SPRAWOZDANIA ARCHEOLOGICZNE 77/1, 2025
PL ISSN 0081-3834
DOI: 10.23858/SA/77.2025.1.4042

Albin Sokół[1], Marcin Maciejewski[2], Łukasz Szczepański[3], Tymoteusz Kosiński[4], Michał Tracz[5]

MANUFACTURING TECHNOLOGY OF BANDED PSEUDO-SPIRAL BRACELETS IN THE LIGHT OF EXPERIMENTAL STUDIES AND COMPUTED TOMOGRAPHY

ABSTRACT

Sokół A., Maciejewski M., Szczepański Ł., Kosiński T., Tracz M. 2025. Manufacturing technology of banded pseudo-spiral bracelets in the light of experimental studies and computed tomography. *Sprawozdania Archeologiczne* 77/1, 285-303.

Knowledge of manufacturing technology of items from various raw materials not only allows for a better understanding of the spheres of human culture associated with their production but also provides a basis for further conclusions on the functioning of prehistoric communities. Copper-alloy objects might be examined using a wide range of archaeometallurgical methods. In this paper, we would like to focus on the manufacturing technology of banded pseudo-spiral bracelets, using an archaeological experiment, macro- and microscopic analyses of traces on copper-alloy items and computed tomography of artefacts from the Lubnowy Wielkie hoard, dated to the Late Bronze Age, Montelius' V period, as well as their reconstructions made during the experiment.

Keywords: Late Bronze Age, Early Iron Age, archaeological experiment, computed tomography (CT), use-wear analysis
Received: 08.02.2025; Revised: 28.05.2025; Accepted: 29.09.2025

1 Archaeological Museum in Biskupin, Biskupin 17, 00-410 Gąsawa; a.sokol@biskupin.pl; ORCID: 0009-0000-0189-3603
2 Institute of Archaeology, Maria Curie-Skłodowska University in Lublin, pl. Marii Curie-Skłodowskiej 4A, 20-031 Lublin; marcin.maciejewski@umcs.pl; ORCID: 0000-0002-5032-9950
3 Ostróda Museum, Ostróda Castle, Adama Mickiewicza 22, 14-100 Ostróda; lukasz.szczepanski@op.pl
4 National Centre for Nuclear Research, Sołtana 7, 05-400 Otwock-Świerk; tymoteusz.kosinski@ncbj.gov.pl
5 Chair and Department of Forensic Medicine, Medical University of Lublin, Collegium Pathologicum, Jaczewskiego 8b, 20-090 Lublin, Poland; michal.tracz@umlub.pl

INTRODUCTION

Archaeological experiments have recently been gaining popularity as a tool for enhancing our understanding of past technological processes. Studying copper-alloy objects is no exception. In the literature, numerous examples of successful experiments can be found that reconstruct procedures used at various stages of production or that elucidate the technological traces visible on artefact surfaces. Observations of the technology used to make metal objects can also provide insight into contacts between particular areas, reconstruct methods of knowledge and skill transfer, and reveal the social role and position of those possessing the know-how. Such studies are part of the archaeology of skills strand (Gener 2011; Kuijpers 2018; Nørgaard 2018; Nowak and Sych 2024).

The archaeological experiment described below aimed to clarify and understand the process of making banded pseudo-spiral bracelets (Fig. 1: 1-6). Various nomenclatures regarding the investigated artefact category occur in the subject literature. The objects in question have sometimes been called banded pseudo-spiral and longitudinally-grooved bracelets (Podgórski 1982, 228). The possibility of forge welding has been suggested for similar (although not identical) accessories (Blajer and Chochorowski 2015, 46; Bugaj *et al.* 2017, 22). Forge welding, also called fire welding, is defined as a solid-state welding process that joins two pieces of metal by heating them to a hot-working temperature range and then creating enough pressure to cause plastic deformation at the weld surfaces (Sharma 2014, 369). Metals such as copper, bronze and brass do not forge weld readily. Although it is possible to forge weld copper-based alloys, it is often with great difficulty due to copper's tendency to absorb oxygen during the heating. To date, no evidence exists of this technique being available in the Late Bronze and Early Iron Age (LBA-EIA) in the area occupied by the Lusatian Urnfield cultures. Above all, it requires the use of substances that prevent the formation of oxides on the heated metal's surface, which would hinder two or more pieces from welding together. These findings suggest searching for a solution by using another technology.

The literature also indicates that items of this type were cast and that the imitation of coiling was intended to refer to earlier wire specimens (*e.g.*, Kaczmarek *et al.* 2021, 99). However, a deeper reflection on the details of this process is lacking.

It was, thus, reasonable to attempt to reconstruct the *chaîne opératoire* leading to the final product and examine the traces indicating the solutions used at the object's various manufacturing stages.

The idea to experimentally verify the hypothesis that banded pseudo-spiral bracelets were made using the lost wax technique and that the wire-like form was obtained using long and thin wax rods came about during one of the meetings of the 'Working group on the phenomenon of mass goods deposition' ('Zespół badania zjawiska masowego deponowania dóbr' – for details on this working group, see Maciejewski *et al.* in press). The inspiration came from the cross-sections generated using computed tomography (CT).

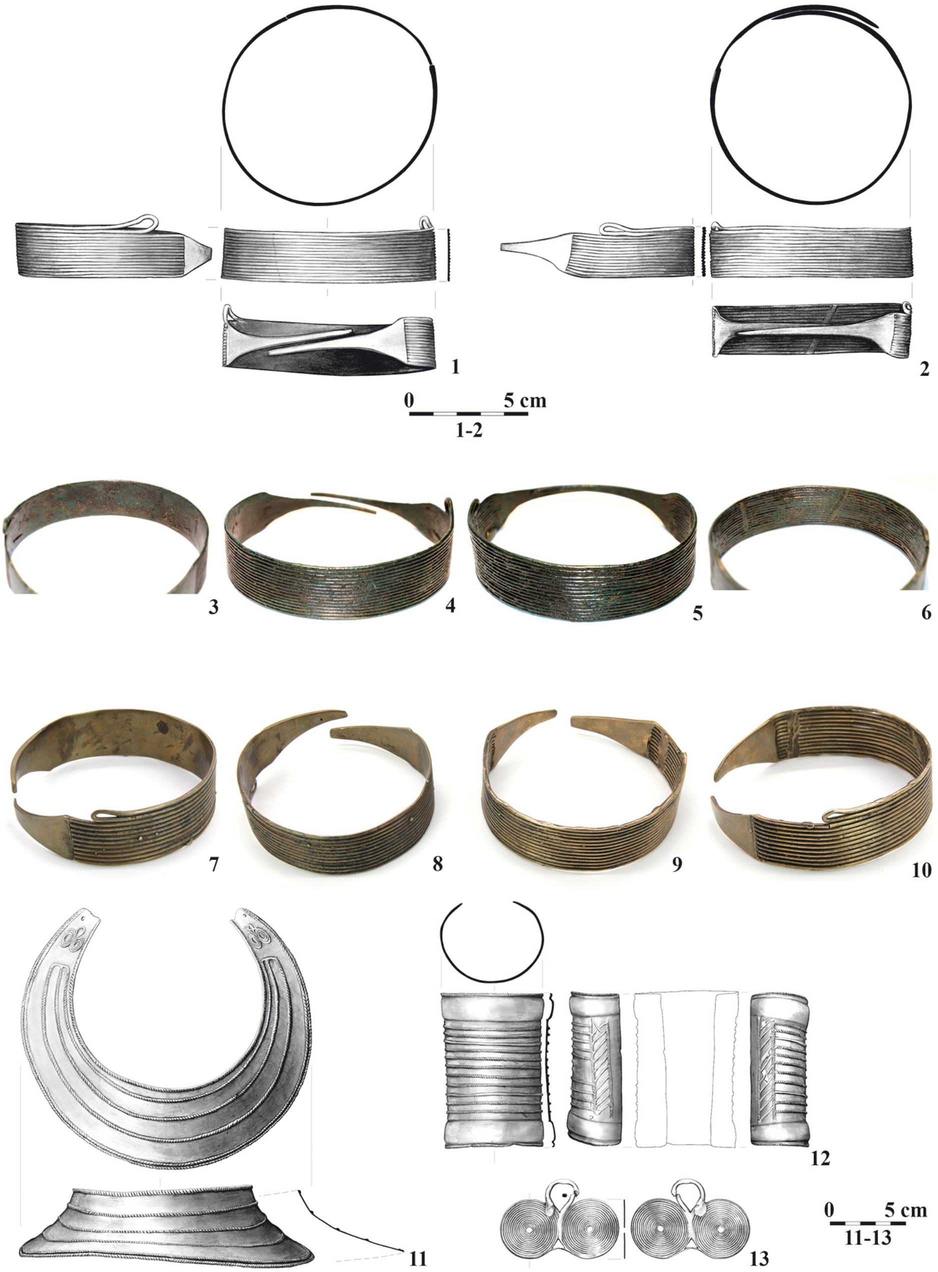

Fig. 1. Lubnowy Wielkie hoard, banded pseudo-spiral bracelets (1-6), and their reconstructions cast for research (7-10), ribbed neck-ring (11), cuff bracelet (12), and binocular pendant (13). 1-2, 11-13: drawn by N. Lenkow, 3-6: photos by M. Maciejewski, 7-10: photos by A. Mazurek

They strongly resembled the structure of interconnected wires. The scans were made as part of the project: Techniques of Ornamentation on Late Bronze Age Metal Objects Based on Artefacts from the Lubnowy Wielkie Hoard (Cast or Applied?) ('Techniki wykonywania ornamentów na ozdobach z późnej epoki brązu na przykładzie zabytków ze skarbu z Lubnowy Wielkich (odlewane czy aplikowane?') carried out as part of the second call for projects for access to the MOLAB/FIXLAB PL research infrastructure offered by the E-RIHS PL consortium (Maciejewski 2017).

Based on images generated during the CT scans, it has been hypothesised that the bracelets were produced using the lost-wax casting method, partly employing long, thin rods that mimic wires. To verify this hypothesis, an experiment and accompanying analyses were planned.

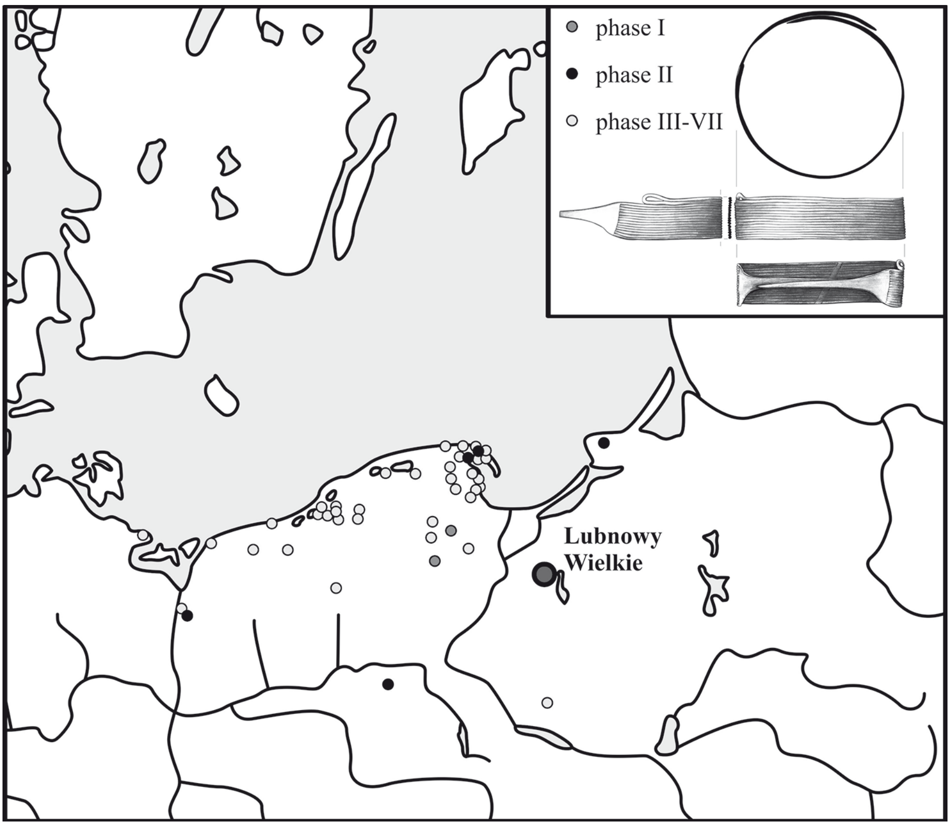

Fig. 2. Map of the distribution of banded pseudo-spiral bracelets. Based on Fogel 1988, with additions. Drawn by M. Maciejewski

NOT ONLY BRACELETS – A SHORT PRESENTATION OF THE LUBNOWY WIELKIE HOARD

The bracelets whose manufacturing technology constitutes the focus of this study formed part of the Lubnowy Wielki hoard, which has not yet been published; therefore, only the most essential information is presented here. The hoard was discovered in late April 2017 during a metal detector survey conducted under a permit issued by the Voivodeship Heritage Protection Officer. The place of its discovery is located in Powiśle, near Ostróda, NE Poland. This is approximately 30 km east of the Vistula, which at that time constituted a significant boundary between cultural traditions, although various traditions intermingle in this area (Bukowski 1998; 2020; Żórawska 2000, 63). The artefacts were handed over to the Museum in Ostróda. The hoard comprised five items, found at a depth of *ca*. 50 cm and arranged in a way suggesting their intentional deposition. The assemblage may be dated to Montelius' V period (see below) and may have been a set of dress accessories belonging to one or two individuals. They have parallels in the South Baltic area, particularly in Pomerania. A comprehensive research programme has been designed for the hoard, including typical work such as conservation, the creation of graphic records, and typological analysis, as well as several other recording and research activities. Attempts were made to carry out three-dimensional recording using photogrammetry, analyse the chemical composition of the alloys from which the artefacts were made, and conduct microscopic documentation before and after conservation (*cf*., Sych *et al*. 2020), as well as analyse these images. The list is completed by examinations with a CT scanner and a settlement analysis of the area around the hoard discovery site. Of course, the presented experimental studies also became part of this informal project. The overall conclusions of this study have not yet been published.

Banded pseudo-spiral bracelets are relatively common in Pomerania and adjacent areas. They are meant to imitate earlier bracelets made of double wire, which were coiled. These simple items occur in various regions. Some specimens from Pomerania, mainly western Pomerania, may have been imported from the Nordic area (the Oder variant). At the same time, in eastern Pomerania, they were thought to have been developed locally (the Vistula variant). In connection with this, banded pseudo-spiral bracelets may have been developed, and their earliest forms are known only from the Kashubian Lake District (Fogel 1988, 20-29). This bracelet type was described in a work on Nordic imports of the Montelius V period (Fogel 1988), but it is not an import. According to Fogel's (1998, 24) division, specimens from the Lubnowy Wielkie hoard might be classified as originating from the second Wielkawieś development phase (Fig. 1: 1-6; 2).

In addition to the bracelets discussed above, the hoard also comprised three further ornaments. The first of these is an oblique ribbed neck-ring (*der steilen, gerippten Halskragen*; Fig. 1: 1 1). Fogel (1988, 59-61) described the Polish specimens as belonging to a single group. Nørgaard (2011, 73-76), however, proposed distinguishing three types according to the number of ribs. Within this typology, the artefact from Lubnowy Wielkie can be classified as a Quedlinburg type. Both authors date these ornaments to Polish territory and to Montelius' Period V. Comparable artefacts are known from both northern Poland and northern Germany. Scholarly debate has raised different views concerning the origins, inspirations, and possible local development of the stylistic traits of these ornaments in Pomerania (see Fogel 1988, 56-61; Nørgaard 2011, 73-76). Definitive statements remain difficult, not least because such items are relatively rare and no identical forms are known. Overall, they belong to the broader tradition of massive neck ornaments widespread in the South Baltic area during the Bronze Age (see Nørgaard 2011).

The hoard also included a rather unique cuff bracelet (Fig. 1: 12), which is stylistically akin to the neck-ring but markedly different from the Nordic cuff bracelets of the Bronze Age (*e.g.*, Baudou 1960, 65, 66, pl. 13). Only a single comparable artefact is known, although it has since been lost, and the surviving drawing is not sufficiently precise to confirm any unmistakable resemblance. This concerns the bracelet from the Szylina Wielka hoard, which has been dated to Montelius' Period VI (*e.g.*, Dąbrowski 1968, pl. 18: 14; Dąbrowski 1997, 66).

The final element of the assemblage is a binocular pendant (Fig. 1: 13), a relatively common artefact in the Bronze Age and Early Iron Age (Dąbrowski 1968, 82, 83; Waluś 2014, 52, 53), which has no chronological value. Interestingly, it had been fastened onto one of the banded pseudo-spiral bracelets.

Taking all this into consideration, we suggest that the assemblage can be dated with considerable confidence to Montelius' Period V.

METHODS

The research methodology applied consists of an experiment in which replicas were produced (as described in greater detail below), a comparison of CT scans of the original artefacts and the replicas, and a comparison of traces observed on the artefacts and the replicas.

The archaeological experiment was conducted as a laboratory study, employing modern methods for mould firing and metal melting. A standardised copper alloy with specific parameters was also used – bronze designated as B10, which, according to the standards (norm EN 1652), should not contain, apart from tin, any additional elements exceeding 0.3% of the composition. The choice of these procedures was motivated by the desire to focus on a specific technological aspect – to confirm or falsify the hypothesis regarding the use of the lost-wax method in the production of the model. Efforts were also made to exclude variable factors that could occur in a field experiment and potentially disrupt observations and conclusions, *e.g.*, those related to the causes of defect formation, which could result from a lack of experience in using the reconstructed foundry workshop rather than the method of designing the model and the mould.

As previously mentioned, the inspiration for conducting the archaeological experiment stemmed from the CT results of the original artefacts. These investigations were conducted at the National Centre for Nuclear Research in Świerk using the Nikon Metrology XT H 225 ST, an instrument designed for detailed quality control. X-ray CT scans were also performed on specimens made during the experiment. In this case, a medical device (Toshiba Astelion TSX-034A) was used, with less power and resolution than the device from Świerk. The study was conducted under the current academic cooperation agreement between the Chair and Department of Forensic Medicine at the Medical University of Lublin and the Institute of Archaeology at the Maria Curie-Skłodowska University.

Microscopic observations of the surfaces of the original artefacts were carried out using a Dino-Lite portable digital microscope at magnifications of ×20-40, both before and after conservation. Photographic documentation was produced with a Canon EOS 100D (18 MPx APS-C sensor) with a Canon EF-S 18-55 mm f/3.5-5.6 IS lens.

The replicas of bracelets produced during the experiment were examined to identify traces of casting defects and post-casting metalworking treatments. A Nikon SMZ800N reflected light stereomicroscope was used for this purpose, equipped with a Plan Apo 1x WF WD: 70 mm lens, providing low magnifications (×10-30). The traces on the bracelets at each stage of production were documented using a Sony α7 camera with a SONY FE 90 mm f2.8 Macro G OSS lens.

EXPERIMENT

The experiment's starting point was macro-observations of traces visible on two specimens of banded pseudo-spiral bracelets from the Lubnowy Wielkie hoard. These were assessed as indicative of lost-wax technology (*e.g.*, casting defects in the form of excess material; Fig. 5: 2, 4, 6), but the artisan attempted to imitate a structure resembling welded wire while forming the model. The two examined specimens might be considered a pair, as they are, in a way, mirror images of each other in terms of the placement of the imitation of the wire loop. However, significant differences can be seen in the working of the inner surface. In one case, it is smooth, while in the other, it mimics welded wire on the outside. It was therefore decided to replicate the manufacturing stages for both specimens (Fig. 1).

At the very beginning of the experiment's planning, problems with raw material selection for models occurred. In archaeological literature, beeswax (meaning the secretion of the bees' wax glands used to build slices in the hive) is often mentioned rather generally as an obvious raw material used in the lost-wax technology, also known as *cire pardue* (Garbacz-Klempka *et al.* 2018; Armbuster and Meyer 2024; Bartz *et al.* 2024; Nordez 2024). However, there have also been discussions about the use of additives (including fats, natural resins, and charcoal dust) that impart specific properties to the raw material (such as stiffness, elasticity, ductility, *etc.*), which allow the shaping of complex models (Rønne and

Bredsdorff 2008, 67-69; Auenmüller *et al.* 2019, 144). Attention is also drawn to the possibility of completely replacing beeswax (Sperlin and Trommer 2024). To better understand the broad possibilities and the influence of the availability of local raw materials, the authors often refer to ethnographic analogies or to contemporary artisans practising traditional production methods (Rønne and Bredsdorff 2008, 69; Martinon-Torres 2015). Modern analytical methods (*e.g.*, fourier-transform infrared spectroscopy or gas chromatography with flame ionisation and mass-selective detection) enable the identification of beeswax residues on tools used for casting (Nadmar *et al.* 2008; Baron *et al.* 2014; 2015). However, the residues and the context of their discovery do not always directly indicate the use of wax as a model-making material; instead, there is ongoing discussion about the possibility that wax may have been employed as an ingredient in a protective paste for the mould surface – serving to improve the quality of the casting and to facilitate the removal of finished objects from the mould (Baron *et al.* 2014, 335, 336; 2015). These observations are especially valuable in the context of metal casting moulds, where wax may additionally have served as a preservation material. Due to the lack of definitive conclusions on the use of specific recipes for materials made from beeswax, as well as challenges in identifying differences in archaeological materials, it was decided to use pure beeswax. Nevertheless, its properties enabled the achievement of the desired model shape. The author's previous observations and experience suggest that additives could be beneficial in achieving the desired properties of the raw material; however, it was decided to limit factors that might detract from the main subject of consideration. The issue of using various recipes and their potential identification in archaeological materials definitely warrants a separate experimental approach. Since this is not the central issue of our discussion, we only signal it here and intend to develop it in future studies.

The actual work on creating bracelet replicas began with preparing long, thin, wire-like rods made of wax mass. They were then arranged side by side to form a band (Fig. 3 : 1). An imitation of the wire loop was also formed at this stage (Fig. 3: 2). The narrowing terminals were formed by squeezing and fusing, giving them a smooth surface (Fig. 3: 2). On the outside, efforts were made to join the rods at a single point, creating a clear transition towards the smooth terminals (Fig. 3: 3). The terminals were left thickened, and no excess wax was removed to facilitate their proper casting and further working.

Next, the rods inside the band were fused, and this is where the first differences between the bracelets became apparent. One of them is smooth on the inside, so during wax model creation, the rods were joined almost entirely, resulting in a uniform surface (Fig. 4). The procedure was performed using a bronze blade heated to the correct temperature, which melted the wax and facilitated shaping. In the second bracelet type, where the inner side also shows separate rods imitating wires, they were joined only in a few places (imitating the original) by making a narrow, band-like fusion (Fig. 4). At this point, it should be added that the wax mass at room temperature (18-25°C) is viscous. The rods can be joined by pressure alone, but such a joint is unstable, and local dislodgement may occur during later processing. Therefore, it is justified to use a welding procedure by over-melting the wax to strengthen the whole.

The sequence of operations presented so far may have been different, as it did not leave traces that would allow for its exact reproduction. For example, the joining of the rods forming the band might have occurred before the ends were formed, but the result and the possibility of capturing the traces would have been identical.

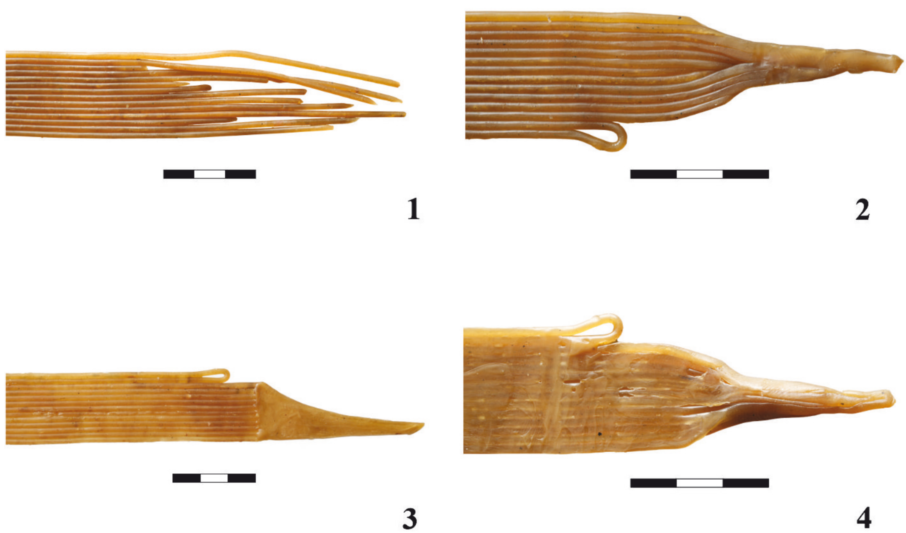

Fig. 3. Selected stages of preparation of wax models; 1 – forming a band by connecting wire-like rods made of wax mass; 2 – forming terminals by squeezing and fusing wax rods; 3 – creating a clear transition towards the smooth terminals; 4 – carefully finishing the inner surface of the rod connections. Photos by A. Sokół

Fig. 4. Differences in the inner surface of bracelet models of both types. Photos by A. Sokół

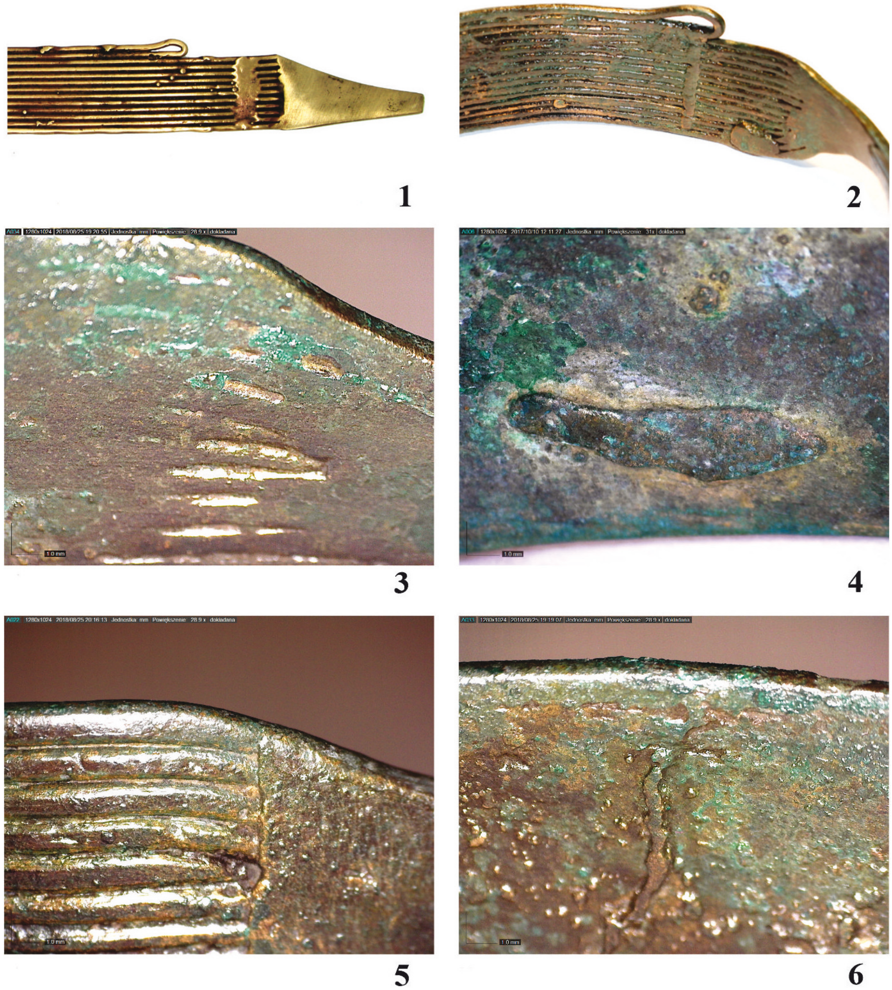

Fig. 5. Traces or defects indicating the use of the lost-wax method:
1 – traces visible on the replica; 2 – various traces visible on the inner surface of the bracelet; 3 – carelessly finished inner surface of rod connections; 4 – surplus material; 5 – cavities; 6 – furrow-shaped lines of surplus material. 1: photos by A. Sokół, 2-6: photos by M. Maciejewski

The next step was preparing a ceramic casting mould. For this purpose, a general knowledge of the technology used to produce metal objects from melted wax models was employed. The information is based on the analysis of artefacts related to Bronze and Early Iron Age metal casting (production waste, such as mould fragments, removed casting jets) coming from several Polish sites (*e.g.*, Piaskowski 1957; Stolarczyk and Baron 2014; Makarowicz 2016; Nowak and Stolarczyk 2016; Stolarczyk *et al.* 2020). Valuable finds in this regard are clay moulds from the Juszkowo site, which Podgórski (1982, 228,

229) interpreted as moulds for casting banded pseudo-spiral bracelets from the same phase as those from Lubnowy Wielkie. The experiment used a ceramic mass with a high temper, *i.e.*, sand and organic additives derived from horse manure. These additives were intended to reduce mass shrinkage during drying and firing significantly. Moreover, after heat treatment, the organic temper imparted the finished moulds with the desirable porosity, which is crucial for casting long, thin-walled objects.

The moulds were dried in a cool and unheated place for two weeks. After this time, firing took place. To control the conditions, the process was conducted in a modern kiln. In the first stage, the moulds were preheated to 90°C for 4 hours to melt the wax mass, and then a systematic heating was performed up to 750°C. A bronze with a tin content of 10% was used to pour into the moulds. Before casting, the ceramic mould was heated to 300°C to ensure that no moisture remained inside it and that the metal stayed molten long enough to fill all the spaces. To extract the as-cast metal product, the mould had to be broken.

The post-casting treatment of the as-cast item included removing the pouring cup by controlled break-off, preceded by chisel cuts. This was followed by shaping the narrowing bracelet's terminals by cold hammering to make them slenderer. The specific hammering stages were preceded by annealing the material to make it easier to form and to prevent breaks during subsequent modifications. Further work included grinding the product on sandstone whetstones with different grain sizes. The final effect was achieved by polishing using ground charcoal applied using animal leather.

Finally, the band was bent to the target shape of the bracelet. This was not done earlier since a flat band was easier to work with and polish. The bracelet's bent shape makes it challenging to access the inner part.

RESULTS – CT SCAN

The CT imaging of the original artefacts provided the impetus for undertaking the experiment described here. We therefore begin the presentation of the research results with a discussion of these observations. As noted, the scanning was performed using equipment designed for the quality control of industrial components. Although metal substantially attenuates X-rays, the images obtained are nonetheless highly detailed (Fig. 6: 1; 7: 1).

In the case of the bracelets under consideration, the cross-sections occasionally reveal distinct oval shapes that resemble the sections of metal wires. This is particularly evident in the bracelet whose inner surface imitates the structure of fine wires. The construction of the loop likewise convincingly imitates a wire form, both in macroscopic observation and in the CT scans (Fig. 6: 1).

These images lend themselves to various interpretations. One possibility was the welding of wires combined with the casting of terminals using the cast-on technique (Überfangguss), as seen, for example, in case bronze pins (Armbruster 2000, 85-87). However, first, no traces of overcasting were visible on the CT scans, and second, welding or soldering – as noted above – poses significant technological difficulties. A second potential method, which was tested during the experiment, involved producing the bracelets from wax models designed to imitate a structure composed of separate wires.

The next stage of the research involved performing CT scans of the bracelet replicas produced during the experiment. Unfortunately, it was not possible to use the same

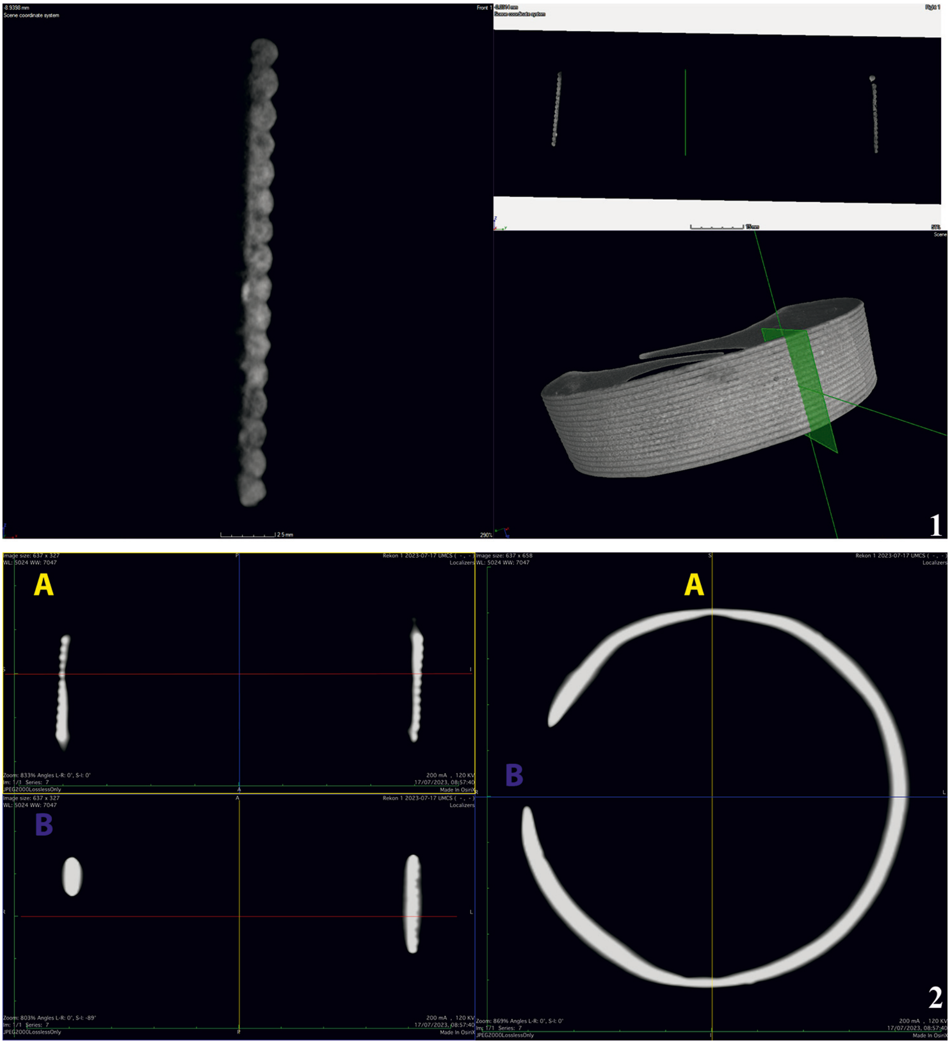

Fig. 6. A so-called bracelet with a smooth inner surface (Figs. 1: 1, 3, 5): computed tomography of the original artefact (1 – CT using Nikon Metrology XT H 225 ST) and the reconstruction (2 – CT using Toshiba Astelion TSX-034A). 1: compiled by T. Kosiński; 2: compiled by M. Tracz

scanner; instead, a medical device was employed, which offered lower resolution and power. As a result, the scans differ markedly in quality (Figs 6 and 7). Nevertheless, in both cases – and once again most clearly in the bracelet whose inner surface imitates a wire-like structure (Fig. 6: 2; 7: 2) – the cross-sections reveal oval shapes resembling those observed in the CT scans of the original artefacts.

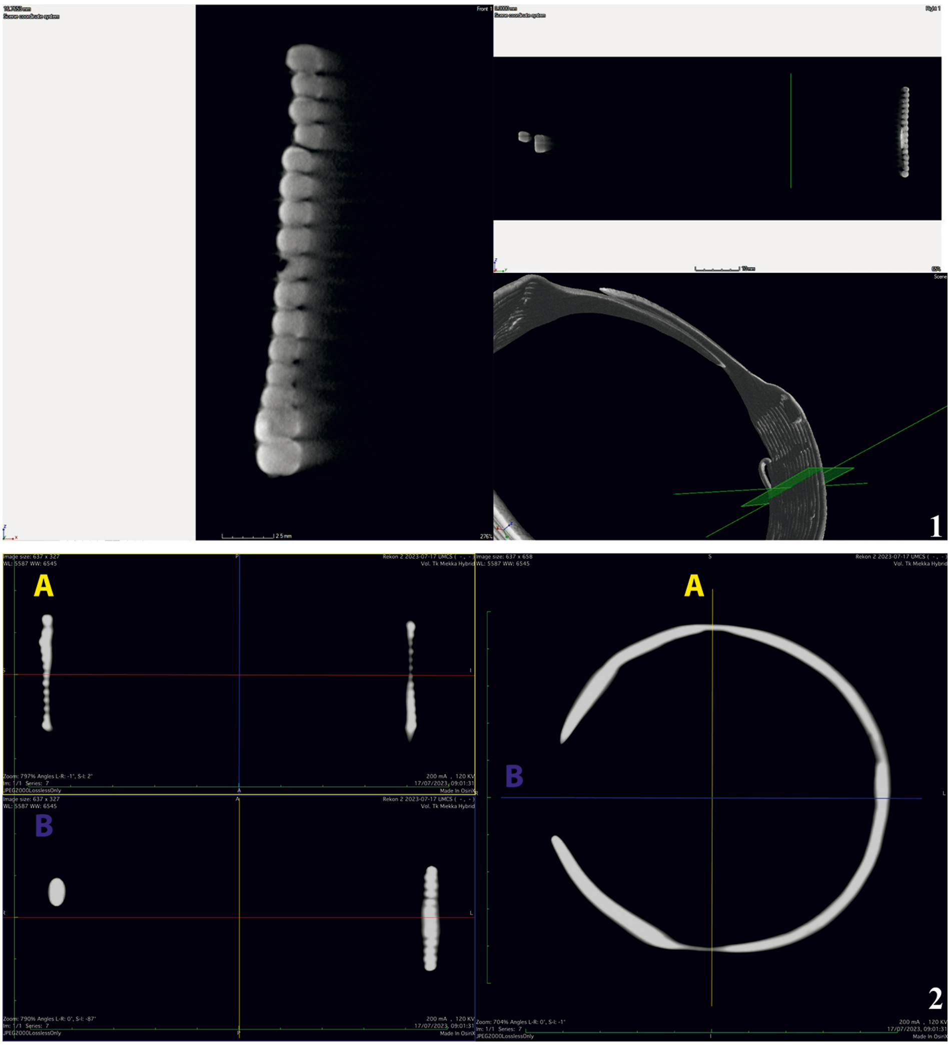

Fig. 7. A so-called bracelet with an inner surface imitating welded wires (Fig. 1: 2, 4, 5): computed tomography of the original artefact (1 – CT using Nikon Metrology XT H 225 ST) and the reconstruction (2 – CT using Toshiba Astelion TSX-034A).
1: compiled by T. Kosiński; 2: compiled by M. Tracz

RESULTS – COMPARISON OF TRACES OBSERVED ON THE ORIGINAL BRACELETS AND EXPERIMENTAL SPECIMENS

The experiment enabled the creation of bracelet replicas and the observation of macro-traces left by the technological operations described above. Many of these traces correspond to those identified on original artefacts.

On the inner side, traces of fusing the wax rods were observed, consistent with both bracelet specimens. In the specimen with visible rods, these are revealed as narrow, smooth bands resulting from the melting of the wax in contact with a heated metal tool (Fig. 5: 1, 2). They were not removed during the working of the item surfaces. On the inner side of these bracelets, a slight flattening of the rods is also visible, which might result from the model adhering to the working surface while it was formed (Fig. 5: 1, 2). Similarities are also noticeable in the specimens with smooth surfaces. Traces of the terminals' manufacture and attempts at smoothing match well. Careless execution of this procedure caused some surface fragments to be left unworked so that the rod structure is visible in places, particularly in the case of the specimen with the flat inner side (Fig. 3: 4; 5: 3).

The numerous casting defects are particularly distinctive traces of the use of the melted model technology. Among these, the most common are variously sized areas with surplus material, resulting from an inaccurate coating of the model with clay mass, leaving additional space for liquid metal (Fig. 5: 1, 4). In this case, the traces should be interpreted cautiously, as they may be mistaken for similar areas formed from wax during the model-making stage. Further defects include cavities or misruns, usually caused by the accumulation of excess casting gases in a given area, preventing the mould from being thoroughly filled with liquid metal (Fig. 5: 5). This trace is particularly distinctive, as it is difficult to imagine using metal rods with cavities to form such bracelets. High-quality products (excellent casts) were used to manufacture the rods and wires, as any defects in the material would have led to cracks during the drawing process.

Defects in the form of furrow-shaped lines of surplus material were only observed on the original bracelets (Fig. 5: 6). They most likely result from cracks in the wax model's ceramic coating. Such cracks might develop from drying the mould too quickly or improper firing. They may also result from using inappropriate or insufficient temper, which results in insufficient shrinkage of the ceramic mass. Cracks may also form during the pouring of metal into the mould due to thermal shock caused by the heated metal and pressure from casting gases. Finally, cracks might result from mechanical damage or dropping the mould. Regardless of the cause, the space thus created is filled with liquid metal, leaving a positive impression of the crack on the finished product's surface. The absence of such traces on the experimental replicas may indicate that the mould was well-made. The fine furrows of surplus material may have been removed during the grinding procedure, especially on the inside of the bracelets.

CONCLUSIONS AND TECHNOLOGICAL OBSERVATIONS

The experiment confirmed the hypothesis derived from the analysis of technological traces on archaeological artefacts and CT scans. They indicated the use of melted wax models and suggested a similar *chaîne opératoire* to produce finished items. By reconstructing the process, it was possible to create replicas with properties resembling those of the original objects. Traces observed on the experimental specimens correspond very well with those identified on the original artefacts. Particularly distinctive were traces of joining wax rods and forming narrow terminals. Equally valuable are casting defects, especially those resulting from imprecise manufacturing of the ceramic mould, such as areas with surplus material, cavities or traces of mould cracking. The above observations provide a clear picture of the process and the range of techniques used to form banded pseudo-spiral bracelets. Additionally, a catalogue of characteristic traces may prove helpful in studying similar items. Not only does it apply to other specimens of banded pseudo-spiral bracelets, but also to objects where specific procedures were used to imitate the use of metal wire, rods or the welding and soldering procedures (*e.g.*, other objects from the Lubnowy Wielkie hoard).

The above-mentioned issues could be resolved through specialised metallurgical studies, such as ToF-ND, which has recently gained popularity in the non-invasive investigation of metal artefacts (Tarbay *et al.* 2023; Nagler *et al.* 2019). By analysing scattered neutrons, data can be obtained on the crystal structure, phase composition, and texture of the material – that is, the arrangement of grains – which allows, for example, distinguishing objects produced by casting, forging, or rolling (Cereser *et al.* 2017). Such analyses enable the documentation of metalworking treatments that can be used to identify the processes applied to the discussed categories of artefacts. Together with the described experiment, this would lead to a precise understanding of the entire manufacturing process. A problematic issue remains the shape of the final model and its position while pouring. Based on initial unsuccessful attempts, it was decided to cast a flat strip vertically, using gravity to fully fill all gaps. This required intensive metalworking treatments of the cast semi-finished product, including forging and bending, which involved the risk of damage. The application of TOF-ND could confirm or exclude whether these treatments were truly applied. The findings of the previously mentioned bracelets from Aleksandrowice, based on models shaped as closed strips, may suggest that they were cast in their final form (Blajer and Chochorowski 2015). The detailed surface preparation makes it impossible to locate potential casting and venting channels using macro observation. However, an analysis of casting defects, porosity, and shrinkage using computer modelling and reverse engineering could prove helpful in dispelling doubts (Garbacz-Klempka *et al.* 2017; 2018, 1334).

The production of banded pseudo-spiral bracelets is an arduous task that testifies to the high skills of the metallurgists. This complex process involved multi-stage preparations, requiring a deep understanding of the appropriate wax mixture, the ceramic mass for the mould, the design of gating systems, and the selection of the optimal alloy composition. Additionally, possessing sufficient manual skills and maintaining good work hygiene are crucial, especially when working with wax, which can easily become contaminated in unsuitable conditions. The very shape of bracelets, being thin-walled and long, generates many difficulties and requires incredible precision in handling. The problematic nature of the process is evident from several unsuccessful castings made during the preparatory stage of the actual metallurgical experiment.

The course of the experiment highlighted the problem of insufficient knowledge and inadequate analysis of the key details of the process of creating copper-alloy objects. Different types of bee wax-based pastes have already been mentioned above. Similarly, the composition and method of making the clay paste for mould-making may vary widely. Such factors affect the cognitive value of the experiment, and further research focusing on the variables mentioned should be a solution. The possibility of identifying wax residues in casting moulds offers hope for the development of analytical solutions that could, in the future, shed light on the use of various wax mixtures. Supported by experimental research, it would be possible to trace the impact of specific formulations on particular effects, such as surface quality or the accuracy of the model's reproduction in the final product.

The studies demonstrated the value of CT methods in archaeology. It must be noted that the nature of the CT method makes the investigation of objects made of high-density raw materials, such as copper alloys, challenging. However, in both cases, the devices were possible. Clearly, there is a difference between the CT results of the two instruments. Nevertheless, it can be concluded that using the more common medical CT scanners makes sense if the National Health Service is not burdened with financing the examinations.

Acknowledgments

The study was partly carried out within the framework of the project titled: 'Techniques of Ornamentation on Late Bronze Age Metal Objects Based on Artefacts from the Lubnowy Wielkie Hoard (Cast or Applied?)' ('Techniki wykonywania ornamentów na ozdobach z późnej epoki brązu na przykładzie zabytków ze skarbu z Lubnowy Wielkich'), carried out as part of the second call for projects for access to the MOLAB/FIXLAB PL research infrastructure offered by the E-RIHS PL consortium coordinated by E. Mista-Jakubowska from NCBJ and within the framework of academic cooperation agreement between the Chair and Department of Forensic Medicine, Medical University of Lublin and the Institute of Archaeology of the Maria Curie-Skłodowska University in Lublin.

We would like to thank the Museum in Ostróda for making the artefacts available for study.

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