# ARCHAEOMETRIC INVESTIGATION OF THE KUNÁGOTA-SWORD – A CASE STUDY

## A KUNÁGOTAI KARD ARCHEOMETRIAI VIZSGÁLATA – ESETTANULMÁNY•

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### *Abstract*

*Among the Early Medieval double-edged swords, excavated in the Carpathian Basin, there are a few which probably have Byzantine origin. The most unique piece of this small but significant group of weapons was unearthed at Kunágota, Southern Hungary. The sword, which has a special sword-guard made of bronze, has been examined by the experts of the Archaeometallurgical Research Group of the University of Miskolc with optical microscopy, SEM-EDS, ED-XRF, and microhardness tests. The primary aim was to study the microstructure of the blade and guard. There was also an important objective of the investigations to explore the possible manufacturing technology.*

*Due to the metallographic examination, it was possible to reconstruct the manufacturing process of the Kunágota-sword. Three samples were taken from the sword for metallographic examination, two of them (K1A and K1B) were collected from the sword-guard and one (K2) from the blade. To summarise the results, it can be established that the basic material of the Kunágota-sword guard is a heterogeneous copper-alloy with high lead content. In the core area of the blade sample a very fine pearlitic structure can be seen. Towards the edge of the blade, a martensitic microstructure can be observed which probably proves a kind of heat treatment of the sword. With the aid of archaeometric investigations, our knowledge related to Byzantine swords can be deepened. Further interesting results can be gained by comparing with the characteristics of other Byzantine swords found of the Carpathian Basin.*

### *Kivonat*

*A Kárpát-medencében előkerült kora középkori kétélű kardok között több olyat lelet is található, amelyek esetében feltételezhető a bizánci eredet. A kis számú, de jelentős csoportot képező fegyverek egyik reprezentatív darabja a Kunágotán előkerült kétélű kard, melyen elsőként a Miskolci Egyetem Archeometallurgiai Kutatócsoportjának munkatársai végeztek komplex archeometriai, metallográfiai vizsgálatokat (OM, SEM-EDS, ED-XRF, keménységmérés). A vizsgálat elsődleges célja nemcsak a lelet anyagszerkezeti tulajdonságainak tanulmányozása volt, hanem a kard feltételezhető készítési technikájának megismerése is.*

*A metallográfiai vizsgálatok elvégzéséhez összesen három mintát vágtunk ki a kardból, kettőt a markolatszerelékből (K1A és K1B) és egyet a fegyver pengéjéből (K2). Az eredményeket összegezve megállapítható, hogy a kunágotai kard markolatszerelék alapanyaga heterogén szerkezetű, markáns ólomtartalmú rézötvözet. A pengéből kimetszett minta belső részén finom perlites szövetelem figyelhető meg, az él felé haladva pedig megjelenik a martenzites szövet, amely esetében feltételezhető, hogy a kardot gyorsan hűtötték le, valószínűleg hőkezelték. Az archeometriai vizsgálatok segítségével jelentősen bővülhetnek a bizánci kardokhoz kapcsolódó eddigi ismereteink. A későbbiekben pedig az egyes leletek összehasonlítása is érdekes eredményeket hozhat.*

KEYWORDS: BYZANTIUM, SWORD, ARCHAEOMETALLURGY, OPTICAL MICROSCOPY, SEM

KULCSSZAVAK: BIZÁNC, KARD, ARCHEOMETALLURGIA, OPTIKAI MIKROSZKÓP, SEM

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## *Introduction*

The Kunágota-sword (currently preserved in the Móra Ferenc Museum, Szeged, Hungary; Bakay 1965; Kovács 1994-1995) is a unique piece of the small but significant group of weapons, called the Byzantine originated swords. These artefacts, which presumably have a Byzantine origin, are very rare and their most significant characteristic is the copper-based alloy or iron sword-guard.

Although, plenty of examinations were carried out on Early Medieval double-edged swords in the last decades (Geibig 1991; Williams 2012; Košta & Hošek 2014; Košta & Hošek 2021), as far as we know, none of these unique swords of the Carpathian Basin were examined by metallographic methods. Considering this fact, our major aim was to study the characteristics of the microstructure in the blade and sword-guard. Besides this, our goal was also to explore the traces of processing in order to find out the possible manufacturing technique.

The Kunágota-sword was examined by the experts of the Archaeometallurgical Research Group of the University of Miskolc in 2020 within the frames of a multiannual project in collaboration with the Pázmány Péter Catholic University. The primary objective of this project is the archaeological and archaeometric examination of the double-edged swords found in the 10-11$^{th}$ century Carpathian Basin.

## *The Byzantine originated swords and the archaeological background of the Kunágota-sword*

The products of the Byzantine Empire are frequent in the Carpathian Basin since the late antiquity. Moreover, Byzantium, as one of the most powerful centres of the Middle Ages played an important role in the cultural, political and commercial history of Europe and, of course, of the early Hungarians which endured until the 10$^{th}$ century. Most of the Byzantine artefacts were coins, jewellery or luxury textiles (Mesterházy 1990; Mesterházy 1991; Mesterházy 1993), while a smaller part of these products were weapons like the Kunágota-sword.

Developing a general typology of the Byzantine weapons and swords is a difficult question because there are only a few artefacts available (Kolias 1988). In spite of this fact, there are some attempts for classification based on the medieval manuscripts, frescoes, and the morphological features of the Byzantine archaeological artefacts (Grotowski 2010; Fehér 2001; Kiss 1987; Yotov 2011; Baranov 2015). In relation to the Kunágota-sword, it is important to emphasize that Valerij Yotov, a Bulgarian researcher, found some examples with very similar morphological attributes to the Kunágota-sword. Based on his research, he named those swords as "Kunágota-type" (Yotov 2011; 2012; 2014).

Among the Hungarian researchers, Attila Kiss was the first who summarised the data of these weapons (Kiss 1987) and assumed their Byzantine origin. According to his article, the swords with Byzantine origin in the Carpathian Basin are the following: Kunágota (Hungary), dated to 10$^{th}$ century; Aradac (hung. Aradi, Serbia), dated to the 7$^{th}$ century; Cierny Brod (hung. Vízkelet, Slovakia), dated to the late 8$^{th}$–early 9$^{th}$ century; and Sfântu Gheorghe (hung. Sepsiszentgyörgy, Romania), dated to the 10$^{th}$ century (Kiss 1987; Gáll 2013). Further swords with Byzantine origin were unearthed at Kölked-Feketekapu (Hungary; 7$^{th}$ century) and Garabonc-Ófalu (Hungary; dated to the 9$^{th}$ century) (Eger 2014).

The examined sword had been found in a destroyed grave (No. 1) of the Kunágota cemetery and the first study about this weapon was published by Ferenc Móra in 1926, former director of the museum at Szeged. Beside the sword, further artefacts were unearthed from the grave: a pair of stirrups, two earrings, and two coins of Romanos Lakopenos. Based on previous studies, the grave was dated to the 10$^{th}$ century (Móra 1926; Kovács 1990).

## *Methods of analysis*

Altogether three samples were taken from the sword for metallographic examination, two of them (K1A and K1B) were collected from the sword-guard and one from the sword blade. To facilitate the easy restoration and to avoid a more serious damage, sample K1A was cut from an originally damaged part of the sword-guard. Sample K1B was taken from the narrower part of the sword-guard from the side of the cutting edge. Sample K2 was cut from the middle of the left side of the blade (**Fig. 1.**).

Before the microscopic examination, the samples were embedded in epoxy-resin. After the process of grinding, the surface was etched (K1A and B: 1 g Potassium bichromate + 4 ml sulphuric acid + 50 ml distilled water; in the case of sample K2: 2% Nital etching, which is a mixture of 2% nitric acid and 98% methanol), the microstructure of the samples was examined with a Zeiss Stereo Axio Imager optical microscope (max. 1000X magnification) equipped with a computer-controlled stage featuring mosaic imaging for the examination of the whole surface, and a Zeiss EVO MA10 scanning electron microscope equipped with EDAX energy dispersive spectroscopy (SEM-EDS) to perform elemental analysis. Sample K1B was investigated without epoxy resin embedding for the sake of easy restoration. It was examined only on a small, gently polished part by electron microscope.

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**Fig. 1.:** The places of sampling on the sword (sample K1A, K1B and K2)
**1. ábra:** Mintavételi helyek a kardon (K1A; K1B és K2)

Furthermore, both side of the sword-guard (one point on each side) had been measured by handheld energy dispersive X-ray fluorescence spectrometer (ED-XRF; Oxford Instrument X-MET8000 Expert handheld portable spectrometer; using Alloy FP method; with 30 second measurement time). The ED-XRF spectrometer is perfectly suitable for the fast and non-destructive chemical analysis. Fundamental parameter method is abbreviated to 'FP' and applied a complex mathematical analysis of the X-ray fluorescence spectrum to calculate the concentrations of elements in the sample. It is less accurate than a similar empirical method, but it is accurate over a much wider range of element concentrations. For metals with inherently unknown composition, such as historical finds, it is recommended to use this method. When using Alloy FP method, the common elements are measured, but the analysis does not include the light elements (e.g., Mg, Al and Si). The concentration range for each element is from 0% to 100%.

To present the EDS and XRF measurement data, no table was deliberately edited since the position, quality and purpose of the examinations by the two methods are different, thus their results cannot be directly compared.

## *Archaeometric investigation of the Kunágota-sword*

### The sword-guard

In the first cycle of data gathering, XRF measurements were carried out on the surface of both sides of the sword-guard where significant tin and lead contents were found in the copper-alloy. Nevertheless, it is important to emphasize that XRF measured those compounds on the surface which could have changed over a long time of the corrosion of copper. For instance, the tin or lead could have segregated on the surface. The results of the XRF measurements are the following: Cu: 81.82 wt% and 78.94 wt%; Sn: 7.90 wt% and 9.59 wt%; Pb: 9.34 wt% and 10.42 wt%; Fe: 0.24 wt% and 0.37 wt%; As: 0.32 wt% and 0.35 wt%; Ni: 0.14 wt% and 0.12wt %, respectively.

In **Figure 2**, the casted microstructure of sample K1A can be seen. There are two size ranges of segregation. The microsegregation can be observed in large quantities as copper-alloy dendrites and another embedding phase. At the same time, macrosegregation appears as a pattern in the core which almost divided the sample into two parts. This phenomenon was caused by the fast cooling and the rapid crystallization of the narrow part of the artefact (**Fig. 2.**). Presumably, the crystallization began at the wall of the mould and propagated to the inside of the artefact where the latest crystallization happened. At the edge of the sample, the material solidified with lower concentration whereas the alloys segregated in the cross section of the sample.

The dendritic microstructure and lead drops between the dendrite arms can be seen in the higher magnification SEM-BSE image of sample K1A (**Fig. 3.**). The average chemical composition of the material is 19.37 wt% Pb, 2.88 wt% Sn, and 77.75 wt% copper, so it shows a quite high lead content. At the edges of the sample, lead oxide layer was formed in large quantities. This oxide layer contains 9.34 wt% O, 70.91 wt% Pb, 4.89 wt% Sn and 14.87 wt% Cu. The lead segregation is closely related to the corrosion of copper.

Interestingly, the XRF measurements detected just a little more lead than tin in both points on the surface which was only the half of the internal lead content. At the same time, the tin content of the inner part was only 2–5 wt%, which can be regarded as basic tin content of the alloy. Quantitatively, this measured content is a borderline case (Davis 2001, 14). Thus, the tin both could originate from the lead ore, and may have used intentionally as an alloy during the manufacturing process. Based on the examination of the compound of the two components with copper, it can be stated that the mixture is susceptible to strong segregation.

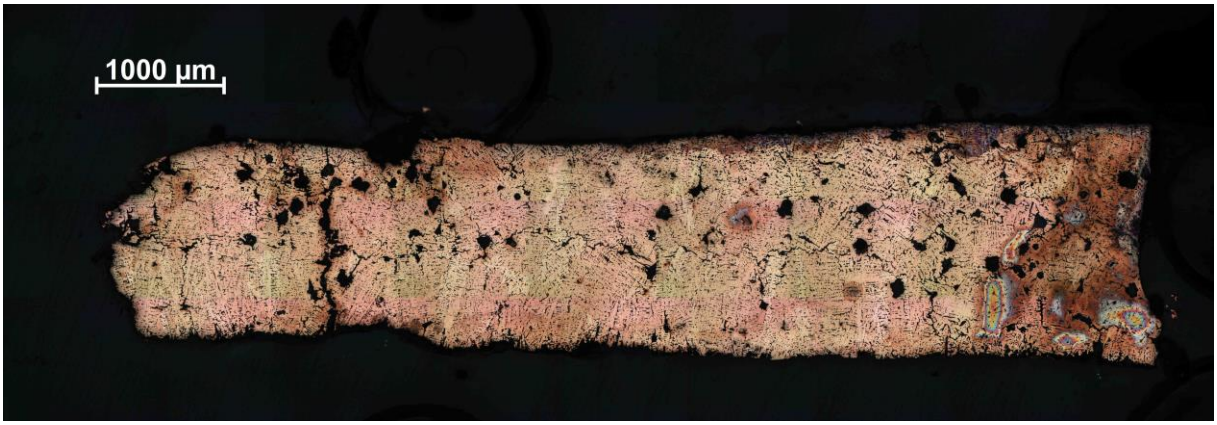


**Fig. 2.:** OM image of microstructure of sample K1A

**2. ábra:** A K1A minta szövetszerkezetéről készült optikai mikroszkópos felvétel.

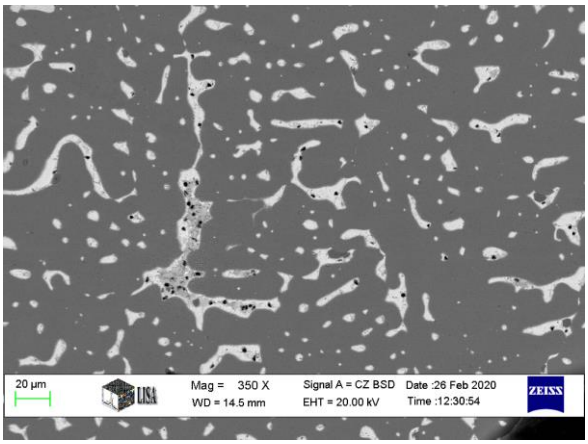


**Fig. 3.:** SEM-BSE image of the dendritic microstructure of sample K1A at a higher magnification

**3. ábra:** Nagyobb nagyítású SEM-BSE felvétel a K1A minta dendrites szerkezetéről

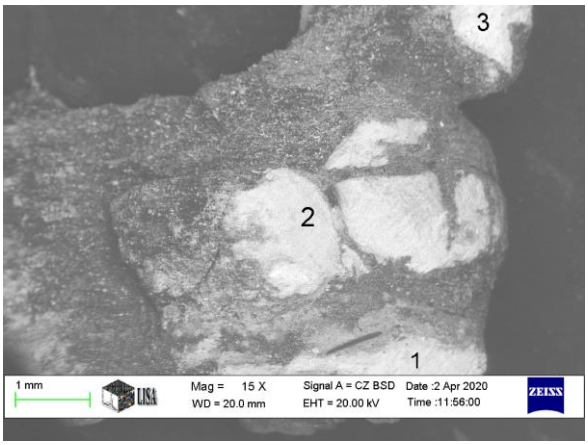


**Fig. 4.:** SEM-BSE image of sample K1B with heterogeneous microstructure at a lower magnification

**4. ábra:** A K1B minta heterogén szövetszerkezetéről készült kis nagyítású SEM-BSE felvétel

During the examination of sample K1B, an interesting heterogeneous part of the material could be observed. In **Figure 4**, Point 1 shows copper with 4.78 wt% tin content, but without any significant lead content. However, at Point 2, a 25.94 wt% tin content and no lead were detected by EDS. The chemical composition of Point 3 showed high copper content. Based on the composition and microstructure, it is concluded that a solder with tin content can be observed in this sample which can be interpreted as a repairing of a possible damage with a small material replacement fixed by soldering. In this case, Point 1 may represent the material of the replacement, Point 2 the solder and Point 3 the original alloy of the sword-guard.

**The blade**

Sample K2 was cut from the cross-section of the blade (**Fig. 1.**). Unfortunately, the corroded blade was restored from several pieces thus, the blade could have broken easily in case of a deeper cut. Considering the bad condition of the weapon, sample K2 was cut from the first quarter of the blade, where enough metal could be found for the examination.

The entirely corroded edge of the blade can be seen in the mosaic image of **Figure 5**. There can be found only iron oxide here, therefore the edge of sample K2 is unsuitable for metallographic examination. Beside the corroded edge, the microstructure of the wooden scabbard can also be seen (**Fig. 5.**). In the higher magnification SEM-BSE image of the remains of the wooden scabbard, the cross-section of the cut of the water- and nutrient supplier tissues can be observed (**Fig. 6.**).

Based on the microscopy images, very fine pearlite structure can be observed on the inner part of sample K2 (**Fig. 7/1-2**). Pearlite is the eutectoid composition of ferrite (body-centered cubic alpha

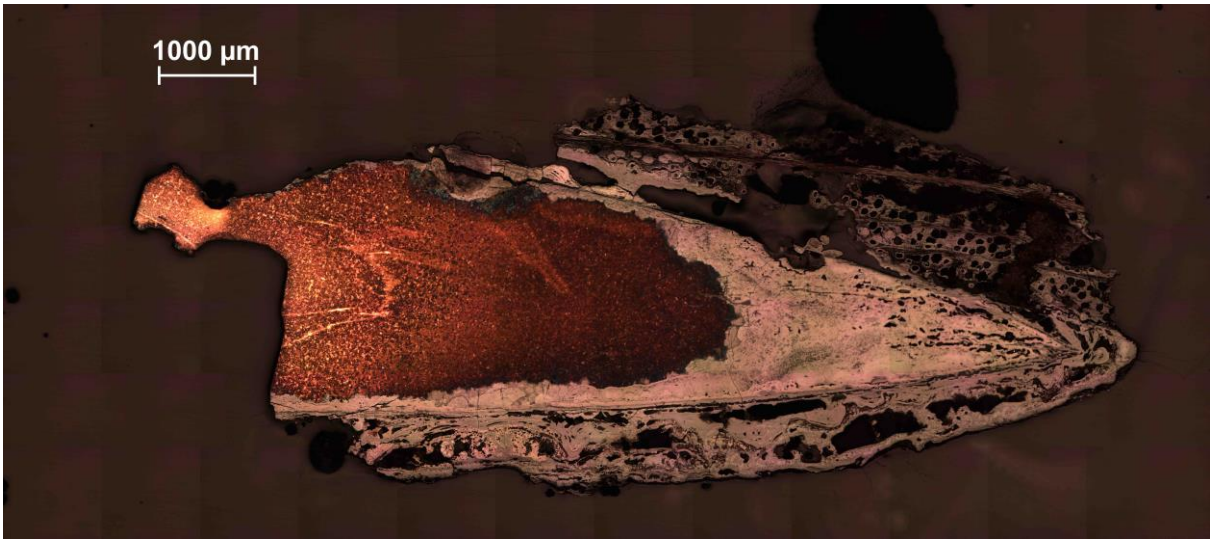


**Fig. 5.:** Mosaic image of sample K2 (OM image)
**5. ábra:** A K2 mintáról készült mozaikfelvétel (optikai mikroszkópos felvétel)

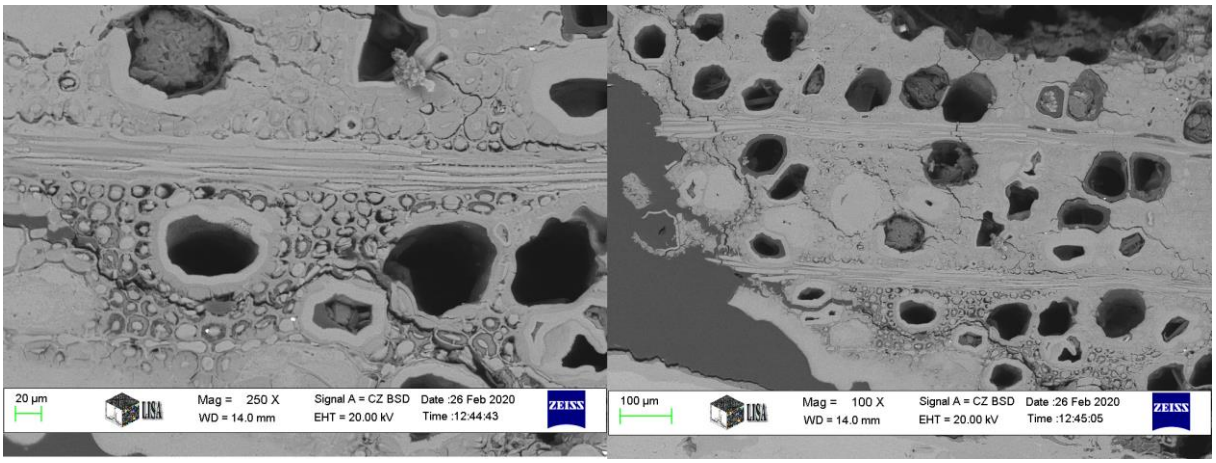


**Fig. 6.:** The remains of the wooden scabbard of the sword (SEM-BSE images)
**6. ábra:** A kard egykori fatokjának maradványai (SEM-BSE felvételek)

iron with minimal carbon content which is ductile and tough) and cementite (iron carbide ($Fe_3C$) with 6.67 wt% C content, a very hard and brittle material) which has a lamellar microstructure. Practically, this structure is the decomposition product of the austenite (face-centred cubic gamma iron which is also ductile and tough) during the slow cooling.

Towards the edge of blade, another very fine microstructure can be observed, which cannot be recognized in the OM images (**Fig. 7/3-4**). In this regard, the SEM-BSE images showed hard bainitic-martensitic structure which may be the consequence of heat treatment (**Fig. 8.**).

The bainitic-martensitic structure formed under non-equilibrium condition during the cooling of the austenite. During intensive cooling, the temperature of austenite is relatively rapidly reduced to such a low level where ferrite grains form by oriented growing. The ferrite is able to dissolve much less carbon than austenite, so that austenite, which is present near the growing ferrite, becomes increasingly enriched in carbon. This is possible because the growth rate of ferrite grains is faster than the diffusion rate of carbon. When the carbon content of the austenite around the growing ferrite reaches the limit of solubility, small cementite particles appear in it, which is called upper bainite. During the formation of lower bainite, as the ferrite grows, the carbon atoms cannot be transferred from the ferrite to the austenite in sufficient amounts. The carbon then reaches its solubility limit in the growing ferrite, which is much smaller than in the case of austenite, so that fine dispersed carbide

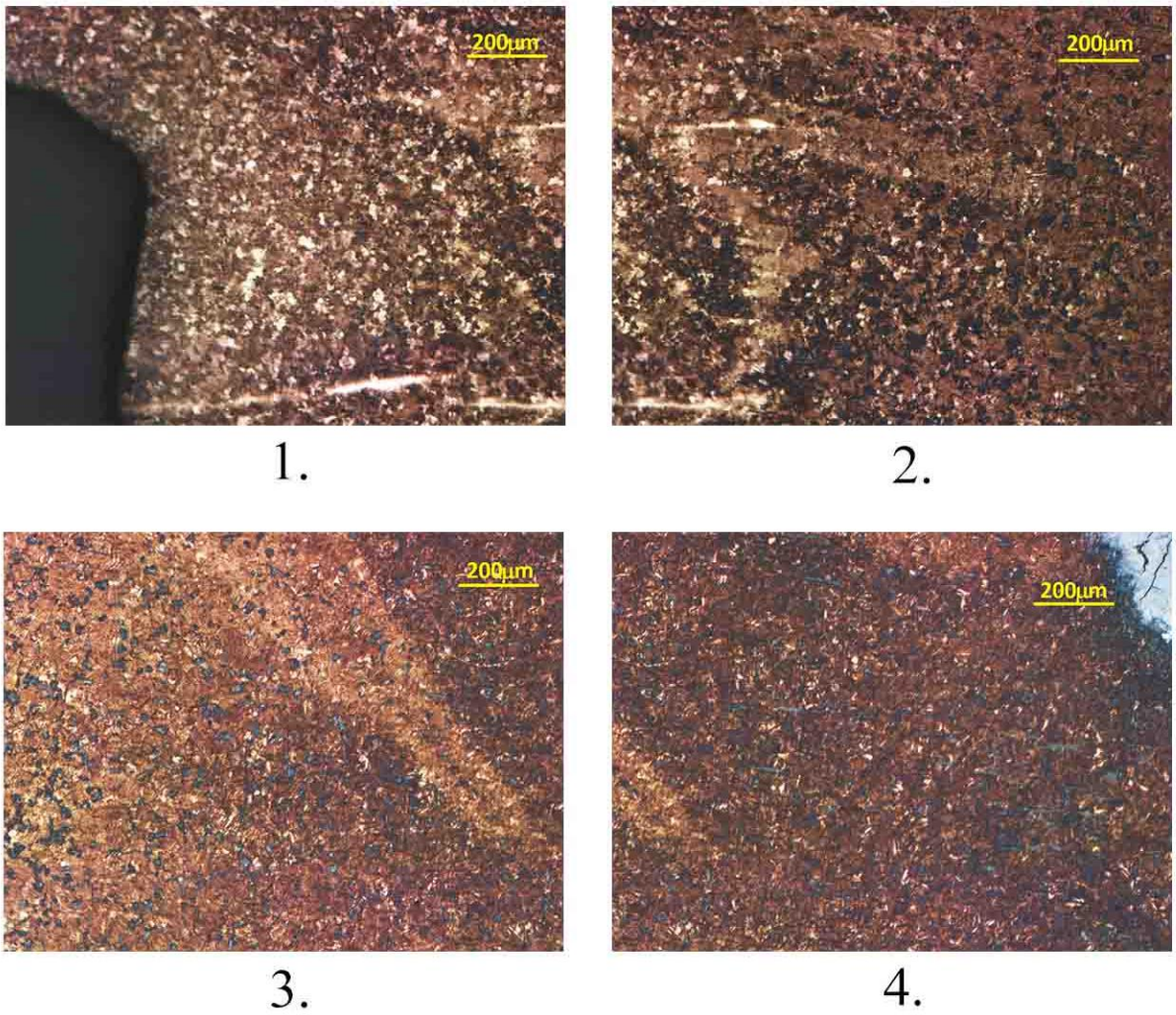


**Fig. 7.:** OM images about the microstructure of the blade, from the cross-section to the edge (1 → 4)

**7. ábra:** A penge mikroszerkezetéről készült optikai mikroszkópos felvételek a minta belsejétől az él felé haladva (1→4)

grains appear in the growing ferrite needles. This requires even faster cooling.

The extreme case of the process is when the ferrite grains grow such that the face-centred cubic lattice is transformed into a body-centred cubic lattice over the extent of several lattice planes. In this case, a coherent phase boundary is formed which is called martensitic transformation and the result is the martensitic microstructure that forms during heat treatment. This structural change increases the hardness of the material, but its toughness is not reduced to the same extent as in case of high-carbon and cementite-rich irons.

Several parts of the sample were tested for microhardness by Vickers-method with 1 kg compressive force till 10 seconds pressure time. During the measurement of the hardness, 429 HV1 was measured on the inner pearlitic part of sample K2, which is the characteristic hardness of the fine pearlite. 654 HV1 was measured nearby the edge which is the hardness of the martensitic structure. The results of microhardness tests confirm the above-mentioned observations.

A few flattened and deformed inclusions can be found in the microstructure of the sample. This flattened form is the consequences of intensive metal forming which was necessary to the shaping of the cross-section of the blade. The local chemical composition of a slag (**Fig. 9.** Point 1), found in pearlitic microstructure, was 26.77 wt% O, 1.23 wt% Mg, 5.28 wt% Al, 42.95 wt% Si, 5.10 wt% K, 11.14 wt% Ca, 3.58 wt% Mn, 3.96 wt% Fe. This slag inclusion with remarkably low iron content is Ca-Al-silicate. Charcoal ash may have contributed to the relatively high K content, but P was not detected. This suggests that these slag inclusions were formed during the process of smithing.

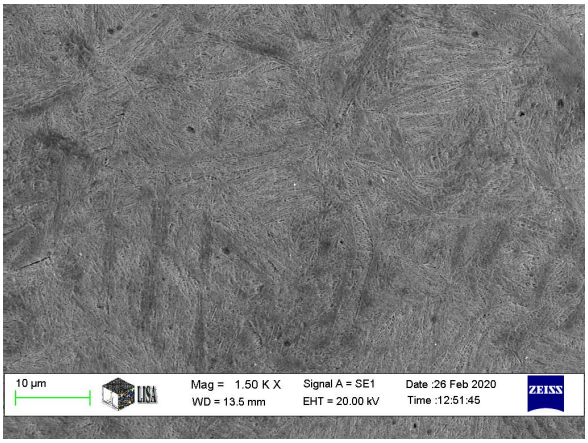


**Fig. 8.:** SEM-SE image of the bainitic-martensitic microstructure of the blade
**8. ábra:** A penge bainites-martenzites szerkezetéről készült SEM-SE felvétel

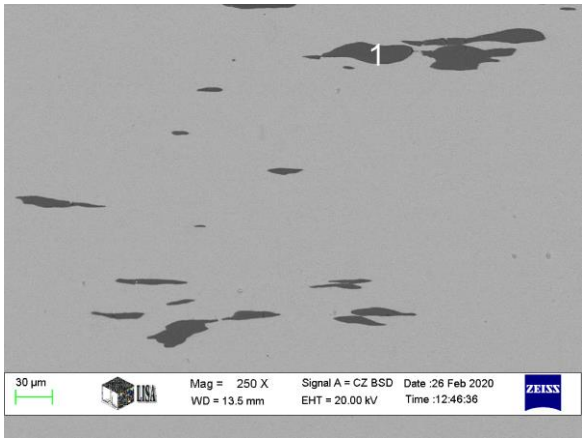


**Fig. 9.:** SEM-BSE image of slag inclusions (1) prolonged by the direction of forming
**9. ábra:** Az alakítás iránya szerint elnyújtott formájú salakzárványok (1) SEM-BSE felvétele

## *Conclusion*

Summarising the results of the examination, it was possible to reconstruct the manufacturing steps of the Kunágota-sword. In the case of the sword-guard, it can be established that the basic material of the sword-guard, namely the bronze sheet, was casted. Traces of additional forming after the casting process cannot be observed which is understandable because of the high lead content. The lead increases the castability of the material, but it makes that more brittle, thus, the bronze sheet rich in lead could have broken easily (Renfrew & Bahn 2005, 323; Hauptmann 2021, 384).

Theoretically, it is possible, that the bronze-guard was casted in two different parts and was connected by tin soldering. But technically it is more justified that the guard was casted as one piece in a two-part mould with an inner core, especially when we consider the good castability of this material with high lead content. In **Figure 3**, the traces of a minor contemporary damage repaired with a material replacement can be seen (Point 1 – replacement material, Point 2 – solder, Point 3 – basic material).

After the examination of the blade, we can state that it does not have layered structure and was made from a piece of a single basic material. As it is mentioned above, the microstructure of the blade showed the traces of some kind of hardening which can be recognised only at the edge of the sword. It means that the blade was not hardened entirely, the smith might have broken the quenching before the completion of the cooling. This treatment resulted in a very fine pearlitic microstructure in the inner zone. But this masterstroke was not a coincidence which refers to the skilfulness of the blacksmith. If the craftsmen had continued the hardening process, the whole cross-section of the blade would have become hard and less tough, which could have broken during the usage of the weapon.

Nevertheless, it is important to highlight that this "quench-like cooling" is not equal with the full-quenching followed by tempering. The latter technique was not usual before the 15$^{th}$ century. In this method, the artefact is cooled so rapidly that only martensite is formed in the microstructure which makes the material brittle and hard. Generally, the so-called "slack-quenching" which results in a harder cutting-edge and a softer core was employed in the Early Middle Ages. In this case, the rate of cooling is slower and beside the martensite, pearlite and bainite are also formed. Thus, the material become less hard, but in the same time, less brittle (Williams 2003, 12; Williams 2012, 22). However, we could not observe the whole microstructure of the weapon because only one sample was cut from the blade. Considering this fact, we can only assume that the further parts of the blade contain also bainitic-martensitic microstructure.

As far as we know, the Byzantine originated swords of the Carpathian Basin were not examined with metallographic methods. Moreover, the archaeometric-archaeometallurgical investigations of the double-edged swords of 10-11$^{th}$ century Carpathian Basin are in the early phase. Due to the lack of complex studies, it is not possible to compare the manufacture technique of the Kunágota-sword with other double-edged weapons from this territory, especially with Byzantine originated swords.

According to our preliminary results, it can be established that the Kunágota-sword is unique. On the one hand, it has special morphological features. On the other hand, it shows an interesting microstructure. Among the examined artefacts, besides the Kunágota-sword, the bainitic-

martensitic structure was observed only in the case of a sabre-hilted sword from Kiskundorozsma (Bakay 1965; Bálint 1963; Kovács 1994-1995). Furthermore, the occurrence of martensite at the cutting and throwing weapons of the Carpathian Basin is not common in the Early Middle Ages which is confirmed by the results of the archaeometallurgical studies of Hungarian sabres dated to 9–10th century. Among the four examined sabres, the presence of martensite was observed only in one case (Sabre, unknown site, Inv. No.: 58.193.1, preserved in Herman Ottó Museum, Miskolc, Hungary; Haramza & Török 2021).

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