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Reconstruction of the Casting Technology in the Bronze Age on the Basis of Investigations and Visualisation of Casting Moulds

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Abstract

During excavation of the cremation cemetery of urnfield culture in Legnica at Spokojna Street (Lower Silesia, Poland), dated to 1100-700 BC, the largest - so far in Poland – a collection of casting moulds from the Bronze Age was discovered: three moulds for axes casting made out of stone and five moulds for casting sickles, razors, spearhead and chisels, made out of clay. This archaeological find constituted fittings of foundrymen's graves. In order to perform the complete analysis of moulds in respect of their application in the Bronze Age casting technology analytical methods, as well as, computer aided methods of technological processes were used. Macroscopic investigations were performed and the X-ray fluorescence spectrometry method was used to analyse the chemical composition and metal elements content in mould cavities. Moulds were subjected to three-dimensional scanning and due to the reverse engineering the geometry of castings produced in these moulds were obtained.

The gathered data was used to perform design and research works by means of the MAGMA⁵ software. Various variants of the pouring process and alloys solidification in these archaeological moulds were simulated. The obtained results were utilised in the interpretation of the Bronze Age casting production in stone and clay moulds, with regard to their quality and possibility of casting defects occurrence being the result of these moulds construction.

The reverse engineering, modelling and computer simulation allowed the analysis of moulds and castings. Investigations of casting moulds together with their digitalisation and reconstruction of casting technology, confirm the high advancement degree of production processes in the Bronze Age.

Keywords: Application of information technology to the foundry industry, Archaeometallurgy, Casting moulds, Tin bronze, XRF

1. Introduction

The biggest collection of Bronze Age casting moulds in Poland was discovered in years 1972-1973, when the cemetery in

Legnica at Spokojna Street (site 102, AZP 77-21, site 3, Lower Silesia, Poland) was excavated. The cemetery is dated at IV-V period of the Bronze Age (1100-700 BC). Artefacts discovered in three burnt burials of metallurgists-foundrymen (graves no. 5, 42,

153) consisted of five ceramic casting moulds (for sickles, razors, spearheads, chisels) and three stone two-part moulds for casting axes with a bushing and a lug (Fig. 1). The artefacts from the cemetery are in the collection of the Copper Museum in Legnica [1].



Fig. 1. Moulds from foundrymen graves, the Legnica cemetery (1100-700 BC). Stone and clay moulds for casting of: razor (a-b), sickles (c-d), spearhead tip (e), chisel (f), axe (g-h), axe (i-j), spearhead tip (k-l)

The collection of moulds from Legnica was subjected to comprehensive research using analytical methods and visualisation with computer aided methods. Research on ancient casting processes includes many aspects – analysing raw materials, metallurgical semi-products, slags and finished products, as well as tools, crucibles, shank ladles, and moulds [2-5].

Moulds are amongst the most important elements of the Bronze Age technology. Their analysis will enable the level of knowledge and skills of ancient foundrymen to be assessed and will answer the question about the quality of castings obtained.

Semi-permanent and permanent moulds have been known from the Bronze Age. They were intended for series production (two-part stone and clay moulds) and for piece production with the investment casting method (clay moulds). Metal moulds much more seldom occur. The simplest moulds consisted of two parts. One part contained a cavity (mapping the casting), whereas the other one was a flat plate. They were used for casting objects with

one-side flat. More complex articles were cast in two-part moulds, and hollow objects in two-part moulds with a core, reconstructing the internal part of a casting. [6-12]

Precise investment casting process (lost-wax casting) was very important [13]. Beeswax patterns were covered with clay, dried and burned in the fire, giving a mould the high-temperature resistance and durability in contact with liquid metal. This method ensured considerable smoothness and the accuracy of pattern reconstruction [5, 14-15].

Moulds were poured with tin bronze or tin-lead bronze, as well as lead bronze. Tin addition to copper reduced the melting temperature, changed colour to more silvery and improved the casting quality. The tin content in tin bronze influences mechanical properties: hardness, tensile strength, yield point and elongation [9,16-21]. Lead improves the alloy workability. Both imported raw material and own scrap were melted and cast. Changes in alloy composition were limited [14-15].

2. Issues and research methodology

The current work had the objective of analysing ancient processes of casting into stone moulds and reconstructing the process with computer aided methods. To present the scope of research and its findings, the paper presents examinations of four out of eight moulds: clay moulds for casting sickles (Fig. 1 c-d) and chisels (Fig. 1 f), and two stone moulds for casting axes (Fig. 1 g-h and i-j). Macro- and microscopic observations of the moulds were carried out and the chemical compositions were examined to identify traces of alloys in the mould cavities. The moulds were also subjected to 3D scanning, and thanks to the reverse engineering the geometry of castings produced in the moulds concerned was obtained. The collected data was used for engineering and research work conducted with program MAGMA⁵.

The macro- and microscopic investigations were conducted with a stereoscopic microscope NIKON SMZ 745 with a digital camera and a system for image analysis Nis-Elements. Chemical composition tests were performed with X-ray fluorescence spectrometry using an energy dispersion spectrometer (ED-XRF), Spectro Midex with an X-ray tube with a Mo anode and a semiconductor detector Si SDD. The qualitative investigations of chemical composition were performed in the mapping system of the internal part of mould halves, and by analysing characteristic elements: Cu, Sn, Pb, As, Sb, Ni. [22-24].

The 3D model acquisition was performed with a triangulation based 3D laser scanner (MetraSCAN 3D), using an optical tracking system (C-Track 780) by Creaform. The whole process was supported with VXelements software, able to create a virtual triangle mesh, mapping the geometry of the scanned object in real time.

The geometry obtained by scanning was subsequently transferred to software MAGMA⁵ to simulate pouring, cooling and solidifying of castings. It enabled the ancient casting processes to be visualised, and improve understanding of the mould preparation process, casting, and solidifying of alloys in a mould. It also allowed the correctness of the process to be evaluated for the obtaining of high-quality castings.

3. The results of mould observations and research

3.1. Macroscopic observations and tests of chemical composition

The moulds were subjected to macroscopic observations. One can notice the technical correctness and the accuracy of mould workmanship using precise and sharp tools for hewing and smoothing the cavity and carving its details (Fig. 2).



Fig. 2. Stone mould for casting axes from Legnica (ML/A 1118/1-2; grave 42)

The moulds examined show marks of use, including mechanical damage, stains resulting from a temperature impact and residues of alloy in the mould cavity and its immediate vicinity (Figs. 3-4).

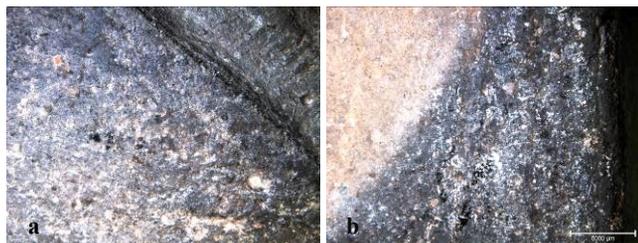


Fig. 3. Clay mould for casting sickles from Legnica (ML/A 1081/5a,b). Macroscopic image: tool marks visible in the mould cavity 5a (a) and stains 5b (b), magnification 6,7x

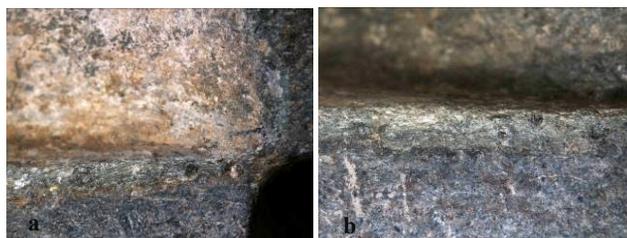


Fig. 4. Stone mould for casting axes from Legnica (ML/A 1118/3-4) Macroscopic image: residues of metal around the mould cavity (a-b), magnification 10x

Stone and clay moulds were subjected to a chemical composition test with a non-destructive method of X-ray fluorescent spectrometry in the mapping mode. The selected elements lied down in the area of the mould cavity and its immediate vicinity (Figs. 5-8). They also marked the runner system's shape.

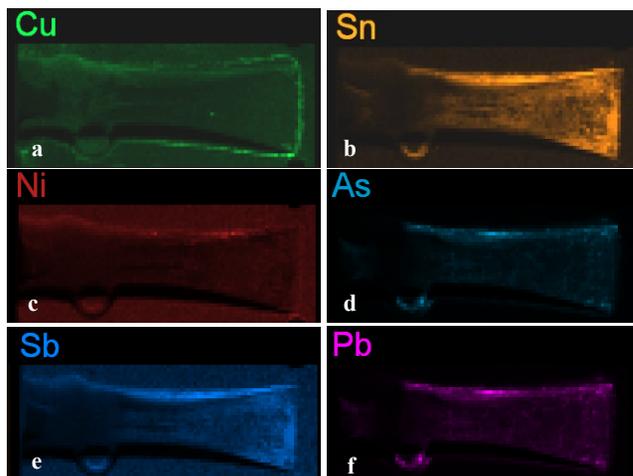


Fig. 5. Map of copper, tin, nickel, arsenic, antimony, and lead distribution in the mould for casting axes (ML/A 1118/3-4, Fig. 1j). Image from the spectrometer camera: Cu content (a), Sn content (b), Ni content (c), As content (d), Sb content (e), Pb content (f)

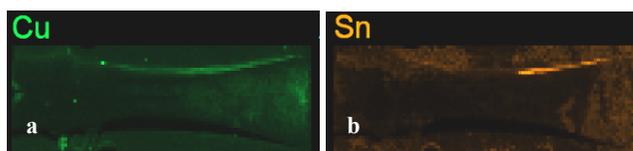


Fig. 6. Map of copper and tin distribution in the mould for casting axes (ML/A 1118/1-2, Fig. 1g). Image from the spectrometer camera: Cu content (a), Sn content (b)

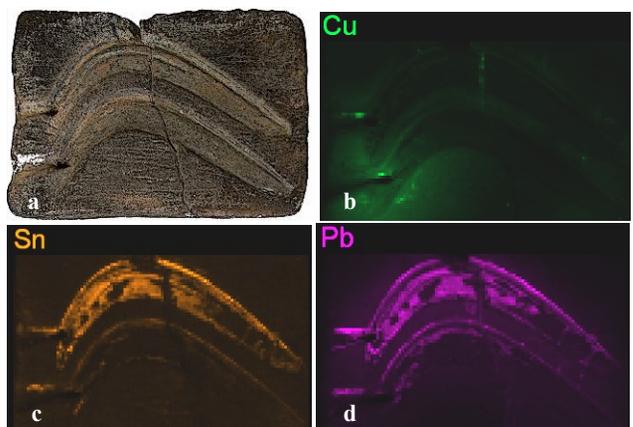


Fig. 7. Map of copper, tin and lead distribution in the mould for casting two sickles ML/A 1081/5a; Image from the spectrometer camera: the mould cavity with the sickle negative (a), Cu content (b), Sn content (c), Pb content (d)

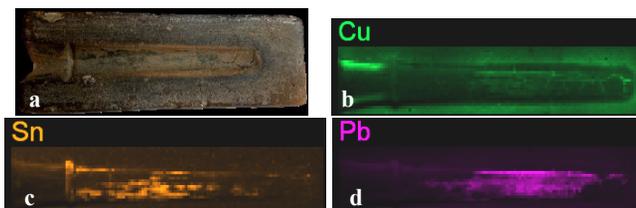


Fig. 8. Map of copper, tin and lead distribution in the mould for casting chisels (ML/A 1081/2); Image from the spectrometer camera: the mould cavity with the chisel negative (a), Cu content (b), Sn content (c), Pb content (d)

The content of metallic elements: copper, tin, lead, arsenic, antimony and nickel was confirmed in the moulds by qualitative spectrometric analysis and is caused by penetration of liquid alloy into rock pores and mould structure. Thus, the use of the moulds in the production processes has been confirmed.

Copper in moulds for casting axes (Figs. 5-6) is concentrated in the mould parting line, along the so-called casting seam, which had to form as a result of a misfit of the mould halves. This misfit is likely to be caused by a long-term mould operation. Tin in the mould occurs in the side part and in the blade part and coincides with the antimony presence. Lead partially coincides with the tin reach zone, but much less lead remained in the mould, similar as arsenic. Nickel is only present in the mould as traces.

The qualitative analysis of chemical composition of the mould for casting sickles in the mapping mode showed traces of metals in the mould cavity, and in the plate covering the mould. Elements such as tin, antimony, lead and arsenic are visible in the sickle negative. Copper in moulds for casting sickles (Fig. 7) occurs more intensively in the area of the runner system. The contents of tin and lead coincide and are distributed within the whole area of the mould cavity.

In the mould for casting chisels (Fig. 8) the highest content of copper also concentrates in the area of the runner system and may indicate the place of supplying metal to the mould, lead and tin are marked in the central area of the cavity.

Macro- and microscopic observations and tests of chemical composition showed evidence of use of the moulds. They were both the areas with an increased content of metallic elements, primarily copper, tin and lead, and traces of mechanical damage. The clay mould for casting sickles also shows evidence of contact with a high temperature resulting from pouring liquid alloy (temperature of about 1100°C).

3.2. Mould digitalisation and computer simulations

A digital model of a stone two-part mould with a core (ML/A 1118/3-4, Fig. 1 i-j, Fig. 5), and a corresponding casting of a bronze axe with a bushing and a lug were made using reverse engineering technology. The digitalisation was conducted by mapping the whole area of the objects with scanning laser head. For each of the mould halves the digitalisation was divided into two stages: scanning the mould cavity area and its external surface. In the process of the acquired geometry processing, discontinuities and deformations created during measurements

were eliminated. Next, each of surfaces was merged, thus creating separate parts of the mould, with the correct geometry.

Before starting the simulation, both halves had to be located relative to one another, as it was during casting of actual components. This operation aimed at juxtaposing scans forming the mould halves to eliminate empty areas between the scans (problematic from the simulation point of view), and at the same time to avoid interfering in the cavity shape.

Then the preliminary core was designed in the CAD software. The core has to recreate the inside of the axe and the runner system. The shape of the core is primarily based upon the analysis of moulds of Legnica (Fig. 2), and on the actual geometry of Bronze Age axes used for comparative tests and analysis of references [10].

The designed geometries of runner systems were directly utilised during further research work to carry out simulations of the casting process in software MAGMA⁵.

On the basis of so prepared core, three various geometries of the runner system were prepared, to simulate various possibilities of casting an axe: the first geometry (Figs. 9-10), in which the pouring cup only uses the space originally cut out in the stone mould, the second (Fig. 11), in which part of the pouring cup also is located on the core surface with a slightly reduced diameter, and the third geometry with a double, symmetrical sprue. The last variant (Fig. 12 a) used for the simulation was created on the basis of the research that showed a two-runner supply of metal to the mould cavity by holes bored in the core [10]. The smooth way of fulfilling mould cavity by metal (visible in figure 12 b) allowed to avoid bubbling air into the mould and propagation of casts defects. Simulations for second and third variants of core geometry were made with the constant initial temperature of the complex of mould and core (800°C). The process was carried out using CuSn12 alloy at the casting temperature value of 1100°C. Simulations for the first variant of core geometry were made with changing temperature, from 300°C to 800°C.

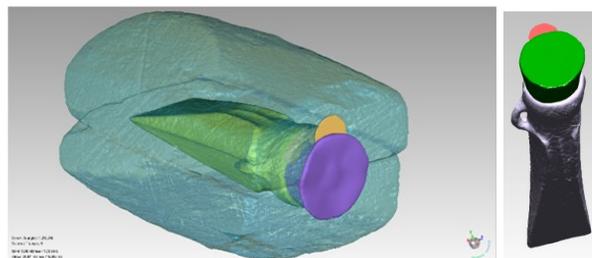


Fig. 9. Visualisation of an axe with the core in the mould, the first variant of core geometry, the pouring cup cut out in the mould (orange colour) [1]

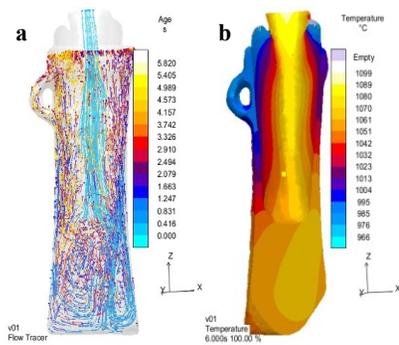


Fig. 10. Simulation of pouring an axe in the mould; the first variant of metal supply to the mould cavity through a pouring cup cut out in the mould; visible Tracers showing the nature of metal flow in the mould (a), visible temperature of metal after 6 seconds of pouring (b)

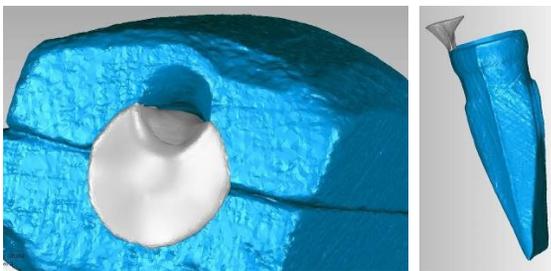


Fig. 11. Visualisation of an axe with the core in the mould, the second variant, the pouring cup cut out in the mould and part of the core [1]

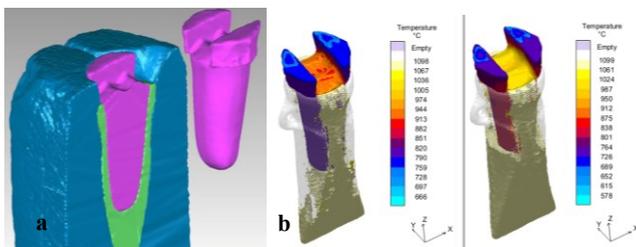


Fig. 12. Visualisation of an axe with the core in the mould (a), temperature distribution during the simulation of pouring and solidifying the axe casting; the third variant, double symmetrical runner system (b)

Analysis of possible casting defects that could have occurred, eliminated first two of the proposed runner systems. The Tracers and temperature of metal after 6 seconds of pouring (see on figures 10 a-b) easily showing the reason of future failures and the possible area of the porosity for the first variant of applied pouring cup. For the second single-channel runner case the situation is similar so that is why the mould cavity was not sufficiently fulfilled by metal. During the stage of solidification, the way of spreading of metal inside the form through single-channel runners caused high porosity of the casting (Figs. 13-14). This was due to the impossibility of fulfilling the mould cavity, even when the most favourable parameters applied: pouring time, flow velocity, temperature of the mould and core.

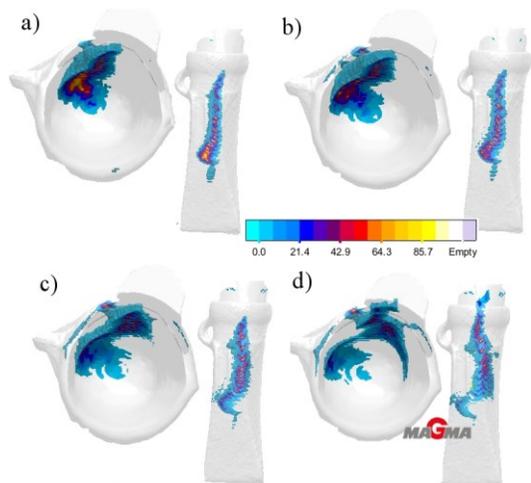


Fig. 13. Simulation of casting porosity when using single-channel runner of the first variant with varying temperature of mould/core: 300°C (a), 500°C (b), 700°C (c), 800°C (d)

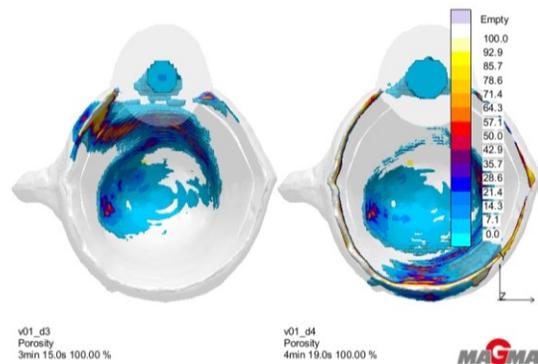


Fig. 14. Simulation of casting porosity when using single-channel runner with circular cross-section of the second variant

Double runner system casting simulation results show that porosity occurs on the inside of the axe (Fig. 15), next to the core, where there is an axe eye by design. Therefore porosity (already significantly reduced) should not affect the item's strength.

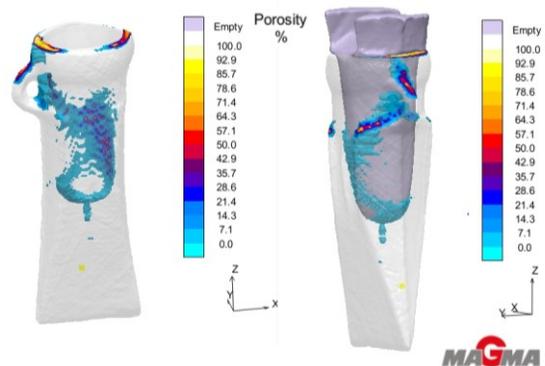


Fig. 15. Simulation of casting porosity when using double-channel main runner

4. The research summary

The paper presents investigations of a clay mould for casting sickles and chisels, and an analysis of the casting process in two-part moulds carried out for two stone moulds for making axes.

The macro- and microscopic observations and tests of chemical composition showed marks of operation of the moulds. These were both the areas with an increased content of metallic elements, primarily copper, tin and lead, and marks of a mechanical damage and a high temperature impact. The qualitative analyses of chemical composition, including characteristic elements: Cu, Sn, Pb, As, Sb, Ni, were conducted in the mapping system within the mould cavities. The presence of elements in both halves of the stone moulds is symmetrical relative to the parting plane. Location of elements around the axe mould cavity indicates a defect in the form of a seam in the place of the mould joint.

The visualisation of moulds was based on 3D scanning, followed by processing geometry of the objects investigated. The axe casting geometry was reconstructed by reverse engineering of moulds. The shape and securing of the axe core, and the shape and location of the runner system were unknown which posed a difficulty. They were reconstructed on the basis of known analogies. The geometries of moulds with core and the runner system were directly used during further research to carry out simulations of the casting process.

With the proposed single-channel runner system process for the mould for manufacturing axes with a bushing and a lug, regardless of its cross-section porosities exist in the casting. A change in the process, assuming that the mould and the core were heated before pouring the mould, only causes a slight shift in porosity, however the defect remains. In all cases the defect occurred at the side of the sprue. Although the simulations showed that axe castings were defective, it cannot be ruled out that correct castings could be obtained with the historical moulds.

The application of the system with a double and symmetrical sprue enabled metal to solidify in the mould and a casting with a reduced porosity to be obtained. Other variants of the casting technology are going to be taken into account in the further research. Changes in the core design that involves rebuilding the pouring cup and the sprue for further simulations can lead to improvement of the casting properties. The planned further simulations will show if it is possible to reduce the porosity significantly by applying additional process changes. Additional changes in the casting technology may enable the production process to be reconstructed much more precisely.

The macro- and microscopic observations and tests of chemical composition proved that the moulds were actually used for the production of bronze castings, while reverse engineering, modelling and computer simulations allowed the manufacturing process to be analysed. Investigations of moulds, along with their digitalisation and reconstruction of the casting process allowed us to learn technique details of the ancient process, and indicate paths of research related to the Bronze Age manufacturing, using modern tools of computer aided casting manufacturing.

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