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Reconstructing manufacturing technologies: microscale analysis on the first Greek metals

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ABSTRACT

At the end of the sixth and the beginning of the fifth millennium BC, inhabitants of the areas in and around the Aegean Sea started to use native or pure metals (copper, gold, and silver) to make tools and ornaments. As a dynamic period in terms of exchange and technical innovations, the Late Neolithic/Chalcolithic provided an ideal background for the first metalwork practices of Greece. More than 370 objects have been recorded so far as evidence of this craft. Knowledge about their manufacturing processes is scarce: neither workshops nor tools have been securely identified yet. However, technical actions have left traces on the objects, still visible when the object is not too corroded. These can be distinguished on their surface under digital microscope (Dino-Lite), up to a magnification of x250. After testing different technical processes through experimental archaeology, one can compare the archaeological and experimental traces. This approach has been conducted for the study of copper finds from northern Greece (Sitagroi, Dikili Tash, Kryoneri, and Dimitra). It allows us to suggest a set of manufacturing techniques integrated in the context of early metalworking.

1. Introduction

Manufacturing and use-wear studies, often combined with experimental archaeology, have been recently applied to reinterpret prehistoric metal artefacts (see Dolfini & Crellin, 2016). This paper applies a similar approach to the emergence of copper metalwork in Neolithic Greece, aiming to a better understanding of the manufacturing techniques specific to a newly introduced material within a predominantly "lithic society". To this end, material from old and new excavations, discovered in securely dated levels of the period, has been re-examined from a technological perspective. Since the findings are concentrated in the northern regions of Greece, this research focuses on eastern Macedonia.

A step forward is made here, moving beyond the unfamiliarity of these objects through an exploration of the techniques involved in their production, framed within a "*chaîne opératoire*". Although the makers are long gone, traces of their technical actions remain inscribed on the artefacts' surfaces. Careful examination of the surviving pieces, combined with experimental replication, allows us to reconstruct the manufacturing techniques used to make them. Yet such work can only offer a partial glimpse into what Neolithic metalworking may have been.

Metal artefacts in Aegean Neolithic contexts have often been overlooked, but they are well attested in archaeological layers alongside tools and ornaments of stone, clay, bone, and shell. By focusing on technological issues, this study reconsiders a scarce yet meaningful material and highlights the recognition it deserves. Beyond applying an original approach to these artefacts, it also aims to encourage future studies to engage more closely with comparable discoveries.

2. The context of the study

Previously, it was assumed by scholars that prehistoric copper metallurgy, in the Levant and the Balkans, passed in a linear way through several stages, starting with cold working of native copper, then annealing and finally, smelting and casting (Forbes, 1964: 24–25; Wertime, 1964: 1260–61; Tylecote, 1987: 90). Lastly, these claims have been questioned (Yener, 2000:8–9; Roberts et al., 2009: 1019; Helwing, 2013: 107; see also Kienlin, 2011, 2016; Pearce, 2019). Indeed, more recent research argued for a non-linear development, with different technical stages from site to site, testifying to the plurality of the first metallurgical practices (see Barthomeuf, 2004 for the Near East; Thornton, 2009 for the Middle East; Radivojević & Rehren, 2015;

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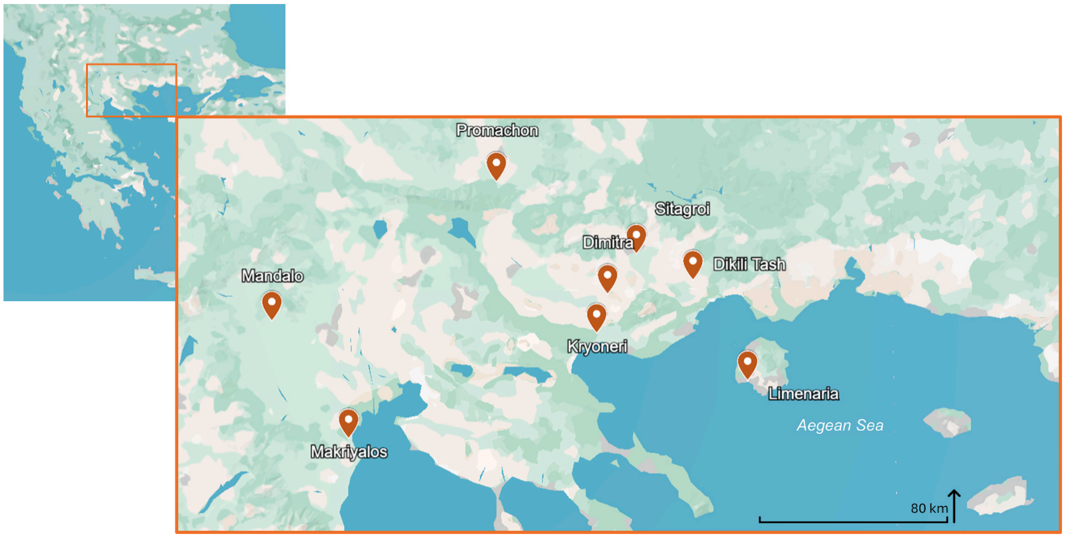

Fig. 1. Map of the sites mentioned in the text. Map lines delineate study areas and do not necessarily depict accepted national boundaries. © Google MyMaps, V. Martin.

Radivojević & Roberts, 2021 for the Balkans). These different forms of metallurgy are encountered in the prehistoric Aegean, albeit in a non-linear and disparate manner, across the inhabited territory (see Papadatos, 2007; Papadopoulos, 2008; Zachos, 2010; Bassiakos, 2012; Bassiakos et al., 2019; Malamidou et al., 2022).

The beginnings of metallurgy and metalworking[1] in Greece are to be found at some point during the Late Neolithic (LN), a period which covered the second half of the sixth millennium BC to the end of the fifth millennium BC.[2] In addition of using native copper, it is known that smelting was practised from the beginning of the fifth millennium BC in northern Greece (Koukouli-Chryssanthaki & Bassiakos, 2002: 193; Malamidou et al., 2022: 460).[3] Different kinds of mineral ores and native metals were used: copper ores, native copper, silver-lead ores, and native gold. The manufactured objects were varied, from tools to ornaments: copper awls, chisels, hooks, axes, blades, pins and beads, gold and silver pendants, beads, and rings (Branigan, 1974: 97–98; Zachos, 1996: 142–43, 2007, 2010).

Of the more than 370 objects recorded by the author from Greek Late Neolithic contexts, the majority – and the oldest examples – come from the northern regions, i.e. Thessaly, Macedonia, and Thrace (Branigan, 1974: 98, 219; McGeehan-Liritzis, 1996: 208) (Fig. 1).

Furthermore, while there is evidence of native copper working (Treuil, 1983: 189), it would also appear that the Aegean populations practised smelting and melting in some places. The sites where we found clearest evidence of metallurgical and metalwork activities are given in the table below (Table 1). Both have been practised simultaneously, as at Sitagroi, as early as the fifth millennium BC (Renfrew, 1970: 300, 1972: 310–11, 1973: 475; Branigan, 1974: 98–99; Muhly, 1985: 114; Elster & Renfrew, 2017: 471; Malamidou et al., 2022: 454–55). Although no moulds were found at Sitagroi, casting could have been practised as well. Indeed, metallographic analysis has shown that some end-products have been shaped by cold hammering and annealing (Renfrew & Slater, 2003: 320, pl. 8.9: a, c), while others have been cast (Renfrew & Slater, 2003: 320, pl. 8.9: b).

Other discoveries in Macedonia provide evidence of metallurgical activities and copper smelting technology in LN levels (Fig. 1). Metallurgical remains, such as fragments of mineral ores, copper prills, crucibles or slags have been found at Mandalo, Makriyalos, Promachon,[4] Limenaria, and Dikili Tash (Table 1).[5] One find is particularly noteworthy because of its rarity: a metallurgical casting-mould from fired clay dated from the LN II from Dikili Tash, with traces of copper inside revealed by XRF-analysis (Darcque et al., 2020: 75, fig. 3.39: e; Malamidou et al., 2022: 456, Fig. 7). Those finds reflect the range of metal related operations during the fifth and the beginning of the fourth millennium BC in northern Greece.

Despite the previously mentioned discoveries, securely identifying metallurgical firing structures requires an adequate technological approach (Sériadès, 1983: 647; Renfrew et al., 1986: 212; Treuil, 1992: 41–42; Koukouli-Chryssanthaki et al., 2007: 48; Malamidou et al., 2022: 456). Smelting could have taken place in the furnaces and hearths excavated at Makriyalos, although none of them is securely associated with metallurgical activities (Pappa et al., 1998: 277–78). The cavities found at Promachon could have also been used as smelting pits. Nonetheless, such places have not yet been firmly established for the Neolithic in Greece. It would be interesting to compare certain presumed metallurgical installations with others confirmed as metallurgical for the same period but in other regions (Radivojević & Rehren, 2021a: 127–28). However, it is quite possible that metalworking in the Levant and the Balkans was carried out on a small scale and in a domestic setting during the Neolithic.[6]

The types of tools used remain so far unknown; indeed, we have never found tools securely associated with metalworking in LN levels in

[1] These terms are separated in this study, as they are associated with two different steps in the making process of a metal object: "metallurgy" refers to the extraction of metal from the ore (i.e. smelting) and "metalworking" to the shaping of an object from this raw material (*i.e.* hammering or casting).

[2] Depending on the region and the authors, the second half of the fifth millennium BC may also be designated as "Chalcolithic" or "Final Neolithic".

[3] More widely, it is accepted that metallurgy was adopted as early as the end of the sixth millennium BC in the Balkans (Radivojević et al., 2010: 2782; Radivojević & Roberts, 2021: 213).

[4] The Promachon material was re-examined with Scanning Electron Microscope (SEM) and XRF-analysis in 2023–2024 by the author in collaboration with E. Filippaki and I. Bassiakos (N.C.S.R. 'Demokritos'). The results have not yet been published.

[5] Those types of archaeological remains have been also well described by M. Radivojević (slags, fragments of ores, "slagged sherds", and copper droplets) for sites located in Serbia and Bosnia and Herzegovina, dated between the end of the seventh and the fifth millennia BC (see Radivojević, 2015).

[6] The fire may have been part of a domestic context, or an artisanal work area. Both scenarios have been suggested for Belovode and Pločnik in Serbia, for the same period that interests us, i.e. the first half of the fifth millennium BC (Radivojević & Rehren, 2021b: 304).

Table 1
Metallurgical and metalworking evidence at LN sites in northern Greece.

Site	Archaeological evidence	Related activities	Datation	Bibliography
Sitagroi	36 fragments of crucibles covered with molten copper	Smelting and melting	Sitagroi III: 4800–4250 BCE	Renfrew & Slater, 2003: 303, fig. 8.4
Mandalo	Slags and a clay crucible	Smelting	Mandalo II: 4200–4000 BCE	Pilali-Papasteriou et al., 1986: 461; Kotsakis et al., 1989: 682–83; Pilali-Papasteriou & Papaefthimiou-Papanthimou, 1989: 24, 26–27; Papaefthimiou-Papanthimou & Pilali-Papasteriou, 1996: 146; Papaefthimiou-Papanthimou, 2017: 273, fig. 536
Makriyalos	65 copper artefacts, including a reduction slag	Smelting and melting	Makriyalos II: 4950–4600 BCE	Pappa et al., 1998: 276–78, tab. 3; Pappa & Besios, 1999: 188–89; Pappa, 2020: 235
Promachon	3 round cavities made up of successive layers of ash and clay, one containing a crucible, surrounded by small fragments of copper and malachite	Smelting	Phase III: 4460–4250 BCE	Koukouli-Chryssanthaki & Bassiakos, 2002; Koukouli-Chryssanthaki et al., 1998: 68–70, fig. 4, 2005: 106, 2007: 48–50, fig. 7.1, 2017: 432
Limenaria (Thasos)	Crucible fragments and slags	Smelting	First half of the fourth millennium BC	Papadopoulos, 2008: 68–70; Bassiakos, 2012: 197–98, 208; Bassiakos et al., 2019: 2744; Malamidou et al., 2022: 8
Dikili Tash	Fragments of crucibles, copper and ore residues	Smelting and melting	Dikili Tash II: 4800–4200 BCE	Not published[a]

[a] This material has been recently found, during the latest excavation programme (2019–2024) on sector 9. It remains unpublished for now and is being studied as part of a doctoral thesis currently conducted by the author.

Greece. On the other hand, several works have been conducted on metalworkers' tools from Bronze Age Europe, which include stone hammers and anvils, stone and clay moulds, and abrasive stones (Armbruster, 2000: 34–65, 2006, 2010; Freudenberg, 2010; Boutoille, 2015; Pieters, 2016). Such stone tools, always present in the metalworker's toolkit[7] and gradually but never entirely replaced by metal tools, were probably already in use in the Neolithic period (Armbruster, 2006: 323, 2010: 12; Boutoille, 2015: 84; Leusch et al., 2017: 106–07; see also Karimali, 2008: 323, 2010: 164). Some of them may have been found but misinterpreted and not associated with metalworking activities, as it already happened in some archaeological collections (see Freudenberg, 2006).

There are probably other less familiar tools, for example to ventilate the hearth (tuyères, bellows),[8] or originally made of organic material and so absents from archaeological contexts (tweezers) (Armbruster, 2006: 324, 2010: 11). The use of multi-purpose tools, such as stone pillars, mortars or pebbles, also employed for other household activities involving crushing or rubbing, is conceivable (Deshayes, 1960: 24; Yener, 2000: 19; Pieters, 2016: 83; see also Karimali, 2008: 317). This second range of tools could have been used for both metal production and metalworking. If annealing or casting were practised, oxygen-supply system parts and tweezers were needed. The aforementioned multi-purpose tools may have been used to crush ores prior to smelting and to shape metal through hammering.

Table 2
List of the original inventory numbers of the objects given by the excavators and, if so, in the related publications.

Code	Inventory number	Publication
DI014	M324	Grammenos 1997
DI016	M242	
DI018	M272	
DI019	M304	
DI020	M294	
DI021	M283	
KR001	Δ5	Malamidou 1997, 2016
KR005	Δ1	
KR007	Δ2	
KR008	Δ9	
SI001	SF 783	Renfrew & Slater 2003
SI007	SF 5334	
SI016	SF 30	
SI017	SF 335	
SI020	SF 1238	
DT002	2053–004	Darcque et al. 2020
DT004	2025–003	
DT008	5.310.104/10/48	
DT009	6266–035	
DT010	6266–048	
DT035	M713	Sériadès 1992
DT036	M632	
DT037	M247	
DT043	M4	
DT045	M173	
DT046	M313	
DT047	M1	
DT048	M225	
DT051	M3	
DT053	Δ22	Zachos 2007
DT054	M194	Séfériadès 1992
DT063	9479–006	–
DT064	9409–005	
DT065	9464–004	
DT074	9664–001	

3. Selecting archaeological finds

The manufacturing techniques of neolithic metalworking have been explored through the direct study of remains from a limited number of archaeological sites. The finds and their contexts have been selected as a representative sample of this phenomenon (Table 2).

[7] Noteworthy is also the case of stone tools from the Neolithic and Bronze Age, re-used in a metallurgical workshop context dated to the Late Geometric (seventh century BC) at the Ancient Methone, Central Macedonia (Manos & Vlastaridis, 2023).

[8] Fragments of *tuyères* or parts of "ventilation system" are known for the EBA in Greece, for example at Agios Sostis, on the island of Sifnos in the Cyclades (Gropengiesser, 1986: 6) or at Agios Dimitrios in the Peloponnese (Zachos, 2008: 77, 98). But to our knowledge, there are no known cases from the LN.

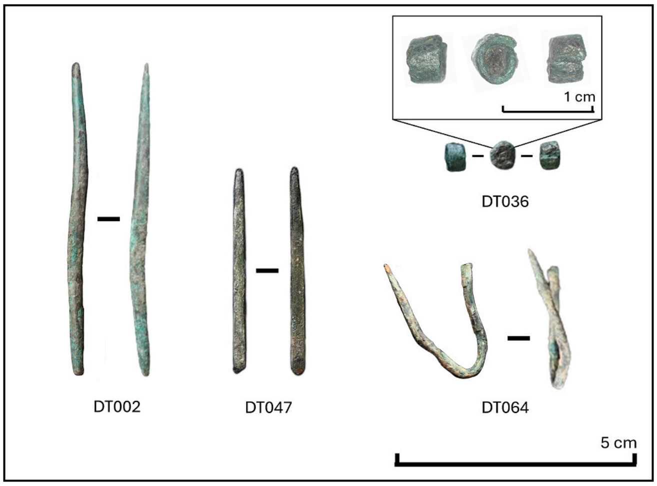

Fig. 2. A sample of the studied copper objects, all coming from Dikili Tash. © Greek Ministry of Culture/Ephorate of Antiquities of Kavala, Archaeological Mission of Dikili Tash/École française d'Athènes, V. Martin.

3.1. The archaeological sites

Northern Greece is a region rich in Neolithic sites, at which numerous surveys have been carried out since the beginning of the twentieth century (Wace & Thompson, 1912: Ch.1; Heurtley, 1939: 1–40). For this study, copper finds have been selected from the LN levels of Dikili Tash, Sitagroi, Kryoneri, and Dimitra (Fig. 1). All these sites are located in eastern Macedonia, in the Strymon valley, which connects Bulgaria and northern Greece. They are spatially close (Darcque et al., 2020: 5), but also chronologically: the levels Sitagroi I–II, Dikili Tash I, and Dimitra I are contemporary, and the same is true for the subsequent levels Sitagroi III, Dikili Tash II, and Kryoneri (Renfrew et al., 1986: tab. 7.3; Treuil, 1992: 32; Grammenos, 1997: 28; Malamidou, 1997: 512; Zachos, 2010: 81; Malamidou, 2016: 302; Tsirtsoni, 2016: tab. 1).

Copper objects, including beads, awls, fish-hooks, pins, needles, and small pieces of copper have been discovered in the related layers of each site.[9] Alongside those from Dikili Tash I, the objects from Sitagroi are the earliest metal finds from the Aegean (Muhly, 1985: 109; Aslanis & Tzachili, 1995: 90). Analysed with the Electron Microprobe Analysis (EMA) technique by E. Slater, they appear to be made of a very pure copper, possibly from native metal or smelted copper (Renfrew, 1970: 300; Renfrew & Slater, 2003: 305–06, tab. 8.2). The use of pure copper was also attested for the copper tools and ornaments from Kryoneri, through Scanning Electron Microscope (SEM) analysis carried out by Y. Maniatis (Malamidou, 1997: 518, 2016: 311). Finally, at Dimitra, fourteen metal items have been analysed with the Particle Induced X-ray Emission (PIXE) technique by E. Mirtsou, U. Zwicker, K. Nigge, and A.A. Katsanos, who detected cold hammering and annealing on pure copper (Mirtsou et al., 1997: 93–94).

3.2. Awls, Hooks, and beads

The first metal objects found for the Levant and the Balkans are described as small, slight, and thin (Lambert, 1981: 216; Tylecote, 2002: 8). These types of objects are considered as the most ancient metal ones, appearing sporadically since the seventh millennium BC in the Near and Middle East, and the sixth millennium BC in eastern and central Europe (Tylecote, 1987: 90, 2002: 1; Mohen, 1990: 48–49; Ottaway & Roberts, 2008: 195). Mohen (1990: 51) even refer to a 'tradition of the first metal objects'. In Aegean Neolithic assemblages, three kinds of copper artefacts have been recurrently found: awls, fish-hooks, and cylindrical rolled-up beads. Some of them have therefore been selected for study from Dikili Tash,[10] Sitagroi,[11] Kryoneri, and Dimitra[12] (Fig. 2).

Two objects from Sitagroi, a "pin"[13] (SI016[14]) and a hook (SI017) have also been included, although those have been found in the levels of Sitagroi IV, that correspond to the second part of the fourth millennium BC, i.e. the EBA (Renfrew & Slater, 2003: 320; Tsirtsoni, 2016: tab. 1). Indeed, both are of the earliest objects of these kinds found on the site alongside SI020, from Sitagroi III.

The numerous awls from Dikili Tash have previously been classified into three different categories, according to their length, thickness, and cross-sectional shape (Séfériadès, 1992: 115). However, the wider dataset indicates a slightly different picture (Table 3). Taken together, two principal groups emerge: thin, long, and quadrangular-sectioned awls (DT035, DT043, DT048, DT053, DT054), and the thick, short awls with bevelled base (SI016, DT008, DT045, DT046, DT047, DT051, DT063). EMA and SEM analysis have been conducted by the excavators on five of the twenty-two awls gathered for this study (Table 3). Their composition appears to be that of pure copper (see Séfériadès, 1992: tab. 12 for DT035 and DT048; Malamidou, 1997: 518, 2016: 311 for KR001; Renfrew & Slater, 2003: tab. 8.2 for SI016 and SI020).

Although slightly less common than awls, fish-hooks have also been found in LN and Early Bronze Age (EBA) levels in Greece (Treuil, 1983: 151–52). The earliest copper hooks appear to be of a simple type, without a loop or a barb (Branigan, 1974: 29; Treuil, 1983: 152; McGeehan-Liritzis, 1996: 101). Of the four selected copper hooks, KR005 and DT037[15] are simple twisted wires, while SI017 is flattened at the end of its shank (Table 4). However, it cannot be ruled out that some Neolithic hooks such as DT064 might originally have had a loop (Fig. 2, lower right; Fig. 18, c). Only DT037 have been chemically analysed by M. Asiménos, indicating copper as main element with a few minor elements (Séfériadès, 1992: tab. 12).

The beads found in Neolithic contexts and associated with metallurgical activities are of two types: the rolled-up beads that have been securely identified as being made from copper, and discoidal beads, made of malachite.[16] This second case will not be discussed in this paper, as their manufacturing processes are closer to stone-bead making (Glumac, 1991: 204). The first type is of interest for its recurrence in Aegean Neolithic and Bronze Age levels (Branigan, 1974: 39; Treuil, 1983: 489). Alongside the seven rolled-up and cylindrical-shaped beads, two additional types have been selected: one tubular-shaped (DT010)

[9] See Malamidou et al., 2022: 453–56, for a recent overview of these copper finds and their contexts.

[10] The metal objects from the different excavation campaigns are stored at the site, in the Archaeological Museum of Philippi, and in the Archaeological Museum of Kavala. The excavators, P. Darcque, H. Koukouli-Chryssanthaki, D. Malamidou, R. Treuil, and Z. Tsirtsoni, as well as the Ephorate of Antiquities of Kavala, kindly authorized the author to study them.

[11] The metal objects from Sitagroi are exhibited and stored in the Archaeological Museum of Drama, under the authority of the Ephorate of Antiquities of Drama, who authorized the author to study them, with the kind permission of the excavators, C. Renfrew and E.S. Eslter.

[12] The metal objects from Kryoneri, as well as those from Dimitra, are kept in the storeroom of the Ephorate of Antiquities of Serres, who gave its authorization for material studies, also with the kind permission of D. Malamidou and D.V. Grammenos.

[13] SI016 has been identified as a pin by the excavators but is considered as an awl in this paper.

[14] This code is given by the author and indicates the object's provenance, i.e., DT for Dikili Tash, KR for Kryoneri, SI for Sitagroi, and DI for Dimitra. Each object has originally received an inventory number from the excavators, listed in table 2.

[15] This object is considered as an awl in the first publication of the excavations of Dikili Tash (Séfériadès, 1992: 115).

[16] Discoidal malachite beads have been found alongside metallurgical finds at Neolithic sites in Northern Greece, such as Makriyalos (Pappa et al., 1998: 175), and Promachon (Koukouli-Chryssanthaki et al., 2007: Fig. 8).

Table 3
Summary table of the examined copper awls for this study.

Code	Context	L.	Th.	Section	Description	Focus area	Trace(s)
DI014	LN I	2.3	0.2	■ ●	Thin awl fragmented into three.	Edges of the proximal section.	Flattening.
DI016	LN I	1.2	0.3	■	Fragment of an awl (?).	One of the two extremities.	Thickening of the section and twist (?).
DI018	LN I	3.4	0.3	■	Distal part of an awl.	Slightly more flattened part on one extremity.	Traces of crushing.
DI021	LN I	2	0.2–0.5	▬	Fragment of a bent awl (?).	One (fractured) extremity, and the bend area.	Flattening, folds (?), torsion.
KR001	LN II	7.9	0.1–0.4	■ ●	Complete double-tipped awl. Pyramidal-shaped tip and slightly curved.	Edges of the flattest section, close to the mesial part.	Waves, small oval imprints, polish.
KR007	LN II	5.1	0.2–0.6	●	Complete thin awl (needle?).	Along the edge of one distal part.	Fissure.
KR008	LN II	5.3	0.6	●	Complete awl, fragmented into four.	Flat edge of the fourth fragment.	Imprints.
SI016	EBA	3.4	0.1–0.2	■	Complete thin awl, sharp tip and square base.	Flat area on the distal part, close to the tip.	Imprints and small hollows with polish inside, ridges.
SI020	LN II	5	0.1–0.2	■	Almost complete bent awl (or hook).	Flat area on the distal part, close to the bend.	Flattening, imprints on it with hollows.
DT002	LN II	6.4	0.1–0.3	■ ●	Complete double-tipped awl. Rounded tips and slightly curved.	Rounded edges of the distal part, close to the centre.	Crushing and imprints, waves on the edges.
DT008	LN II	2.5	0.5–0.8	■ ●	Fragment of an awl, with rather rounded edges (twisted shape?).	Proximal part.	Ridge.
DT035	LN II	7.9	0.3–0.6	■	Complete bent awl, sharp tip and bevelled base.	Mesial part.	Ridge and crushing.
DT043	LN II	7.8	0.1–0.3	■	Complete thin bent awl, sharp tip and bevelled base.	Mesial part, towards the base.	Imprints and small hollows.
DT045	LN II	4.7	0.2–0.4	■	Complete awl with a slight depression towards the centre. Damaged tip, square base.	Distal part, towards the tip.	Flattening on the upper part, crushing with hollows on the lower part. Notches on the ridge.
DT046	LN II	4.5	0.1–0.3	■	Complete awl, thin and bevelled base. Rhomboidal tip, almost pyramidal. Widening of the section towards the tip.	Edges of the distal part, towards the tip.	Fold, notch, crushing, flattening, striations (covered by the patina but still visible).
DT047	LN II	4.1	0.1–0.2	■	Complete awl, bevelled base.	Extremity of the bevelled base.	Flattering, notch, and tear.
DT048	LN II	12.7	0.1–0.3	■	Complete thin and long awl. Slightly flattened and square base. Sharp edges and tip.	Edges of the mesial part.	Hollows, crushing, waves.
DT051	LN II	3	0.3	●	Complete short and thick awl. Slightly rounded and flattened base, possibly bevelled before.	Distal part.	Imprints and flattening.
DT053	LN II	5.2	0.1–0.3	■	Complete thin and bent awl, bevelled base.	Bent area.	Ridge, flattening, torsion.
DT054	LN II	9.9	0.2–0.3	■	Complete long, thin, and bent awl. Sharp tip and irregularly squared base.	Edges of the distal part, towards the tip.	Oval imprints repeated.
DT063	LN II	3.5	0.2	■ ●	Fragment of an awl, sharp edges.	Edges of the distal part, towards the square side (base?).	Waves, flattening, folding.
DT065	LN II	8.8	0.2–0.7	■	Complete awl, square tip and base.	Proximal part (tip).	Microfold.

Dimensions (in cm): D.: diameter; L.: length; Th.: thickness; NM: non-measurable.
Cross-section shape: ●: circular section; ■: quadrangular section; ▬: quadrangular and flat section; ■ ●: one part quadrangular-sectioned, and the other circular-sectioned.

Table 4
Summary table of the examined copper hooks for this study.

Code	Context	L.	Th.	Section	Description	Focus area	Trace(s)
KR005	LN II	2.8	0.1–0.3	●	Fragment of a wire or a hook. One slightly pointed end, the other fractured.	Mesial part (around the bend). Fractured end.	Crushing. Folding.
SI017	EBA	5.6	0.1–0,3	●	Complete hook. Slightly deformed on the point (barb?).	Flat tip on the end of the shank. Bend.	Fold, notches, and small ridge on the border. Striations parallel to the length, twist, flattening.
DT037	LN II	6	0.2	●	Twisted copper fragment, possibly a hook. Slightly bevelled end.	Mesial part (around the bend). Bend.	Imprints, crushing (but not flattened). Torsion, flattening, rib.
DT064	LN II	5.5	0.1–0.2	●	Fragment of a thin wire or a hook, one end fractured.	Narrowing of the point. Beginning of the bend.	Folding, folding/microfold. Imprints and striations on the flattening, rib, fissure.

and one ring-shaped (DT074) (Table 5). Three of them have been previously analysed physically and chemically (PIXE and XRF), showing the use of pure copper (see Mirtsou et al., 1997: 93–94 for DI020; Malamidou et al., 2022: 7 for DT009 and DT010).

4. Reconstructing manufacturing processes

4.1. Prehistoric Metalworking: State of the Art

According to earlier scholars, the first copper objects in the Levant and in the Balkans have been made through different processes, from the

Table 5
Summary table of the examined copper beads for this study.

Code	Context	D.	Th.	Description	Focus area	Trace
DI019	LN I	0.2–0.6	0.1–0.3	Complete bead.	Edge. View from above (with the hole).	Joint and folding. Junction point.
DI020	LN I	0.2–0.4	0.1	Complete bead with flat edges. Obstructed hole but general structure still visible.	Edge. View from above (with the hole).	Imprints and microfold. Folding and rib on the borders.
SI001	LN I	0.1–0.4	0.1	Complete bead with rounded edges.	Edge. View from above (with the hole).	Joint, flattening, folding. Joint, folding, rib on the border.
SI007	LN II	NM	0.1	Five tiny fragments of a bead (?).	Around the hole.	Twist and folding.
DT004	LN II	0.2–0.3	0.1	Complete beads, with a slightly concave surface.	Edge of the bead View from above (with the hole).	Joint, imprints, crushing. Joint and crushing.
DT009	LN II	0.2–0.4	0.1	Complete bead, with a slightly deformed ring shape.	All around the edge. Inner edge of the hole.	Groove. Notches.
DT010	LN II	0.2–0.3	0.1	Completed bead, with an elongated and tubular shape.	Edge. View from above (with the hole).	Fold and imprints. Microfold and joint.
DT036	LN II	0.3–0.6	0.2	Complete bead, with an obstructed hole.	Edge. View from above (with the hole).	Imprints and flattening. Notches, crushing, rib, twist.
DT074	LN II	0.4–0.6	0.1	Complete ring bead with a semi-flattened and a semi-circular section.	Edge of the bead. Inner and outer part of the edge.	Joint, flattening, imprints. Torsion, joint, crushing.

earliest to the latest: cold hammering of native copper with stone hammers and hammerstones; light heating of copper at low temperatures (500 °C)[17] to make it more malleable and easier to hammer, i.e. annealing; melting (1084 °C) of copper to cast or pre-cast a shape that can be reworked (Forbes, 1950: 9–10; Wertime, 1964: 1260; Renfrew, 1969: 31; Coghlan, 1975: 76–77; Tylecote, 1987: 3; Mohen, 1990: 48; Craddock, 1995: 122–23). Shapes can also be cut out from hammered metal sheets and native copper can be shaped through cold work into sheets or wires. Those are described as "simple shapes" in previous works and were considered to be the starting point for the manufacturing process of prehistoric metalwork (Deshayes, 1960: 17; Treuil, 1983: 188).[18] Ancient experiments also demonstrated that native copper cannot be cold worked in the long-term and needs repeated phases of annealing (Tylecote, 2002: 2; Coghlan, 1975: 77–79). Yet there are no indications about the time required for these phases. The cold hammering of native copper pieces from Iran, this time to make 'small useful shapes', has also been successfully tested previously by Cyril Stanley Smith (Wertime, 1964: 1260). Yet nothing is said about whether or not these pieces need to be annealed.

Since then, new archaeological data have been collected (Radivojević & Roberts, 2021: 221–22). The wide range of technical practices granted to prehistoric metallurgists is constantly being documented. Techniques do not disappear to leave place for others but interact and alternate over time, up to form systems that need to be studied in context (Lemonnier, 1986: 154, 2010: 50–51). Manufacturing the earliest copper objects may have involved cold work for shaping, annealing for softening and avoiding cracking, and again cold work for hardening (Ottaway & Roberts, 2008: 209). Hot-and cold-hammering may have also coexisted in the same "*chaîne opératoire*" during the Neolithic (see Mirtsou et al., 1997: 93; Kienlin & Pernicka, 2009: 265–66), as well as cold work can still be used in the making-process of a casted copper axe in the EBA (see Kienlin, 2011: 129, 2016: 126 –27). So, the prehistoric metalwork techniques, far from being patterned after stonework, were perfectly suited to this material (Thornton, 2009: 308).

On the other hand, there is no secure evidence that annealing was a common practice during the LN. As pointed out in other works on prehistoric metal production, cold-hammering and annealing cycles are not a technological consensus, involving the search for hardness and durability for utilitarian objects (see Artioli, 2007, for chalcolithic axes from Southwestern Europe, and Kienlin, 2008, for such artefacts but from Southeastern Europe). The picture can be more complex and evolve over time, depending on the various contributions of technological know-how and social and technical needs. Only two objects of the selected finds have been metallographically analysed, both showing a cold-worked and annealed microstructure: SI020 (Renfrew & Slater, 2003: pl. 8.9: a) and DI020 (Grammenos, 1997: pl. 42; Mirtsou et al., 1997: 93–94). In absence of further microstructural data, the use of work-hardening for all the objects cannot be guaranteed. Yet this provides a basis for initiating future research into better-preserved material from recent excavations, such as that at Dikili Tash.

Recent experimental studies have also been conducted on native copper, implying cold work with stone tools and, but not systematically, annealing (Kory Cooper et al., 2015; Peterson, 2023). However, those experiments took place in the context of North American's native copper work.

The following manufacturing process has been suggested for small copper beads found at Dikili Tash: a fragment of copper, native or obtained by smelting, was shaped by hammering and finished by polishing (Séfériadès, 1992: 114). These technical processes would have been involved in other small-object manufacturing, such as for awls, during the LN and EBA (Séfériadès, 1992: 114). The same inferences, through metallographic analysis, have been drawn for the beads from Sitagroi, which were obviously made by hammering with several annealing phases (McGeehan-Liritzis, 1996: 103). This has been noted for one bead, SI007, but also for some awls, like SI016 and SI020 (Renfrew & Slater, 2003: 319–20). The hooks could have been made from copper wire, hammered into a circular or 'V shape', with one end generally tipped, and the other either bracket-shaped, or left as it was (McGeehan-Liritzis, 1996: 100–01).

The fact remains that few Neolithic copper objects from Greece have

[17] Lower temperatures have been proposed: 150 °C (Tylecote, 1987: 90) or even 200–300 °C (Mohen, 1990: 48).

[18] However, such shaping techniques are known elsewhere, including through the making of complex and varied shapes from sheets of native copper metal by the native people of North America (see Wayman, 1993; Craddock, 1995: 99–101; Ehrhardt et al., 2000; Ehrhardt, 2014).

Fig. 3. Experimental forging process of the native copper to prepare a starting shape. a. Cold hammering before annealing; b. Cold hammering after annealing; c. The shape starting to break. © E. Eschenlauer/Chalcophore, V. Martin.

been studied in sufficient detail to enable their manufacturing process to be reconstructed, and in those cases, only a limited range of techniques have been identified.[19] This lack of technical information has already been highlighted before (Aslanis & Tzachili, 1995: 90). However, other examples can be mentioned from regions that also developed early metalwork in the Neolithic and Chalcolithic periods, in the Near and Middle East.

At Cayönü Tepesi in Anatolia, more than forty awls, hooks, beads, copper sheets, and wires have been found in layers dated to 7250–6750 BCE (Çambel, 1981: 534; Mohen, 1990: 49; Maddin et al., 1991: 375). Several analyses have been carried out on these objects, including visual examination and metallographic analysis. A manufacturing process has been proposed for the awls and hooks: native copper would have been hammered into a copper sheet; this sheet was then rolled up to make the required shape (Mohen, 1990: 49–50; Maddin et al., 1991: 378). Within this process would have been inserted phases of annealing, around 500 °C, to soften the metal and avoid cracking (Mohen, 1990: 50).[20] Moreover, a recent study of new metal artefacts found at Çatalhöyük, dated from the seventh millennium BC, confirmed that the same manufacturing processes were applied (Birch et al., 2013: 315).

At Ali Kosh in Iran, copper pins and tubular beads dated to 6750–6000 BCE would have been produced by cold hammering (Wertime, 1968: 927, 1973: 483–84; Hole et al., 1969: 244–45, 427–28; Lambert, 1981: 214).[21] The examination of the microstructure and the composition of one of these copper beads have led to suggest its manufacturing process: native copper was hammered into a sheet, of a thickness of 0.4 mm, and this sheet was then rolled up (Mohen, 1990: 50; Tylecote, 2002: 2).

Finaly, a more recent study of copper ornaments from tombs dating from the eighth millennium BC at Tell Halula in Syria revealed precisely, through XRF, PIXE and metallographic analysis, how those were made (see Molist et al., 2009). Some copper beads and a pendant appeared to be of native copper, shaped by cold hammering alternated with annealing phases (Molist et al., 2009: 42).

We intend to call on experimental archaeology to make objects like those known from this period (Fig. 2), using manufacturing processes such as those previously identified. By applying the traceological method (see Gutiérrez Sáez & Muñoz Moro, 2020), replicas and archaeological artefacts will be compared in order to reconstruct their "*chaînes opératoires*".

4.2. *"Trying it by Ourselves": Experimental manufacturing processes*

The experiments were carried out by a professional, as highly recommended for archaeometallurgical experiments (Kucera, 2004; Heeb & Ottaway, 2014: 163). His awareness of prehistoric smithing activities was developed in the context of the so-called 'craftsmen's village' at the archaeological site of Cucuruzzu-Capula in southern Corsica.

To produce informative results, stone tools were used during the experiments, like hammers and chisels, hammerstones,[22] anvils, and abrasive stones. As mentioned earlier, hammerstones have been identified and associated with metallurgical activities in several ancient metalwork and smithing contexts from Europe (Cert, 2005; Armbruster, 2006, 2010; Freudenberg, 2006, 2010; Ambert et al., 2011; Boutoille, 2015; see also Leusch et al., 2017; Hamon et al., 2020). Apart from the scientific aspect of this approach, it also provides an insight into metalworking under Neolithic conditions. Working native copper only with stone tools, sometimes with unmodified pebbles, and annealing it in a small open-hearth, is an experience in itself.

The raw materials used for the experiments were native copper and pure copper obtained by the smelting of copper oxides. The stone toolkit was constituted by two dolerite[23] hammers, of the reworked polished axe type, and a block of the same material fixed to a wooden base as an anvil. The dolerite hammers, of two different sizes, were fitted into a deer antler socket fixed to a wooden handle. A granite pebble[24] was also used as a larger hammer, without a handle – and other granite pebbles of different sizes were used throughout the experiment as dictated by the needs. Sandstone[25] tools with several grain sizes have been selected as polishers.

The native copper was easily deformed by cold hammering, and a dozen hammer blows were enough to compact a fragment. Eight cycles were sufficient to obtain a small, square, and irregularly flat strip. Each cycle combined two interdependent techniques (Scott, 1991: 7): cold-working the metal by hammering, and annealing it (Fig. 3, a, b). Numerous breaks appeared during the forging process, from tiny hollows originally present in the native copper fragment (Fig. 3, c). This

[19] Furthermore, the scarcity of remains means that very few destructive analyses, such as metallographic analyses, are carried out. Analyses that remain visual, such as those conducted as part of this study, are often favoured.

[20] These annealing phases have been identified through metallographic analyses, with the characteristic twin-grain microstructure found in five objects, including an awl and a hook (Maddin et al., 1991: 378–79, Fig. 9).

[21] See also Helwing, 2013, for cold working and annealing as manufacturing processes of copper objects in Iran during the LN and the Chalcolithic.

[22] *Hammerstone* is a term from lithic technology and designates a percussion tool that has been chosen for its initial shape and is unmodified before its use. It is differentiated here from the *stone hammer*, which is a forging tool shaped from a stone.

[23] Metalworkers' working surfaces and hammers generally require to be smooth and fine-grained (Armbruster, 2006: 324, 2010: 11), but also great solidity (Pieters, 2016: 81). Magmatic rocks such as basalt or dolerite are sometimes chosen for such work (Boutoille, 2015: 92; Hamon et al., 2020: Fig. 2).

[24] The use of simple pebbles in metallurgical activities has been observed in some contexts (see Freudenberg, 2010: 26; Ambert et al., 2011: 392; Gaál & De Angelis, 2021: 251–53).

[25] Sandstone is generally used for grinding and polishing by metallurgists (Armbruster, 2010: 11), although its effectiveness on copper-based alloys is sometimes questioned (Pieters, 2016: 81).

Fig. 4. Experimental making process of a copper awl. a. Cold hammering of an elongated square rod; b. The awl-shape being finalised; c. Grinding of the awl on a sandstone plate. © E. Eschenlauer/Chalcophore, V. Martin.

Fig. 5. Experimental making process of a double-tipped copper awl. a. Elongating the cast pre-shape; b. Finalising the awl-shape through cold hammering; c. Sharpening by grinding on a sandstone plate. © E. Eschenlauer/Chalcophore, V. Martin.

Fig. 6. Experimental making process of a copper hook. a. Cold hammering of the wire after annealing; b. Folding and cracking on one end of the wire after hammering; c. Bending of the wire. © E. Eschenlauer/Chalcophore, V. Martin.

forged strip of native copper was then divided into three parts, each intended for making an object.

The pure copper was obtained by smelting malachite,[26] in the form of small prills and nuggets. One of these was selected to make a rolled-up bead.

The shaping processes started with the transformation of the material into an initial shape, either a sheet or a wire. This is a general process common within the mechanical working of metals (Cottrell, 1995: 428). The following stage transforms these initial shapes into more complex ones, and can require more technical processes: rolling, stretching, pressing, flattening, etc. The initial shapes were a copper sheet for the bead, and copper wires for the awls and the hook.

The first awl replica is circular-sectioned towards the tip, and rectangular towards the base, which is square and bevelled. One part of the forged strip of native copper was selected to begin the shaping. The initial shape, the thick wire also named rod, was obtained by a basic technical process called elongation, i.e. the lengthening of the metal along its longitudinal axis (Cottrell, 1995: 429). The rod is then forged, by alternating hammering with the largest dolerite hammer and annealing (Fig. 4, a). When obtained by forging, the final shape does not require much grinding to finish the shaping (Semenov & Thompson, 1970: 206) (Fig. 4, b).[27] The first awl was tapered by grinding on a sandstone plate (Fig. 4, c), while its other end was stretched and cut to make the base. The final step consisted of light abrasive shaping with the sandstone polisher, to decrease the roughness of the surface, and to regularize the edges.

The second awl replica is double-tipped, with both rectangular and circular sections – the mesial part is circular. Pure copper was melted and directly casted to obtain a pre-shape. This thick copper mass was first elongated by cold hammering with the granite pebble (Fig. 5, a). This was then stretched into a wire. This was then heavily hammered with the largest dolerite hammer to obtain sharpened edges (Fig. 5, b). The mesial part was hammered with another stone tool, a rounder small granite pebble, to round the edges. The sharpening of the two tips was

[26] As this paper is not about prehistoric smelting, no further details will be given on the experimental smelting done for this experiment.

[27] The same inference is true for the hook replica.

Fig. 7. Experimental making process of a rolled-up copper bead. a. First cycle of cold hammering on the copper prill; b. Elongating of the prill to obtain a small strip of copper that can be rolled up; c. Rolling-up of the strip. © E. Eschenlauer/Chalcophore, V. Martin.

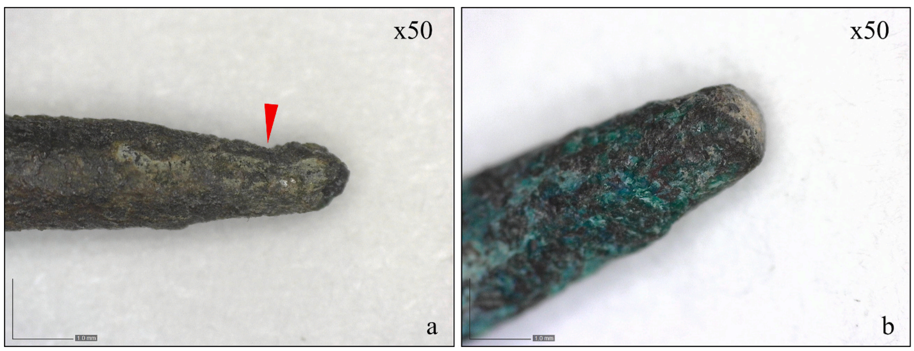

Fig. 8. Some use-wear traces seen on the archaeological objects. a. Deformation of a copper awl tip (DT047); b. Blunt tip of a copper awl (DT002). © Greek Ministry of Culture/Ephorate of Antiquities of Kavala, Archaeological Mission of Dikili Tash/École française d'Athènes, V. Martin.

done by grinding (Fig. 5, c).

The hook replica also started from stretching a pure copper pre-shape. The wire was forged and stretched to have a thin and circular section (Fig. 6, a). One end was shaped by slight hammering with the largest dolerite hammer, generating folds and cracks (Fig. 6, b).[28] The bend was made by twisting it slightly with a small and round hammer (Fig. 6, c).[29] The flat end of the shank was flattened with a small flat hammer.

For making the bead, the copper prill was first flattened to be shaped into a sheet – also called a small strip (Fig. 7, a). Regardless of its thickness, the main technical process to achieve this is forging, which involves 'compressive forces' (Cottrell, 1995: 431) applied between the hammer and the impact surface, i.e. the anvil. The hammer is exercising stress on the material, but nothing restrains the edges of the object from expanding outwards, as the forging is here practised openly. This can be managed by alternating between forging the flat face and elongating the edges (Fig. 7, b). Shaping continues with the rolling-up of the strip (Fig. 7, c). Rolling is considered a technical development of the forging process in a modern context (Cottrell, 1995: 439). However, it can simply correspond to the use of a rounded hammer going along with the metal. In both cases the plastic deformation is the same. Finally, the two ends of the rolled-up sheet were joined by light hammering. This had the effect of slightly deforming the bead, making it more cylindrical than circular. Only part of it was polished with sandstone tools, so as not to erase the manufacturing traces for the study.

5. Comparing experimental and archaeological results

5.1. Applied Methodology

The plastic deformation of a metal can be observed with the naked eye or with low-magnification microscopy at the surface of the objects (Semenov, 2005a: 76; Gutiérrez Sáez & Martín Lerma, 2015: 176; Dolfini & Crellin, 2016: 82).[30] As a microstructure may indicate hammering or casting practices (Cottrell, 1995: 428; Notis, 2014: 58–59; Scott, 1991: 5–10, 2014: 70–71), some traces are also characteristic of specific mechanical actions (Gutiérrez Sáez, 2002: 263; Gutiérrez Sáez & Soriano Llopis, 2008: 440–41, tab. 1; Gutiérrez Sáez & Martín Lerma, 2015: tab. 9.1; Gutiérrez Sáez & Muñoz Moro, 2020: tab. 1).

Use-wear or shafting traces are distinguishable from manufacturing marks, by examining their shapes and position on the object (Vivet, 1998: 176; Gutiérrez Sáez & Martín Lerma, 2015: 175). This study focuses on the manufacturing process of prehistoric copper products. Thus, our experimental replicas are finished products left unused, so that use-wear traces do not cover manufacturing traces. However, it is not excluded that the selected studied archaeological objects also have use-wear and shafting traces: some are easily visible (Fig. 8; Fig. 12, a, b). Other issues can be encountered with this material: the state of corrosion may impede the reading of traces, as well as conservation

[28] Nevertheless, as none of the examined hooks seem to have a sharpened tip, hammering and not grinding was preferred for the making of the point of the replica hook.

[29] Annealing was done just beforehand, to give the metal more malleability.

[30] For a better understanding of the terms used to describe the traces, the reader should refer to the glossary at the end of the paper. The selected terms can be used to describe both manufacturing and use-wear traces, even if the focus of this study is on manufacturing processes. They are sourced from many previous works published in traceological studies on pre- and protohistoric metal objects (Kienlin & Ottaway, 1998; Vivet, 1998; Armbruster et al., 2003; Gutiérrez Sáez 2002; Gutiérrez Sáez & Soriano Llopis, 2008; Dolfini, 2011; Gutiérrez Sáez & Martín Lerma, 2015; Dolfini & Crellin, 2016; Reich, 2016; Horn, 2017; Gutiérrez Sáez & Muñoz Moro, 2020).

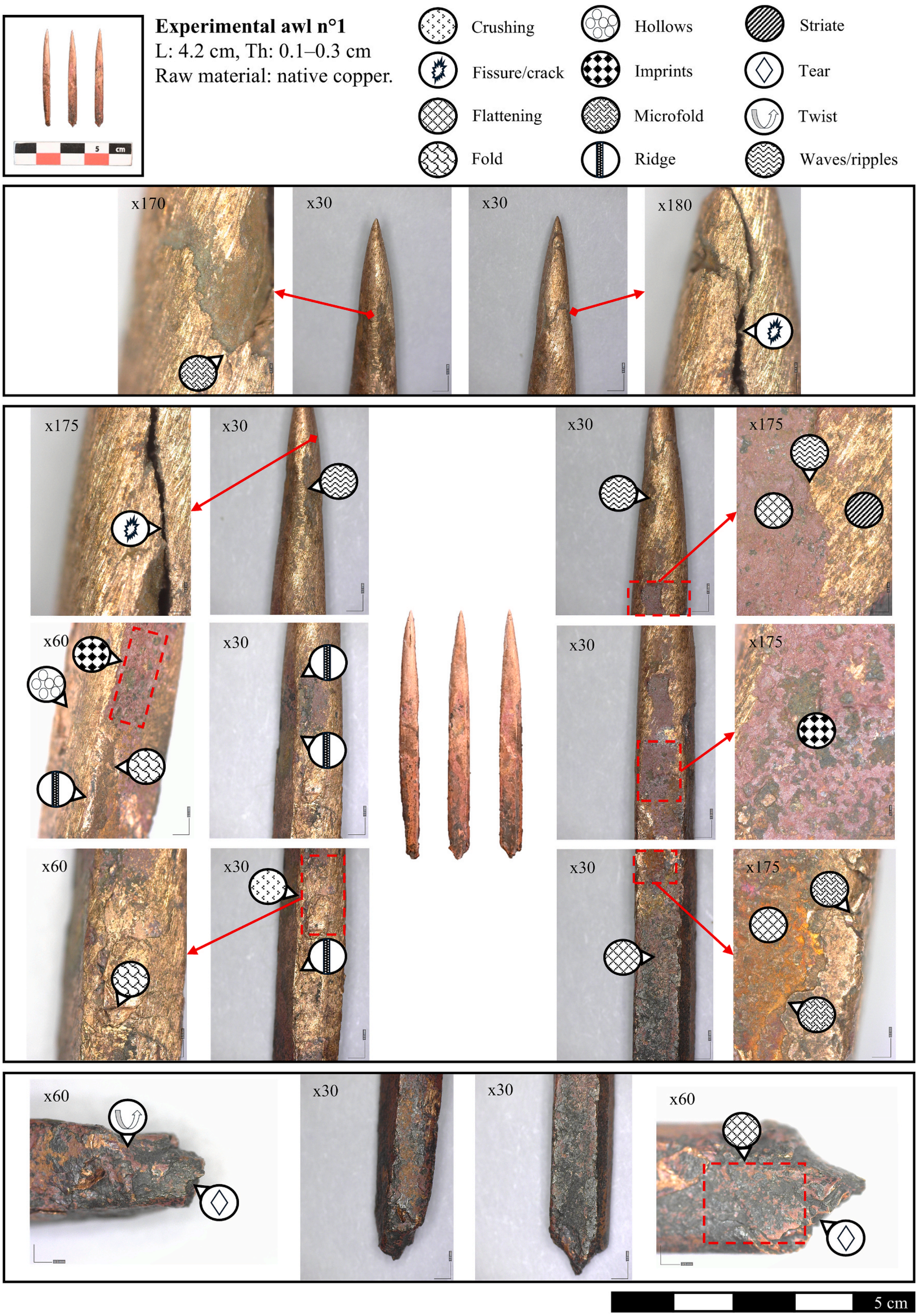

Plate 1. Manufacturing traces on a copper awl replica. © V. Martin.

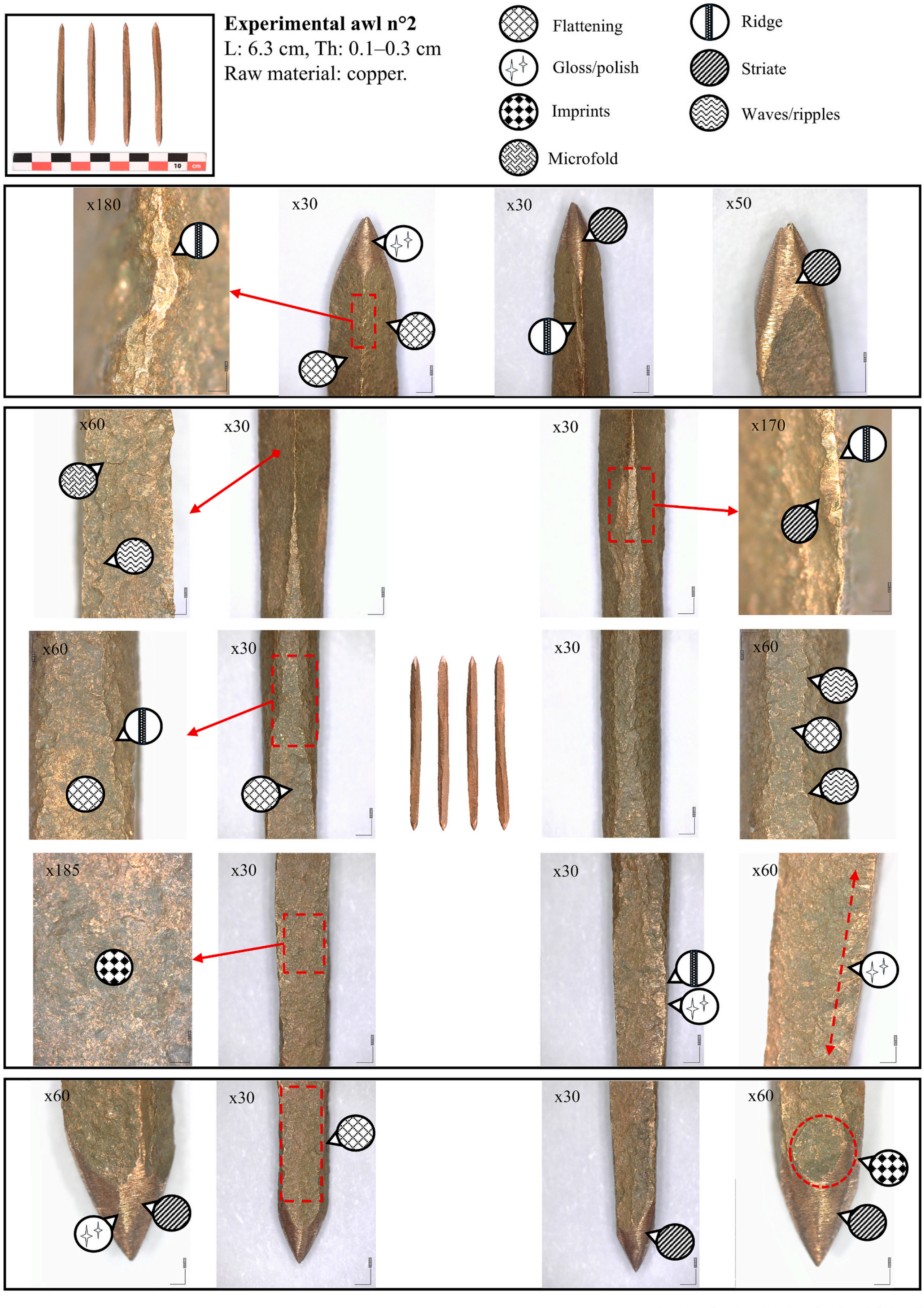

Plate 2. Manufacturing traces on a copper double-tipped awl replica. © V. Martin.

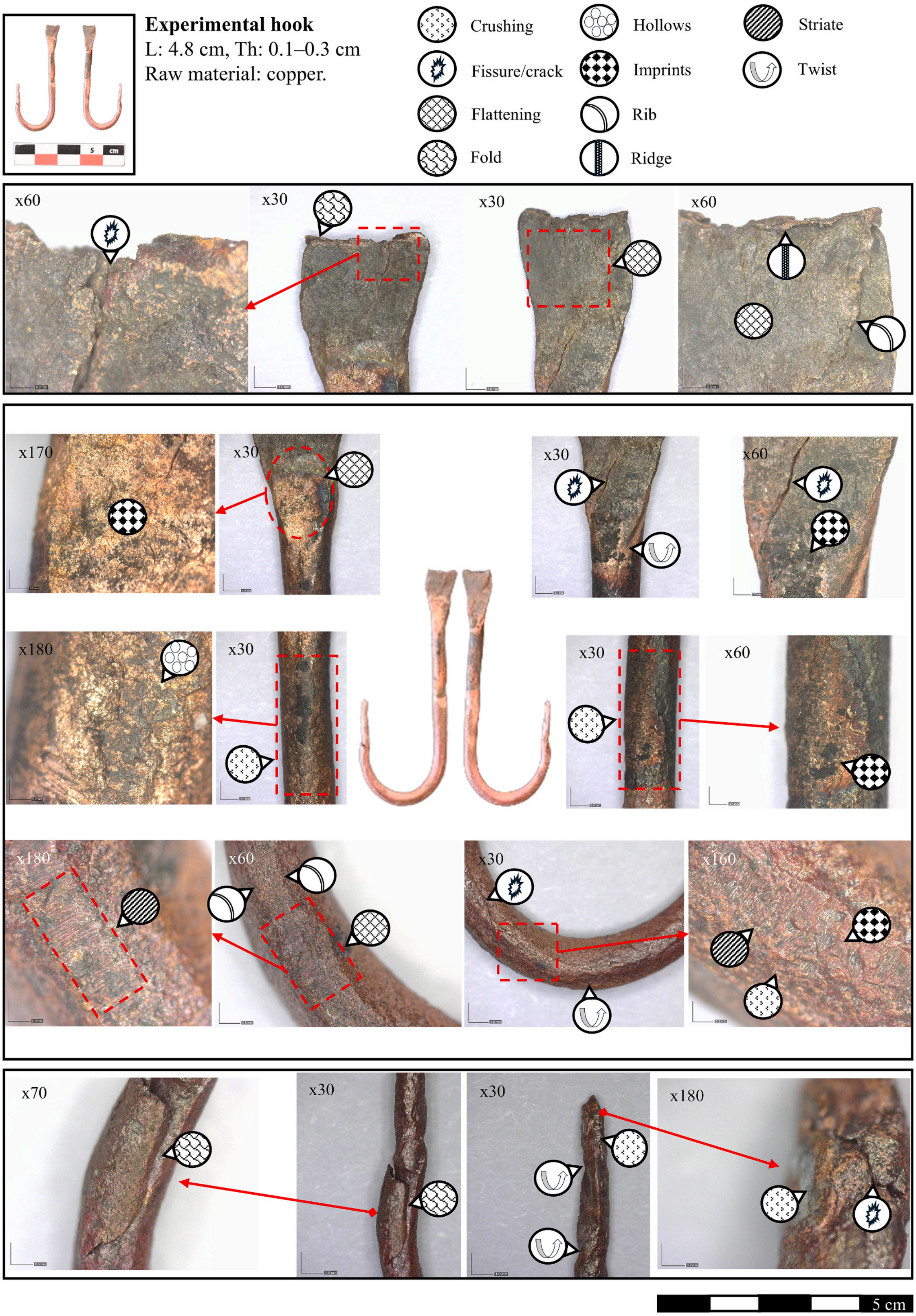

Plate 3. Manufacturing traces on a copper fish-hook replica. © V. Martin.

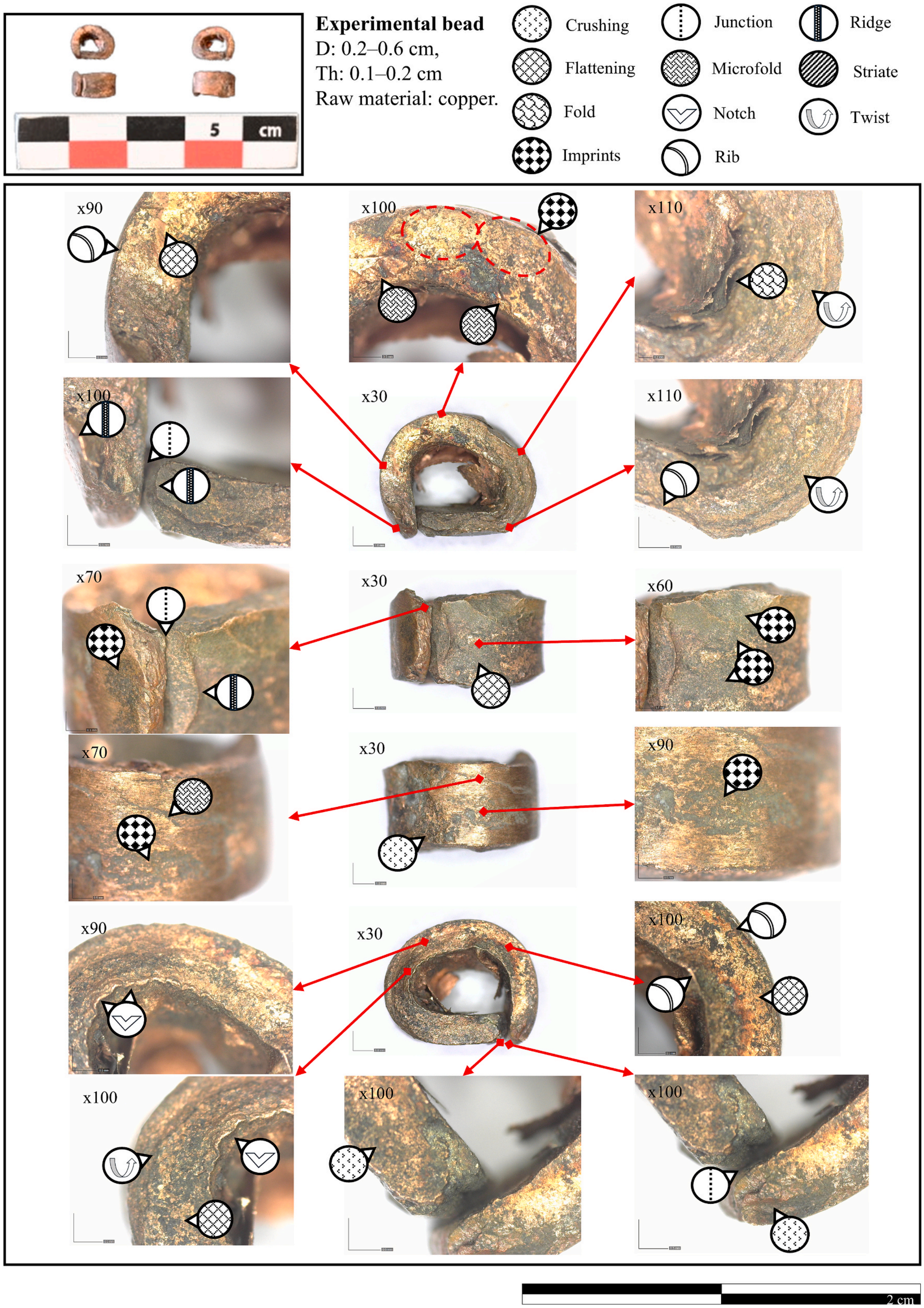

Plate 4. Manufacturing traces on a copper bead replica. © V. Martin.

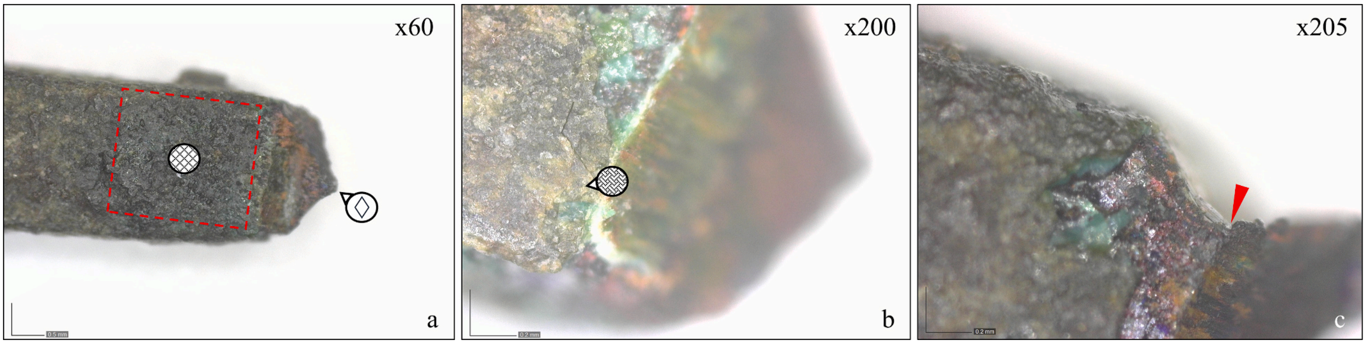

Fig. 9. Microphotographs of DT047. a. Flattening on the edge and tear on the bevelled base; b. Focus on the edge of the base and possible folding remains; c. Focus on the tear mark. © Greek Ministry of Culture/Ephorate of Antiquities of Kavala, V. Martin.

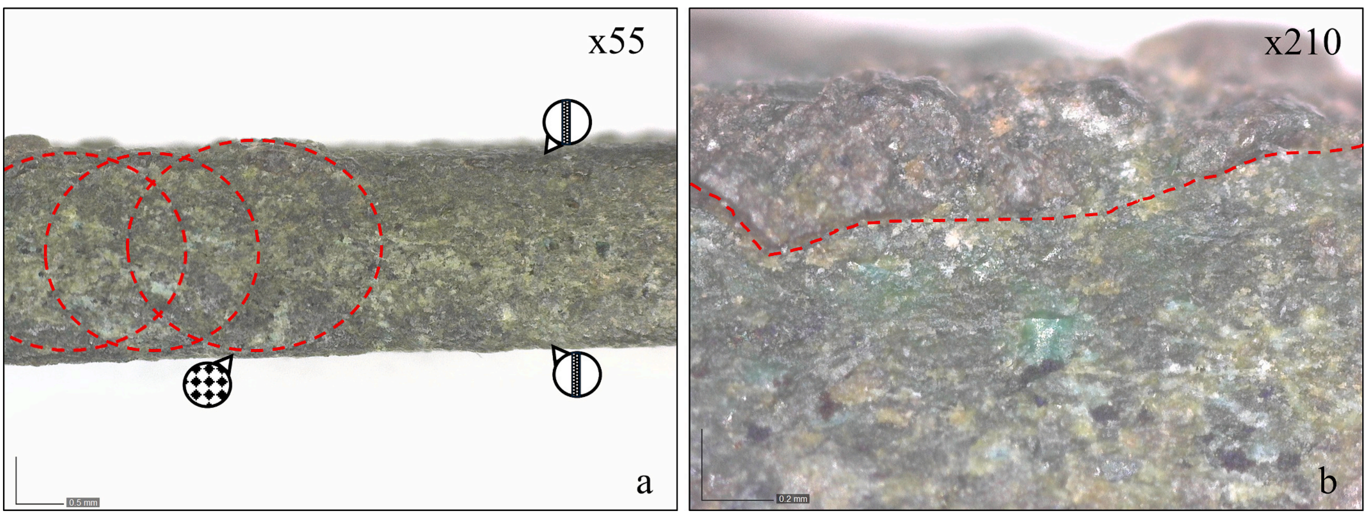

Fig. 10. Microphotographs of DT047. a. Flattened area with oval imprints of 1.5 mm of diameter on the mesial part and ridges along the edges; b. Focus on the upper ridge. © Greek Ministry of Culture/Ephorate of Antiquities of Kavala, V. Martin.

treatment marks may overlap other traces (Gutiérrez Sáez, 2002: 264–65; Felix Bernard, 2013: 30–31; Gutiérrez Sáez & Martín Lerma, 2015: 177–78; Gutiérrez Sáez & Muñoz Moro, 2020: 173, 176). As the experimental replicas are not covered by these specific marks, they make good comparison patterns.

To observe the surface traces on these selected finds, a digital microscope (Dino-Lite model AM4515ZT), was used. Its magnification is up to x250 and offers to observe traces, which can be interpreted according to their shapes, size and position on the object's surface (Morero et al., 2018: 78). Adjusting the magnification made it possible to see the

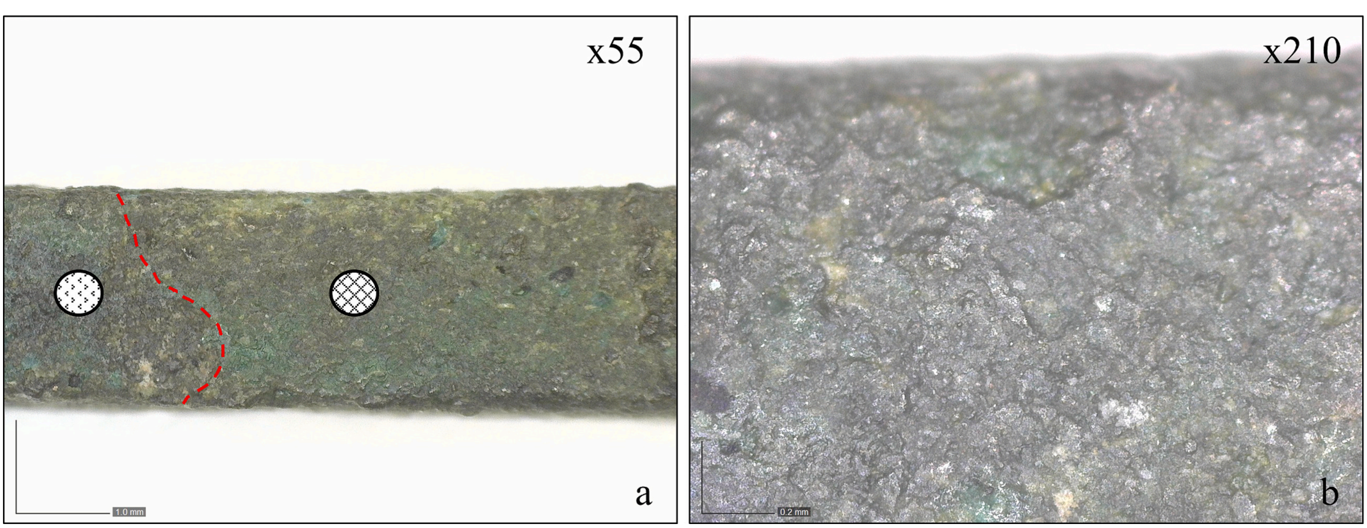

Fig. 11. Microphotographs of DT047. a. Flattening on the right side of the mesial part, and crushing on the left side, towards the tip; b. Focus on the crushed area. © Greek Ministry of Culture/Ephorate of Antiquities of Kavala, V. Martin.

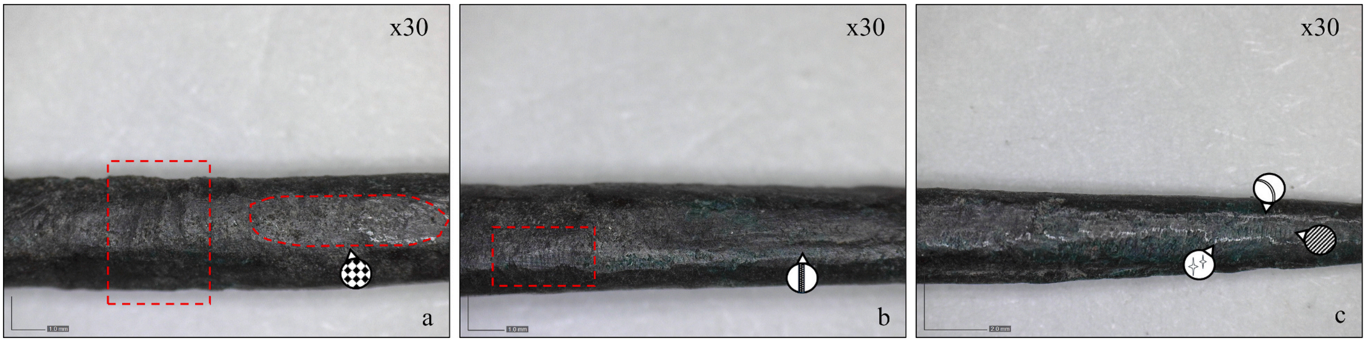

Fig. 12. Microphotographs of DT002. a. Grooves (possible use-wear traces) and imprints on the mesial part; b. Striates (possible use-wear or conservation treatment, i.e. mechanical cleaning) and thick ridge; c. Combination of traces towards the tip. © Archaeological Mission of Dikili Tash/École française d'Athènes, V. Martin.

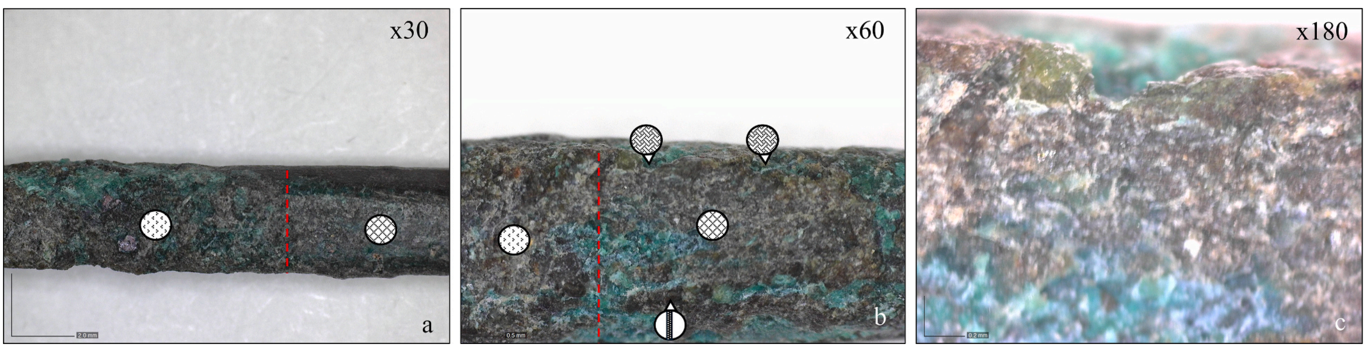

Fig. 13. Microphotographs of DT002. a. Flattening on the right side of the mesial part, and crushing on the left side, towards the tip; b. Crushing and group of traces on the flattened part; c. Focus on the microfolding (possibly caused by corrosion). © Archaeological Mission of Dikili Tash/École française d'Athènes, V. Martin.

entirety of a trace (x30/x50), or to gain a more detailed appreciation of its depth and density (x100/x200). Some traces appeared to be common to the same part of several artefacts, and combinations of traces were also noticeable (Gutiérrez Sáez & Martín Lerma, 2015: 186). Each trace has been pinpointed on the plates depicting the experimental artefacts and can be associated with a technical process or a reaction of the metal to different kinds of pressure (Plates 1–4).[31] The same system is used for the archaeological objects, of which four are illustrated (Fig. 2; see also the last column of each table for the main traces recorded on each object[32]). Thus, based on these observations, manufacturing processes, or at least some techniques involved in the making of awls, hooks, and beads, are suggested.[33]

5.2. Visual Examinations

5.2.1. Experimental and archaeological awls

The combination between flattening and folding on the awls' edges is noted on the replicas (Plates 1–2): when the cold hammering heavily deforms the metal, especially when trying to obtain a regular shape (a rectangular section, for example), folding occurs. The metal delaminates, which can sometimes lead to a minor loss of material. When making the experimental pieces, this happened when the metal was hammered for too long and not annealed enough.

The combination of small oval imprints with flattening, also seen on the replicas, appears to be a form of hammering mark (Gutiérrez Sáez & Soriano Llopis, 2008: 44; Dolfini, 2011: 1043, Fig. 2; Armbruster, 2013: 465; Gutiérrez Sáez & Martín Lerma, 2015: 176–77; Martin, 2021: 88, fig. 20, 2023: 20–21, Fig. 5: a). They are often distinguishable on flattened edges.

When the awl was heavily hammered to give it a more elongated aspect, the tapering of its edges or tip became greater. This is also connected to crushing marks, indicating the increase in hammering intensity, and the metal becoming more compact. Moreover, there are fewer hollows on long awls than on thicker and shorter awls.

Crushing marks in the form of irregular ovals of approximately 2 mm in diameter appear also on circular-sectioned parts, such as on the hooks. During the experiment, when a full circular section was sought, the replica was heavily hammered, and this left crushing traces on the edges.

Waves on the double-tipped awls' edges could be a consequence of the double-section-making process, i.e. the transition from a circular to a quadrangular section. It could also be a general reaction of the metal to the pressure of hammering on its edges, as the hammering was slightly intensified at this point during the experiment. Similar traces, but named 'burrs', have been pointed out in previous traceological studies, as marks caused by material shifting: this could have been caused by pressure exercised on the metal, and is to be found on the edges or embossed on the sides (Gutiérrez Sáez & Soriano Llopis, 2008: 441).[34] The waves could be one type of 'burrs', as other traces listed in this study are also caused by material shifting, such as folds, microfolds, ribs and ridges.

The archaeological awls often show flattening on the edges (Fig. 9, a), particularly when the section is quadrangular, or both quadrangular and circular. This mark is frequently associated with folding (Fig. 9, b; Fig. 13, b, c). Small oval imprints appear also on the edges (Fig. 10, a; Fig. 12, a). Crushing seems to be specific to circular-sectioned parts, for

[31] The graphic layout used in the plates was created for this study by the author.

[32] The examination of each object and the principal inferences are presented in the two last columns of the tables.

[33] This approach was used in a pioneering way by S.A. Semenov, the father of the traceological approach in archaeology, during experimental sessions conducted in Russia in 1956 and 1957 (Semenov, 2005b: 128).

[34] As opposed to marks related to the removal of material.

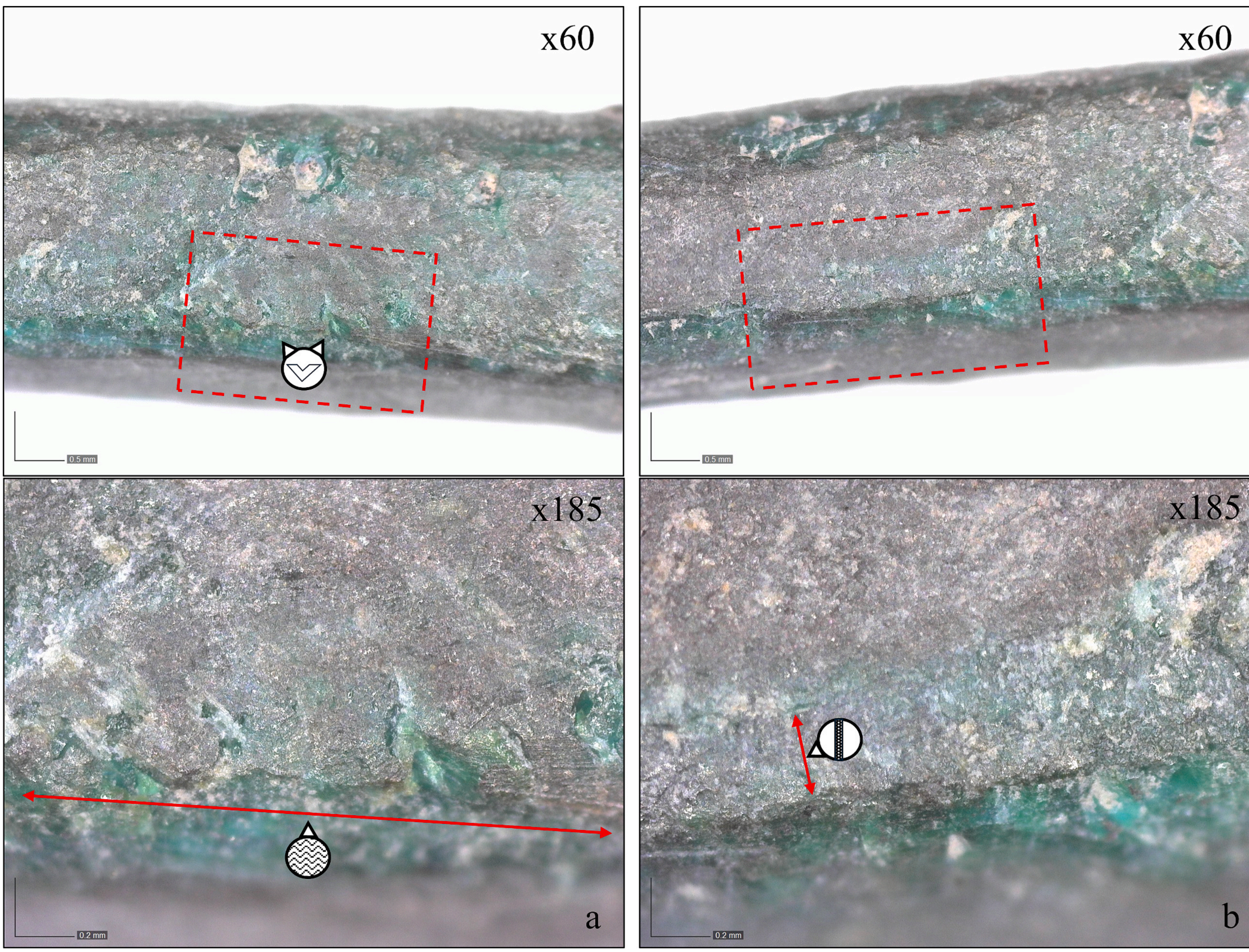

Fig. 14. Microphotographs of DT002. a. Waves and notches on the edges of a large flattened area; b. Ridge of 0.5 mm wide on the edge of a thinner flattened area. © Archaeological Mission of Dikili Tash/École française d'Athènes, V. Martin.

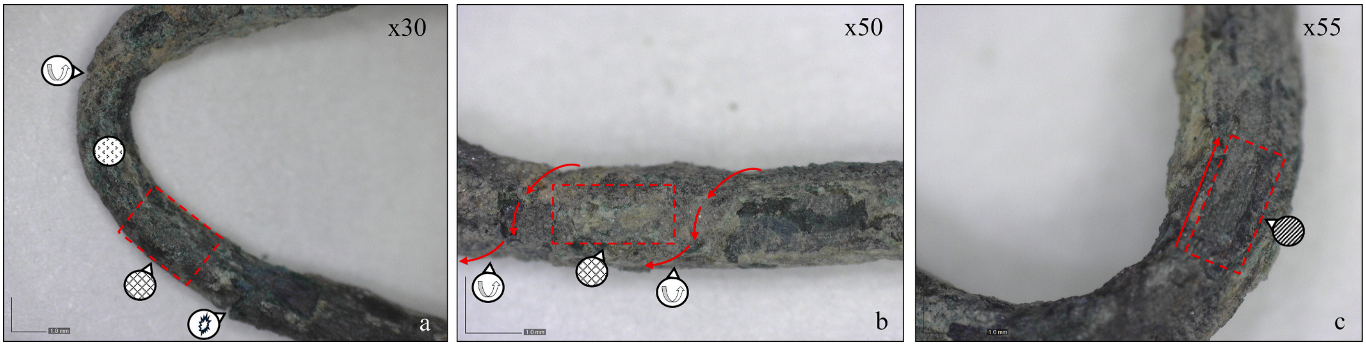

Fig. 15. Microphotographs of DT064. a. Traces on the hook's bend; b. Twist direction on the bend, also with flattening; c. Group of striates on a flattened area, but uncertain interpretation. © Archaeological Mission of Dikili Tash/École française d'Athènes, V. Martin.

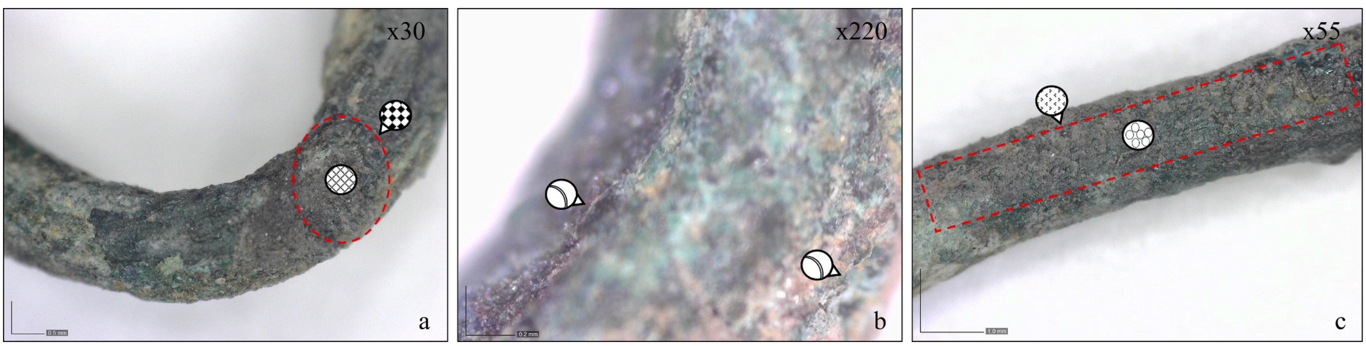

Fig. 16. Microphotographs of DT064. a. Flattening on the bend, within an oval imprint of 1.5 mm; b. Focus on the ribs along the edge of the flattening area, still on the bend; c. Crushing on the mesial part covered with small hollows, but possibly from corrosion. © Archaeological Mission of Dikili Tash/École française d'Athènes, V. Martin.

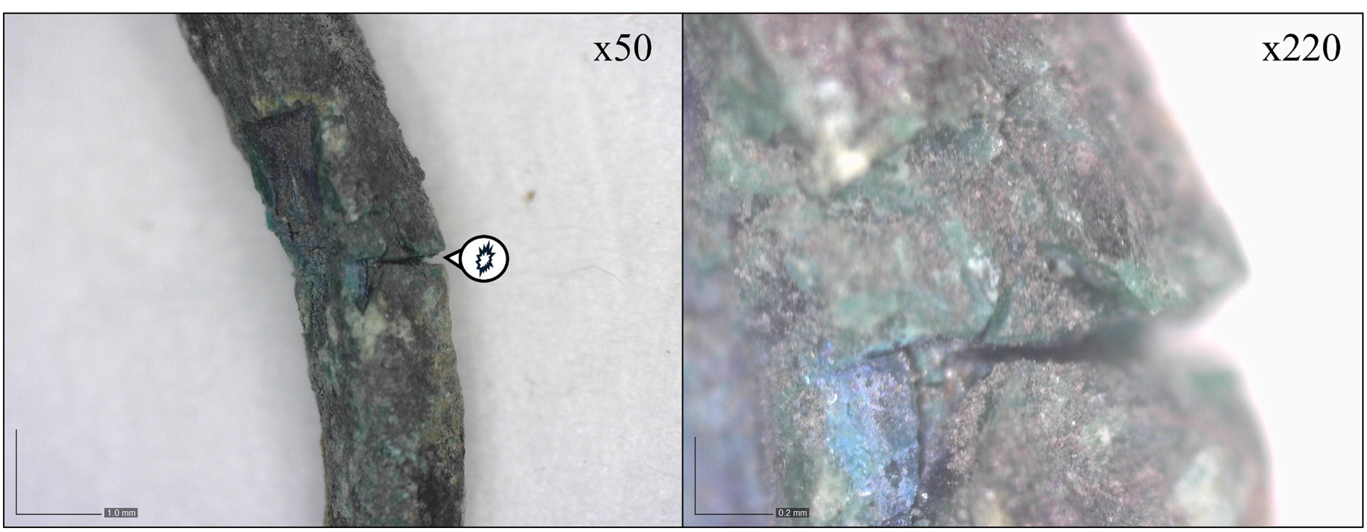

Fig. 17. Microphotographs of DT064: Focus on the fissure placed perpendicular to the bend. © Archaeological Mission of Dikili Tash/École française d'Athènes, V. Martin.

example towards tips (Fig. 11; Fig. 13, a): according to our experiment, it could have been created by important material displacement, with a bigger tool, when the edges are hammered to erase sharpened edges. Waves are seen on the edges of the double-tipped awls (Fig. 12, c; Fig. 14, a); striations and polish are noticed on the edges (Fig. 12, c).

Flat edges could have been made on a flat surface or with a flat tool: where flattening has been noted, this might indicate hammering on a plane surface or with a kind of a flat tool; however, where crushing has been noted, this could imply the use of a less regular striking surface or tool (Fig. 11, a; Fig. 13, a). On the other hand, if rounded edges were wanted, the wire could have been turned while hammering. The ends of the awls were tapered, twisted, or cut. The bevelled base seems to have been obtained by stretching and cutting, leaving a tear at the end (Fig. 9, a, c).

The observation of the awls leads us to several conclusions: they seem to have been shaped by forging a pre-shaped quadrangular rod, then stretched into a wire towards the tips. If so, this process could have been used to produce a circular or quadrangular section, rounded or sharp edges, and both longer and shorter awls. The needs have probably guided the shaping.

Fig. 18. Microphotographs of DT064. a. Folding on the tip, but possibly also corrosion layer; b. Large folding near the bend; c. Breakage of the upper part of the hook. © Archaeological Mission of Dikili Tash/École française d'Athènes, V. Martin.

Hammering leaves marks on the surface of a metal object, by deforming it, i.e. widening or rounding of the cutting edge (Deshayes, 1960: 22; Kienlin & Ottaway, 1998: 175; Gutiérrez Sáez & Soriano Llopis, 2008: 440; Dolfini, 2011: 1045–46, Fig. 2; Armbruster, 2013: 465; Gutiérrez Sáez & Martín Lerma, 2015: 176–77). These traces, such as flattening, small oval imprints, and hollows, are noticed on the edges of not too corroded awls (SI016, DT008, DT035, DT053) or with the naked eye (DT045). When not covered, these hammering marks are easily seen, as on DT047 where imprints on a flattened area are noticeable (Fig. 10, a). For example, it has been shown that striations, related to grinding, polishing, or use of the tool, can cover these traces (Gutiérrez Sáez & Soriano Llopis, 2008: 440; Gutiérrez Sáez & Martín Lerma, 2015: 174). Changing the analysis tool could be envisaged when polishing traces are covering manufacturing marks, as suggested by B. Armbruster with X-ray analysis (Armbruster et al., 2003: 255). However, some deeper marks, such as grooves possibly caused by grinding, can still be seen visible after polishing (Kienlin & Ottaway, 1998: 275; Martin, 2023: 21). Other experiments have already shown that hammering traces can still be discernible after polishing (Martin, 2021: 86).

5.2.2. *Experimental and archaeological hook*

For both artefacts and replica, the whole bending process was characterised by this group of traces: flattening, ribs, and torsion. During the experiment, the twist was made by hammering. The torsion trace is more accentuated for hooks, with added striations, because the wire is not just folded, but also twisted. We noted after the experiments that this twist makes it more difficult to reopen the bend, giving the hook more durability.

The folding of hook tips, also distinguishable on the replicas (Plate 3), is explained by the tapering of hooks only by hammering and not by grinding. Less gentle than grinding, hammering causes the delaminating of the tip where it is too thin for the pressure applied through the hammer.

The recurrence of traces located at the bends of hooks and some bent awls were noted: twist of the section (Fig. 15, a, b), flattening and ribs on either side of the flattened area (Fig. 16, a, b), and sometimes parallel striations on the flattening (Fig. 15, c). Furthermore, on the mesial part of the hooks, where the section is completely circular, crushing is often seen (Fig. 16, c). The tip of some hooks, when not too worn, shows signs of folding (Fig. 18, a, b).

As for awls, the first steps to make a hook probably aimed to produce a wire. Another possible shaping process is the bending mechanism, which may lead to 'macroscopic kinks' (Scott, 1991: 10). On the bend of DT064, a fissure cuts perpendicularly to the section, probably under the pressure of the torsion and emphasized by the corrosion (Fig. 15, a; Fig. 17). The final length of the hook can be adjusted before or after bending, by cutting the ends. In that sense, DT037 has small oval hollows in places (see also on DT064, Fig. 16, c), evidence of hammering, and tears at its extremities, so it was probably cut at both ends.

5.2.3. *Experimental and archaeological bead*

The marks seen on the replica's perimeter edges (imprints, crushing, folding…) are all connected to the hammering of the copper sheet before rolling it (Plate 4). The two ends are joined by light hammering, but the sheet was not thin enough to make an overlap junction. Both cases are found on archaeological beads, showing varying degrees of finishing. Light hammering is somewhat too intense for this step, as it deforms the shape of the bead.

The traces associated with the intensity of forging are less pronounced at the extremities than at the distal and mesial parts. Indeed, the thinner the object, the more likely it is to break. During the Neolithic, people who made metal objects may have had more experience of producing these particular forms, allowing them to master the degree of impact force and on specific areas so that it elongated and took on the desired shape, without breaking. As a matter of fact, very few *cracks* are seen at the ends of the artefacts, which was not the case with the replicas.

Shaping by abrasion seems to principally leave long parallel striates on the edges of the objects. This is observable on some replicas, but not so much on the archaeological artefacts. Shaping appears to have been made mostly by hammering. Abrasive work was more used on ornaments than on tools, to polish the surface. Only some awls could have been sharpened at their ends by grinding, which was not the case for hooks.

The recurrent marks on the archaeological beads' edges are folding and microfolding, plus oval-shaped imprints (Fig. 19; Fig. 22, c). A junction is seen on all the selected beads (Fig. 20; Fig. 22, a), except for DT010. Folding and microfolding are also discernible close to the hole, often in the inner part of it.[35] A rib is recurrently seen on the hole's outer edge (Fig. 21, a, b; Fig. 22, a).

The visual examination of these copper beads leads to the following proposed reconstruction of the manufacturing process: a fragment of copper was cold hammered to create a sheet, and this small sheet of copper then rolled (joined ends) or wrapped (overlapped ends) by light hammering around a cylindrical form. The thickness of the sheet is important, as it determines the diameter of the hole, which will be narrower. The hole is generally large if the sheet is thin, and the two edges overlap. If the sheet is thicker, the hole is smaller, and the two edges meet.

Where the junction does not hide the ends of the sheet (see on

[35] But this cannot be seen on DT036, as the inner hole is obstructed and verry corroded.

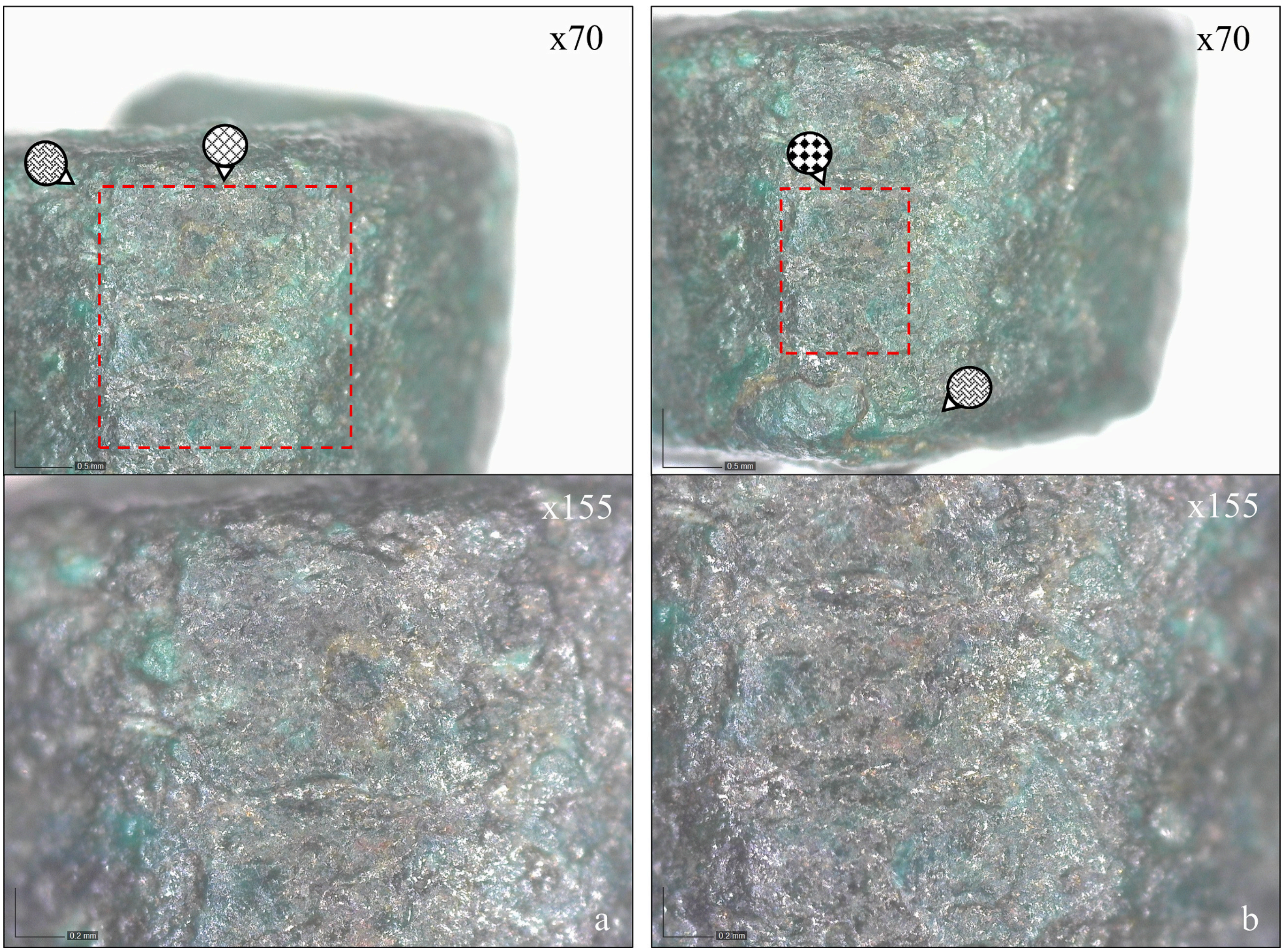

Fig. 19. Microphotographs of DT036. a. Flattened area with microfolding on one edge; b. Small oval-shaped imprints on the same flattened area. © Greek Ministry of Culture/Ephorate of Antiquities of Kavala, V. Martin.

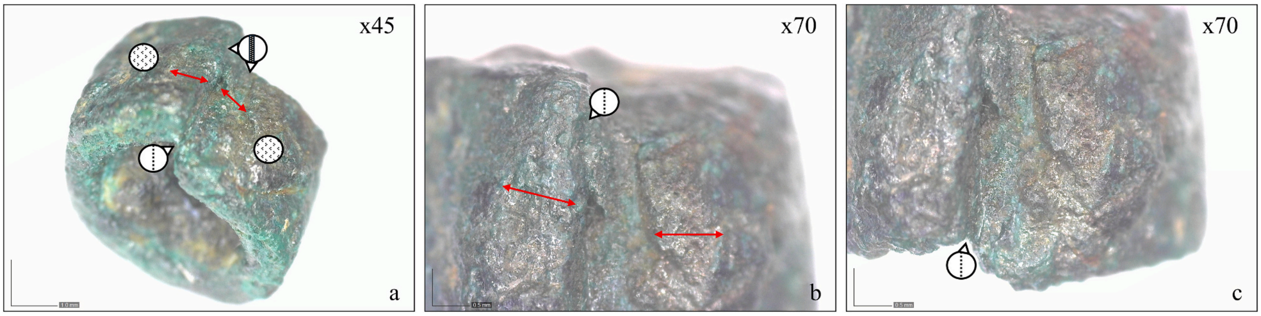

Fig. 20. Microphotographs of DT036. a. Side view of the bead for a clear look on the junction point and surrounding traces; b. Focus on the ridge; c. Focus on the junction. © Greek Ministry of Culture/Ephorate of Antiquities of Kavala, V. Martin.

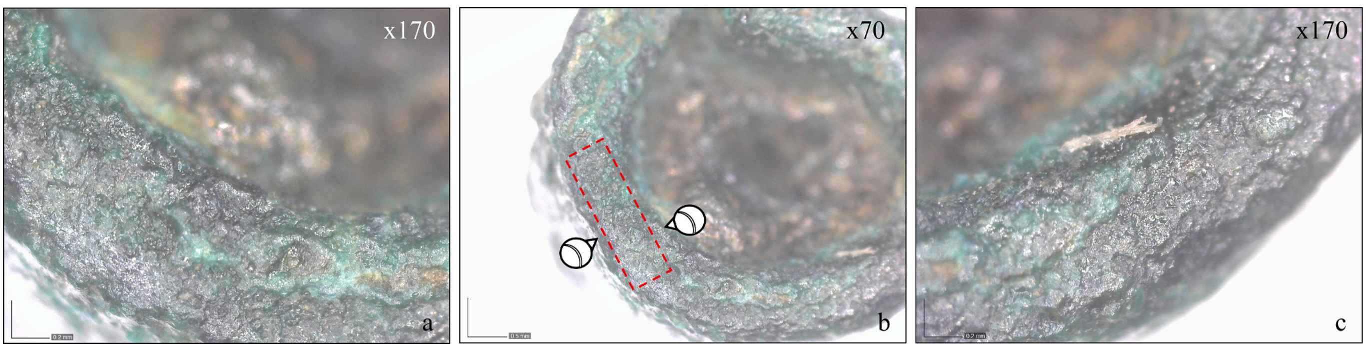

Fig. 21. Microphotographs of DT036. a. Focus on the flattened area; b. Flattened area lined with ribs; c. Focus on a less regular area (crushing or corroded flattened area). © Greek Ministry of Culture/Ephorate of Antiquities of Kavala, V. Martin.

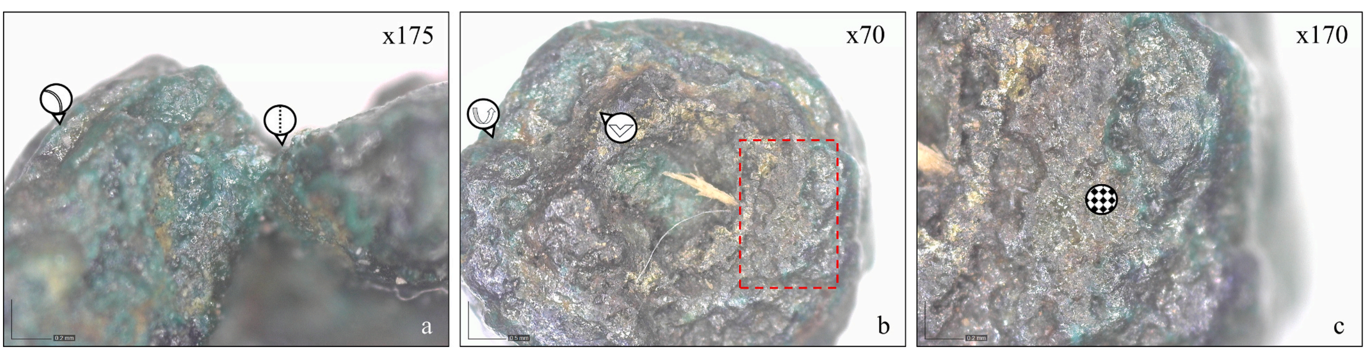

Fig. 22. Microphotographs of DT036. a. Focus on a rib near the junction point; b. Possible notch(es) and twist on the hole's outer edge; c. Focus on a flattened area with imprints. © Greek Ministry of Culture/Ephorate of Antiquities of Kavala, V. Martin.

Fig. 20, b, c), traces of cutting or grinding are discernible. Cutting marks have been noted on the two ends of DT074, i.e. slightly bevelled ends. It cannot be ruled out that the production of this bead was more akin to a ring, by making a wire through hammering, then cutting and joining the ends, which do not overlap. Classified as a bead and not a ring because of its small size, it could nevertheless be another type of ornament.

Finaly, no traces related to casting practices are to be found on the objects. When they are seen through macroanalysis, these are usually described as 'casting defects' or traces left by the mould, such as 'casting seams' (Kienlin & Ottaway, 1998: 275; Dolfini, 2011: 1042), 'blows and drops' (Garbacz-Klempka et al., 2016: 31) or simply a certain roughness[36] (Kienlin & Ottaway, 1998: 275; Gutiérrez Sáez & Muñoz Moro, 2020: 174). However, casting cannot be completely excluded from the manufacturing processes of prehistoric metallurgy, as we already mentioned the capacity to melt metal during the fifth millennium BC. To verify it could necessitate another study with a similar approach as proposed here.

6. Concluding Remarks

The experimental reconstruction of manufacturing processes has made it possible to 1) demonstrate the possibility of cold working pure copper to create shapes that meet specific technical needs, and 2) produce the same features and traces as those observed on archaeological objects. These "diagnostic traces"[37] can be referred to for a better

[36] S.A. Semenov also refers to the 'rough texture' of a casted awl (Semenov & Thompson, 1970: 206).

[37] The "diagnostic traces" or 'diagnostic features', as they are defined by V. Roux, are the characteristic elements of a manufacturing method (Roux, 2010: 6). Noteworthy is the fact that an object does not always present all the "diagnostic traces" of a "*chaîne opératoire*", and this may be for a variety of reasons: disappearance of the traces, object broken or too damaged, etc. This is why increasing the number of studied objects is needed (Roux, 2010: 6).

understanding of how an object could have been produced.

This study aimed to give a technical perspective to the beginning of early metalworking in Greece through microscale analysis. This approach enables the reconstruction of the manufacturing processes of ancient objects using analysis of technical traces with portable and non-destructive microscope techniques. Technical actions have marked the material, by deforming, displacing or removing it. The forging cycles are at the heart of our "*chaîne opératoire*", shaping the metal by deformation and leaving the most recognisable "diagnostic traces".

The result is a set of simple-looking techniques, but their importance lies in the way they are combined. Faced with pure copper, and in cold-working conditions, many issues come into play, such as surface cracking or surface delamination. Neolithic populations seem to have succeeded in controlling these parameters to produce small objects in low quantities that were, nevertheless, fully functional and durable.

However, it can by no means be assumed that the manufacturing processes discussed here were the only ones used to create the first metal objects from the Aegean. A diversity of operations may have existed. What is gleaned from the previous inferences of the traces is the technical ability of manufacturing these objects. The marks on the edges attest to a long shaping process, which appears to have been carried out in two stages: the preparation and general shaping of the copper, followed by a succession of small technical processes leading to the final shape. Shaping by abrasion did not seem to have played such a major role and was used instead to taper the tips. As for polishing for aesthetic purposes, this is rarely seen on copper beads, possibly because it is covered by the corrosion layer.

All these small traces are evidence of technical actions, which also result in a certain irregularity of the surface of the objects. The metalworking production in the Aegean Neolithic does not appear to have been standardized: artefacts that are similar in shape often differed in their surface appearance. This traceological study is focusing on manufacturing traces and is demonstrating the variability of the technical choices offered to the manufacturer. To obtain a finished object in pure copper, the material characteristics must be known and controlled. Although we are not able to speak of a specialised craft evolving in specialised areas or workshops, we can nevertheless recognise the technical know-how of the prehistoric smiths. Moreover, if the physical and chemical properties of the metal were probably unknown to Neolithic populations, the 'qualities' of the copper were certainly well appreciated (Smith, 1975: 609; Kuijpers, 2013: 143, 2017: 29).

Neolithic populations "modelled" objects from pure copper. Without attempting to mass-produce, they embraced this new material, which they managed to control by adapting to it. By playing on its malleability rather than the ability of the metal to be melted, they probably developed great expertise in shaping small objects by forging.

CRediT authorship contribution statement

Valentine Martin: Writing – original draft, Visualization, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

No data was used for the research described in the article.

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Glossary

Blunt/dulling: Surface slightly damaged and dulled by possible friction.

Breakage: Loss of part of the object signified by a fracture point.

Crushing: Area that has undergone significant deformation due to high stress, which has compacted the material and created an irregular surface (compare flattening).

Fissure/crack: Fracture point within the metal, visible on the surface as a narrow, usually longitudinal, slit.

Flattening: Compression of the material, creating a uniformly flat area or 'slightly curved' (Gutiérrez Sáez & Martín Lerma, 2015 179).

Fold/folding: A tab, variable in size, that protrudes from one side, folded inwards.

Hollows/cavities: A deeper recess (more than an imprint) of variable depth, but not yet forming a hole because the two sides are not pierced; generally circular.

Gloss/polish: Shiny area that reflects light, generally concentrated in a particular and limited part of the object.

Groove: A long, narrow but regular indentation, of variable depth.

Imprint: Shallow depression that can take various forms, caused not by the removal of material but by deformation due to the pressure applied to the material.

Joint/junction point: The area where two extremities (the edges of a wire or a strip) meet. This can be an overlapping junction (the two edges are covering each other) or an opposing junction (the two edges are facing each other, whether touching or not).

Microfold: Same as a fold, but on a much smaller scale, visible at medium magnification (x50), and can be located on a surface and not necessarily on an edge.

Notch: A small, incised mark that cuts across the surface or edge of an object, which may have a particular shape (e.g. V-shaped notch, rounded notch, U-shaped notch…). In contrast to grooves, this does not imply a removal of material, but a displacement of it (Gutiérrez Sáez & Martín Lerma, 2015, 179).

Rib/vein: A relatively fine line or band that appears on the surface, forming a relief of variable lump.

Ridge: A small surplus of metal material pushed over an edge, usually oblong, caused by pressure exerted on the material (Gutiérrez Sáez & Martín Lerma, 2015: 179).

Striate: Fine straight scratches, often in groups and overlapping one another, which mark – but not deeply – the surface of an object.

Tear: Removal of material from a quite thin edge, all at once and suddenly, by stretching and then breaking.

Thickening: Area where more material is accumulated than in other parts, making the thickness more substantial.

Twist/torsion: Deformation of the material in a cross direction, generally caused by turning.

Waves/ripples: Slight deformations of the surface that occur regularly and take the form of waves.