LEADED BRONZE SPEARHEAD FROM BUDAKESZI-ŐZVÖLGY-TETŐ 'HOARD A'

ÓLMOS LÁNDZSA A BUDAKESZI-ŐZVÖLGY-TETŐ "A DEPÓBÓL"•

TARBAY, János Gábor[1] & MARÓTI, Boglárka[2]

[1]Department of Archaeology, Scientific Directorate, National Institute of Archaeology, Hungarian National Museum, Hungarian National Museum Public Collection Centre, Múzeum körút 14–16, H-1088, Budapest, Hungary, tarbay.gabor@hnm.hu

[2]Nuclear Analysis and Radiography Department, HUN-REN Centre for Energy Research, Konkoly-Thege Miklós út 29–33, H-1121, Budapest, Hungary, maroti.boglarka@ek.hun-ren.hu

Abstract

Hoard A from the Budakeszi-Őzvölgy-tető (site ID: 93179) contains a spearhead that is typologically common, but, in its technological characteristics, it reveals a unique biography of the short life of defective castings. In our work, we have subjected this artefact to prompt gamma activation analysis (PGAA) and neutron radiography (NR) to clarify our previous results of metalwork wear analysis and the qualitative elemental compositional data provided by on-site X-ray Fluorescence (XRF) measurement series. The results of these two analytical techniques provided a more accurate picture of the short use-life of this weapon. The PGAA showed a specific elemental composition for the spearhead, with copper (55 m%) and lead (21 m%) as its main components, in addition to high levels of antimony (9.1 m%) and 2.7 m% of tin. This result is in good agreement with the elemental compositional pattern of contemporaneous Ha B1 finds from Transdanubia and its adjacent regions analysed so far. Due to its high lead content, this alloy might indeed pose a risk during casting (e.g., lead segregation phenomenon) or during use as an object, such as reduced resistance to wear and use. However special this alloy may seem; it may not necessarily have caused the defective casting of the object alone. The neutron radiography images of the casting defects showed shrinkage porosity, and a better visualised horizontal mismatch of the cast sides, indicating that these defects had originated in casting preparation and occurred at the moment of casting. The combined occurrence of these casting defects can be attributed to several reasons. The most likely is that the moulds and cores were not properly preheated, which could have triggered the formation of gas and metal vapour in the casting during the casting process. The resulting solid cast object, completely useless as a weapon, was probably first sorted into the raw material stock of the foundry and then deposited in a twin ritual bronze hoard, which contained finished products and used objects of various object-biographical phases as part of a larger set of defective castings and castings.

Kivonat

A Budakeszi-Őzvölgy-tetőről származó A kincs (lelőhely azonosító: 93179) egy olyan lándzsahegyet tartalmaz, mely tipo-kronológiai sajátosságai alapján átlagos, technológiai jellemzőit tekintve viszont egy különleges tárgybiográfiáról, a hibás öntvények rövid életútjáról ad számot. Munkánkban ezt a leletet prompt gamma aktivációs analízisnek és neutron radiográfiai vizsgálatnak vetettük alá annak érdekében, hogy pontosítsuk a korábbi használati nyom elemzési eredményeinket és a kézi XRF széria által szolgáltatatott kvalitatív összetételi adatokat. A két új vizsgálat hozzájárult ahhoz, hogy pontosabb képet vázolhassunk fel ennek a fegyvernek a be nem teljesült használati életútjáról. A PGAA alapján a lándzsahegy különleges összetétellel bír, fő összetevője réz (55 m/m%) és ólom (21 m/m%), amely mellett nagy mennyiségben tartalmaz antimont (9,1 m/m%) és 2,7 m/m% értékben ónt. Ez az elemösszetételi mintázat alapvetően jól illeszkedik a Dunántúl és környező régiók esetén vizsgált, hasonló korú, Ha B1-es leletek elemösszetételi sajátosságaihoz. Bármennyire is különlegesnek hathat ez az ötvözet; mely elsősorban a magas ólomtartalom miatt valóban rejthet kockázatokat az öntés során (pl. ólom szegregáció jelensége) vagy a tárgy használata esetén, mint a kopásnak és használatnak való ellenállóság csökkenése; mégsem feltétlenül ez okozhatta a tárgy hibás öntését. A neutronradiográfiás felvételeken látható öntvényhibák, mint a zsugorodási porozitás vagy a módszer által jobban megjelenített öntvény oldalak osztósík menti vízszintes elcsúszása mind arról tanúskodnak, hogy ezek a hibák valószínűleg az öntés előkészítéséből erednek és az öntés pillanatában jöhettek létre. Számos lehetőség állhat ezeknek az öntési

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hibáknak az együttes létrejötte mögött. A legvalószínűbb, hogy a nem megfelelően előmelegített öntőformák és öntőmag beindíthatta a gáz és fémgőz képződést az öntvényben az öntés során. Az eredmény egy fegyverként teljesen használhatatlan, tömörre öntött tárgy lett, melyet valószínűleg először az öntőműhely fémnyersanyag készletébe válogattak, majd egy nagyobb hibás öntvényekből és öntecsekből álló készlet részeként egy késztermékeket és különböző tárgy-biográfiai fázisú használt tárgyakat tartalmazó, kettős rituális bronzkincsben deponáltak.

KEYWORDS: PROMPT GAMMA ACTIVATION ANALYSIS (PGAA), NEUTRON RADIOGRAPHY (NR), LATE BRONZE AGE (HA B1), HIGH LEAD CONTENT, DEFECTIVE CASTINGS

KULCSSZAVAK: PROMPT GAMMA ACTIVÁCIÓS ANALÍZIS (PGAA), NEUTRON RADIOGRÁFIA (NR), KÉSŐ BRONZKOR (HA B1), MAGAS ÓLOMTARTALOM, HIBÁS ÖNTVÉNYEK

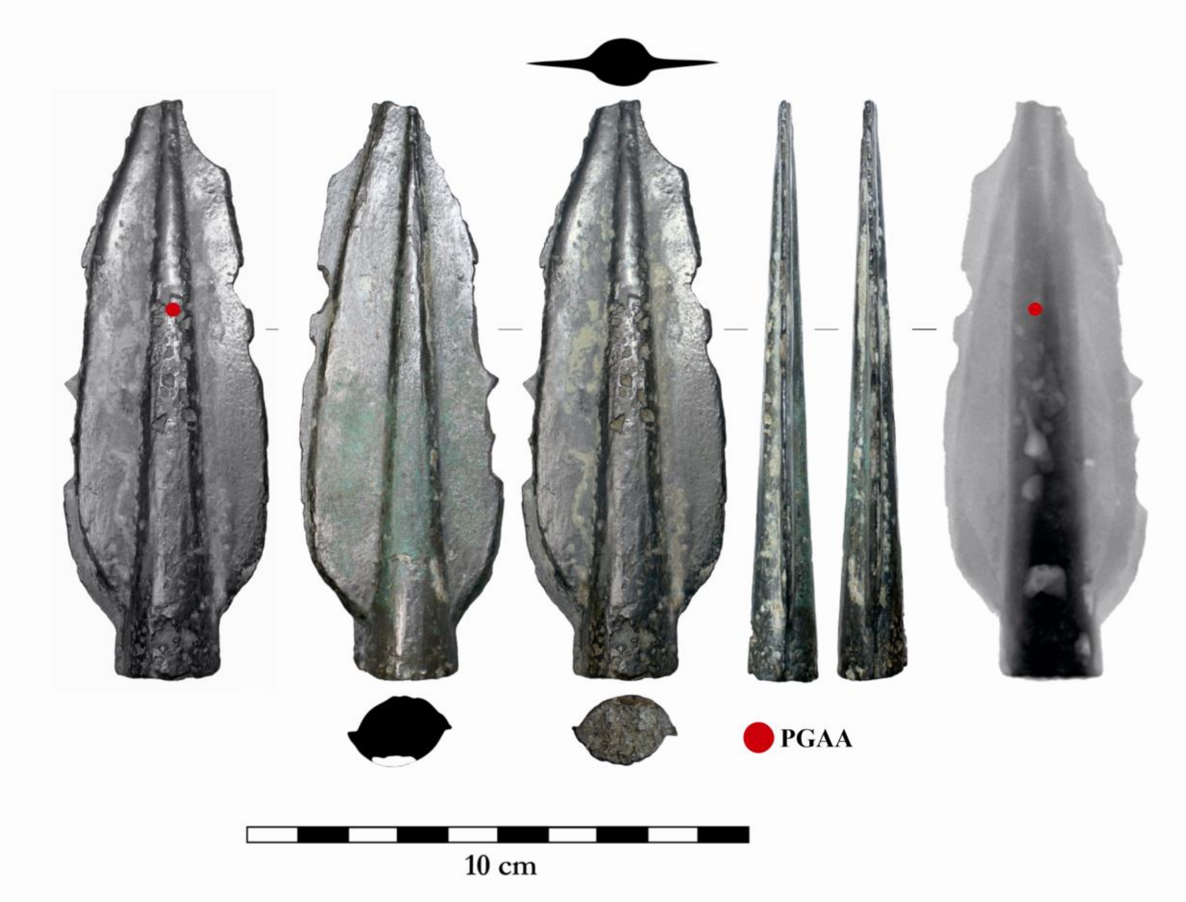

Fig. 1.: Photos and Neutron radiogram of the No. 1 spearhead from Budakeszi-Őzvölgy-tető Hoard A and its part measured by PGAA

1. ábra: A Budakeszi-Őzvölgy-tető A depóból származó, 1. számú lándzsa fényképei, neutron radiogramja és PGAA-val mért része

Introduction

In the Late Bronze Age Hoard A from the Budakeszi-Őzvölgy-tető site (Site ID 93179), a technologically special spearhead was deposited (**Fig. 1.**). This object, named No. 1, was found on the north-western edge of the sondage trench containing the hoard, at the edge of the heap, partly under stones, in a layer where as-cast socketed axes and plano-convex ingots were deposited. Typologically, this weapon is nothing special. It has a regular leaf-shaped blade and a conical socket. Similar spearheads can be classified into Tiberius Bader's C variant of Group A3, which can be dated between Br D and Ha B based on its parallels all around the Carpathian Basin and beyond. Belonging to a weapon style group widely distributed in space and prevalent for an enormous amount of time, the object is difficult to date (Bader 2015, 376, Tab. 1.16). Spearhead No. 1's chronological position is rather given by the time of deposition of the Budakeszi A Hoard, which is Ha B1 based on the thorough analyses of all finds from this assemblage (Tarbay 2022, 33–34, Fig. 2.11).

The metalwork wear analysis (MWA) (see the method in Dolfini & Crellin 2016) of the artefact revealed casting defects like mismatching, presumed solid casting, shrinkage, and flashing. Its uncharacteristically short socket can be considered as an incomplete defect as well, instead of a conscious design (Tarbay 2022, 56, Pl. 56.A–B). Thus, from a technological point of view, this object is not common at all. An MWA re-analysis of all the available Transdanubian spearheads within the framework of *The Technology, Use and Manipulation of Weapons from the Late Bronze Age Transdanubia* research project between 2020 and 2024 showed that only a few finds exhibit comparable technological phenomena and can be classified as unused as-casts or defected castings. Based on the observation of the No. 1 spearhead's surface, hypotheses have been proposed on the formulation of these defects (Tarbay 2022, 56). However, essential archaeometallurgical data on the inner structure and elemental composition of the artefact was not available at that time, and its interpretation was also restricted by the limited capacity of the MWA. However, these data are invaluable in refining defect characterization, interpreting the cause of these phenomena, and formulating an opinion about what the craftsman's choice was for alloying and how such an object was created in the first place. As part of the second phase of the Budakeszi hoard's evaluation, a complete preliminary XRF series has been done on the entire assemblage to identify trends in the hoards' elemental composition and potential objects for further in-depth characterization by advanced analytical techniques. This series has been published and serves as a basis for our future project concerning the evaluation of the Budakeszi A and B hoards (Tarbay & Maróti 2023). For the No. 1 spearhead, the choice fell into prompt gamma activation analysis (PGAA), a non-destructive and non-invasive bulk analytical technique to refine XRF elemental composition results. The XRF measurement provided data on the composition of the objects' patina, suggesting that the find has no typical Cu-Sn alloy content, but it failed to precisely characterise quantitatively its bulk composition. Because the No. 1 spearhead exhibited the traces most identical to shrinkage porosity, we assumed that defects could have formed in the inner structure of the object; therefore, neutron radiography was performed on the entire find to gain a more accurate 2D image of these phenomena. In this paper, the results of these new analyses are presented, with particular attention to the questions of alloy choice and the interpretation of casting defects.

Prompt Gamma Activation Analysis

The spearhead was analysed using the PGAA technique in the Budapest Neutron Centre (BNC) (Szentmiklósi et al. 2010, 501–505). The cross-section of the neutron beam was set to 5 mm^2 to achieve the appropriate count rate during the spectrum acquisition. The measured part is located about 40 mm from the tip of the object, where the thickness of the spearhead is 5 mm (**Fig. 1.**). Thus, the results represent the average bulk composition of the irradiated volume which was 10 mm^3. The spectrum evaluation and concentration calculation were performed using HyperLab (Szentmiklósi et al. 2024) and ProSpeRo software (Révay 2009), respectively. The PGAA results are listed in **Table 1**.

Table 1.: Chemical composition result of the No. 1 spearhead from Budakeszi-Őzvölgy-tető hoard A (Inv. No. 2021.8.1) in mass percentage (m%) together with standard deviation (std (±)), and with the relative uncertainty in percentage (unc%) determined with PGAA method.

1. táblázat: A Budakeszi-Őzvölgy-tető A depóból származó, 1. számú lándzsahegy (ltsz. 2021.8.1) PGAA módszerrel mért kémiai összetétele, tömegszázalékban (m%), a standard (std (±)) és a százalékban kifejezett relatív hibát (unc%) feltüntetve.

Element	**Detection limit (m%)**	**m%**	***std (±)***	***unc%***
Cu	*0.9*	55	*0.94*	*1.7*
Fe	*0.5*	1.7	*0.07*	*4.*
Co	*0.05*	0.35	*0.013*	*3.6*
Ni	*0.03*	4.5	*0.13*	*2.9*
As	*0.1*	4.8	*0.13*	*2.8*
Ag	*0.06*	0.500	*0.025*	*5.*
Sn	*0.4*	2.7	*0.2*	*7.*
Sb	*0.26*	9.10	*0.28*	*3.1*
Pb	*1.9*	21	*1.0*	*5.*

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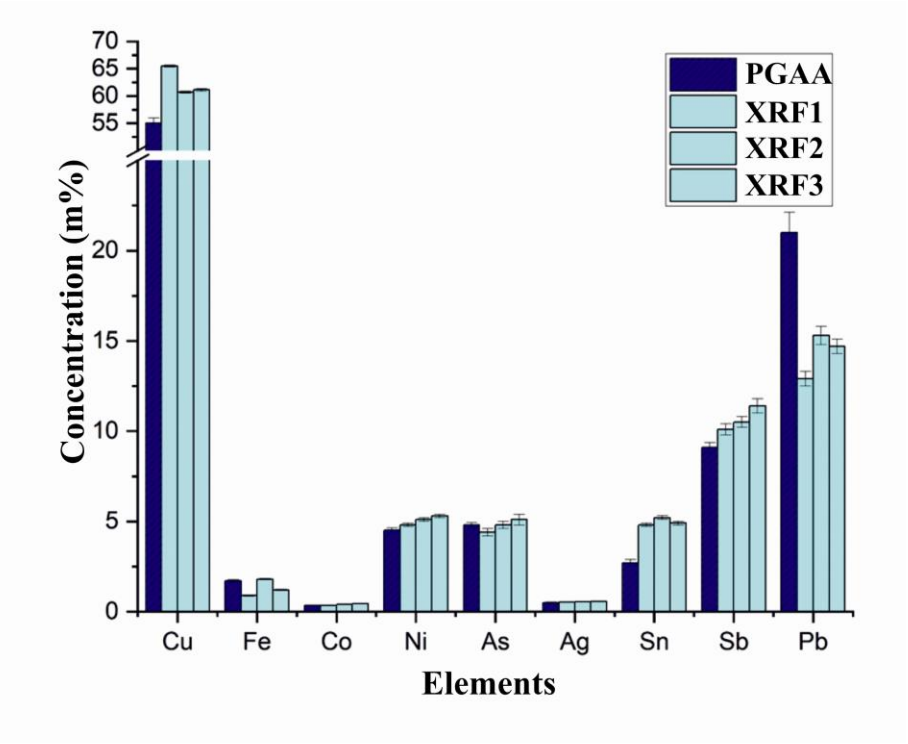

Fig. 2.: Comparison of the bulk PGAA and handheld XRF results.

2. ábra: A PGAA tömbi és a kézi XRF eredményeinek összehasonlítása.

Handheld XRF measurements were performed earlier on the object, see Appendix 1 of Tarbay and Maróti (Tarbay & Maróti 2023), XRF measurement ID 1–3. (https://doi.org/10.55023/issn.1786-271X.2023-002.app1). The most striking differences occurred in the Cu, Sn and Pb concentrations, which were 60.7–65.5, 4.8–5.2 and 12.9–15.3 m%, using the XRF technique, respectively. The Cu concentration in the bulk is 10–18 m% less than in the surface, while the Pb content is 37–63 m% more in the bulk. The Sn results obtained using handheld XRF were about two times the amount determined with PGAA (see **Fig. 2.**).

Neutron Imaging

A neutron radiography experiment was performed in the NIPS-NORMA facility (Kis et al. 2015) of the BNC. The dimensions of the artefact exceeded the field of view of the NORMA imaging facility which is 40×40 mm^2. Therefore, five projections were taken at six different positions each, to cover the whole object. The image processing included the following steps: first, all pictures were stacked or grouped according to their types (dark current image, open beam image, open beam image with object. By taking the medians of the recorded sets of images, the outliers could be successfully removed. In this study, a Fiji routine (Z-functions; Image/Stacks/Z Project…) (https://imagej.net/imaging/z-functions; Szentmiklósi et al. 2021) was used. Afterwards, the median of the raw 2D projections (i.e., transmitted intensity) was corrected with the median of the open beam image and the dark beam image using the following formula (1). These calculations have been carried out on each pixel of the images. This procedure is called normalization.

$$\frac{I}{I_0} = \frac{I_{tr} - I_{dc}}{I_{ob} - I_{dc}} \qquad (1)$$

Where:

I_{tr} – transmitted intensity

I_0 – incoming intensity

I_{ob} – intensity of the open beam

I_{dc} – dark current of the camera, when the neutron beam is closed

Fig. 3. shows the transmitted image, and the normalized image using formula (1). The value of the brightest pixels is 1. These are the areas, where the object was not in the beam path and the neutron beam reached the camera unchanged. To visualize the inclusions better, we can compute the negative logarithm of the normalized image. In this case, the structure and shape of the inclusions are more noticeable.

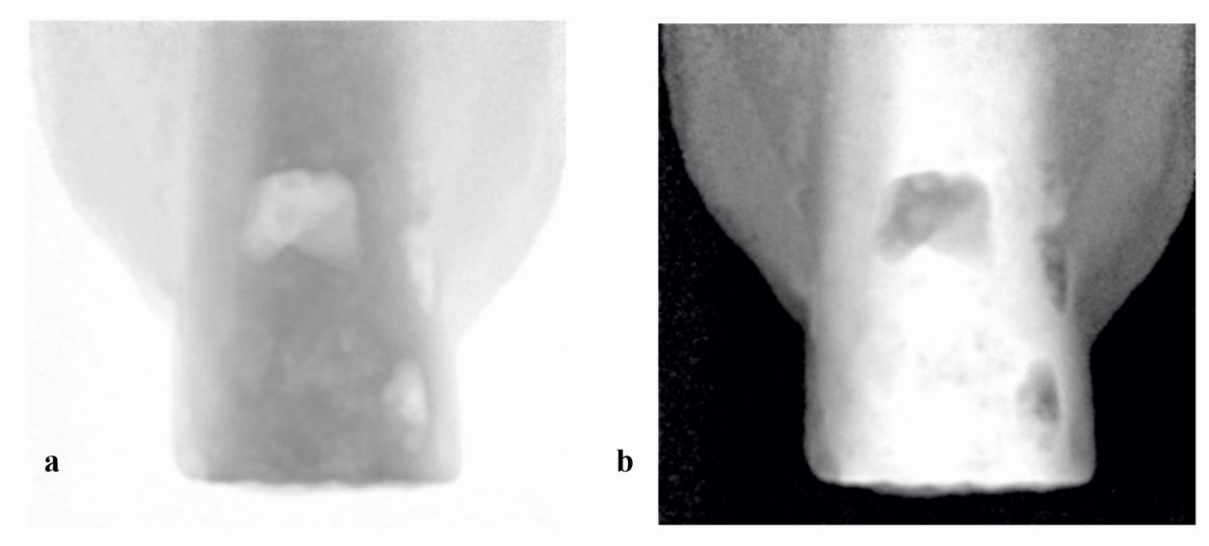

Fig. 3.: a) normalized (transmission) and **b)** negative logarithm (attenuation) image. In the normalized image the pixel values range from 0 to 1. The lower values correspond to darker, while the higher values to brighter pixels. In the negative logarithm image, the darkest pixels have 0 value, while the brighter pixels have larger grayscale values, and these correspond to the parts that are thicker and/or have larger neutron attenuation.

3. ábra: a) normalizált (transzmissziós) és **b)** negatív logaritmus (attenuációs) kép. A transzmissziós kép esetén a pixelek értéke 0 és 1 közötti. A kisebb értékekhez sötétebb, míg a nagyobbakhoz világosabb pixelek tartoznak. A negatív logaritmus képen a legsötétebb pixelek értéke 0, míg a világos pixelekhez nagyobb szürkeskála értékek tartoznak. Ez utóbbiak a tárgy azon részeihez tartoznak, amelyek vastagabbak, vagy nagyobb neutrongyengítő tulajdonságokkal rendelkeznek.

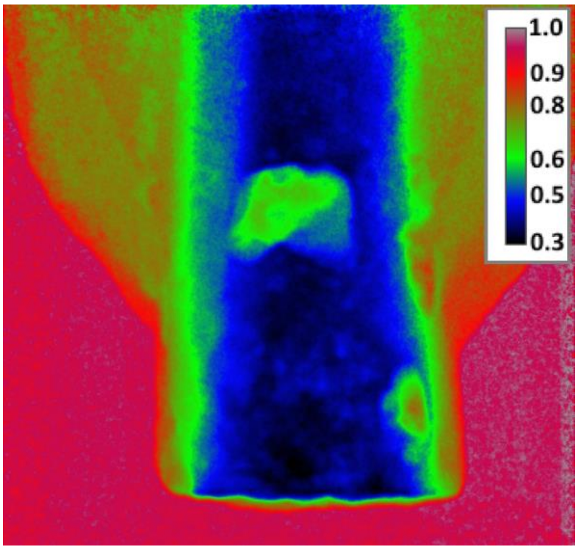

Fig. 4.: Rainbow-coloured version of Fig. 3a. The corresponding transmission values are depicted on the scale in the upper right corner.

4. ábra: A 3.a ábra RGB szivárvány-színezett változata. A jobb felső sarokban levő skálán a színekhez tartozó transzmissziós értékek láthatók.

The transmission values can be visualized more manifest if the Image/Lookup Tables/Rainbow RGB module (Rainbow RGB; https://imagej.net/imaging/color-image-processing) is used (see **Fig. 4.**). The calibration bar was created using an open-source macro named CalibrationBarMacros (Calibration Bar Macro; https://imagej.nih.gov/ij/macros/CalibrationBarMacros.txt). The magenta-coloured parts are where the beam intensity did not change, thus, transmission (TR) is equal to 1. The red-coloured, the green-coloured and the blue-coloured parts correspond to TR values of 0.8–0.99, 0.6–0.79 and 0.3–0.59, respectively.

Prior information is needed on the constituents of the object to estimate its thickness. Considering that the spearhead is pure copper, the following estimation can be done for the thicknesses of its various parts (see **Fig. 5.**). Pure copper sheets of known thickness were placed in the neutron beam after one another. After performing the normalization of each image, their thickness versus TR is depicted. If the object is pure copper, the red, green, and blue parts have thicknesses of about 0.1–2.0 mm, 2.1–4.5 mm, and 4.6-10 mm, respectively, based on these preliminary data.

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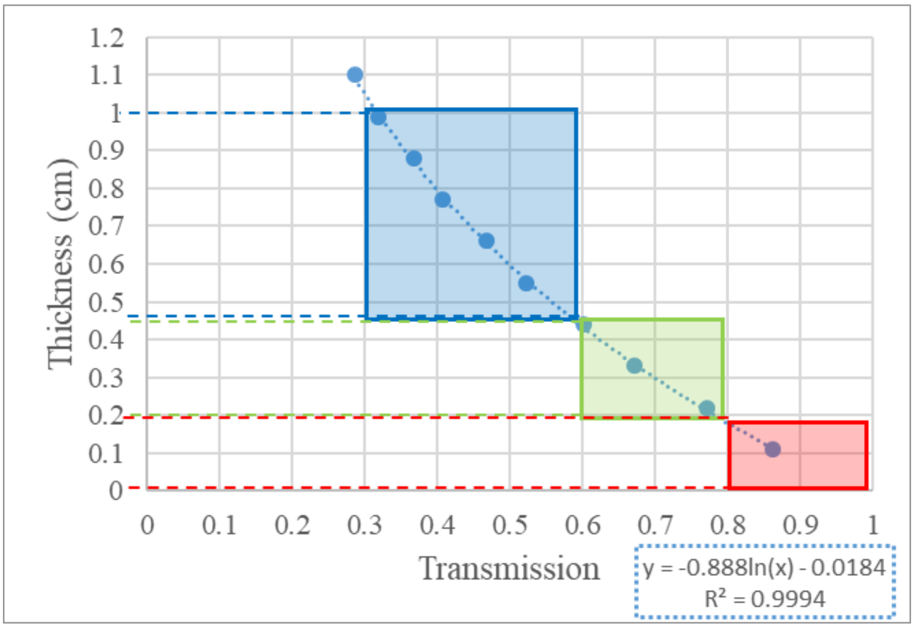

Fig. 5.: Transmission of pure copper sheets of different thicknesses.

5. ábra: Különböző vastagságú rézlemezek transzmissziója.

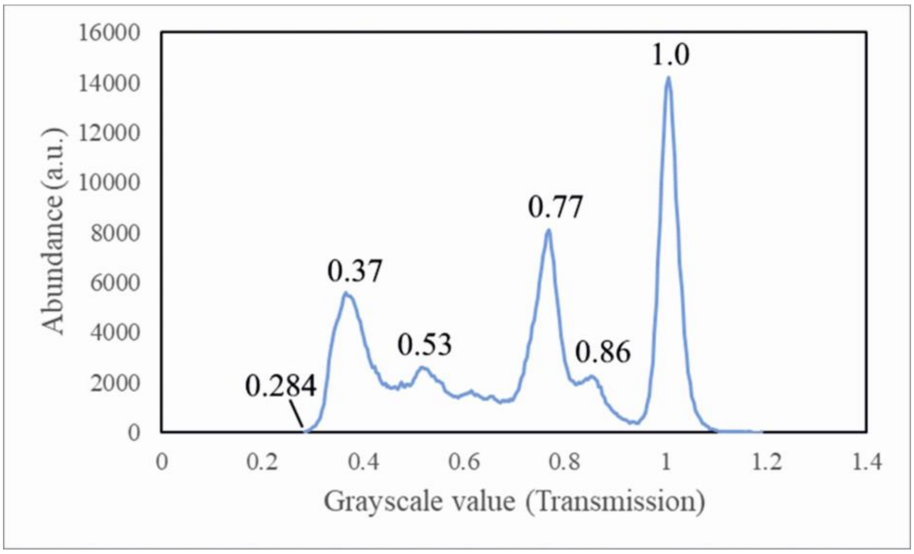

Fig. 6.: Grayscale value histogram of Fig. 3a.

6. ábra: A 3.a ábra szürke skálaértékek hisztogramja.

From the PGAA results, it is known that the spearheads' two major components are Cu and Pb. In an earlier study, the linear attenuation coefficients (Σ_n) of the Budapest NIPS/NORMA facility were determined for the elements Cu, Sn and Pb (Szentmiklósi et al. 2021). The experimental Σ_n value for copper is 1.17±0.04.

Considering that the object is macroscopically homogeneous, and simplifying the composition to Cu, Sn and Pb, an atomic ratio of 8.75:2.3:10.2 is obtained. Using the mixing rule ($0.875\times1.17+0.023\times0.19+0.102\times0.36=1.06\pm0.06$) the change in the overall linear attenuation coefficient can be calculated. This is about a 10% decrease in the overall neutron attenuation of the object, not considering the other constituents that have also lower attenuation than copper. From the grayscale value histogram, i.e., the abundance of the grayscale values (**Fig. 6.**), it is apparent that the lowest grayscale value is 0.284. Considering that the object is pure copper, the thickness here is 11 mm. This means that the thickest part of the object from this projection angle is at least 11×1.1=12.1 mm. Using a caliper it was obtained that the greatest thickness of the object is 14.2 mm. The difference can be due to the missing components not considered in the calculation of the Σ_n, the presence of air inclusions, as well as the diffuse scattering due to the large sample size, resulting in additional intensity, and apparently reduced thickness.

To reconstruct the radiography image of the entire object, the Plugins/Stitching/MosaicJ module of the Fiji routine was used (MosaicJ Plugin; http://bigwww.epfl.ch/thevenaz/mosaicj/). The normalized images were converted to 8-bit and were fed to the MosaicJ. The reconstructed radiogram is depicted in **Fig. 7.**

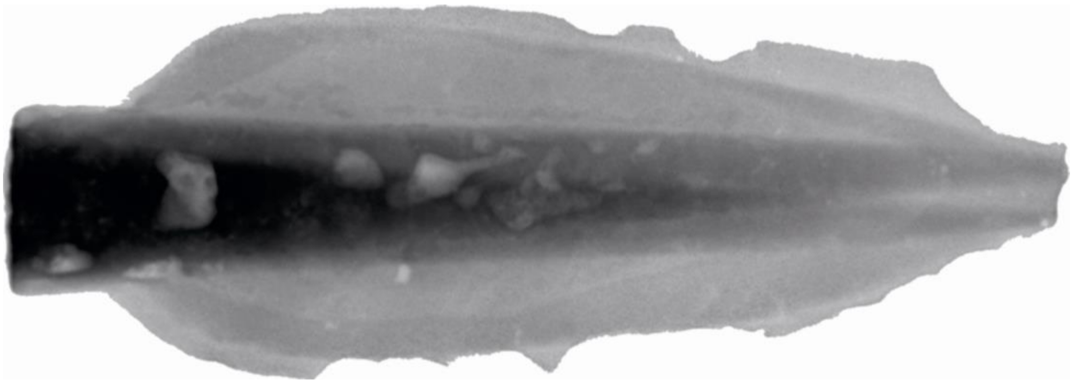

Fig. 7.: Neutron radiogram of the No. 1 spearhead processed using 2D projections taken at six different positions and reconstructed using MosaicJ plugin

7. ábra: Az 1. számú lándzsahegy hat különböző pozícióban készült 2D projekciók felhasználásával, MosaicJ plugin-nal rekonstruált neutron radiogramja

Along its longitudinal axes, numerous amorphous and elongated bubble-like pores can be observed in the spearhead that are most probably caused by shrinkage porosity. The image also illustrates the mismatch defect along the cutting edge of the spearhead. It is also well observable in the image that the weapon is a solid cast, with no casting core trapped inside its socket part.

Discussion

Weapon production in the Late Bronze Age was a conscious process. The choice of alloy materials influences the physical capabilities of the weapon, like its resistance to wear, toughness, and plasticity. Weapon design and style were also not the result of a random process; those were affected by workshop traditions, local tastes, and probably negotiation between the craftsman and the 'customer' (combatants). The life of the latter literally depended on the quality of the weapon, and the chosen product should fit his or her preferred fighting or hunting style (Horn 2013, 108–109; Gutiérrez Sáez & Lerma 2015, 175; Molloy 2018, 202, 210–211; Molloy & Mödlinger 2020, 201).

In the Late Bronze Age Carpathian Basin, the local material generally consists of products made of binary alloys (Cu-Sn). In the Hungarian prehistoric material, the appearance of ternary bronzes (Cu-Sn-Pb) is documented during the Late Iron Age (Molnár et al. 2012, 255–256, 260, 263; Molnár et al. 2021, 61, 72–73). Changes in the elemental composition of Early Iron Age bronze products are not yet fully known, but during the second half of the Hungarian Late Bronze Age (ca. Ha A2/Ha B1 and Ha B1), there were pronounced changes in the elemental composition of the local bronzes. Besides binary alloy objects with special compositions, which can be either ternary bronzes (mainly Cu-Sn-Sb and Cu-Sn-Pb) or even quaternary bronzes (Cu-Sn-Sb-Pb), such as the Budakeszi spearhead. As mentioned above, two elements beside Sn play a key role: Sb and Pb (Trampuž Orel 1996, 196–197, 204–210, 211; Liversage & Pernicka 2002; Czajlik 2012, 94–98, 103–104; Molnár et al. 2012, 263–265; Tarbay et al. 2021, 17–19). In the following, we discuss the three elements Sn, Sb and Pb measured above 2 m% in the Budakeszi spearhead. A percentage of around 10 m% Sn is needed for a bronze weapon or tool to be functional and perform its primer function properly during work and combat. Bronze-Age craftsmen, however, did not follow a standard and produced objects with a percentage of Sn determined by the preferences of individual craftsmen, access to tin, aesthetics, and melting preferences, according to Barry Molloy and Marianne Mödlinger (Molloy & Mödlinger 2020, 202–206, Fig. 8). The No. 1 spearhead from Budakeszi-Őzvölgy-tető Hoard A has only 2.7 m% bulk Sn content based on the PGAA analysis. In the so-far sampled Transdanubian material, only two spearheads are known with such a low (2–3 m%) Sn content (see Tarbay 2023). One is the spearhead analysed by XRF from the Velem-Szent Vid IA hoard (1.92–2.03 m% Sn, 10.5–11.7 m% Sb) (Miske 1907, Pl. 30.13; Költő, Kis Varga & Maclean 2002, Tab. 2. Velem 52–53). The other object is from Kapuvár with an uncertain date (2.26 m% Sn, 2.96 m% Sb), which was studied by wet chemical analysis back in the 19^{th} century (Loczka 1889, 284). But does the lack or low ratio of Sn results in a dysfunctional cast? In the case of the Budakeszi A1 No. 1 spearhead and both the above-mentioned parallels, low Sn content is paired with elevated Sb content (Kapuvár: 2.96 m% Sb; Velem IA 10.5–11.7 m% Sb; Loczka 1889, 284; Költő, Kis Varga & Mclean 2002, Tab. 2. Velem 52–53).

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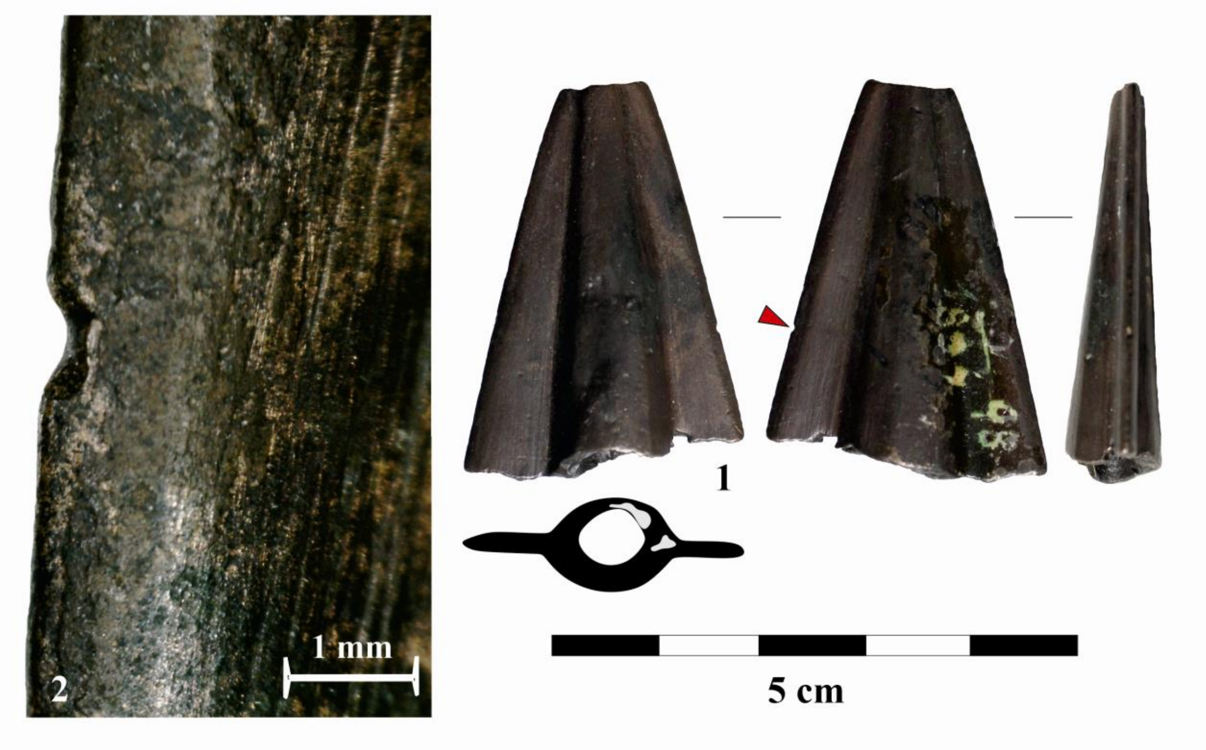

Fig. 8.: The high-leaded spearhead tip from Biatorbágy-Herceghalom: **8/1:** the tip and its MWA results, **8/2:** grinding striations and a bow with material displacement (Photo & Microscope-camera images: J. G. Tarbay)

8. ábra: A nagy ólomtartalmú lándzsahegy Biatorbágy-Herceghalomról: **8/1:** a lándzsahegy és a fém használati nyomelemzésének eredményei: **8/2:** csiszolásnyomok és ívelt csorbulás nyom, anyagelmozdulással (Fotó & mikroszkóp-kamerafelvételek: Tarbay J. G.)

During the Ha A2/Ha B1 and Ha B1 in Transdanubia and adjoining areas like the present-day territories of Slovenia and Austria, an increase of Sb in bronzes is observed (see in Tarbay 2023; Tarbay & Maróti 2023, with further references). Whether it is an intentional alloying process or the use of a special ingot of copper with high antimony, nickel, and arsenic content, is not entirely clear to us (see Czajlik 2012, 52–53, 96). However, Sb adds many advantageous characteristics to bronze objects, such as expanding solidification to produce detailed cast surfaces, low liquidus temperature, hardening, and colouring effect. Many of those characteristics make it a perfect substitute for tin, and based on its increase in contemporaneous casts, it can be assumed that craftsmen were aware of this material and consciously added it to their products (Maclaen & McDonnel 1996, 79–81). The bulk Sb percentage of the No. 1 spearhead reaches 9.1 m%, which would satisfy the pre-conceptual ideal percentage of Sn alloying, combined with the Sn m% of the find, it is way above the presumed optimal 10 m% (11.8 m% Sb+Sn). Thus, the Sn-Sb alloy combination of the object hypothetically would result in a functional product. Nevertheless, the high lead content of the object, reaching 21 m%, is strange.

Lead has many advantageous characteristics as an alloy, such as high resistance to corrosion, low melting point, and high formability, which contribute to the proper filling of the mould cavity (Percy 1870, 1–10; Scott 1991, 24; Recht 2017, 76–78; Molnár et al. 2021, 70). However, it also has negative effects on the cast, such as reduced durability (Bridgford 2000, 86; Molloy 2011, 69), which can be disadvantageous for a functional combat weapon. Besides, this ratio of lead can increase the chance of lead segregation, rendering the product useless if the lead segregates at the bottom of the cast, which would be the tip of the weapon since it was cast from the direction of the socket (see Harrison et al. 1981; Hughes et al. 1982; Molnár et al. 2021, 67, 73). In order to exclude lead segregation completely, PGAA measurement series should be extended over the entire length of the object to compare whether significant differences in lead content are observed between the top and the bottom of the object from the casting direction. In the Transdanubian Ha B1 material, it is also observable that high-leaded objects are usually not finished products but either different types of ingots or as-cast objects (Liversage & Pernicka 2002; Tarbay et al. 2021;

Fig. 9.: Core rising defects: **9/1:** Experimental socketed axe; **9/2:** A socketed axe with core rising defect from Beremend (modified after Tarbay 2018, Pl. 256.4).

9. ábra: Öntőmag felemelkedés: **9/1:** Kísérleti tokos balta; **9/2:** Tokos balta öntőmag felemelkedéssel a beremendi depóból (módosítva Tarbay 2018, Pl. 256.4 alapján).

Tarbay & Maróti 2023). An important exception is the spearhead tip fragment from the Biatorbágy-Herceghalom hoard, which also has a high Pb content (16.6 m%) (Liversage & Pernicka 2002, Tab. 2. Inv. no. 1894.1.98). Surprisingly, the new MWA results on this weapon fragment suggest that even if it has pores along its breakage surfaces, it may have been a finished and perhaps even a used product (**Fig. 8/1**). Along its blade part, vertical grinding striations can be observed, which is a characteristic trace for a finished product spearhead (**Fig. 8/2**). There is also a small bow (or bulge) with irregular material displacement on its cutting edge, which is a damage type originating from edge-on-edge contact (Bridgford 2000, 105–106; Bell 2019, 153, Fig. 10.1d; Gentile & van Gijn 2019, 137, Fig. 5.F), possibly resulted by binding and twisting motions in fencing based on experiments (see Hermann et al. 2020a, 105, 114, 119–120, Fig. 5.20, Fig. 5.43; Hermann et al 2020b, 1057–1058, 1066–1067, Fig. 9) (**Fig. 8/2**). The example of the spearhead tip from Biatorbágy-Herceghalom illustrates that high-leaded objects could be functional products if their casting procedure went smoothly. This is something that has not been yet tested with experimental archaeological research. The recent weapon experiments of Gentile and van Gijn have only used objects with low Pb content (2 m%) which were typically combined with an ideal ratio of tin (Gentile & van Gijn 2019, 131–132). The example from Biatorbágy, however, raises the possibility that the atypical alloying combination alone did not cause the object to become dysfunctional, although to confirm this hypothesis, the capability of weapons with identical alloying ratios should be tested by experimental archaeological work or casting simulations. The cause of the casting defect is not related only to the specific alloy composition of the spearhead. The new neutron radiography results further contributed to the better characterization of the weapons' defects. The 2D images showed no traces of trapped clay, metal, or stone casting core inside the casting. The most likely scenario is that the casting core has been ejected from the mould by the gases and metal vapours produced during the failed casting process, as well as air and gas inclusions formulated inside the casting. We can also observe the results of shrinkage porosity on the surface and inside the cast in the form of elongated cavities (**Fig. 7.**) which distribute along the line where the casting core was inserted into the moulds. Such defects could be triggered by several causes; one could be the improper drying of casting mould halves and the casting core (see gas and shrinkage porosity in Ersfeld 1990, 18, 20, Fig. 14; Zhang et al. 1995, 607–609; Binggeli 2011, 17–19; Gener 2011, 121). We observed a similar phenomenon while carrying out experimental archaeological casting of socketed axes with Csaba Bíró bronzesmith (Tűzvarázs Művészeti Műhely). The ejection of the casting core was in this case caused by the insufficiently preheated mould and core that contributed to the formation of gases, accompanied by metal splashing, and a partially ejected casting core, the tip of which was fused into the casting, resulting in an axe which cannot be hafted (**Fig. 9/1**). Similar solid cast objects from the Late Bronze Age, as well as socketed tools with partially ejected casting core traces, are known in the Carpathian archaeological record (see Tarbay 2022, 56) (**Fig. 9/2**). It is also possible that the mismatch defect is connected to the core rising defect as well, and in this case, the defect was not only the result of carving non-matching negatives into the mould halves. The energy generated by the formulation of gases and metal vapours can dislocate imprecisely fixed (buried or tied) casting mould halves. The large flash defect, which is technically an extremely large casting seam, a sort of unwanted metallic projection (Bridgford 2000, 122; Quilliec 2007, 406; Molloy & Mödlinger 2020, 196), may also have occurred at this time when the molten metal filled the available space. After removing the No. 1 spearhead from the mould, these flashes were broken off, partly damaging the tip of the weapon. Its original state could be similar to the Nordic fibula found in Stenbro, Denmark (Lindqvist 1924, Fig. 25–26).

The breaking-off of the flashes from the edges is the last trace that provides concrete information about the peri-depositional lifestage of the object. Since this spearhead was unfit for use due to its solid-cast body being unsuitable for hafting, together with the fact that it does not show any signs of use-wear or abrasion, we are confident that this object was treated as a defective product, even by prehistoric 'standards' (Gener 2011). It was probably stockpiled along with other defective products in the foundry as raw material awaiting remelting. However, at some point, it may have been separated from this stock with other objects of the same character and deposited as a set in the Budakeszi A Hoard together with used and usable tools and ornaments of different biographical stages. Thus, the spearhead became something more than a defective object, perhaps a symbolic artefact of its own, substituting a real weapon in the hoarding ritual, or it gained meaning through the selection of the raw material set, which was one component of this votive assemblage from Budakeszi (Tarbay 2022).

Conclusions

In this study, the No. 1 spearhead from Hoard A of the Budakeszi-Őzvölgy-tető was analysed. The results of prompt gamma activation analysis and neutron radiography provided new data on the alloy type and the casting defects of the weapon. Our results showed that this spearhead was a defective product that was unsuitable for use as a weapon in combat. The composition of the object was not the Cu-Sn binary alloy common for Late Bronze Age objects, but a Cu-Pb-Sb-Sn multi-component alloy with a remarkably high Pb content at the point measured by PGAA. It may be questioned whether an object with such a composition was indeed capable of fulfilling its function and had sufficient hardness to be used as a weapon if it's casting was successful. To answer this question, experimental archaeological research must be carried out in the future to reveal the combat capabilities and durability of this type of alloy. Based on the results of the MWA of the high-leaded spearhead at Biatorbágy, we do not rule out that this composition, however strange, could have been a proper material to produce a functional weapon. The extent to which the unusual elemental composition, in particular the high lead content, may have contributed to the dysfunctionality of the Budakeszi socketed spearhead is an open question and requires further future investigation as well. Based on the available data, strengthened by the neutron radiography results, the object could also become unusable for its intended function due to production technological shortcomings. These occurred during the preparation for casting and the moment of the casting. The formation of shrinkage porosity probably led to the ejection of the casting core of this spearhead that ultimately resulted in a solid-cast object, unsuitable for hafting. It was left unworked and at some point, during its accumulation life stage, it was selected along with other defective products and raw materials to a ritual hoard for deposition.

Contribution of authors

János Gábor Tarbay Conceptualization, Writing – Original Draft, Writing – Review and Editing, Visualization, Funding acquisition. **Boglárka Maróti** Writing – Original Draft, Writing – Review and Editing, Visualization, Investigation, Validation, Data Curation.

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