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Technological characterisation of early Medieval gilded copper hollow pendants (*gombiky*), from Mikulčice (Moravia) and Prague Castle (Bohemia)

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Abstract

Gilded copper hollow spherical pendants known as *gombiky* (s. *gombik*) were examined to identify the technology of gilding and the material chosen as the substrate. The examined ornaments dating from the ninth and tenth centuries AD were recovered from elite graves of two major political, ecclesiastical and economic centres of the Early Medieval period located in the territory of the present-day Czech Republic: Mikulčice and Prague Castle, major sites of Moravia and Bohemia, respectively. Taking into account the state of degradation and possible bias due to earlier restorations, surface and bulk characterisation of the gilded material has been performed combining optical observation, X-ray radiography, metallography, scanning electron microscopy with energy-dispersive spectrometry (SEM/EDS analysis) and focused ion beam (FIB) milling mounted on FEG-SEM. The manufacturing procedure was reproduced by experimental archaeology. A detailed investigation of the gilded artefacts revealed several types of *gombik* construction involving different mounted elements, including the main body parts and the suspension system elements joined by hard soldering. The different constitutive parts are made with almost pure copper or low-purity copper. The systematic use of fire gilding (mercury amalgam gilding) was documented. Differences in the materials that were used and technical quality show the coexistence of finely produced objects by highly skilled and knowledgeable jewellers alongside more coarsely manufactured imitations. These variations are discussed in terms of different workshops in a possible relationship with their origin of manufacture.

Keywords Fire gilding · Hard soldering · Jewellery · *Gombik* · Manufacturing process · Metallography · SEM/EDS · FIB FEG-SEM

Supplementary Material: see page 23

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Introduction

The Early Middle Ages in Moravia and Bohemia (present-day Czech Republic) witnessed the rise of elites for which specific jewellery and dress ornaments were adopted to designate social status in connection with the development of early states—Great Moravia and Bohemia (Galuška 2013; Kouřil 2014; Boháčová and Profantová 2014; Štefan 2019).

Among the different jewellery and dress ornaments recovered from archaeological sites, one remains very characteristic for this historical period and geographical area. Known as *gombik* (pl. *gombiky*), these are spherical hollow pendants, a few centimetres in size, often richly decorated with chasing, filigree, granulation work, coloured glass cabochons and gilding (Chorvátová 2008a, 2009; Krupičková *in press*).

These hollow spherical pendants were usually found in pairs in the wealthiest graves, around the collarbones of the deceased, mostly in very young children (aged 2–4) and also in older children, mature male and female's graves (Poláček 2017; Chorvátová 2008a; Krupičková *in press*).

They are principally made from gilded copper or silver and are mainly decorated with chasing. In rare cases, they are made of solid gold or, in modest graves, of copper alloys, lead or glass (Chorvátová 2008a).

They appear in Moravia in the first half of the ninth century (Ungerma 2011; Chorvátová 2018) and are interpreted as symbols of the ruling elite in Moravia. They were adopted by the Bohemian elite in the second half of the ninth century. They were still used there after the fall of Great Moravia (906 AD), probably up to the second half of the tenth century.

Some *gombiky* are of a very good technical quality, while others seem to be of a lower grade, suggesting possible imitations of less-competent goldsmiths. This difference raises not only the issue of manufacturing related to different workshops, but also the question of potential foreign origins and influences.

Most studies have focused not only on the typology of *gombiky* based on size, shape, decoration and their possible origin (Hrubý 1955; Dostál 1966; Pavlovičová 1996; Klanica 2006; Macháček et al. 2016), but also on their occurrence in graves and their hypothetical function (Klanica 1970; Chorvátová 2008; Krupičková et al. 2019). Several technical studies have been performed to characterise their material composition by surface analysis, mostly by X-ray fluorescence (Smetánka and Štverák 1992; Smetánka and Staňa 1996; Profantová and Frána 2003) and more recently by SEM/EDS (Kavánová 2009; Ottenwelter et al. 2014; Ottenwelter 2016; Ottenwelter et al. 2017; Hasil et al. 2019). Innovative experimental approaches have focused on the different steps involved in their manufacture (Čáp et al. 2011; Barčáková 2014; Barčáková et al. 2014).

In Moravia and Bohemia, gilding was widely used on copper base materials for jewellery and dress ornaments (Kouřil

2014). This decorative technique consists of applying a thin gold layer on a less valuable metal to create the appearance of solid gold objects (Oddy 1993, 171). Mainly applied on copper alloys, several techniques of gilding were used (Darque-Ceretti and Aucouturier 2013), involving the application of either gold foil (thickness > 1 µm) or gold leaf (< 1 µm), but also by using a spreadable Au-Hg amalgam paste. As regards the fire gilding method, mercury added to gold particles forms an Au-Hg amalgam, which can be spread over a cleaned metallic surface (Anheuser 1997, 58–59; Northover and Anheuser 2000, 116; Chiavari et al. 2015). The heating of this amalgam paste induces porous and dull surfaces due to the evaporation of mercury which partially remains in the gilding depending on the firing temperature applied (Northover and Anheuser 2000, 118–119). Burnishing with an agate stone is usually required to compact the porous structure and create a smooth and reflective surface. Although the gilding layer usually adheres well to the substrate, in time, it can induce a pronounced corrosion of the copper base due to galvanic coupling (Chiavari et al. 2015, Masi et al. 2016, Ingo et al. 2016, 2018). This is often enhanced by aqueous corrosion in burial conditions, notably in grave contexts, where the copper metallic substrate can be completely mineralised.

The present work describes the technological investigation performed on a selection of nineteen gilded copper *gombiky* from Mikulčice (Moravia) and from the Lumbe Garden cemetery at Prague Castle (Bohemia). Most of these artefacts are in an advanced state of mineralisation and have been restored in the past. A new approach on the characterisation of these artefacts has been performed combining optical stereomicroscopy, X-ray radiography, SEM/EDS analysis, metallography, focused ion beam (FIB) milling mounted on field-emission gun scanning electron microscopy (FEG-SEM) and experimental archaeology. The FIB technique was used more specifically for the investigation of the gilding layer for the first time here on ancient corroded gilded ornaments. This recent method offers new perspectives of observation in archaeometry than classical methods: it allows cross section and observation to be performed *in situ* (Goldstein et al. 2003, 553; Johnson et al. 2012; Masi et al. 2016, 2017). More specifically, in the case of the gilding layer on copper substrate, unlike the usual polishing method, the ionic ablation does not deform the gold plating, allowing a very precise structural characterisation up to a few nm in scale.

In the first part of the work, the detailed surface examination and preservation state of the *gombiky* will be presented. The different constructions (mounting) will then be typed from optical and electronic observations and X-ray radiography. In order to get deeper insight into the technology employed by craftsmen, the elemental surface analysis of the different components of the *gombiky*, including solders, will be also reported. The results of metallographic examinations of cross sections carried out on fragments of seven artefacts

will be given. In addition, analysis of two specimens from Prague Castle by FIB mounted in FEG-SEM will be reported with the aim of characterising gilding and soldering techniques in greater depth.

The results of experimental archaeology will be presented to gain a better understanding of the different steps involved in the manufacture of the chased *gombiky*. Finally, elements of comparison and evidence of the transfer of knowledge and skills between the two localities, Mikulčice and Prague Castle, will be discussed.

Archaeological context

As previously mentioned, the studied *gombiky* were recovered from elite graves at Mikulčice (Moravia) and Prague Castle (Bohemia), which are two major political, ecclesiastical and economic centres of the Early Medieval period located in the territory of the present-day Czech Republic (Fig. 1a).

Mikulčice is one of the main Moravian central places and possibly the capital of Great Moravia—the first Slavic early dominion—whose core was situated in present-day southeast Moravia and southwest Slovakia along the Morava River Basin (Fig. 1b). Prague Castle became the main seat of the Bohemian rulers at the turn of the tenth century after the fall of Great Moravia.

This period is characterised by the rise of the aristocracy and the beginning of Christianity (Třeštík 2001; Kalhous 2012, 2018; Boháčová and Profantová 2014; Macháček and Wihoda 2019; Štefan 2019).

The elites, their retinue and their family members were buried in the graveyards of the newly built churches or cemeteries together with precious grave goods, including weapons such as swords, axes, spears, spurs and their fittings, buckles and strap ends, as well as jewellery, e.g. earrings, finger rings, cross pendants, necklaces and the so-called *gombiky*, made from gilded copper, solid silver or gold (Kouřil 2014; Poláček 2017; Frolík and Smetánka 2014; Ungerman 2018).

In Mikulčice, the estimated number of excavated *gombiky* is 274 (Krupičková in press), but 59 specimens were lost in a recent accidental fire. A total of 35 *gombiks* were recovered in the cemeteries surrounding Prague Castle, with the majority being found in the Lumbe Garden cemetery (20 specimens), others in the Royal Garden (2 specimens), in Prašný most (Míladý Horáková) (5 specimens) and in the Sřešovice-Triangle (Strahov) cemeteries (8 specimens) (Frolík 2014; Boháčová and Profantová 2014, 147; Frolíková et al. in press).

Gombiky seem to have a symbolic function related to the social status of the deceased, but their exact function is still a matter of debate among scholars (Chorvátová 2008; Krupičková et al. 2019). They were probably used in different

ways, as luxurious cloth fasteners, amulets or pendants (Galuška 2013, 182–183; Chorvátová 2008; Krupičková et al. 2019).

Several types of *gombiky* can be distinguished according to their decoration type and base material: plain, ribbed, chased, granulated or decorated with rich filigree work associated sometimes with granulation work. The hemispherical gilded copper *gombik* with chased decoration is the prevailing type (Fig. 2) and represents around half of the identified *gombiky* in Mikulčice and slightly more at Prague Castle. These copper gilded *gombiky* are essentially chased or, in a proportion of 1 to 9, can be also decorated with granulation. To a much lesser extent, other shapes are known, including polyhedral (Fig. 2Af) and octolobed (Fig. 2Bg).

The majority of the gilded copper *gombiky* are decorated with chasing (Fig. 2). While vegetal motifs predominate (Fig. 2Aa–Ae–Bc), geometric (Fig. 2Aj–Ba) and zoomorphic motifs (mainly birds) are also observed (Fig. 2Ah–Ag). Christian symbols (standard crosses, Maltese crosses, a dove, *Manus Dei*, peacocks and fish) are also represented, especially on objects found in Prague Castle's Lumbe Garden cemetery (Fig. 2Ba–Bb–Bd). The motifs are usually depicted on a dotted background, delimited by arcades and columns, heart-shaped meanders, ribbons and, occasionally, medallions in Mikulčice. The *gombiky* from Prague Castle are typically delimited by medallions, rhomboids, inverse single leaves and interlaced braids. To a lesser extent, gilded *gombiky* were decorated with granulation work (Fig. 2Af–Ak–Bh) and sometimes combined with coloured glass cabochon settings (Fig. 2Bg–Bh).

Experimental section

Materials

Eleven gilded copper *gombiky* exhumed from the Mikulčice site (Fig. 2A) and eight from the Lumbe Garden cemetery at Prague Castle (Fig. 2B) were investigated for this study. The selection of the *gombiky* from Mikulčice was guided by their representativeness and variety in terms of quality and decoration as well as availability, while one specimen of each type of the gilded copper *gombiky* from the Lumbe Garden cemetery was investigated. In addition, one Byzantine coin (solidus) found in Mikulčice (236z) (Klanica et al. 2019, 260) was also considered a comparative archaeological gold alloy sample. It is made from a ternary Au–Ag–Cu alloy, which is close to the gilding composition as it will be seen in the part with EDS results. The characteristics of these artefacts and their archaeological context are given in Table 1.

All the investigated *gombiky* are old finds that were restored in the 1950s (Mikulčice) and 1970s (Prague Castle),

a



b



Fig.1 **a** Localisation of Mikulčice and Prague Castle archaeological sites (conception J. Hošek). **b** Map of Great Moravia after Kouřil 2014, Institute of Archaeology, the CAS, Brno

stored in the Collection of Precious Metal Objects of the Czech Academy of Sciences, at the Institute of Archaeology

in Brno and in Prague Castle Administration, in the Art Collections Department.



Fig. 2 Studied *gombiky*. **A** From Mikulčice. **B** From Prague Castle, Lumbe's garden cemetery. **A** a- *gombik* 76/š, grave 290-3rd church; b- *gombik* 129/š, grave 420b-2nd church; c- *gombik* 190/š, grave 550-3rd church; d- *gombik* 217/š, grave 625-3rd church; e- *gombik* 220/š, grave 662-3rd church; f- *gombik* 110/z, grave 498-3rd church; g- *gombik* 115/

z, grave 508-3 rd church; h- *gombik* 117/z, grave 508-3 rd church; i- *gombik* 255/š, grave 43-6th church; j- *gombik* 26/z, grave 91-2nd church; k- *gombik* 45/z, grave 141-2nd church. **B** a- *gombik* H 104-4; b- *gombik* H 115-8; c- *gombik* H108-2; d- *gombik* H84-1; e- *gombik* H104-3; f- *gombik* H99-5; g- *gombik* H 74B-2; h- *gombik* H 53-14

The studied gilded copper alloys were found in an advanced state of mineralisation due to galvanic corrosion and as a result of having been buried in an aerobic wet environment for many centuries. However, the *gombiky* from

Mikulčice were better preserved than their highly mineralised counterparts from Prague Castle.

The copper gilded *gombiky* had also previously undergone invasive restoration treatment (immersion in

Table 1 Characteristics of studied artefacts (selected *gombiky* and the golden Byzantine coin reference)

Locality	Number	Ref. Fig.	Body construction	Suspension system	Decoration	Quality	Diam. (mm)	Archaeological context
Mikulčice	26/z	Aj	Type 1	Type 1	Chased	Low	18	Grave 91, Mikulčice-2nd church, child aged 7, grave goods: 2 gilded copper <i>gombiky</i>
Mikulčice	45/z	Ak	Type 1	Type 1	Granulation	Low	16	Grave 141, Mikulčice-2nd church, child aged 7, grave goods: 2 copper gilded <i>gombiky</i> with granulation work.
Mikulčice	76/s	Aa	Type 3	Type 2	Chased	High	26	Grave 290, Mikulčice-3rd church, child aged 2, grave goods: 2 gilded copper <i>gombiky</i> , 1 earring.
Mikulčice	110/z	Af	Type 1	Type 2	Granulation	High	15	Grave 498, Mikulčice-3rd church, child aged 3–4 buried in a wooden coffin with iron fittings, grave goods: 2 gilded copper <i>gombiky</i> decorated with granulation work, 1 iron knife.
Mikulčice	115/z	Ah	Type 1	Type 2	Chased	High	15	Grave 508, Mikulčice-3rd church, male aged 50–60, grave goods: 2 gilded copper <i>gombiky</i> , spurs, dagger.
Mikulčice	117/z	Ag	Type 1	Type 1	Chased	Average	17	Grave 508, Mikulčice-3rd church, male aged 50–60, grave goods: 2 gilded copper <i>gombiky</i> , spurs, dagger.
Mikulčice	129/s	Ab	Type 3	Type 1	Chased	High	28	Grave 420b, Mikulčice-2nd church, child aged 5, grave goods: 1 copper gilded <i>gombiky</i> , 1 silver globular earring.
Mikulčice	190/s	Ac	Type 3	Type 1	Chased	High	28	Grave 550, Mikulčice-3rd church, child aged 4–5, grave goods: 2 gilded copper <i>gombiky</i> , 1 golden lunule pendant, 1 silver <i>gombiky</i> , 1 silver bead, 2 ring earrings, 3 iron knives.
Mikulčice	217/s	Ad	Type 1	Type 1	Chased	High	33	Grave 625, Mikulčice-3rd church, female aged 20–30, buried in a wooden coffin with iron fittings, grave goods: 2 gilded copper <i>gombiky</i> , 1 sherd.
Mikulčice	220/s	Ae	Type 1	Type 1	Chased	High	28.6	Grave 662, Mikulčice-Valy, 3rd church, female, child aged 4 years, grave goods: 2 copper gilded <i>gombiky</i> , 1 silver <i>gombiky</i> , 1 silver grape shaped earrings.
Mikulčice	255/s	Ai	Type 2	Type 1	Chased	Low	19	Grave 43, Mikulčice-6th church, child, aged 7, grave goods: 2 gilded copper alloys <i>gombiky</i> , spurs, hollow bone artefact plated with a copper alloy foil.
Mikulčice	236/z	Golden	Byzantine coin-solidus					Grave 480-3rd church, male, aged 40–50, coin in mouth, no other find
Prague Castle	H53-14	Bh	Type 1	Type 2	Granulation, glass cabochon	High	15	Grave 53, Lumbe's garden cemetery, female, mature, grave goods: 2 gilded copper <i>gombiky</i> , 2 gilt silver globular earrings, 2 gold globular earrings, 4 silver globular earrings, 1 silver amulet case (kaptorga), 3 silver beads, 2 glass beads, 1 iron knife.
Prague Castle	H74B-2	Bg	Type 1	Type 2	Octolobed shell, glass cabochon	Medium	14.5	Grave 74B, Lumbe's garden cemetery, child, aged 2, grave goods: 2 gilded copper <i>gombiky</i> , 1 copper gilded jingle bell, 1 glass <i>gombiky</i> , 1 miniature iron axe, 1 iron knife.
Prague Castle	H 84-1	Bd	Type 1	Type 1	Chased	Average	44	Grave 84, Lumbe's garden cemetery, child, female, aged 10, grave goods: 2 gilded copper <i>gombiky</i> , 5 silver grape-shaped earrings, 2 silver S-shaped temple rings, a copper alloy ring 1 iron knife, a necklace with 25 amber and glass beads, egg's shell.
Prague Castle	H 99-5	Bf	Type 1	Type 2	Chased	Low	27.3	Grave 88, Lumbe's garden cemetery, child, female, aged 2.5–3.5, grave goods: 7 silver temple rings, 2 gilded <i>gombiky</i> , 1 iron knife, 1 crystal bead.
Prague Castle	H 104-3	Be	Type 1	Type 1	Chased	Low	23	Grave 104, Lumbe's garden cemetery, child, aged 2.5, grave goods: 4 gilded copper <i>gombiky</i> , necklace of glass beads, 6 temple rings with an eyelet, iron knife, gilt silver grape-shaped earring, egg's shell.
Prague Castle	H104-4	Ba	Type 1	Type 1	Chased	High	29.5	Grave 104, Lumbe's garden cemetery, child, aged 2.5, grave goods: 4 gilded copper <i>gombiky</i> , necklace of glass beads, 6 temple rings with an eyelet, iron knife, gilt silver grape-shaped earring, egg's shell.
Prague Castle	H 108-2	Bc	Type 1	Type 1	Chased	High	35.5	Grave 108, Lumbe's garden cemetery, child aged 3, grave goods: 2 gilded copper <i>gombiky</i> , necklace with three amber beads, 1 silver bead, 1 iron knife, 1 temple ring with eyelet.
Prague Castle	H 115-9	Bb	Type 1	Type 1	Chased	High	30	Grave 115, Lumbe's Garden cemetery, female, aged 14, grave goods: 2 gilded copper <i>gombiky</i> , 2 silver <i>gombiky</i> , 12 silver grape-shaped earrings, two iron knives.

chemical solutions), significantly impacting their material constituents and resulting in the partial dissolving of mineralised bulkmetals (Ottenwelter et al. 2014, Ottenwelter 2016).

Additionally, the surface of the gilding layer was sometimes tarnished or covered by the remaining copper corrosion products as detailed later. It was therefore necessary to first remove the acrylic coatings on the surface and then strip back the tarnished layers and the remaining external corrosion products prior to analysis.

Methods

Surface observation: optical microscopy

Observations under a stereomicroscope, including documentations of tool marks, state of preservation and solder area, were performed using an Olympus SZX7 stereomicroscope (magnification $\times 10$ – $\times 40$) and an Olympus E-450 digital camera.

X-ray radiography

X-ray radiography was systematically carried out on each artefact, with an X-test 225/200Testima® digital X-ray radiography unit coupled to an X-Y stage manipulator. The apparatus includes an IXS1203 X-ray generator and an XRD 1622 AO14 flat panel detector (up to 41×41 cm) with an image resolution of 2048×2048 pixels. The present examinations were carried out at the following exposure conditions: from 70 to 120 kV at 3 mA. A great deal of information was collected thanks to the X-ray radiography regarding the internal construction of the finds, the identification of the different components, the presence of the solder area, metallic coating and the state of preservation.

Surface observation and elemental analysis: SEM/EDS

Observation and analysis were performed directly either on the cleaned *gombiky* placed in the chamber without a conductive coating or on polished cross sections. For the polished cross sections (see the following section), a thin layer of carbon a few nm thick was added to improve the surface conductivity. SEM observation and EDS elemental analysis were performed on a PHILIPS XL30 scanning electron microscope equipped with an energy-dispersive X-ray spectrometry (Edax system), ZAF quantification method. EDS analyses of the metallic core, solder areas, gilding layer, alloy phases and inclusions were conducted in multiples areas on each sample, with a field of view ranging from $\sim 11 (\times 150)$ to $0.4 \text{ mm}^2 (\times 4000)$. Locally on most of the *gombiky*, a micro-scratch

was made up to the sub-surface (Blakelock 2016, 918) in order to limit the corrosion impact on the elemental composition of the metallic core ded (analysis ($\sim 1.5\text{-}\mu\text{m}$ diameter of analysed volume) was also performed to analyse inclusions, particles or eventually corrosion products. An analysis was conducted at 20 kV at a current beam of 1 nA, applying laboratory standards in the same EDS analysis configuration. With the exception of non-corroded metallic polished cross sections, the analytical values have to be considered semi-quantitative results performed on non-flat surfaces.

Metallographic examination

Seven fragmented *gombiky* (Fig. 2Ad–Ba–Bb–Bc–Bd–Be–Bf) were available for metallographic examination. After embedding in epoxy resin (Struers® Specifix-20 kit), they were polished with silicon carbide papers up to P4000 and diamond paste up to a size of $0.7 \mu\text{m}$. They were then observed with an Olympus BX60 optical microscope equipped with an Olympus 350 digital camera. Only one well-preserved sample (Mikulčice 217š—Fig. 2Ad) was etched with alcoholic ferric chlorides to reveal its metal-lurgical structure. This etching was not performed on other fragments, as very few metallic islands were present in the corroded matrix.

In situ cross section: FIB on FEG SEM

Two fragmented gilded *gombiky* from Prague Castle, H115-9 (Fig. 2Bb) and H84-1 (Fig. 2Bd), were investigated using an FIB FEG-SEM coupled with energy-dispersive spectroscopy (EDS). The two selected fragments were respectively representative of poor and good-quality gilding.

The apparatus used was a FEI Helios NanoLab 600i coupled to an Aztec Oxford EDS system (SDD detector, WD 4 mm). Before SEM observation, samples were coated with an amorphous carbon layer applied by sputtering (Leica ACE 600), with a film thickness of around 5–10 nm to ensure the sample conductivity. In situ cross sections were produced by focused ion beam (FIB) milling using Ga^+ ions. Prior to applying FIB milling, a representative area was carefully selected from surface examinations (Fig. 3a). The sample was tilted at 52° (Fig. 3b) and a platinum (Pt) layer with a width of about $1 \mu\text{m}$ (indicated by the red arrow in Fig. 3c) was laid down for protection on the selected surface. An ionic ablation of Ga^+ ions was then applied on the gilded surface, producing cross sections from 100 to 130 μm in length and 10 to 20 μm in depth (Fig. 3d). FEG-SEM observation and semi-quantitative EDS analysis of the cross sections were then carried out using an acceleration voltage of 20 kV.

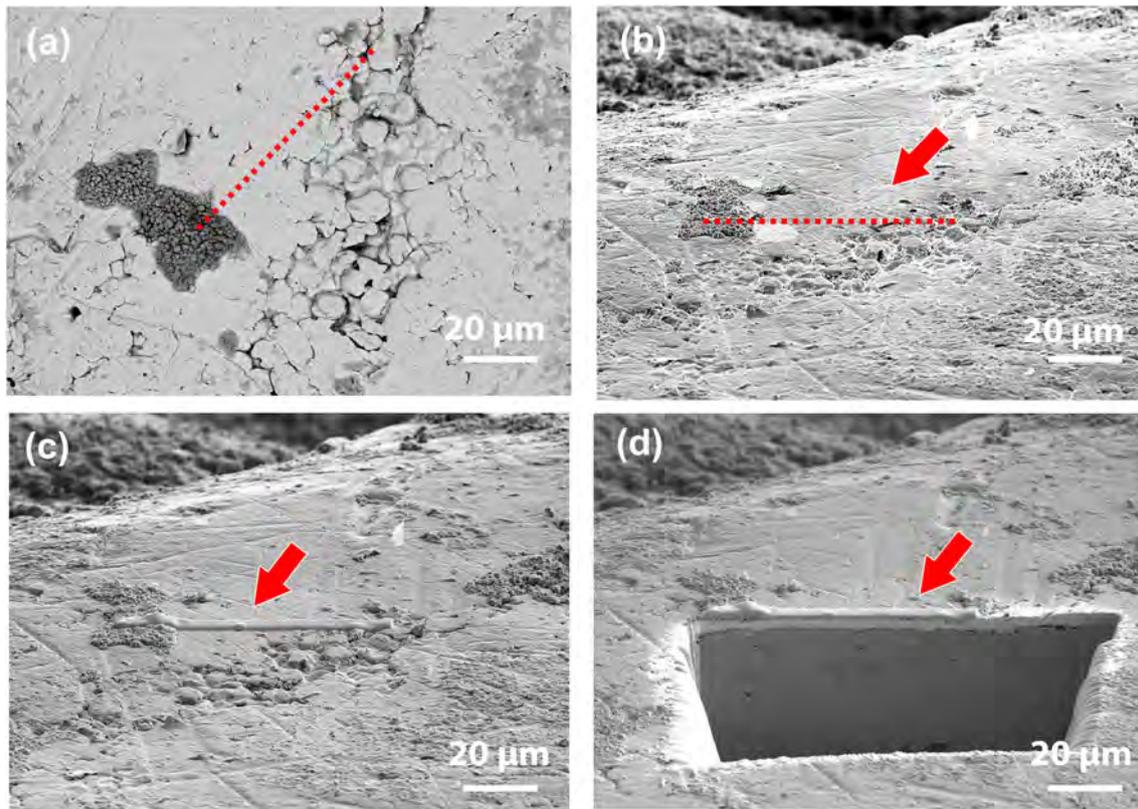


Fig. 3 In situ cross section preparation—fragment of the gilded *gombik* H115-9 (Prague Castle). **a** Selection of a representative gilded surface including polished and porous areas—red dashed line (BEI). **b** Same

selected area tilted 52° for FIB milling (SEI). **c** Pt-C layer deposit (red arrow) for protection of selected area (SEI). **d** Cross section obtained after milling of the sample surface using a focused beam of Ga⁺ ions (SEI)

Results

Surface examination and preservation state

As the studied *gombiky* have been restored before, a careful observation of the surface under a stereomicroscope is always required. This makes it possible not only to reveal ancient technical details masked by residual corrosion products, but also to uncover the impact of old restorations and storage conditions which could bias the observation and the technological understanding.

The typical and important cases of alteration usually encountered on these artefacts are illustrated in Fig. 4. For example, a precisely controlled cleaned surface reveals smeared solder under the worn gilded layer as shown in Fig. 4a and b. Gilding can also be simply masked by the tarnishing due to smeared Ag-Cu silver solder (Fig. 4c and d) or by copper corrosion deposits forming a compact thin homogeneous layer (Fig. 4f). Corrosion layers of cuprous oxide (reddish brown) and cupric hydroxylated species (greenish blue) are thus formed below and above the gold layer. The thickness of the hemispheres is very thin (c. 0.2 mm) and the metal can be completely mineralised. Thus, the gilding layer can be completely lost after the dissolution of the mineralised core metal by past invasive chemical treatment (Fig. 4e).

Optical observation enables the identification of several tool marks and features providing information about the skills of the goldsmiths and clues to identify decorative techniques. In the different steps of chasing, which will be described in detail in the “Experimental archaeology” section, several successive chasing tools leaving characteristic features on the surface are used. The presence of a drawing compass depression or slightly incised lines, as illustrated in Figs. 4b and 5a, points to preliminary work regularly laying the motifs on the surface, also indirectly revealing high skills. Planishing tools (Fig. 5b) and dotting punches (Fig. 5a) leave specific marks which sometimes may help identify the production of a specific jeweller.

Construction—mounting

As revealed from optical observation (Fig. 6) and X-ray radiography (Fig. 7), *gombiky* are spherical hollow pendants made of different components joined together. Two main parts can be distinguished: the body and the suspension system.

The body can be made of two hemispheres soldered together, as shown in Figs. 6c and 7a, or it can be made by a single globe as shown in Fig. 7b. A slightly embossed disc of metal sheet called a collar can sometimes top the two joined

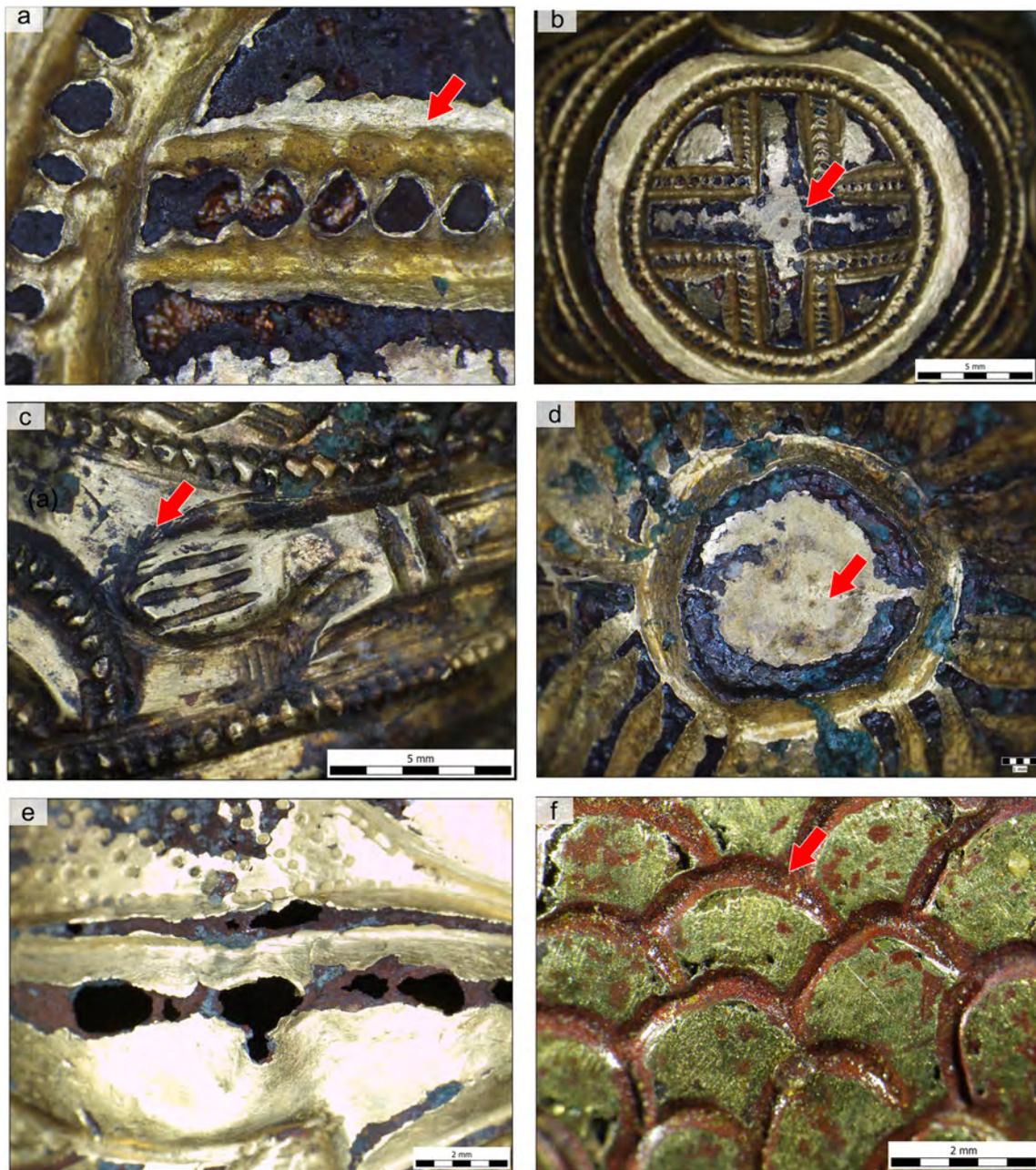


Fig. 4 Representative examples of surface state of preservation-optical observation. **a** Smeared solder under the worn gilded layer (H 104-4). **b** Smeared solder under worn gilding layer and depression of drawing compass (H 104). **c** Black silver and copper sulphides over the gilding layer (

H 115-8). **d** Tarnished layer over the gilding (H 104). **e** Dissolved mineralised bulk metal by past chemical treatment (H 104-3). **f** Brown red copper oxides masking the gilding layer (H 84-1)

hemispheres or the single globe as illustrated in Figs. 6b and 7c. This collar is soldered on the top hemisphere or single globe with a hard solder as shown on Fig. 6d. A vent is sometimes made near the collar (Fig. 6b) to permit the evacuation of the trapped humidity during soldering. The second part of the *gombik* is the suspension system mounted in the previous one. It is inserted in the upper pierced hemisphere, through the collar if present, and soldered to it. Different cases are depicted in Fig. 6a and b. The suspension system can be made

of three elements: a loop, a clamp and a ring (Fig. 6a) or by two elements: a split loop and a ring (Fig. 6b). A round section drawn or hammered wire is used to form the loops (Fig. 6a). The clamps are usually of a triangular section and the ring can be either plain or formed with beaded wires (Fig. 6a and b). X-ray radiography also revealed an interesting feature: the presence of a pellet inside the *gombik* (Fig. 7a) which means that several of these artefacts were meant to ring like jingle bells.

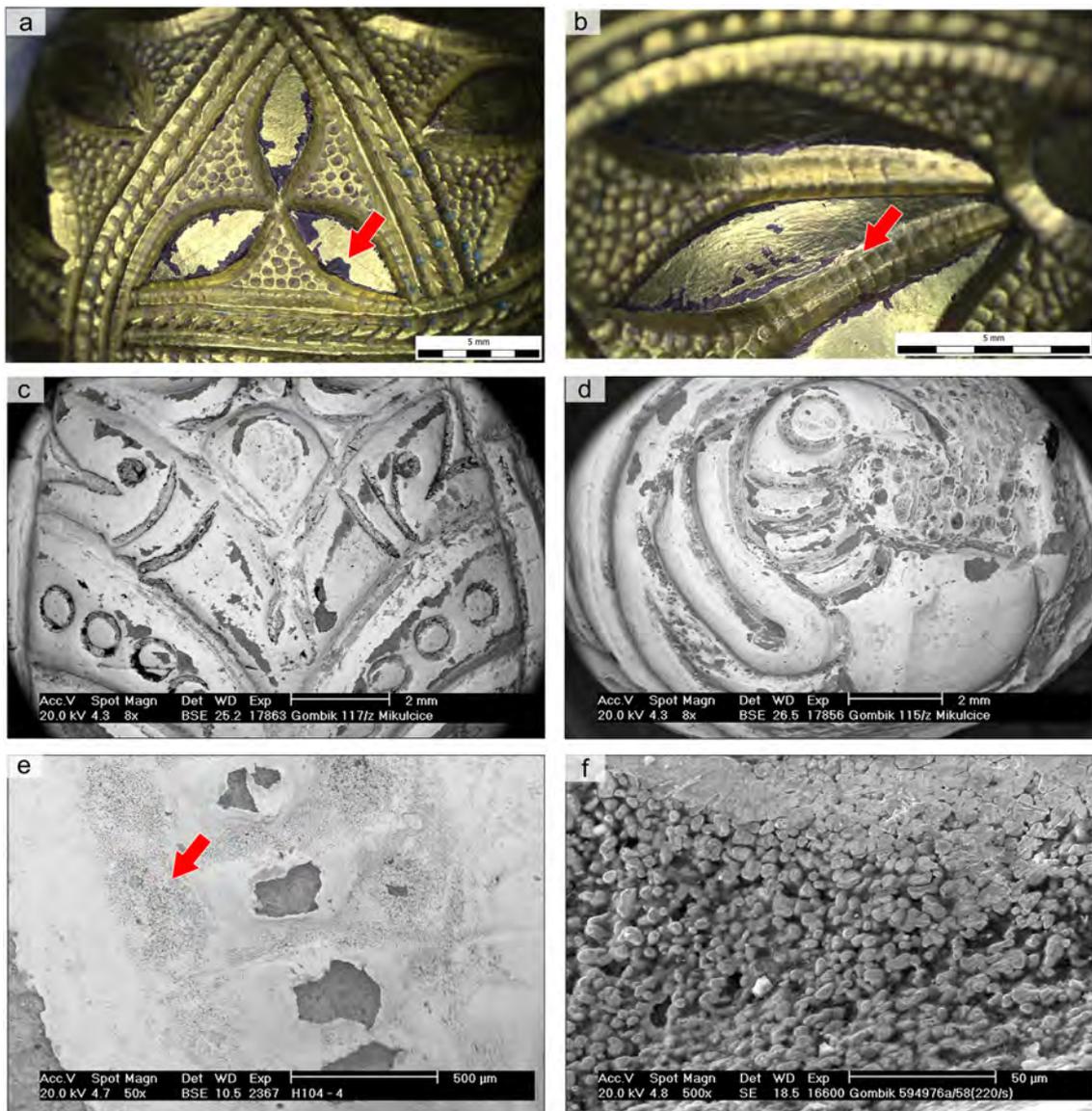


Fig. 5 Characteristic tool marks and gilding. **a** Sketch lines (190/§). **b** Chasing tool marks (190/§). **c** Chased fish motifs (117/z). **d** Chased bird of prey (115/z). **e** Porous structure of the unburnished gilding layer in

recesses (H 104-4). **f** Granular structure of unburnished gilding layer obtained by fire gilding in a recess (220/§)

Thus, from a technical point of view, three main types of body construction can be defined as reported in Fig. 8A. In the first type, two soldered hemispheres are soldered together (Fig. 8Aa). The second type is represented by a single globe topped by a collar (Fig. 8Ab). The third type is a combination of these two constructions involving two soldered hemispheres topped by a collar (Fig. 8Ac). Two types of a suspension system can be mounted on the different types of body. The first and most common one is composed of three elements: a loop-a clamp and a ring as shown in Fig. 8Ba. The other comprises only two elements: a split loop and a ring as shown in Fig. 8Bb.

Material composition (EDS analysis on SEM)

An SEM/EDS analysis was performed on the bulk materials of the main components of the *gombiky*. The elemental analysis was conducted on polished cross sections of available fragments and or sub-surfaces created by micro-scratches performed under a stereomicroscope on the surface. The results have been normalised to 100 wt% for the metallic elements, even though some of them were affected by the presence of corrosion species, including light elements (cases of 109/z and 110z, and H99-5). Here, the presented EDS results are semi-quantitative results. They will be considered only to identify the main categories of copper base materials as well as the different hard solder and gilding.

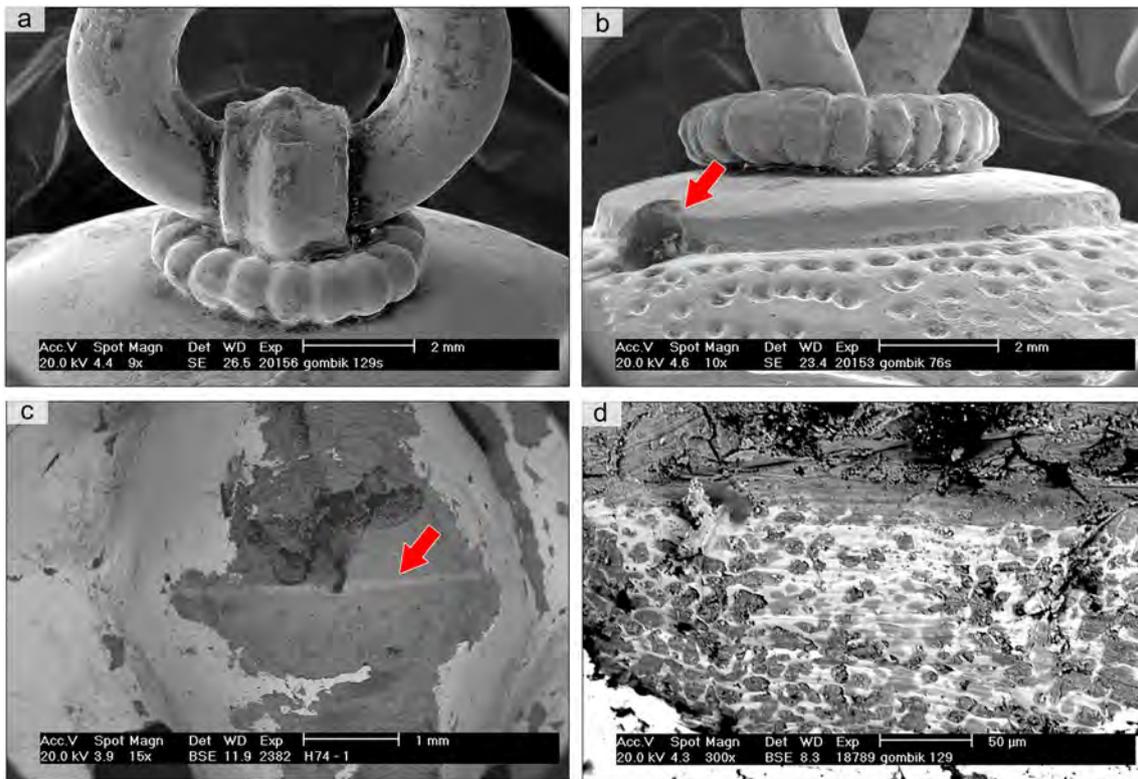
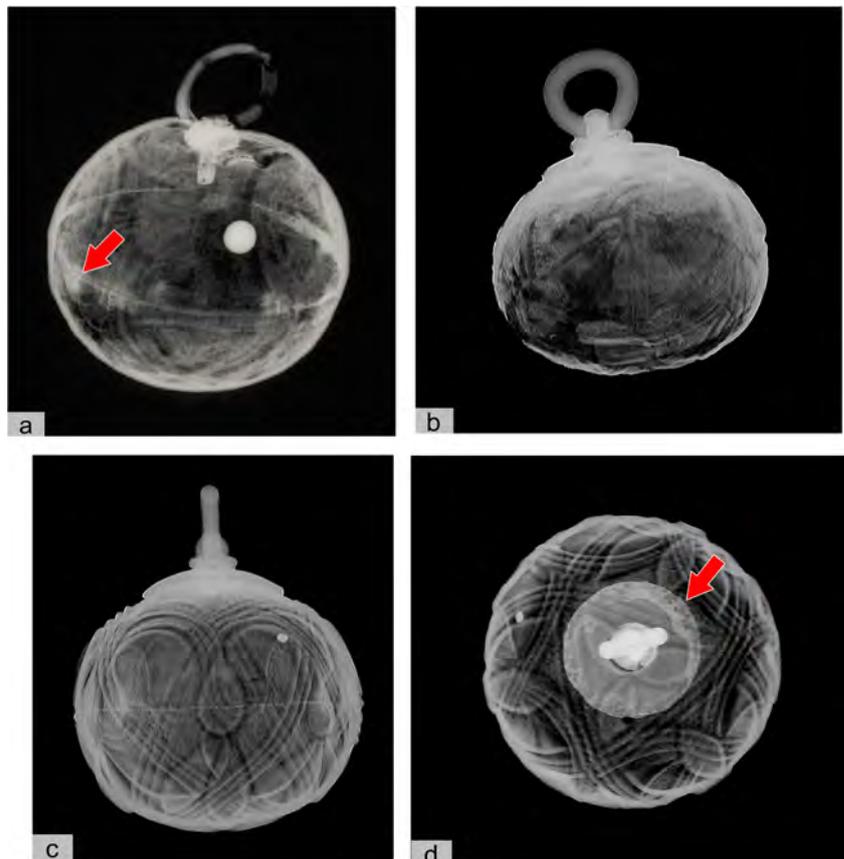


Fig. 6 Surface characterisation-SEM observation. **a** Three component suspension systems (loop-clamp-ring) of the *gombik* 129s. **b** Two component suspension systems (split loop-ring), vent and collar (76s). **c**

Solder area between the two shells (H74B-2). **d** Eutectic mixture of the hard Ag-Cu solder used to solder the two hemispheres (129s)

Fig. 7 X-ray radiography revealing the different types of body construction. **a** *Gombik* H104-4. **b** *Gombik* 255/s. **c** and **d** *Gombik* 190s (the red arrows are pointing to the features discussed in the text (smearred solder between the two hemispheres, under the collar, presence of collar))



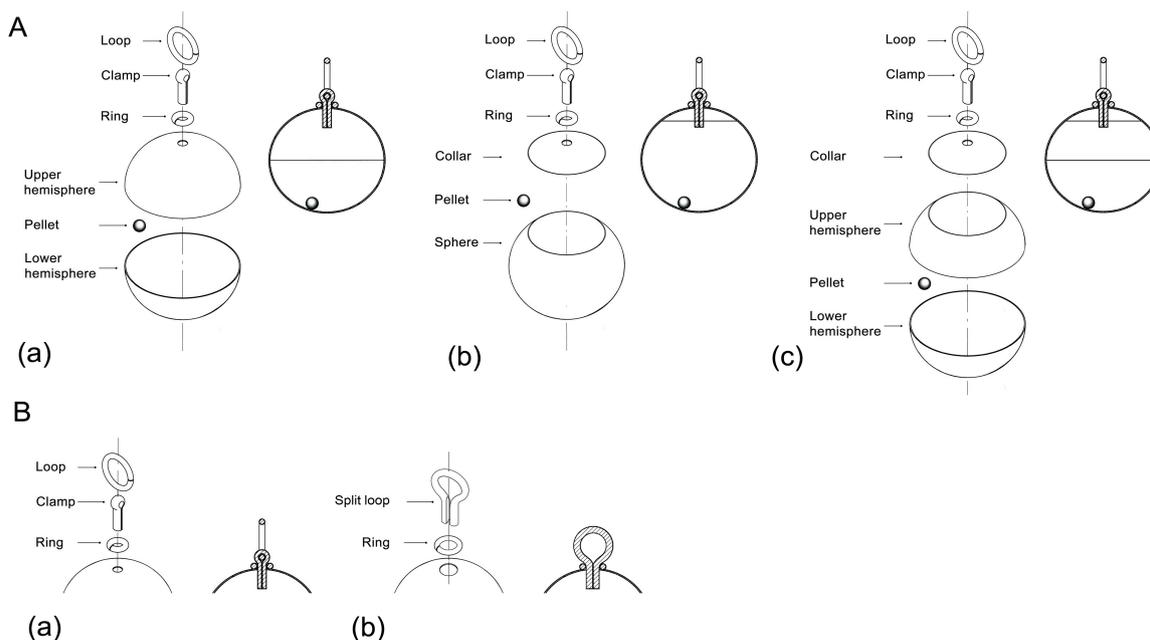


Fig. 8 *Gombik* manufacture. **A** Three types of body construction (drawing G. Plítková in Ottenwelter et al. 2014, p.171 modified by L. Zahradníková). **B** Two main types of suspension system. a- Three

components (loop-clamp-ring); b- two components (split loop-ring) (drawing G. Plítková in Ottenwelter et al. 2014, 171 modified by J. Hošek)

Mounting elements

Body composition As regards the hemispheres, shells or globe, the EDS results are given in Table 2. Unalloyed copper is the prevailing material used. However, several categories of copper are documented: (1) high-purity copper (>99 wt%) for around half of the studied jewels, (2) copper with a non-negligible amount of impurity(ies) (99 > Cu > 96 wt%) and (3) copper base alloy with Cu <96 wt%.

In the category (2), the minor element detected is essentially Sn (Sn < 3 wt%), but in some instances, it is Pb (129/š) or Ag (217/š). The copper hemispheres can also contain both Sn and Pb (117z, 115z) or Sn and Ag (H74B-2) as minor impurities. Due to the low content of Sn, Pb and Ag (most often < 2 wt%), Sn, Pb and Ag cannot be considered intentional alloying elements but rather as the main impurities in connection with the ores used or with possible recycling. When an analysis on both hemispheres was possible, the results showed that the same material was used.

The last category of composition (3) only concerns two *gombiky* of poor technical quality from the Prague Castle cemetery (H99-5 and H104-3). Very high Sn and Pb contents are found for the hemisphere of *gombik* H99-5. This could be linked to a decuprification process due to corrosion, as is usually observed for archaeological bronze (Robbiola and Portier 2006). For *gombik* H104-3, it is a very particular Cu-Pb-Sb alloy also characterised by a very low quality of chasing, which can be identified as a poor imitation.

Thus, with the exception of specimen H104-3 and possibly H99-5, only pure or almost pure copper has been used by craftsmen.

It also appears that no specificity of composition has to be related to a specific geographical area (Moravia, Bohemia), nor to a special type of construction or decoration as reported in Table 1. Only a correlation between the poor quality of chasing and a poorly appropriate material can be established. In both cases (H99-5 and H104-3), it concerns poor imitations of Moravian *gombiky* found at Prague Castle.

Suspension system As for the body, different qualities of copper are evidenced: (1) high-purity copper (> 99 wt%), (2) low-purity copper and (3) copper base alloys with Cu < 96 wt%. The results are reported under Supplementary Information (Table S1). It must be noted that even though the analysis was performed on sub-surfaces, the analysed surfaces often remained oxidised. Thus, a relative increase in the content of minor elements must be expected due to a preferential copper dissolution in connection with the corrosion process (Robbiola and Portier 2006). As a consequence, it remains difficult here to differentiate low-purity copper from a copper alloy with a very low content of alloying elements. Additionally, high Ag content was sometimes detected on rings and/or clamps (*gombiky* 110/z, 117/z, 190/š, 255/š and H108-2), which here could be related to a possible contamination of the smeared solder.

Pure copper (1) is identified only for a few suspension elements of *gombiky* from Mikulčice (26/z loop and clamp, 45/z, 76/š). For the category (2) identified on artefacts of both

Table 2 Chemical composition of the hemispheres and solder areas between hemispheres on polished cross sections and sub-surface areas—EDS analysis on SEM, semi-quantitative results on polished cross

sections and sub-surfaces (normalised wt% on the metallic elements—light elements (except C) not reported but considered for quantification)

Locality and number		Body (hemisphere and shell)						Solder		
Locality	Number	Cu	Sn	Pb	Ag	Sb	Remarks	Ag	Cu	Remarks
Mikulčice	26/z	100	-	-	-	-		45	55	Sub-surface
Mikulčice	45/z	100	-	-	-	-		88	12	Sub-surface
Mikulčice	76/š	100	-	-	-	-	Corroded (chloride)	78	22	Cross section
Mikulčice	109/z	100	-	-	-	-	Highly corroded	n.d	n.d	not accessible
Mikulčice	110/z	100	-	-	-	-	Highly corroded	51	49	Sub-surface
Mikulčice	115/z	96.4	1.6	2	-	-		29	71	Sub-surface
Mikulčice	117/z	98	1.2	0.8	-	-		29	71	Sub-surface
Mikulčice	129/š	99	-	1	-	-	Corroded	46	54	Cross section
Mikulčice	190/š	98.8	1.2	-	-	-	Slightly corroded	67	33	Cross section
Mikulčice	217/š	98.9	-	-	1.1	-		67	33	Sub-surface
Mikulčice	220/š	100	-	-	-	-		26	74	Sub-surface
Mikulčice	255/š	100	-	-	-	-	Corroded	49	51	Sub-surface
Prague Castle	H 74B-2	98.2	0.6	-	1.2	-		83	17	Sub-surface
Prague Castle	H 84-1	100	-	-	-	-	Corroded (oxide)	71	29	Sub-surface
Prague Castle	H 99-5	91.6	5.3	3.1	-	-	Highly corroded (oxide)	49	51	Cross section
Prague Castle	H 104-3	81.6	-	11.3	-	7.1	Corroded (chloride)	93	7	Sub-surface
Prague Castle	H104-4	100	-	-	-	-	Slightly corroded	67	33	Sub-surface
Prague Castle	H 108-2	98.1	1.9	-	-	-		81	19	Sub-surface
Prague Castle	H 115-9	97	3	-	-	-		58	42	Cross section

sites, the main minor elements are Sn, Pb or Ag (< 4 wt%) mainly forming low content Cu-Sn or Cu-Pb alloys. For the category (3) affecting only a few artefacts, the alloys identified correspond to ternary Cu-Sn-Pb (115/z loop, 190/z ring, H104-4 clamp and H104-4 ring) and quaternary Cu-Sn-Pb-Sb (only for the 110/z clamp).

No correlation is found between the metal composition and the type of suspension element (loop, clamp or ring). For a large majority of *gombiky*, the suspension elements are composed of different types of metallic material. For example, the metal used for clamps can be pure copper (H115-9, 190s, 45/z or 25/z), but it can be also copper with different minor element(s): Sn (H104-3 or 220s), Pb for H84-1, or Sn and Pb for 129/š or 217/š. Furthermore, the metals of the suspension components differ from those used for the body of the *gombiky* given in Table 2. Thus, no precise relationship between the composition of the different elements of suspension and of the body of each *gombik* can be established.

Solder

The analyses of solders used to join the hemispheres are given in Table 2. Due to gilding, the soldering areas were mainly accessible between the hemispheres. No solder analysis was

performed for the granulation work or the suspension system. The solder used for all the *gombiky* is a hard Ag-Cu solder. As shown in Fig. 9, the Ag-Cu system is characterised by a low melting point at 780 °C (eutectic temperature at Ag = 71.9 wt%), forming a mixture of rich Cu(Ag) and Ag(Cu) phases—alpha and beta phases respectively (Scott 1991, Fig. 205, 129). Usually the choice of solder composition is guided by its melting temperature, which should be much lower than that of the bulk element to be soldered. Thus, for low-purity copper with a melting point lower than pure copper, a solder close to the eutectic Ag-Cu composition would be the best choice. However, this is not always the case for the solder used (Table 2). The melting temperature of the solder of four representative solder compositions is illustrated in Fig. 9.

It is interesting to note that an Ag-Cu hard solder close to the eutectic composition was deliberately chosen to manufacture the finest *gombiky* (76/š, 129/š, 190/š, 217/š, H84-1, H104-4), while inversely a different composition increasing the melting temperature of the solder up to 160 °C was recorded in several cases (115/z, 117/z, 220/š). Another interesting fact is that an Ag-Cu solder containing around 50 wt% or 90 wt % of Ag has almost the same melting point (880 °C). However, for the production of *gombiky*, the impact of the solder composition is not as important in comparison with the thinness of the soldered materials.

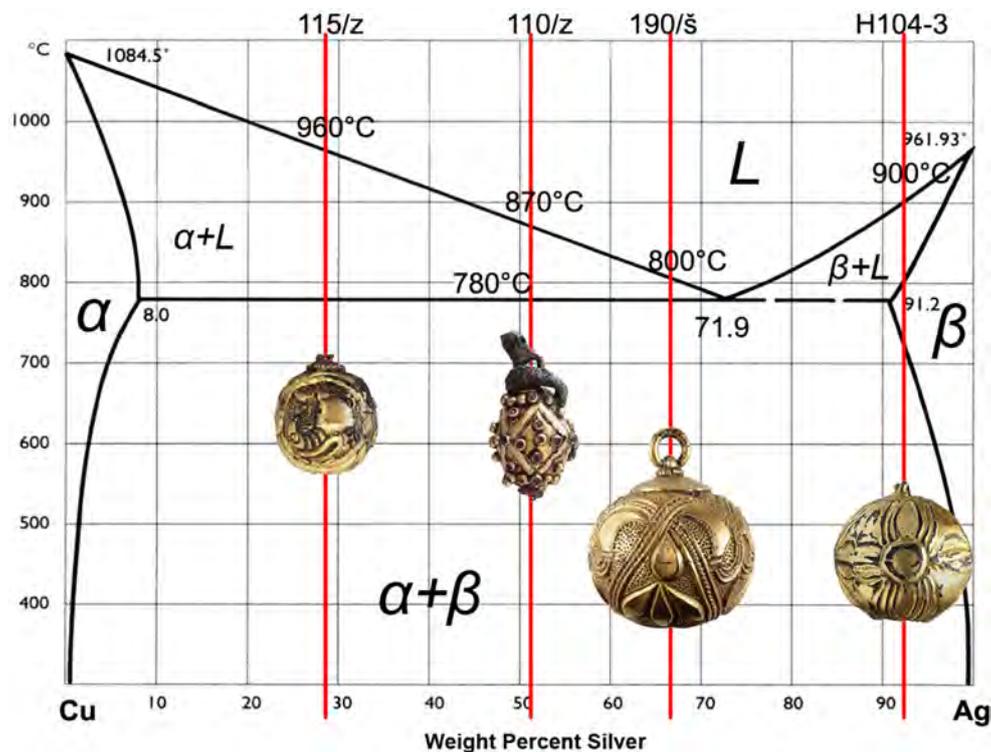


Fig. 9 Phase diagram of the Cu-Ag system showing the liquidus temperature of the hard solder (in red), used to join the hemispheres of *gombik* 190š closed to the eutectic point (800 °C), H 104-3 (900 °C), 110/z (870

°C), 115/z (960 °C) according to their chemical composition (after phase diagram of the Cu-Ag system in Scott 1991, Fig. 205, 129, modified)

Table 3 Chemical composition and thickness of the gilding layer on polished cross sections and sub-surface areas and of the Byzantine coin (solidus)—EDS analysis on SEM (normalised wt% on the metallic elements)—n.d. not determined

Locality	Number	Thickness (µm)	Analysed area	Chemical composition (wt%)			
				Au	Ag	Hg	Cu
Mikulčice	26/z	n.d	Gilding layer, surface	82.6	4.4	8.3	4.7
Mikulčice	45/z	n.d	Gilding layer, surface	76.8	6.7	13.5	3
Mikulčice	76/s	n.d	Gilding layer, surface	87.4	2.3	8	2.3
Mikulčice	109/z	n.d	Gilding layer, surface	76.2	9.9	11.3	2.6
Mikulčice	110/z	n.d	Gilding layer, surface	88.8	3.7	4.7	2.8
Mikulčice	115/z	n.d	Gilding layer, surface	74.6	9.4	12.7	3.3
Mikulčice	117/z	n.d	Gilding layer, surface	70.8	12.2	13.5	3.5
Mikulčice	129/s	n.d	Gilding layer, surface	83.4	1.9	10.7	4
Mikulčice	190/s	n.d	Gilding layer, surface	85.6	2.5	9.4	2.5
Mikulčice	217/s	5.3–8	Gilding layer, cross section	75	2.5	12.7	9.8
Mikulčice	220/s	n.d	Gilding layer, surface	86.2	1.6	9.8	2.4
Mikulčice	255/s	n.d	Gilding layer, surface	84.8	3.5	9.7	2
Mikulčice	236/s	-	Solidus, sub-surface	94.6	3.2	-	2.2
Prague Castle	H74B-2	n.d	Gilding layer, surface	82.8	6.1	9.4	1.7
Prague Castle	H84-1	8.3–11	Gilding layer, cross section	80	-	16.6	3.4
Prague Castle	H99-5	7–10	Gilding layer, cross section	67.4	6.5	23.2	2.9
Prague Castle	H 104-3	19–28.8	Gilding layer, cross section	75.2	2.3	20.8	1.7
Prague Castle	H104-4	8–10.4	Gilding layer, cross section	84	2.3	12	1.7
Prague Castle	H 108-2	7	Gilding layer, cross section	78.6	5.2	13.7	2.5
Prague Castle	H 115-9	3.3–7.5	Gilding layer, cross section	75.6	3.4	19.1	1.9

Gilding

The presence of mercury was detected in all of the analysed gilding (Table 3). Fire gilding was thus the method used to gild all these objects. The average amount of mercury detected is 13%, but varies from 5 to 23 wt%. The amount of Hg detected is related to the heating time and temperature applied. According to the experimental work of Peter Northover and Kilian Anheuser, the average temperature at which the gilded *gombiky* were heated can be estimated to be between 280 °C and 300 °C (Northover and Anheuser 2000, 118).

The typical feature of the fire gilding layer after heating corresponds to a typical granular structure (Northover and Anheuser 2000; Chiavari et al. 2015; Ingo et al. 2016; Masi et al. 2016). This typical structure was observed on all of the investigated *gombiky* in recesses which have not undergone the burnishing process (Fig. 5e and f).

The analysis results are reported on the ternary Au-Ag-Cu diagram in Fig. 10. The composition of the gilding of these *gombiky* seems to be quite homogeneous, except in the case of *gombik* H84-1 from Prague Castle, in which no Ag was detected.

The average content of Ag and Cu in the gilding layer is around 4 wt%. Both may have been present in the amalgam in particular if recycled scrap material was used to produce it. In this regard, it is interesting to note that the Byzantine coin (solidus) found in grave No 480 in Mikulčice Valy—3rd church—has a composition which matches quite well with the average composition of the gilded layers as shown in Fig. 10. Recycled solidi coins from long-distance trade

could be an eventual source of raw material used to gild *gombiky* by fire gilding, with gold coinage being possibly a primary source of gold for goldsmiths (Oddy and La Niece 1986, 23–25).

Structural observation

Metallographic examination

A metallographic examination was performed on the hemisphere cross sections of seven *gombiky* (six from Prague Castle and one from Mikulčice). The thickness of the copper hemispheres ranges from 0.2 to 0.3 mm for all of the examined samples. With the exception of the unique available sample from Mikulčice (*gombik* 217/š), the metallic core of the *gombiky* was poorly preserved. It was observed only as a few metallic islands embedded in the mineralised matrix, as shown in Fig. 11a, c, e and g.

The examination of the well-preserved copper core of *gombik* 217š (Fig. 11Ah) revealed a recrystallised microstructure marked by twinned grains globally equiaxed and of a very large size (300 µm circa). This is a characteristic of a pronounced annealing operation. Immediately under the gilding layer (cf. arrow in Fig. 11h), an area of small grains with a thickness of 5–10 µm parallel to the surface is observed in connection with the flattening of the surface, inducing a strain-

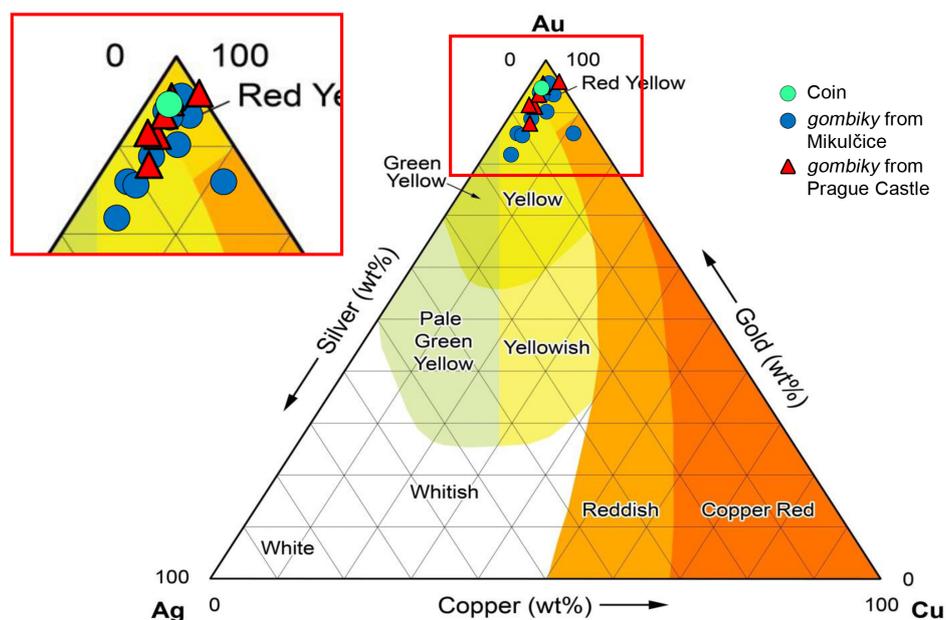


Fig. 10 Ternary system Au-Ag-Cu (after Hauptmann and Klein 2016, Fig. 2 modified) indicating the composition of the gilding layer and the reference Byzantine coin

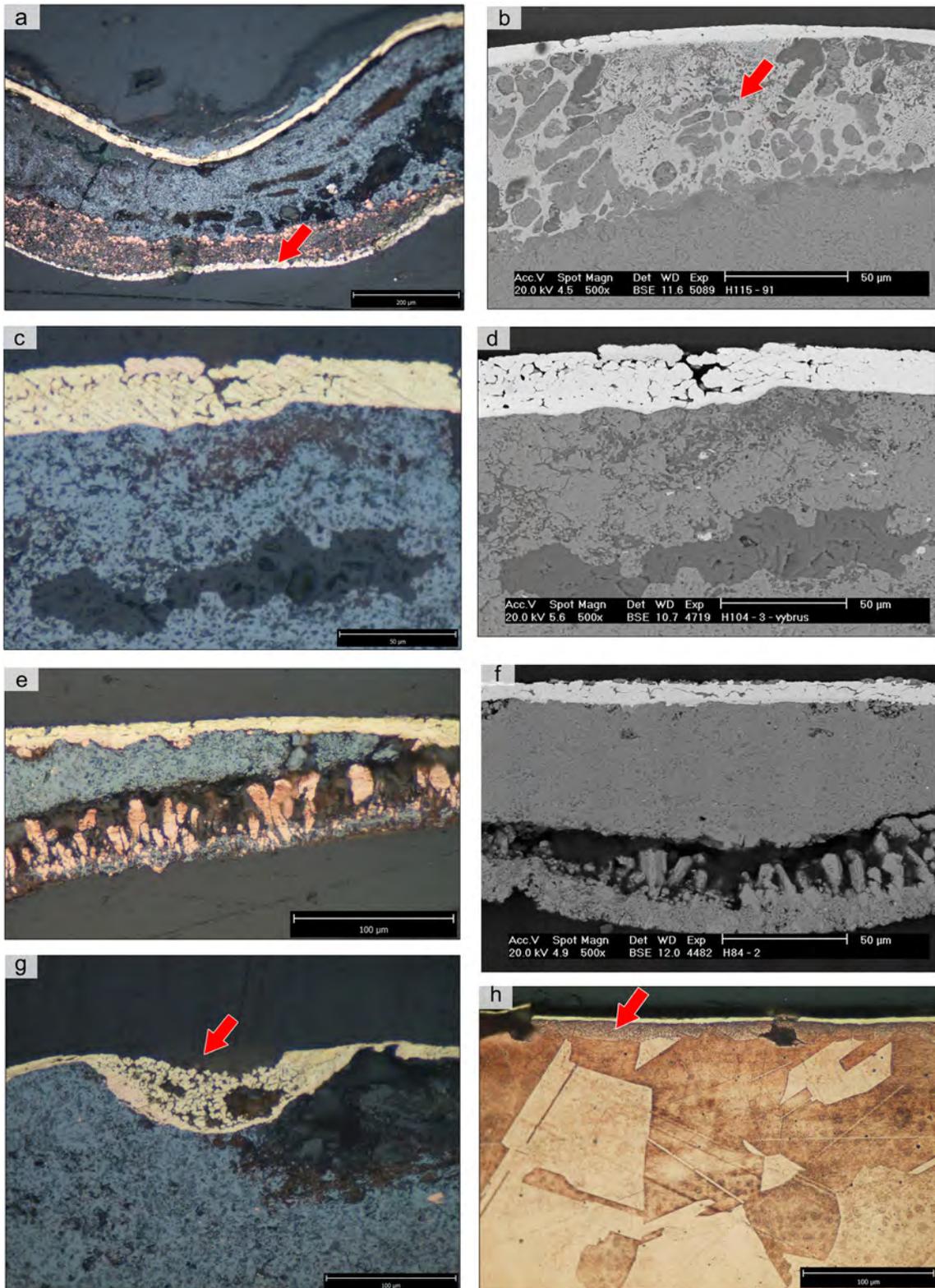


Fig. 11 Polished cross section of available fragments from hemispheres **a** *Gombik* H115-8. **b** Smeared solder under the gilding layer, *gombik* H115-9. **c** Thick and porous gilding layer on *gombik* H104-3. **d** Thick and porous gilding layer, *gombik* H104-3. **e** Gilding layer on almost

completely mineralised matrix, *gombik* H84-1. **f** Gilding layer on almost completely mineralised matrix, *gombik* H84-1. **g** Granular structure of the fire-gilded layer in a recess, *gombik* H108-2. **h** Polished and etched cross section, *gombik* 217/§

hardened surface. The composition of the hard Ag-Cu solder, closed to the eutectic composition, the quality of the gilding layer and the chasing work rank this *gombik* among the finest examined *gombiky*.

As evidenced from X-ray radiography and experimental work, the solder often smears along the joining areas (Figs. 7a, 7d and 13a). Two polished cross sections of the identical pair of *gombiky* H115-8 and H115-9 showed the presence of smeared solder on the internal wall (Fig. 11a) and under the gilding layer, the eutectic composition of which is clearly visible (Fig. 11b).

It is also important to note that variable gilding quality has been observed, revealing that the skills of goldsmiths varied. Fine gilding is characterised by a thin (a few μm), compact and well-burnished layer. Typical examples of this are revealed on *gombik* 217š (Fig. 11h) and H84-1 (Fig. 11e). This last one also has a thin gilded layer (from 7 to 10 μm), but is more porous and without an Ag content, which is unique in the set of examined *gombiky*. Usually, the gilding layer is well-bonded to the substrate due to an interdiffusion of the Au-Cu zone formed during heating. However, due to the impact of corrosion and past restoration treatment, as shown here for *gombik* 115-9 (Fig. 11a), the gilding can be locally poorly adherent due to the dissolution of the oxidised copper matrix in past restoration chemical bath.

In contrast to previous well-gilded *gombiky*, *gombik* H104-3 from Prague Castle (Fig. 11 c and d) is a poor imitation revealing no mastery of fire gilding. The gilding layer is very porous and very thick (from 19 to 29 μm). Another case of poor gilding quality is shown in Fig. 11g (*gombik* 108-2) revealing that a granular structure is often related to a recess in connection with chasing or decoration, i.e. parts that are poorly accessible for burnishing.

Gilding characterisation from FIB cross section

Two fine gilding layers, a very thin and a thicker one, were investigated on FIB cross sections. The results are shown in Fig. 12.

The thin gilding layer (*gombik* H115-9) in Fig. 12a is $\sim 2 \mu\text{m}$ thick and is very homogeneous and compact. As shown from the Au, Hg and Cu X-ray profiles (Fig. 12c), mercury is present in the gilded layer, even though caution must be applied in the exact distribution of this element within the gilding as regards the partial overlapping of the Hg and Au M alpha lines. An interfacial diffusion of copper from the substrate within the gold layer is also documented. The quality of the gilding is revealed by the good adherence on the copper substrate, even if this one exhibits internal corrosion (cuprous oxide in dark grey, Fig. 12a) characterised by variation in the Cu content as shown in Fig. 12c.

As regards the thicker gilding (*gombik* H84-1), the transversal examination revealed porous areas as well as some

disrupting lines at the top of the gold layer (Fig. 12b). This is a characteristic of a granular structure related to the incomplete flattened action of the initial gold grains during burnishing. However, very good adhesion of the gilded layer on uncorroded copper substrate is observed. Small porosities of around 0.5 μm are also documented in the gold layer. They are relative to the interdiffusion of gold with copper at the interface gilding/substrate, as confirmed in Fig. 12d by the X-ray profiles of Au and Cu.

Experimental archaeology

The manufacture of a replica of chased *gombik* 217š from Mikulčice by the professional goldsmith Ludmila Barčáková identified the different steps in the manufacture of chased gilded *gombiky* with a Type 1 body and suspension system. This is illustrated in Fig. 13.

First, the various components necessary to produce the *gombik* are individually fabricated. Hemispheres are produced by embossing disc blanks in a dapping block (Barčáková 2014, 327). Round sectioned wires are manufactured by drawing (Barčáková 2014, 317) and beaded wires are produced with a beading file (Barčáková 2014, 319). The loop, ring and clamp are produced by cutting bending, hammering and with drawn wires.

The upper hemisphere is then pierced and the two hemispheres joined together with a hard Ag-Cu solder. The solder smears around the joining area (Fig. 13a).

A chaser's pitch (Untracht 1982, 121) is then inserted inside the soldered hemispheres to support the walls of the *gombik* and prevent deformation during the chasing process. The decoration is then sketched with a blunt-ended liner and the globe fixed in a pitch bowl for chasing (Fig. 13a). Chasing is performed with several chasing tools, including tracer punches, planishing punches and dotting punches. The motifs are first underlined with a narrow punch (Fig. 13a). Then, a thicker chasing tool is used to deepen the lines. Planishing punches with a flat surface are then used to form a field around the motifs and flatten the surfaces (Fig. 13b). Finally, the dotted background is made with a dotting punch (Fig. 13c). When the chased decoration is achieved, the *gombik* is heated to melt down the chaser's pitch and facilitate its removal (Fig. 13d). The suspension system is then inserted in the pierced upper hemisphere (Fig. 13e) and soldered to the upper hemisphere (Fig. 13f).

Finally, the *gombik* is gilded by applying a paste of Au-Hg amalgam and then heated. In the end, the gilding layer is burnished with an agate stone. A replica of the fire gilding medieval process was reported in Chiavari et al. (2015) and will not be detailed here.

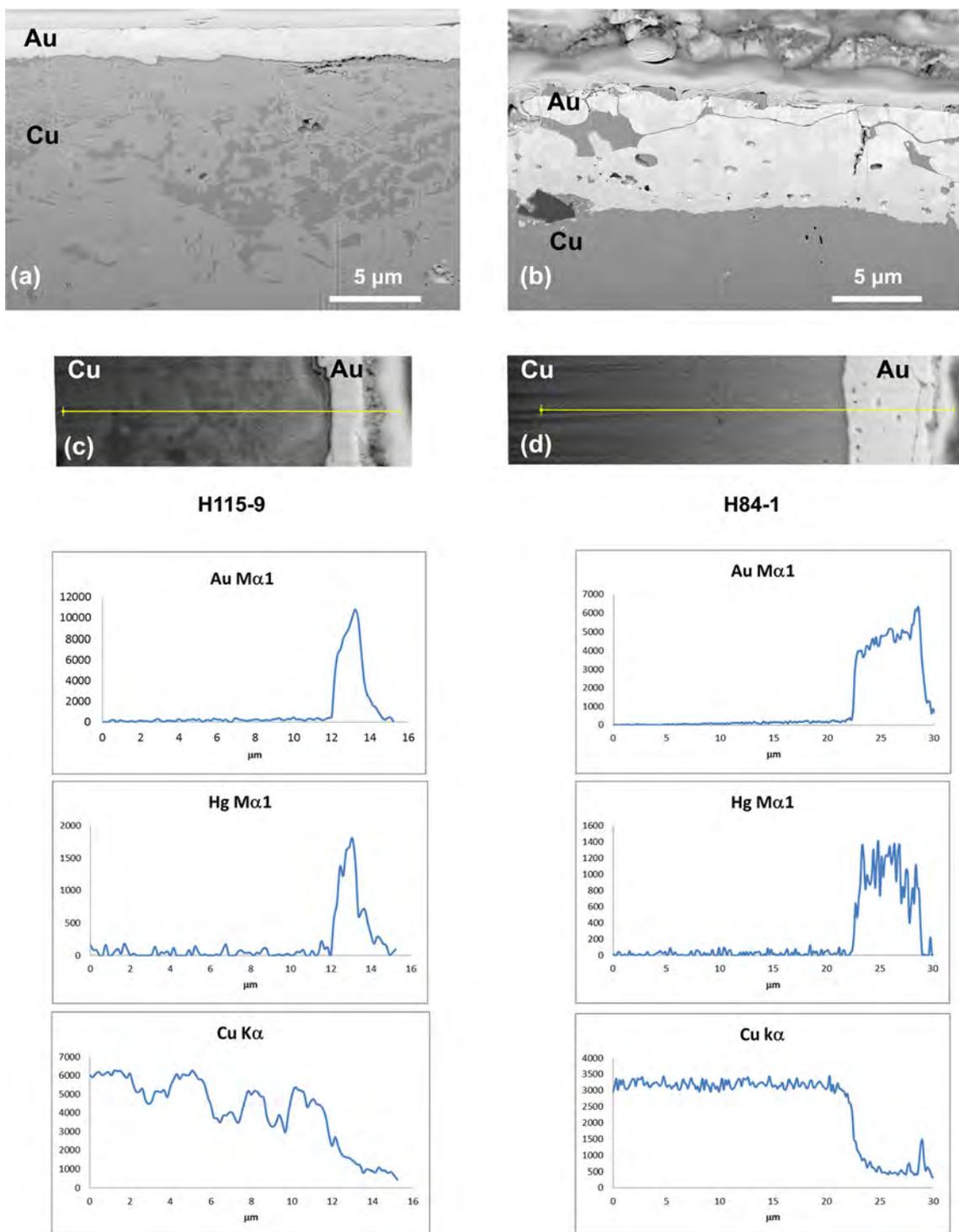


Fig. 12 Detailed observation of fire-gilded layer from FIB cross sections obtained on FEG-SEM and X-ray linescan profiles. **a–c** *Gombik* H115-9. **b–d** *Gombik* H84-1

Discussion

An approximate interval of time of only 20–80 years separates the gilded *gombiky* of Mikulčice from the *gombiky* of Prague Castle, but several technical variations can be pointed out:

The first noteworthy difference between the gilded *gombiky* from Mikulčice and Prague Castle is their size. A tendency to increase in size with time is observed for Mikulčice and clearly encountered for the *gombiky* at Prague Castle, which are larger.



Fig. 13 Manufacture of a replica of *gombik* 217/8 by the professional goldsmith Ludmila Barčáková. **a** Chasing of the palmette motive with a narrow chasing tool, note the smeared Ag-Cu hard solder around the joining area. **b** Working on the edge and plane surface with a planishing

tool. **c** Making the dotted background with a dotting punch. **d** Removal of the chaser's pitch. **e** Insertion of the suspension system in the pierced upper hemisphere. **f** Soldering of the suspension system on the upper hemisphere

Furthermore, an evolution towards a “standardisation” of the construction pattern can be observed. As regards the body construction, three types of construction are present for the *gombiky* of Mikulčice, while those of Prague Castle only have one (Type 1). Concerning the suspension system, in contrast with Moravian *gombiky*, the Type 1 system made of three elements prevails at Prague Castle. This is probably related to their overall larger size. In fact, the two-element suspension system (Type 2) is present in small- and occasionally in medium-sized *gombiky*.

Another noticeable difference is apparent in the profile of the wires used to manufacture the different components of the suspension system. In Mikulčice, beaded wire is often encountered to manufacture the rings, while at Prague Castle, round plain drawn wires are always used.

An evolution in chased motifs can also be followed. At Mikulčice, palmette motifs in a heart meander, arcades and columns predominate while geometric motifs, single leaves and lily buds, Christian motifs (cross, doves, peacocks, *Manus Dei*), in medallions, rhomboids and inverse single leaves or braids are typical at Prague Castle.

As regards material composition, the main categories of copper materials used to manufacture *gombiky* both from Mikulčice and Prague Castle are similar. The prevailing metal is essentially unalloyed copper and almost pure copper. However, no clear rules are observed which could have been

applied in the mounting. In fact, no evidence from this study was found between the quality of the copper used and the various mounting elements. As a matter of fact, no relationship between the typology of the gilded copper *gombiky* and the quality of copper used by goldsmiths can be established. It should be pointed out that a bronze alloy was used in only two cases (H 104-3 and H99-5) at Prague Castle. These two specimens are poor imitations of Great Moravian *gombiky*. In all other cases, the metal could be of high purity or, in contrast, with several metallic impurities (Sn, Pb, Ag, Sb) in relatively high amounts.

Great differences in the impurities of the different copper used are revealed. This has to be linked to probable different origins of copper raw materials. It could also indicate that the different *gombiky* components were manufactured without selecting a precise grade of copper. As a consequence, the raw copper materials could have been used as needed, piecemeal: the craftsmen being not totally able to control their copper source of supply.

While the solder used to join the different copper base components is an Ag-Cu hard solder in all cases, the Ag and Cu contents are found in different proportions. Here also no specific rule has been evidenced revealing that each craftsmen or workshop had their own recipe.

The method for gilding—fire gilding with mercury amalgam—is applied in all cases at both sites. With the

exception of H84-1 (Fig. 2Bd), all the gilding layers contain Cu and Ag in small amounts and the gilding composition is rather homogeneous.

The presence of *gombiky* with different manufacturing qualities is clearly visible on the two examined groups of gilded *gombiky*. In Moravia, the very fine *gombiky* from Mikulčice (76š, 110z, 127š, 129š, 190š and 220š) show perfect knowledge of the chosen material: pure or alloyed copper for hemispheres, a eutectic mixture of Ag-Cu for soldering, perfect skills in chasing (regularity, sketch lines) and gilding technique by fire gilding (thin and compact layer). On the contrary, some poor-quality specimens revealing local production by an unexperimented craftsmen are present (26z, 45z and 255š). Very fine pieces can also be observed in Bohemia at Prague Castle (H104-4, H108-2 and H119-9) revealing the work of very skilled goldsmiths: in performing chasing (the use of a drawing compass to sketch the motif, regular chased lines), fine fire gilding and proper choice of material and solder composition. Also, poor production at Prague Castle is characterised by coarse chasing work and the inadequate choice of material (H99-5, H104-3). It is thus evident that the *gombiky* at both Mikulčice and Prague Castle were produced by several goldsmiths and craftsmen with varying skill levels. On the one hand, very fine productions highlight the work of specialised goldsmiths with a long tradition in the art of chasing, and in fire gilding. On the other, coarse production reveals the production of craftsmen adopting new technologies with poor chasing work, a poor choice of material and a low quality of gilding.

The difference in quality of *gombiky* found at Mikulčice and Prague Castle shows that a process of acquisition of technology took place in Moravia and in Bohemia. The overall technologies are though very similar. It can be assumed that a transfer of technology certainly occurred between Moravia and Prague Castle. It is thus probable that craftsmen working for the Moravian elites moved to Prague after the fall of Great Moravia.

Furthermore, the fineness and quality of several of the *gombiky* as well as the depicted chased motifs could suggest that some of them were diplomatic gifts made to the elite of Mikulčice and Prague Castle. They may have been imported from the two major Christian kingdoms of that time, namely, the Byzantine and the Frankish empires, which were trying to expand their sphere of influence in Central Europe. The depicted chased motif of *Manus Dei* depicted on *gombiky* H115-8 from Prague Castle (Figs. 2Bb and 4c) is a strong symbol of theocracy potentially pointing to a Byzantine origin. Imported Byzantine metalwork was evidenced by comparative and technical studies on multi-component belt fittings and pierced lunate earrings found in Avar graves (Daim 2000; Bühler 2011). Their identification as Byzantine imports was confirmed by direct parallels with Byzantine artefacts. Although no chased gilded *gombiky* are known from the

Byzantine Empire so far, the applied techniques (multi-component artefacts, fire gilding, chasing, sketch marks, beaded wire) are very similar to Byzantine metalwork techniques. A Byzantine origin or influence cannot therefore be ruled out for the *gombiky* of the highest quality, especially if Christian motifs are represented (Maltese cross, *Manus Dei*, doves). Besides, Byzantine imports after the collapse of the Avar Khaganate are still documented in elite graves from Central Europe (Kouřil 2014, 367, 395; Eichert 2018). Prestigious goods and diplomatic gifts from the Byzantine Empire (Daim 2000, 79) were therefore still circulating in Central Europe. Local craftsmen may have used these imported ornaments as models and tried to imitate them, but the results were often coarse, since the manufacture of this kind of jewellery involved new manufacturing processes they had not yet mastered.

Conclusion

This research illustrates the diversity of the *gombiky* excavated at Mikulčice (Moravia) and in Prague Castle's Lumbe Garden cemetery (Bohemia) in terms of construction and material.

Different types of mounting are evidenced combining three types of body parts and two types of suspension systems. It also revealed that different qualities of copper materials were used, though without identified relationships with the chronology. This result suggests that the supply of copper materials was not precisely controlled by craftsmen who were using the copper raw materials as needed. Hard Ag-Cu solder and fire gilding were systematically identified on all *gombiky*.

A trend in the evolution of the construction appears comparing the Bohemian *gombiky* to those of Moravia: the assembly of the body and the suspension system seems to simplify over time. The objects reveal similar manufacturing processes involving a probable transfer of technological knowledge from Moravia to Bohemia.

However, local differences are also documented, pointing to diverse centres of production. A prevailing feature of the items found at both sites is the coexistence of finely produced objects by highly skilled and knowledgeable craftsmen alongside more coarsely manufactured imitations, indicating a less sophisticated understanding of materials, including soldering composition and decoration techniques. This phenomenon reveals a process of acquisition of new technologies probably initiated by the arrival of specialised jewellers in Great Moravia and later in Bohemia. Some of them could have been of Byzantine origin, accompanying Christian priests undertaking their missionary activities in the Moravian centres (Galuška 2014), or foreign itinerant experienced jewellers attracted by the emerging power centres at the cross roads of long-distance trade routes. Additionally, high quality specimens of *gombiky* could also have been imported as luxurious

goods or could have been diplomatic gifts from Byzantine emissaries that were subsequently used as models by local craftsmen as it was the case in the Avar period (Daim 2000; Bühler 2011).

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Supplementary Information

Table S1: Chemical composition of the components forming the suspension system on sub- surface analysis - EDS analysis on SEM (normalized wt% on the metallic elements – light elements are not reported but, except C, were considered in the ZAF quantification).

Locality	Number	Analyzed area	normalized composition [wt.%]						Remarks
			Cu	Sn	Pb	Ag	Sb	As	
Mikulčice	26/z	Loop	100	-	-	-	-	-	
		Clamp	100	-	-	-	-	-	
		Ring	97.6	-	2.4	-	-	-	
Mikulčice	45/z	Loop	100	-	-	-	-	-	
		Clamp	100	-	-	-	-	-	
Mikulčice	76/s	Loop	100	-	-	-	-	-	corroded (oxide)
Mikulčice	110/z	Loop, cor.	93.5	5	-	1.5	-	-	highly corroded (oxide)
		Clamp, cor.	66.6	15.4	4.5	2.2	11.3	-	highly corroded (oxide)
Mikulčice	115/z	Loop	93.2	2.8	4	-	-	-	
		Ring	100	-	-	-	-	-	
Mikulčice	117/z	Loop	97.6	1.4	1	-	-	-	
		Clamp	97.1	-	-	2.9	-	-	
		Ring	95.7	-	-	4.3	-	-	
Mikulčice	129/s	Loop	97.8	2.2	-	-	-	-	highly corroded (oxide)
		Clamp	96.3	1.6	2.1	-	-	-	corroded (oxide)
		Ring	96.7	1.6	1.7	-	-	-	highly corroded (oxide)
Mikulčice	190/s	Loop	100	-	-	-	-	-	corroded (oxide)
		Clamp	100	-	-	-	-	-	corroded (oxide)
		Ring	91.6	1.4	3.7	3.3	-	-	corroded (oxide)
Mikulčice	217/s	Loop	96.2	2.1	1.7	-	-	-	slightly corroded (oxide)
		Clamp	94.2	3.8	2	-	-	-	corroded (oxide)
Mikulčice	220/s	Loop	-	-	-	-	-	-	
		Clamp	96.5	3.5	-	-	-	-	
Mikulčice	255/s	Loop	98.7	1.3	-	-	-	-	
		Clamp	97.1	1	-	1.9	-	-	
		Ring	96.3	1.8	-	1.9	-	-	
Prague Castle	H84-1	Loop	96.7	-	3.3	-	-	-	highly corroded (oxide)
		Clamp	97.7	-	2.3	-	-	-	highly corroded (oxide)
		Ring	96.5	-	3.5	-	-	-	highly corroded (oxide)
Prague Castle	H 104-3	Loop	-	-	-	-	-	-	
		Clamp	96.9	3.1	-	-	-	-	
		Ring	-	-	-	-	-	-	
Prague Castle	H104-4	Loop	95.7	4.3	-	-	-	-	highly corroded (oxide)
		Clamp, cor.	73.2	22.2	4.2	-	0.2	0.2	
		Ring	94.1	4.6	-	-	1.3	-	highly corroded (oxide)
Prague Castle	H 108-2	Loop	98.3	1.7	-	-	-	-	highly corroded (oxide)
		Clamp	95.8	2.8	-	1.4	-	-	
		Ring	96.4	2.1	-	1.5	-	-	highly corroded (oxide)
Prague Castle	H 115-8	Loop	96.6	3.4	-	-	-	-	highly corroded (oxide)
	(H 115-9)	Clamp	100	-	-	-	-	-	corroded (oxide)
	H 115-8	Ring	96.1	3.9	-	-	-	-	highly corroded (oxide)