reasonable to suggest that the poor casting was deliberate, and the original shape itself may have been a recognisable symbol for Irish copper that was ultimately lost during the alloying process. Similarly, the light polishing may simply have been performed to show the quality of the metal (see Gandois et al., 2019; Burlot, 2019). Deliberate poor casting has been studied elsewhere, namely from Loyettes (Ain) in eastern France, where a hoard of eight flanged axeheads of the Early Bronze Age/Middle Bronze Age transition was recovered. All the axeheads were cast in the same bivalve mould, but each time the valves were slightly offset, thus resulting in poorly cast objects. Moreover, the core metal of some of the axeheads contains degassing bubbles. Therefore, these can be considered as axe-ingots (Delrieu et al. 2015; see Gandois et al., 2019, p.26, figure 16).

The production of metalwork in Chalcolithic and Early Bronze Age Ireland, and especially with copper from the Ross Island mine, is substantial. Yet, the evidence for contemporary metalworking elsewhere on the island is extremely limited. That said, some open stone moulds (Lough Gall, Co. Antrim, Ballynahinch, Co. Down and Lyre, Co. Cork for example) attest the production of flat axeheads across the island (see Collins, 1970; O'Kelly, 1970). The use of sand for casting may have played an important role in the production of early metalwork. The problem with ancient casting in sand is that it very rarely leaves any archaeological evidence, although it has been sporadically attested in some parts of Asia (in the Levant and Thailand for example) (Ottaway and Seibel, 1998). In Ireland, sand moulds may have been used for the production of Early Bronze Age ingots as no evidence for the use of other materials exists. In addition, according to the metallographic analysis performed on a Killaha type axehead recovered at Newgrange, Co. Meath, the cooling process was slow. This would not have been the case if the object was cast in stone (ibid., p.60). Consequently, the use of sand for casting the axe-ingots from Brittany can be considered. The Ross Island copper mine is located on the shores of Lough Leane where sand is widely available. A quartz sand deposit, similar to that found on the lake's shoreline, was studied at the mineral processing work camp associated with the mine. It appears to have been purposely brought to the camp in association with a furnace (O'Brien, 2004, p.232). Furthermore, considering the maritime context for the trade of copper between Ireland and Brittany, casting using beach sand cannot be excluded.

Past Experiments

A few experiments were previously conducted to recreate Ploukilla axe-ingots. Mixed results were obtained as on some occasions porosity was achieved, and on others it was not.

First experiments by F. Papillon (Papillon, 1997)

Papillon (1997) was the first to attempt recreating such artefacts. Her experiments included recreating various ingots including one axe-ingot which is namely similar to an example from the Plouhinec hoard (Finistère) (Papillon, 1997, pp.92 and 129, figure 4-23). For this object, she used pure copper (already in metal form), that was melted at 1200° C for 15 minutes in a clay crucible which was entirely covered with charcoal. Air was blown in from above with a tuyère (reduced atmosphere). The metal was then poured into an unheated clay mould. The clay used for the mould was tempered with sand but no further temper was used on the surface of the mould (ibid., pp.90 and 92). The results were positive as she achieved significant porosity and oxidation which was more substantial on the upper (open) surface than the on lower one which was in contact with the mould. A macrographic study also revealed the presence of bubbles trapped in the core of the metal (ibid., p.129, figure 4-23). On a microscopic level, inside the core was a strong second phase of cuprous oxide (Cu_2O), of homogenous size and distribution, which also contained bubbles (ibid., p.129, figure 4-24). There were equiaxed grains near the outer surface but grain sizes varied elsewhere (ibid., p129, figure 4-25). Papillon (1997, p.143) also cast some ingots in univalve wood moulds (of un-specified species). For this, she alloyed arsenic (5-6 %) to the liquid copper. The melting process was the same as for casting in clay moulds. This technique resulted in ingots with ripples on the lower surface but no porosity (ibid., p.149, figure 4-32a). This particular pattern is similar to the triangular tin-bronze axe-ingot also from the Plouhinec hoard (Finistère) discussed above, and it may thus be suggested that a wooden mould was indeed used to cast this atypical axe-ingot (ibid., pp.149 and 161, figure 4-39; see also Gandois et al., 2019, p.18, figure 14.3a-b).

Papillon's experiments demonstrate that various mould types could be used to cast some of the axe-ingots of the Plouhinec hoard. The clay mould experiment, especially, produced results similar to the original artefact. In turn, this also suggests that an arsenic-rich copper is not automatically necessary to achieve such porosity.

Second experiments by H. Gandois and A. Burlot (see Gandois et al., 2019; Burlot, 2019)

As a continuation of Papillon's experiments, a more recent series of experiments was performed for a publication discussing the Ploukilla axe-ingots (Gandois et al., 2019), and for a doctoral thesis exploring the influences and metal exchanges between France and Ireland during the second half of the third millennium BC (Burlot, 2019). For these experiments, various mould materials were used by H. Gandois including stone (granite, sandstone, limestone and mica-schist), and wood (beech, alder, oak, elm and hazel). For my experiments, sand moulds of homemade green sand and delft clay (Petrobond), an oil-rich modern material for comparison, were used. All the castings were performed in univalve moulds, using gas-fired furnaces, graphite crucibles and scrap copper. Pouring temperatures varied, as did the cooling conditions (quenched or not). Also, the stone moulds were pre-heated to prevent thermal shock (see Gandois et al., 2019, p.18). For the sand moulds, the prime material was homemade green sand, consisting of a mixture of dry fine sand (regular play sand sieved with a 1 mm mesh), bentonite clay powder (approximately 15 % of the sand weight) and water. Water was sprayed lightly over the sand until it could be shaped into a ball that broke cleanly when pulled apart but which did not feel wet. Delft clay was also used, and while ancient metalworkers would, of course, not have utilised it, oil-rich sands could theoretically have been in use in prehistory.

The combined results were not particularly conclusive in that porosity and major defects of the original axe-ingots were not replicated. Nevertheless, some degassing on the lower sides (in contact with the mould) was visible when using various mould types (mica-schist, hazel, green sand and delft clay) (See Figure 3 for sand moulds; see also Gandois et al., 2019, figure 14). Also, a large depression was noted on an example cast in hazel, that echoes a similar defect on the axe-ingot from Belz (Morbihan), but the rest of the molten metal did not fill the mould on this occasion (Gandois et al., 2019, figure 14.2a-b). In addition, the casting of an axe-ingot in oak caused ripples similar to those on the triangular axe-ingot from the Plouhinec hoard (Finistère) (ibid., figure 14.3a-b), as was discussed above in Papillon's experiment.

Neither of the sands (green sand and delft clay) produced the desired result of porosity. However, the post-casting state of both types of sand is interesting. Once copper/copper alloy has been poured into green sand, the surface of the mould is not scorched since it does not contain any oily components. The surface is hardened but friable, and when crushed, with just the fingers, it reverts back into sand (See Figure 4). In turn, the oil-rich delft clay is scorched after the pour, and becomes much more resistant than the burnt green sand (See Figure 4). Such scorched remnants could potentially leave archaeological evidence on ancient metallurgy sites, but as was noted earlier, those remains are elusive.

Third experiments by A. Burlot

This experiment was entirely accidental as the actual results were obtained while pouring excess bronze from the crucible after casting a dagger in a bivalve mould, for a completely unrelated project. For this, a green sand mixture was made using some damp leftover sand that was only intended to receive the excess metal from the crucible. This particular sand was much more humid than what is required for green sand, and when the bentonite clay was added, the mixture was significantly sticky and clumpy. I had simply made an imprint in the sand employing a clay template used for the previous Ploukilla axe-ingots, as the excess metal ingot had a rather convenient shape and could fit in the crucible for future casting. This accidental result consisted of an axe-ingot with a large central depression and a smaller one below, towards the cutting edge. These coincide with the defects visible on the original example from Belz (Morbihan) (See Figure 5). Two low swells are present on the upper surface. This was encouraging for future experiments, as it demonstrated that wet green sand could indeed reproduce some of the casting defects present on the Breton artefacts. This also determined that it could be achieved using tin-bronze and not simply copper. As was previously noted, experimental casting in wet moulds was considered but was never undertaken. Nonetheless, it has been noted (Hesse, 1941, pp.6-7) that when casting in green sand, gas bubbles can be trapped inside the metal or cause further defects, mainly from the steam created on the mould's surface, but also by air that cannot escape, or even by other chemical reactions. If the molten metal is too viscous, gases create irregular blowholes across the surface (ibid., p.7).

In his experiments with recreating Late Bronze Age ingots from the Uluburun shipwreck discovered off the coast of Turkey, Larson (2009, pp.50-51) noted that casting in green sand created swells and blistering on the upper surface of the ingot, but that the surface in contact with the mould was rather smooth and no perforations occurred. He observed (ibid.) that sand was the material with less reaction when the copper was poured, as opposed to other mediums, such as stone and clay. A limestone mould created the most violent reaction, while pouring in clay also resulted in a strong, sudden outcome with noticeable defects. This is similar to the reaction noticed during Papillon's experiment discussed above (ibid.). Larson's sand mould (2009, p.44) was made using coarse sand with large grains (coarser than the one I used) as it allows for the gases to escape more readily. The sand to bentonite clay powder ratio also differed at 7:1, as well as the moisture content which was not excessive (5%) (ibid.).

Present Experiments

Consequently, building on the accidental casting result, I decided to experiment further by deliberately casting in wet green sand. For this, the plan was to make moulds with high-moisture content in the sand. The material and equipment used were:

- Finely sieved play sand
- Bentonite clay powder
- Water
- Two air-dried clay templates of axe-ingot (based on the examples from Lough Gur Co. Limerick)
- Steel rings for the moulds
- A steel tray lined with wooden panels as a base for casting
- Gas-fired furnace

- Graphite crucible
- Metal tongs
- Some ground charcoal thrown in the crucible just before the pour for deoxidising
- Digital pyrometer calibrated for copper alloys
- Safety equipment (goggles, helmet, mask, apron, gloves, safety shoes)

The experimental casting

The green sand was originally mixed to the same consistency as the sand used during the previous (accidental) casting event. The green sand was compacted inside a steel ring 24 cm wide and 4 cm tall (Mould A) for two thirds of the height. The top third was filled with compact but slightly lose sand, then two clay templates were pushed down on this upper surface. Finally, the templates were removed to create imprints (See Figure 6). These imprints were sprayed twice with water (from a spray bottle) while the copper melted in order to keep the base moist but not saturated. A similar second set of moulds (Mould B) was created, but the plan for this double mould was to spray it multiple times while the metal melted. A third set of moulds (Mould C) was also made, using only wet play sand this time. No bentonite clay was used. The idea was to potentially recreate a makeshift mould with beach sand. The sand was mixed with water until an imprint could be pushed into it and hold the shape. This mould was covered with plastic film while the copper melted, to avoid loss of moisture and damage to the imprints. This experiment was not undertaken at the same time as the green sand experiments, but the melting and pouring conditions were identical.

It took approximately 20 minutes with the gas-fired furnace for the copper to reach 1200° C. The imprints from Mould B were sprayed five times during this period. Each time, the base of the imprints took longer to absorb the water. After the final spraying, and just before the pour, the bases were almost saturated. For safety reasons, as splattering was expected owing to thermal and chemical shocks, the rings were placed in a large and deep rectangular steel container (an old barbecue) with some sand covering the base, and wood panels were placed around the edges of this metal base to prevent the metal from spraying in every direction (See Figure 9).

There was no splattering when the copper was poured into Mould C. The reaction of the molten metal in Mould A created some splatter but it was not too substantial. In contrast, the reaction of the metal from the first pour on one of the imprints in Mould B was more significant, and the experiment was aborted before casting into the second imprint. For the imprint that did cast, pouring was done in two parts in rapid succession only a few seconds apart, as when it splattered, I backed off before finishing the pour. Nonetheless, an entire axe-ingot was cast. Finally, the axe-ingots were quenched in cold water, and then cleaned up with an electric wire brush to remove any sand mixture and the oxide layer that formed on top, while avoiding to scratch the metal.

Results of the experiment

Despite the setback of aborting the second pour entirely, the results are actually positive as pitting, depressions and entire perforations were achieved in all sets of moulds. Only one axe-ingot from each set of moulds (the ones with the most significant defects) are discussed below.

One axe-ingot, Experimental Axe-Ingot 1 (or EAI1), from Mould A exhibits these defects on its lower surface (See Figure 7):

- Pitting around the irregular edges
- A large central depression
- A swell just below this depression
- A funnel-shaped entire perforation toward the cutting edge that runs diagonally to the upper surface, through which a thin needle can be inserted. Due to the awkward angle of the perforation, it is impossible to photograph the hole, but light is visible from the lower surface through an opening approx. 1mm wide.

On its upper surface, it has (See Figure 7):

- A large swell on the top right onside, that coincides with the zone above the central depression from the lower surface
- Another swell at the bottom left
- Vacuoles
- The small opening (approx. 1mm wide) of the funnel-shaped perforation
- Some grain-like protrusions in the same portion of the object
- The sides overflowed on the edges of the central area next to the large lower surface depression and upper surface swells. This overflow was facilitated by the slight weakening of the top of the edge when removing the template.

The Experimental Axe-Ingot 2 (EAI2) cast in very wet sand displays the following defects on its lower surface (See Figure 8):

- Irregular edges
- A wrinkled surface with light pitting
- A wide but shallow dip in the central portion of the piece
- An elongated depression near the cutting edge, with a small (2 mm long) perforation in it. Again, the perforation is impossible to photograph due to its angle
- A triangular depression below the central depression, that pierces metal diagonally, and ends in a small almond-shaped hole on the other side.

On its upper side, the surface is irregular since the pour was done in two parts as noted above. Nonetheless, the defects are the following (See Figure 8):

- The edges are irregular with some overflowing
- There are grain-like protrusions on the edges and one near the cutting edge
- The surface is wrinkled with some small cracks and light depressions toward the cutting edge
- The largest depression coincides with the perforation noted above.

Whilst there was no splattering during the pour in Mould C, defects are still noticeable (See Figure 9). These include on the lower surface:

- Pitting across the surface except for the top right corner at the butt
- Irregular edges
- One small, shallow depression in the central left portion

The edges of the upper side are rather well defined, but defects are more pronounced than on the lower surface (See Figure 9) including:

- Some small vacuoles
- Wrinkled surface
- A large central swell
- A smaller swell underneath this central defect.

To further assess the defects within the core metal, the three axe-ingots were cut width-wise across some of the most pronounced surface imperfections. An electric cutting disc was used to do this. On EAI1, a first cut was made across the wide, but not tall, swell located below the central depression, about one third of the entire length toward the cutting edge. The only visible defect is a trapped bubble centrally located near the top. This bubble is 5.3mm across and 5.7 mm high (See Figure 10). Interestingly, this bubble actually burst the upper surface in a 2 mm wide perforation. This detail is only visible because light came through from both sides once the artefact was cut. Vacuoles were indeed noticed on the original Breton axe-ingots, and they appear as small burst bubbles on the surfaces. They do not look deep however, but this assessment may only be superficial as no light shines through them and some may actually be much deeper. A second cut was made at the top third of the piece, across the much-pronounced swell. The imperfections consist of an off-centre large bubble that did not burst through the top surface, and some smaller peripheral bubbles (See Figure 11). This large bubble is almost ovoid with a small hollow at the top. It is 16.9 mm long, 11.8 mm across and 10.4 mm high. The two largest bubbles studied on this axe-ingot (top third and bottom third), are in swells on each side of the large central depression, demonstrating that when the dip formed, excess gases were pushed within the core metal on its margins and got trapped.

A cut across the middle of EAI2 revealed no defects but solid metal only. This cut was made in a section that does not exhibit any substantial imperfections except for a shallow dip running width-wise. In turn, a cut across the highest depression toward the cutting edge (broadly two thirds down), shows a small triangular cavity that began on the lower surface and goes almost to the top. This of course, is part of the defect that resulted in a diagonal hole. A small crack is also visible near this depression and runs to the top surface (See Figure 12).

Only one cut was made across EAI3. This was performed almost halfway up the piece, across the large central swell, the only major visible defect. The imperfections consist of trapped bubbles across most of the section. The smaller bubbles are located near the base (lower surface) and the edges. In the upper half, there are two larger bubbles on each side of the vertical central line. The largest is 6.7 mm across and 4.5 mm high (See Figure 13).

Experimental axe-ingot	Sand type	Lower surface	Upper surface	Core
accidental' cast	Wet green sand	Light pitting; large depressions	Low-swells	-
EAI1	Wet green sand	Pitting; depressions; perforations	Swells; vacuoles; perforation; grain-like protrusions; overflow on the edges	Trapped bubbles
EAI2	Very wet green sand	Light pitting; central dip; large depressions; perforations	Rippled surface; depression; grain-like protrusions; light overflowing on the edges	Cavity; crack
EAI3	Wet sand	Pitting; shallow depression	Rippled surface; vacuoles; swells	Trapped bubbles

TABLE1. SUMMARY OF VISIBLE CASTING DEFECTS ON THE 'ACCIDENTAL' EXPERIMENTAL AXE-INGOT AND THE THREE AXE-INGOTS DISCUSSED IN THIS PAPER.

Discussion

The present experiments with wet green sand were quite successful since the aim was to obtain porosity and perforations. However, some noticeable differences with the original Ploukilla type axe-ingots still remain. The Breton artefacts have better defined edges, and some of the surfaces appear somewhat flatter or at least more levelled. The lower surface of EAI1 may be compared to the 'accidental' cast, which in turn exhibits similar defects to the Belz (Morbihan) axe-ingot as was previously discussed (see Figure 5). Indeed, there is a large central depression and as well as a perforation towards the cutting edge (see Figures 5 and 7). The Belz axe-ingot also has a clearly visible perforation in the smaller depression toward its cutting edge also. This defect however, goes straight through the artefact, whereas the imperfection on EAI1 runs obliquely through the experimental piece. Where the upper side of EAI1 is concerned, the surface is in no way comparable. The grain-like protrusions and swells are simply not present on the axe-ingot from Belz (See Figure 14). The upper surface of the latter is indeed flat and the only notable defect is the exhaust hole towards the cutting edge, opposite the smallest depression. Moreover, the fin-like overflows created by the surge of metal towards the top of the edges, which appears on the experimental cast, are definitely not present on the Belz piece despite the obvious depression on the lower surface that would have pushed the copper in the opposite direction. Where the grain-like protrusions are concerned, it is interesting to note that those defects were only obtained on this axe-ingot and during Papillon's experiment using a clay mould. They are not present on any of the Breton artefacts.

A positive comparison can be made between the lower side of EAI2 and the lower sides of one of the axe-ingots from the Keranou, Ploudaniel hoard (Finistère) and one of the unprovenanced examples (See Figure 15). Indeed, these three axe-ingots exhibit similar defects, namely in their uneven surfaces and shallow depressions, and in their absence of swells. There are no perforations on the Ploukilla axe-ingots, however, and their outlines are much more regular (See Figure 15). Nonetheless, despite the double pour of EAI2, the results are here convincing.

The light porosity obtained on the lower surface of EAI3 echoes the defects visible on the corresponding side of another axe-ingot from the Keranou, Ploudaniel hoard (Finistère) (See Figure 16). The porosity on both axe-ingots is shallow and compact as opposed to the more pronounced porosity noticed elsewhere (EAI2 for example). However, the porosity on the Keranou axe-ingot is finer than on the experimental cast. The upper side of the Keranou artefact is very different to that of the experimental piece, as it does not have any swell or vacuoles (see Figures 8 and 16). The Breton artefact's upper surface is flat but some striations on the bottom half of the axe-ingot suggest some grinding and/or light polishing (see Figure 16). Even if there was originally a swell, it is problematic to suggest that it would have been ground off, as even if that was the case, trapped bubbles would most likely be visible in that portion of the artefact, as can be seen in the swell on EAI3.

Conclusion

Overall, those experiments demonstrate that wet green sand and wet sand could have been used for casting some of the original Ploukilla axe-ingots, as the casts obtained display similar defects as the original pieces. Yet, there are still noticeable differences such as straight/oblique perforations, presence/absence of swells and well-defined/poorly-defined edges. Despite the variations, porosity and perforations were achieved and since this was the aim of the present experiment, the results are positive. The various experiments performed over the years demonstrate that the Ploukilla axe-ingots were likely cast using various mould material such as wood, clay and sand. The results cannot constantly be compared like-for-like and many factors can affect the desired result. Those include the type of copper (amount of impurities in the metal for example), variations of casting temperature and of course mould material. The state of the Breton axe-ingots also differs from the similar examples recovered at Lough Gur, Co. Limerick. The two axe-ingots are solid pieces with only some light pitting on the lower surfaces (see Gandois et al. 2019, figure 8 for details). It can be suggested here that they were cast in green sand with low humidity content. This indicates that the copper destined to be traded between Ireland and north-west France was deliberately poorly cast as its function was most likely to be re-melted and alloyed with tin to create bronze metalwork. Poor casting also reflects a varied technical approach by ancient Irish metalworkers who were skilled enough to produce high-quality material (axeheads, daggers and halberds). Whilst the casting of the axe-ingots in an open mould is rather straight forward, a different technique had to be used for making the porous material. This is especially challenging from a safety point of view, as pouring molten copper in a wet sand mould will inevitably cause splattering.

Acknowledgements

I wish to thank my experimental casting colleague Henri Gandois for the pictures of the two axe-ingots from Plouhinec.

Keywords copper
axe
casting

Country France
Ireland

Bibliography

Briard, J., 1965. *Les Dépôts Bretons et l'Âge du Bronze Atlantique*. Rennes: Travaux du Laboratoire d'Anthropologie Préhistorique de la Faculté des Sciences de Rennes.

Briard, J. and Giot, P.-R., 1956. Typologie et chronologie du bronze ancien et du premier bronze moyen en Bretagne. *Bulletin de la Société Préhistorique de France* 53 (7-8), pp.363-373 [online] Available at < https://www.persee.fr/doc/bspf_0249-7638_1956_num_53_7_3348 > [Accessed 04 March2020].

Briard, J. and Maréchal, J.-R., 1958. Etude technique d'objets métalliques du Chalcolithique et de l'Âge du Bronze de Bretagne. *Bulletin de la Société Préhistorique de France* 55 (7-8), pp.422-430 [online] Available at < https://www.persee.fr/doc/bspf_0249-7638_1958_num_55_7_3680 > [Accessed 04 March 2020].

Burgess, C., 1974. The bronze age. In: C. Renfrew, eds., *British Prehistory, a New Outline*. London: Duckworth, pp.165-232.

Burgess, C., 1979. The background of early metalworking in Ireland and Britain. In: M. Ryan, eds., *The Origins of Metallurgy in Atlantic Europe. Proceedings of the Fifth Atlantic Colloquium, Dublin 30th March to 4th April 1978*. Dublin: The Stationery Office, pp.207-247.

Burlot, A., 2019. Ireland and France 2500-1900 BC: Evidence for Contacts and Influences. Unpublished PhD thesis. Cork: University College Cork.

Collins, A. E. P., 1970. Bronze Age moulds in Ulster. *Ulster Journal of Archaeology. Third Series* 33, pp.23-36 [online] Available at < https://www.jstor.org/stable/20567664?seq=1 > [Accessed 02 July 2020].

Delrieu, F., Gandois, H., Le Carlier, C., and Mélin, M., 2015. Un nouvel assemblage de haches-lingots dans la vallée du Rhône : le dépôt de Loyettes (Ain). *Bulletin de l'APRAB* 13, pp.41-49 [online] Available at < https://halshs.archives-ouvertes.fr/halshs-01844770/document > [Accessed 04 March 2020].

Gandois, H., Burlot, A., Mille, B., and Le Carlier de Veslud, C., 2019. Early Bronze Age axe-ingots from Brittany: evidence for connections with south-west Ireland? *Proceedings of the Royal Irish Academy* 119C, pp.1-36 [online] Available at < https://doi.org/10.3318/priac.2019.119.04 > [Accessed 01February 2020.

Gandois, H., Rousseau, L., Gehres, B., Le Carlier, C., Querré, G., Poissonnier, B., and Gilbert, J.-M., 2020. New hints of metallurgical activity on the Atlantic coast of France in the mid third millennium BC: overview and perspectives on Beaker metallurgy in western Europe. *The Antiquaries Journal*. Cambridge University Press Online Available at < https://www.cambridge.org/core/journals/antiquaries-journal/article/new-hints-of-metallurgical-activity-on-the-atlantic-coast-of-france-in-the-mid-third-millennium-bc-overview-and-perspectives-on-beaker-metallurgy-in-western-europe/FE84C719A687A179A2E60B5C912A7B94# > [Accessed 02 July 2020].

Harbison, P., 1969a. *The Axes of the Early Bronze Age in Ireland*. Munich: Prähistorische Bronzefunde 9.1.

Harbison, P., 1969b. *The Daggers and Halberds of the Early Bronze Age in Ireland*. Munich: Prähistorische Bronzefunde 6.1.

Hesse, A. H., 1941. Some Causes for Porosity and Leakage in Non-ferrous Castings. *Professional Degree Thesis* 283 [online] Available at < https://scholarsmine.mst.edu/professional_theses/283/?utm_source=scholarsmine.mst.edu%2Fprofessional_theses%2F283&utm_medium=PDF&utm_campaign=PDFCoverPages > [Accessed 04 March 2020].

Larson, T. S., 2009. Experiments Concerning the Mold Materials Used in the Production of the Copper Ingots from the Late Bronze Age Shipwreck Excavated at Uluburun, Turkey. Unpublished Masters thesis. San Diego: University of San Diego [online] Available at < https://www.semanticscholar.org/paper/Experiments-Concerning-the-Mold-Materials-Used-in-Larson/dab28268e6018699feb12dd92e1e8e1c47dbf61d > [Accessed 07 April 2020].

Needham, S. P., 2000. Power pulses across a cultural divide: cosmologically driven acquisition between Armorica and Wessex. *Proceedings of the prehistoric Society* 66, 151-207 [online] Available at < https://www.cambridge.org/core/journals/proceedings-of-the-prehistoric-society/article/abs/power-pulses-across-a-cultural-divide-cosmologically-driven-acquisition-between-armorica-and-wessex/65106BCCAA5241206B1BCCACE33AFC50# > [Accessed 02 July 2020].

Needham, S. P., 2017. *The Classification of Chalcolithic and Early Bronze Age Copper and Bronze Axe-heads from southern Britain*. Archaeopress, Access Archaeology [online] Available at < http://www.archaeopress.com/Public/displayProductDetail.asp?id=%7B7ADE470C-A94F-43E4-9B42-8454BFFBC170%7D > [Accessed 05 March 2018].

O'Brien, W., 2004. *Ross Island. Mining, Metal and Society in Early Ireland*. Galway: Bronze Age Studies 6 National University of Ireland.

O'Flaherty, R., 1995. An analysis of Irish Early Bronze Age hoards containing copper or bronze objects. *The Journal of the Royal Society of Antiquaries of Ireland* 125, pp.10-45 [online] Available at < https://www.jstor.org/stable/25549788?seq=1 > [Accessed 04 March 2020].

O'Kelly, M. J., 1970. An axe mould from Lyre, Co. Cork. *Journal of the Cork Historical and Archaeological Society* 75 (221), pp.25-28 [online] Available at < https://www.corkhist.ie/wp-content/uploads/jfiles/1970/b1970-003.pdf > [Accessed 07 April 2020.

Ottaway, B. S., and Seibel, S., 1998. Dust in the wind: experimental casting of bronze in sand moulds. In: M.-C., Frère-Sautot, eds., *Paléométallurgie des Cuivres. Actes du Colloque de Bourg-en-Bresse et Beaune, 17-18 octobre 1997. Instrumentum* 5, pp.59-63.

Papillon, F., 1997. Contribution à l'Étude de la Paléométallurgie du Cuivre et du Cuivre-Arsenic à Partir de l'Analyse des Éléments Légers et de Fusions Expérimentales. Unpublished PhD thesis. Paris: Université de Paris XI.

Corresponding Author

Aurélien Burlot
Department of Historical Studies
Gothenburg University
Box 200
40530 Göteborg
Sweden
E-mail Contact

Gallery Image

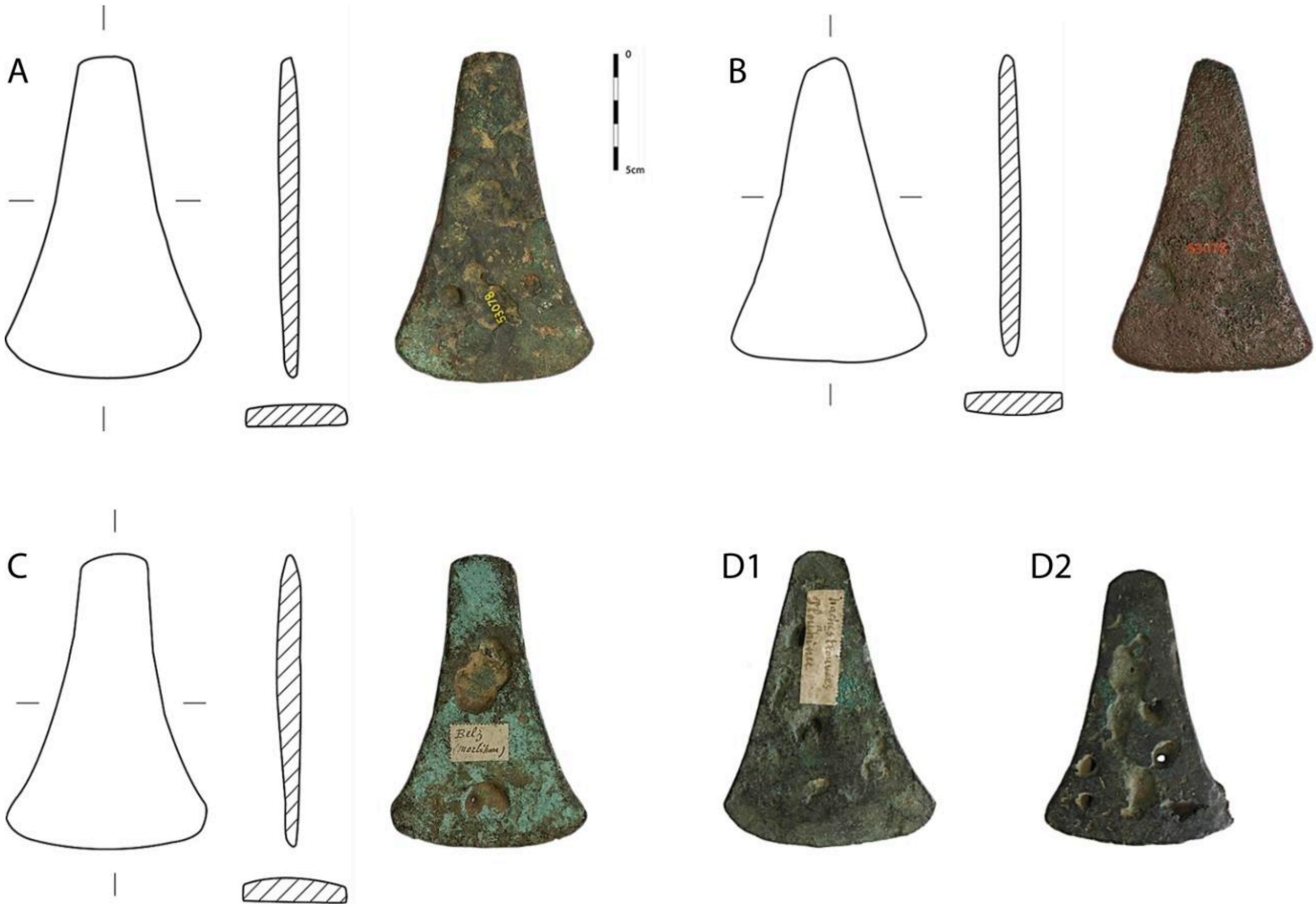

FIG 1. SOME OF THE PLOUKILLA TYPE AXE-INGOTS RECOVERED IN BRITTANY INCLUDING TWO EXAMPLES FROM THE KERANOU, PLOUDANIEL (FINISTÈRE) HOARD (A AND B), THE SINGLE FIND FROM BELZ (MORBIHAN) (C) AND TWO EXAMPLES FROM THE PLOUHINEC (FINISTÈRE) HOARD (D1-2) EXHIBITING VARIOUS CASTING DEFECTS (ILLUSTRATIONS AND PICTURES BY THE AUTHOR EXCEPT FOR D1 AND D2 COURTESY OF HENRI GANDOIS).

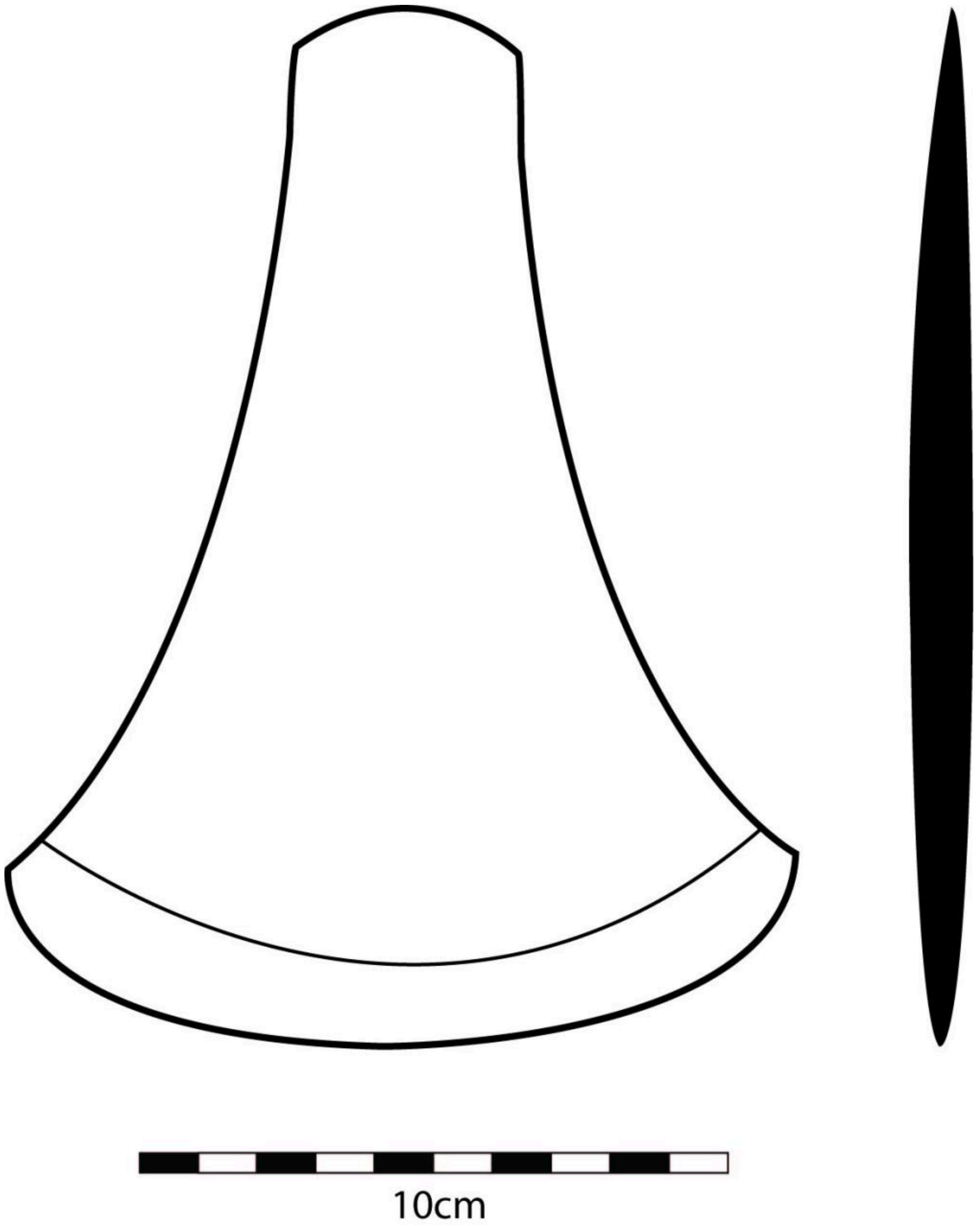

FIG 2. GENERAL SHAPE OF A KILLAHA TYPE AXEHEAD FROM IRELAND. OUTLINES REDRAWN BASED ON THE ARTEFACT FROM KNOCKASARNET, CO. KERRY (ILLUSTRATION BY THE AUTHOR BASED ON O'BRIEN 2004, FIG.231).

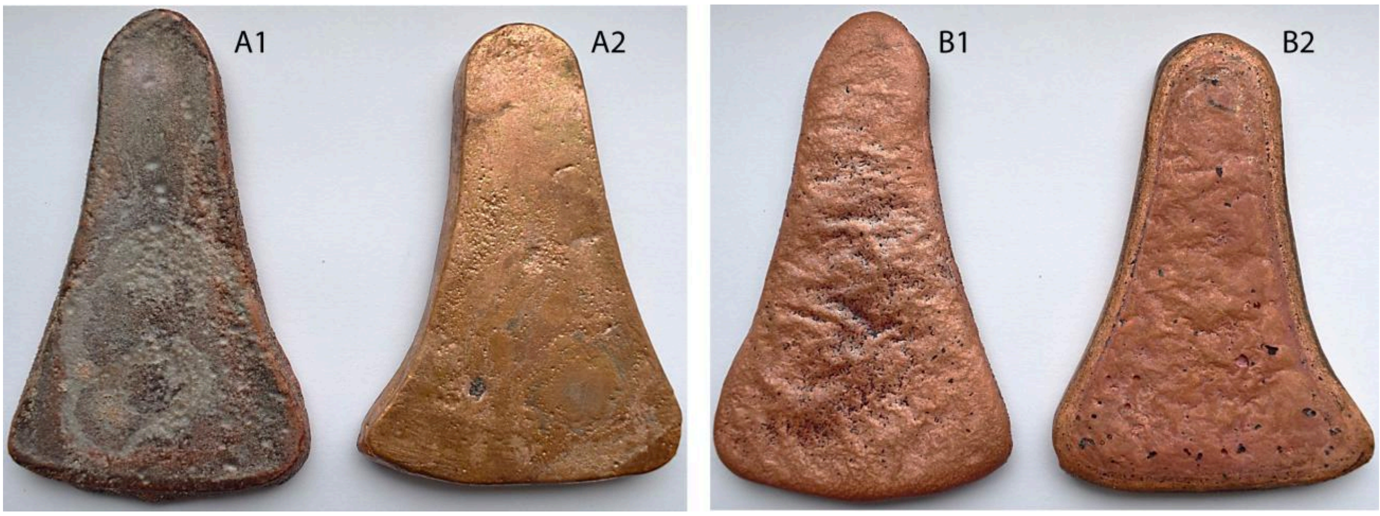

FIG 3. AXE-INGOTS CAST IN HOMEMADE GREEN SAND AND DELFT CLAY. MINIMAL CASTING DEFECTS ON LOWER SURFACE IN GREEN SAND (A1), LOWER SURFACE IN DELFT CLAY (A2), UPPER SURFACE IN GREEN SAND (B1) AND UPPER SURFACE IN DELFT CLAY (B2). PHOTO BY AURÉLIEN BURLOT

FIG 4. SURFACE OF THE SAND MOULDS AFTER CASTING. HOMEMADE GREEN SAND WITH A CRUMBLY SURFACE BUT NO BURNT MARKS (LEFT) AND SCORCHED AND FLAKY SURFACES IN DELFT CLAY (RIGHT). PHOTO BY AURÉLIEN BURLOT

FIG 5. SIMILAR CASTING DEFECTS (HIGHLIGHTED IN RED) ON THE BELZ (MORBIHAN) AXE-INGOT AND THE ‘ACCIDENTAL’ PIECE CAST IN WET GREEN SAND, INCLUDING LARGE CENTRAL DEPRESSIONS AND THE SMALLER DEPRESSIONS UNDERNEATH ON BOTH ARTEFACTS. PHOTO BY AURÉLIEN BURLOT

FIG 6. THE DOUBLE MOULDS MADE FOR EACH EXPERIMENT. THE SAND WAS COMPACTED WITHIN A METAL RING AND THE CLAY TEMPLATES PRESSED DOWN TO MAKE THE IMPRINTS. THE TEMPLATES WERE REMOVED USING A SCREW INSERTED WITHIN THE HOLE ON THE TOP. NOTE THE CRUMBLING TOP EDGE WITHIN THE LEFT IMPRINT. THIS CONTRIBUTED TO SOME OVERFLOWING WHEN THE COPPER WAS PUSHED UPWARDS AS IT REACTED WITH THE WET SAND AS SEEN ON THE FIRST EXPERIMENT (SEE FIGURE 7). PHOTO BY AURÉLIEN BURLOT

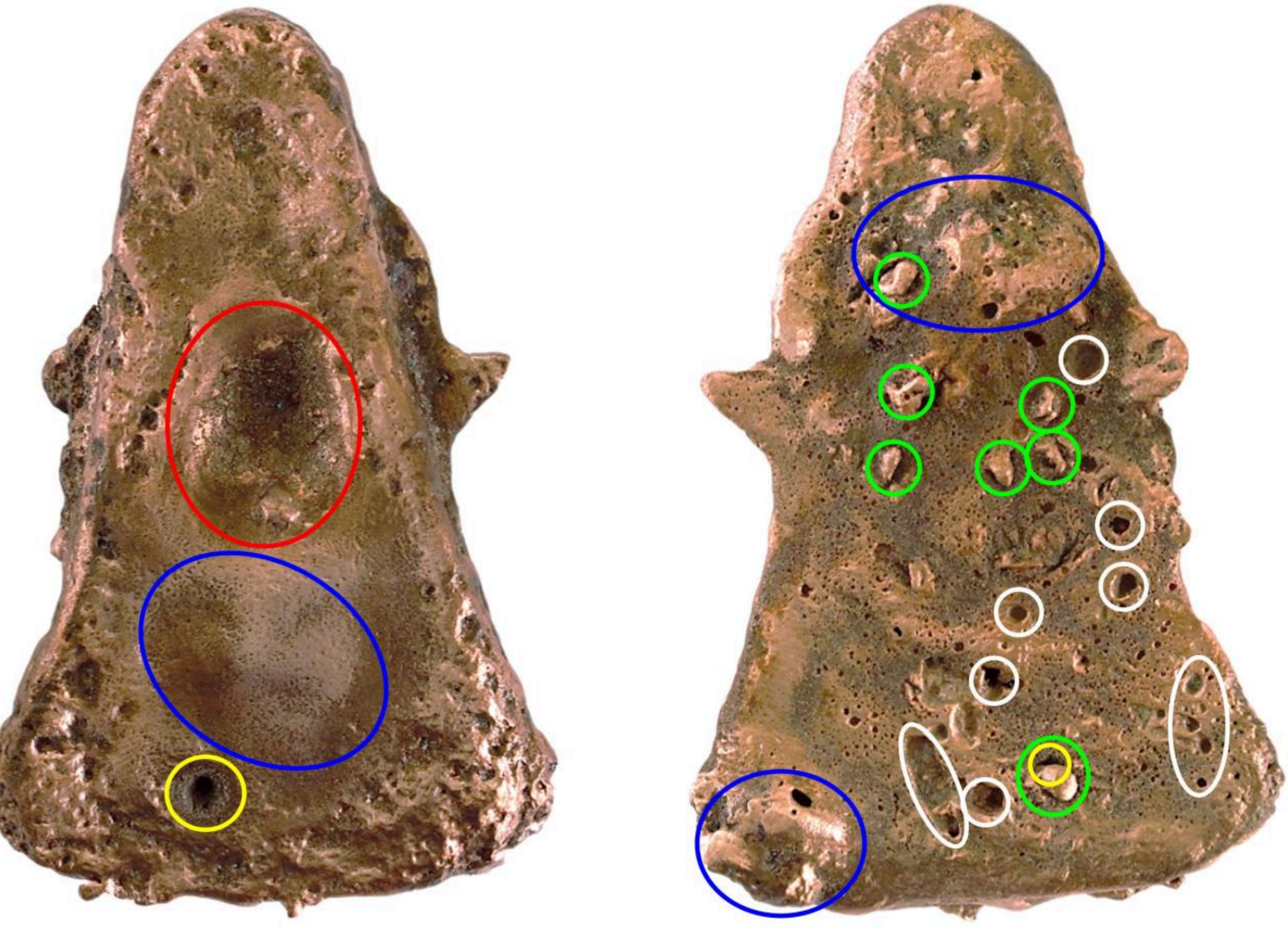

FIG 7. MAIN DEFECTS VISIBLE ON THE LOWER (LEFT) AND UPPER (RIGHT) SURFACES OF EAI1, INCLUDING THE LARGE DEPRESSION (IN RED), SWELLS (IN BLUE), AN ENTRANCE HOLE (ON THE LEFT) AND CORRESPONDING EXIT HOLE (ON THE RIGHT) (IN YELLOW), LARGE GRAIN-LIKE PROTRUSIONS (IN GREEN) AND SOME OF THE LARGEST VACUOLES/GROUPED VACUOLES (IN WHITE). PHOTO BY AURÉLIEN BURLOT

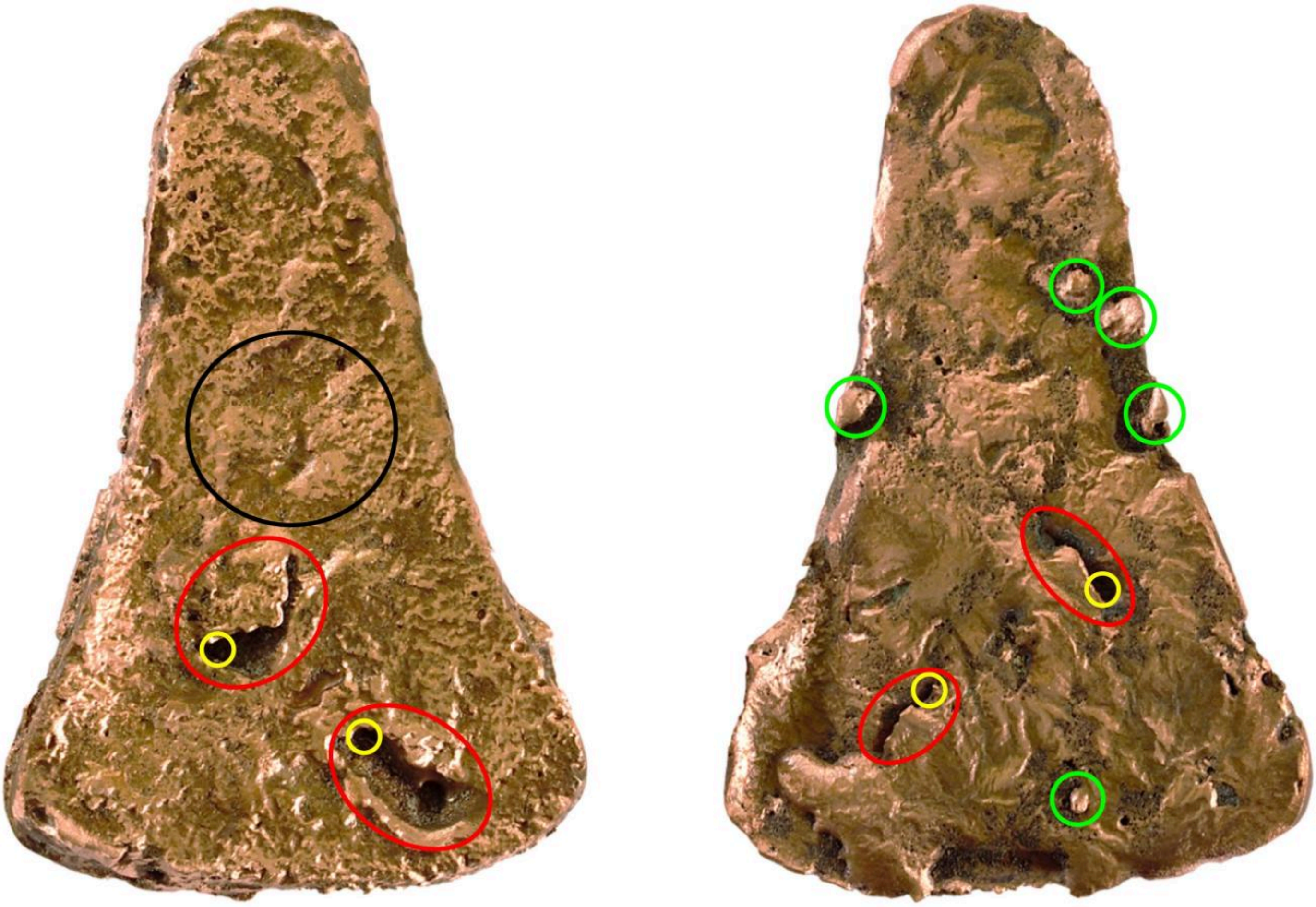

FIG 8. MAIN DEFECTS VISIBLE ON THE LOWER (LEFT) AND UPPER (RIGHT) SURFACES OF EAI2, INCLUDING THE WIDE BUT SHALLOW DIP (IN BLACK), LARGEST DEPRESSIONS (IN RED), ENTRANCE HOLES (ON THE LEFT) AND CORRESPONDING EXIT HOLES (ON THE RIGHT) (IN YELLOW) AND LARGE GRAIN-LIKE PROTRUSIONS (IN GREEN). PHOTO BY AURÉLIEN BURLOT

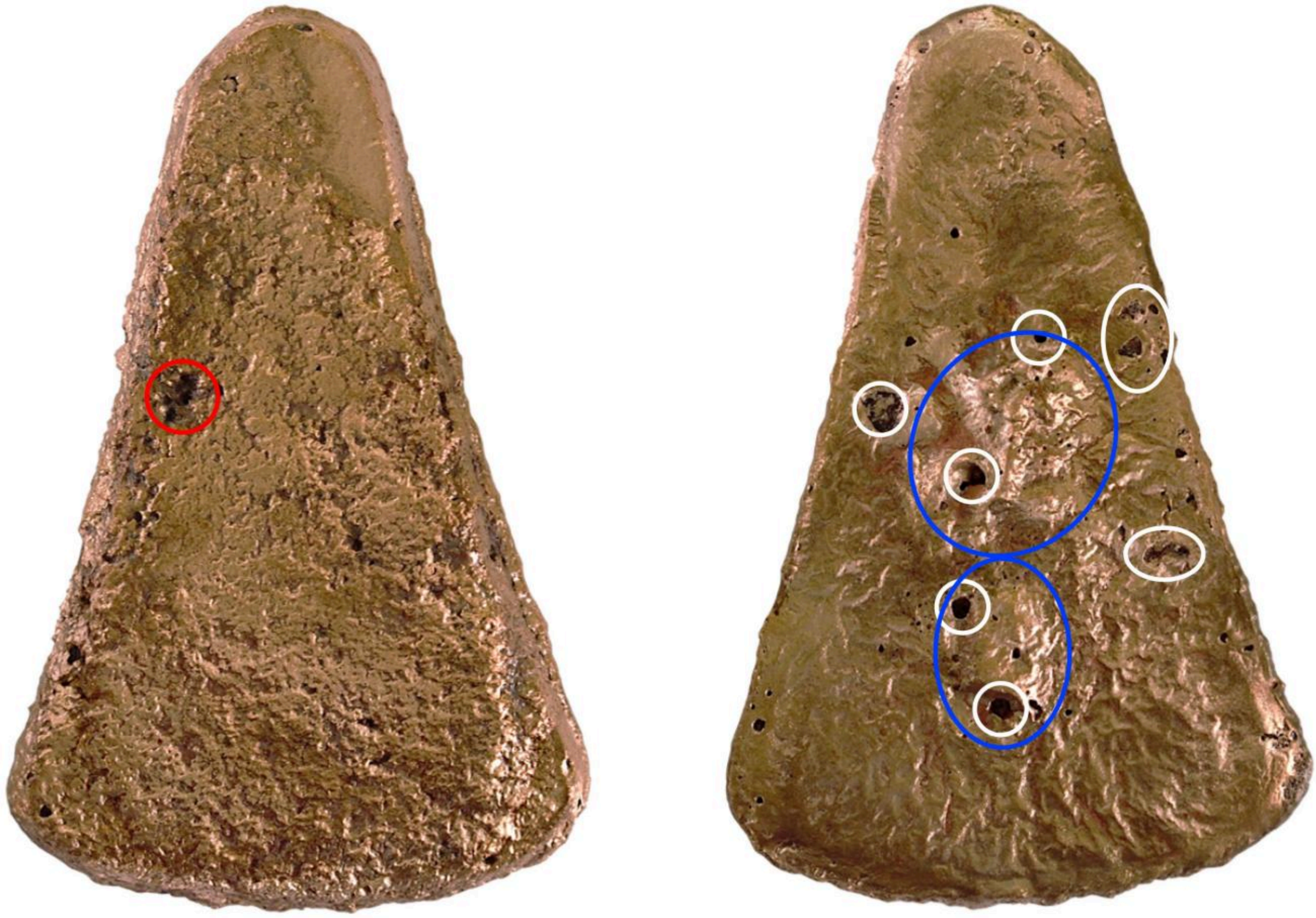

FIG 9. MAIN DEFECTS VISIBLE ON THE LOWER (LEFT) AND UPPER (RIGHT) SURFACES OF EAI3, INCLUDING PITTING ACROSS MOST OF THE LOWER SURFACE, THE ONLY SIGNIFICANT DEPRESSION (IN RED), THE TWO MAIN SWELLS (IN BLUE) AND SOME OF THE LARGEST VACUOLES/GROUPED VACUOLES (IN WHITE). PHOTO BY AURÉLIEN BURLOT

FIG 10. TRAPPED GAS BUBBLE WITHIN THE CORE OF EAI1 WITHIN THE MAIN SWELL (SEE FIGURE 7 IN BLUE). THE ARROW SHOWS THE LOCATION AND ANGLE OF THE EXHAUST VACUOLE. PHOTO BY AURÉLIEN BURLOT

FIG 11. LARGE TRAPPED GAS BUBBLE WITHIN THE CORE OF EAI1 WITHIN THE SWELL TOWARDS THE BUTT (SEE FIGURE 7 IN BLUE). PHOTO BY AURÉLIEN BURLOT

FIG 12. DEFECTS WITHIN THE CORE OF EAI2 INCLUDING THE SMALL DEPRESSION LOCATED BELOW THE CENTRAL DIP WHICH HAD A HOLE IN IT (SEE FIGURE 8 IN RED AND YELLOW), AS WELL AS A SMALL BUT NOTICEABLE CRACK RUNNING TOWARDS THE TOP SURFACE. PHOTO BY AURÉLIEN BURLOT

FIG 13. TRAPPED GAS BUBBLES WITHIN THE CORE OF EAI3 INCLUDING TWO CENTRALLY LOCATED AND SOME SMALLER ONES ON THE EDGES, NOTABLY NEAR THE BASE. PHOTO BY AURÉLIEN BURLOT

FIG 14. COMPARISON OF THE UPPER SURFACES OF EAI1 (LEFT) AND THE BELZ (MORBIHAN) AXE-INGOT (RIGHT). DESPITE SOME CLEAR SIMILARITIES ON THE LOWER SURFACES, THE UPPER SURFACES ARE TOTALLY DIFFERENT. PHOTO BY AURÉLIEN BURLOT

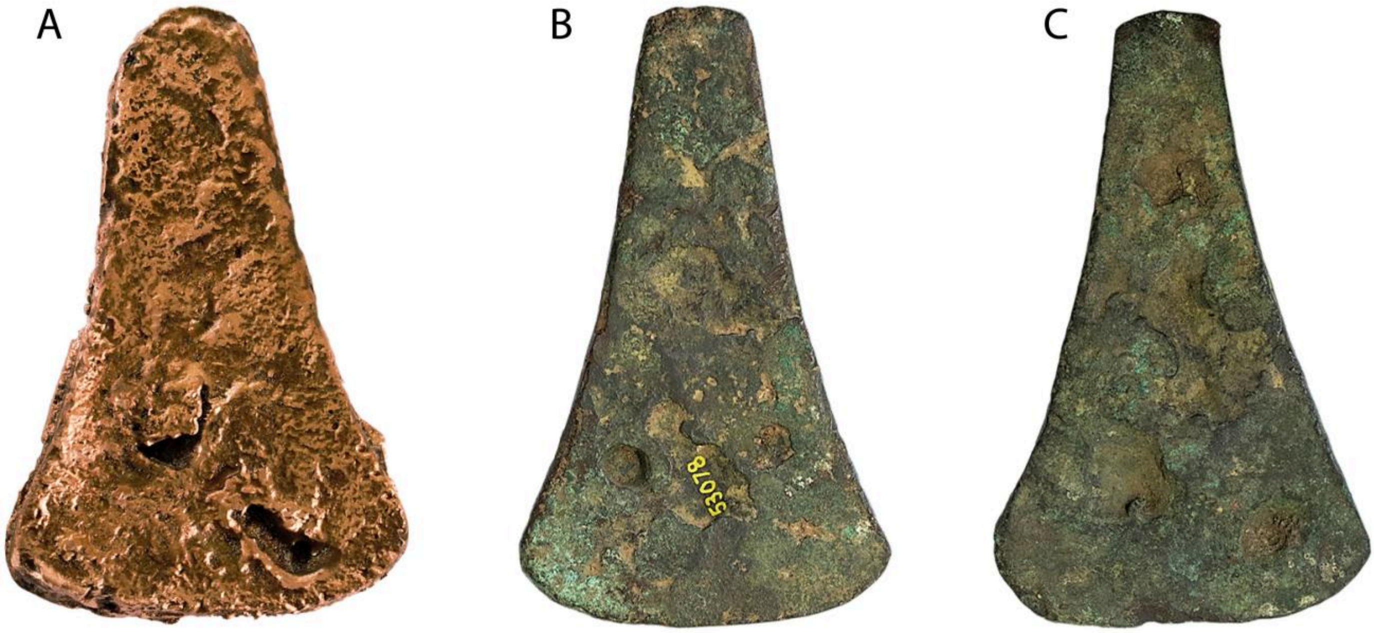

FIG 15. COMPARISON OF THE LOWER SURFACES OF VARIOUS AXE-INGOTS INCLUDING EAI2 (A), AN EXAMPLE FROM THE KERANOU, PLOUDANIEL (FINISTÈRE) HOARD (B) AND AN UNPROVENANCED EXAMPLE (C). THESE OBJECTS CLEARLY EXHIBIT SIMILAR CASTING DEFECTS. PHOTO BY AURÉLIEN BURLOT

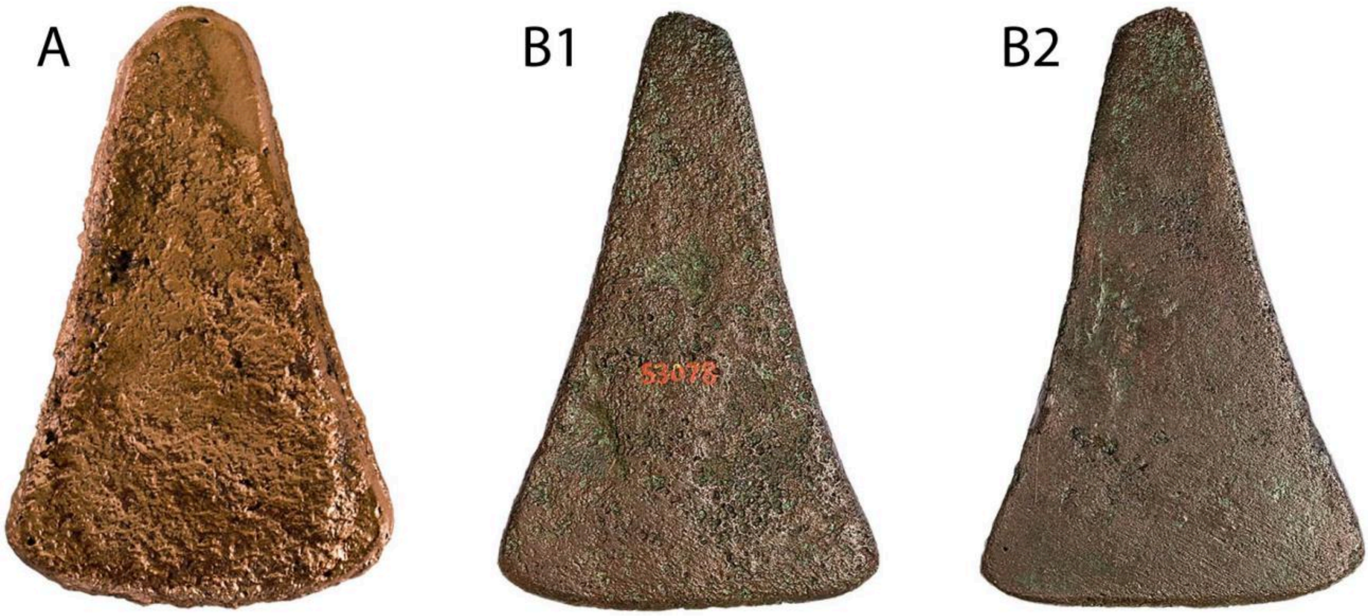

FIG 16. COMPARISON OF THE LOWER SURFACES OF EAI3 (A) AND OF AN EXAMPLE FROM THE KERANOU, PLOUDANIEL (FINISTÈRE) HOARD (B1), SHOWING SIMILAR POROSITY ACROSS THE SURFACES. THE UPPER SIDE OF THE KERANOU AXE-INGOT (B2) DIFFERS FROM THE UPPER SIDE OF EAI3 (SEE FIGURE 8). NOTE THE STRIATIONS ON B2 RUNNING TOWARDS THE BOTTOM RIGHT CORNER DEMONSTRATING SOME LIGHT GRINDING OR POLISHING. PHOTO BY AURÉLIEN BURLOT