Tradecraft of the Avars’ metalworking – manufacturing of iron axes and a special multi-metallic method used for belt accessories

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ABSTRACT

Metallographic analyses were performed on several types of early medieval iron axes (hammers) and on a piece of a belt set, found in Hungary, using optical and SEM-EDS microscopes. The examinations were focusing on defining structural constituents, determining their distribution and grain size. Inclusions were also investigated. On the basis of the result traces and characteristics of different technological methods of forging could have been detected. The examined axes were supposedly forged from a piece of inhomogeneous iron without folding, kept at high temperature for a longer period and forged the edges multiple times, not intensely. The belt accessories were covered by an iron oxide layer, however, the complex investigation revealed that these belt ornaments are made of various metals. Sandwich-type iron-tin plates, thin iron wires as well as brass and bronze plates have been used in the product. We were able to reconstruct the steps of the production process.

Introduction

The empire of Avars was a significant military power in the Carpathian Basin between the 6th and 9th centuries. Metal finds that have been found, at archaeological sites of Avar graves and settlements, are remarkable signs of iron and bronze cultures. Pannonian workshop sites from the second half of the Avar period prove that considerable ironworking activities were carried out in the Avar Empire (Gömöri, 2000: 234-240.). In the recent years, numbers of selected iron tools of everyday life (knives, nails, needles, etc.) from Avar settlements and metallurgical workshops were examined by the Archaeometallurgical Research Group of University of Miskolc (ARGUM) (Török, et al. 2015).

Nevertheless, up to the present, only one of the Avar age axes – an L-shaped cleaver – has been analysed (Piaskowski, 1974: 121-122, 128), so we decided to investigate more types and subtypes: a hammer axe, a T-shaped cleaver and a double headed war hammer.

Another important part of this study is a detailed metallographic analysis of a piece of belt-set called Kölked-Feketekapu. The name of these types of belt sets is originated back to the name of the area of the cemeteries where most of those have been found. A belt set of a blacksmith from the Grave 80 of Kölked-Feketekapu B was demonstrated by Orsolya Heinrich-Tamáska (2006: 22). Attila Kiss dated Grave 80 which was filled up with goldsmith and blacksmith tools from between the end of the 6th century and the first third of the 7th century (Kiss, 2001: 335, 345). He dated the belt set type to the early Avar age, saying that all of the datable parallels of these belt sets are made with similar techniques came from this period (Kiss, 1996: 213). Heinrich-Tamáska drew attention to the fact that the Kölked-Feketekapu type belt sets could be only dated from the second third of the 7th century, because of their analogy with the multi-part belt sets with silver inlay (Tauschierung) have been classified into the A form group of the horizon (Zeitschicht) 3 of Rainer Christlein (Christlein, 1966: 49; Heinrich-Tamáska, 2006: 22). Beyond the formal matching, she proves that the close relationship between the two types is the fact that they were basically made from iron, and their distribution was restricted to East Pannonia and the few parallels outside the Carpathian Basin which are all known from Germanic cemeteries of South–Germany (Heinrich-Tamáska, 2005: 32, 167-168, Karte 1; Heinrich-Tamáska, 2006: 22).

Materials and methods

The examined archaeological findings

Double headed war hammer from Előszállás (Fejér County, Hungary)

Double headed war hammers differ from the axes in their lack of a blade. There are butts on both sides of the socket. Recently, researchers considered them as
weapons (Szücsi, 2014: 126–127). The item from Grave 2014/25 of Előszállás–Öreghegy (Figure 1, 1) can be described with the code V-G-V (Szücsi, 2014). Its length is 13.8 cm, d. of the eye: 2.7×2.3 cm, butts: 5 cm and 6 cm, Wt: 126 g. It can be dated from the middle of the 8th century until the middle of the 9th century (Török, et al., 2016: 31).

T-shaped cleaver with butt and hammer axe from Úrhida (Fejér County, Hungary)
The T-shaped cleaver with butt from Grave 87 (Figure 1, 2) can be described with the code 8a-I-I (Szücsi, 2014). Its length is 13.5 cm, the cutting edge: 9 cm, d. of the eye: 2.3×2.3 cm, butt: 5 cm, Wt: 159 g. The form is a Late Antique origin, but it appeared again in the burials of the Carpathian Basin (Szücsi, 2014: 131) in the second half of the Middle Avar period (ca. 670–680). Based on its peculiar shape and the subsequent West-European depictions (a miniature of the manuscript of St. Gallen from the 9th century and the Bayeux Tapestry from the 11th century) we can consider it has been used as working tool (Cs. Sós, 1955: 215–216).

The hammer axe of Grave 56 from Úrhida–Arany János utca (Figure 1, 3) is a weapon that can be categorized with the code 2a-I-VI (Szücsi, 2014). Its length is 15.4 cm, the cutting edge: 3 cm, d. and the eye: 2.7×2.1 cm, butt: 2.9 cm, Wt: 207 g. It might have been used as a tool as well, but it mainly functioned as a cutting and crushing weapon (Szücsi, 2014: 122). It can be dated to the late 7th or 8th century (Török, et al., 2016: 31).

Belt accessory from Nagyvenyim (Fejér County, Hungary)
From Grave 1 of Nagyvenyim–Munkácsy Str.–Fűzfa Str. we recovered a multi-layered iron–copper alloy belt set with cell work (cloisonné) consisting a main strap end, two shield-shaped belt-mounts and eight small strap ends (Szücsi, 2015: 16, 24–25, 51; Török & Kovács, 2015: 66). There are two pieces from the set which can be seen pieces in Figure 2. There is no evidence of inlays in the cells (Heinrich-Tamáska, 2006: 34). This belt is a so-called Kőlked–Feketekapu-type, which are multi-part belt sets with cell works. These items can be dated from the second third of the 7th century, and those are most likely local productions. The workshop can presumably be localized around Kőlked–Feketekapu (Baranya County, Hungary), due to the frequent occurrence of this type in the region and to a grave of a blacksmith equipped with such a belt set (Heinrich-Tamáska, 2006: 22; Kiss, 1996: 213).

Analytical methods and the aims of the study
In Figure 1a metallographic analysis can be seen on the three iron artefacts, which were carried out by the ARGUM. The microstructure was studied with a Zeiss Axiosmager optical microscope and a Zeiss EVOMa10 scanning electron microscope equipped with EDAX energy dispersive spectroscopy to perform elemental analysis. The investigation focused on defining structural constituents, determining their distribution and grain size. Moreover, chemical compositions, structures and shapes of the inclusions were also examined. Another aim of this study is to reveal the production techniques of forging, heating and cooling.

The finds were sampled by cutting, and embedding the fragment in epoxy-resin. The examined section’s surfaces, which are marked, on the photograph of artefacts in Figure 1, were grinded and mechanically polished. Diamond paste (3 µm) was used in the final
polishing step. After polishing, the samples were etched in 2% natal solution.

Particularly concern of this paper is a thorough analysis of a multi-layered belt accessory from the Avar Period (Figure 2). The SEM-EDS investigation was carried out on multidirectional sections:

1. SEM-micrographs were taken from the spot on the narrow side (A-A) of the artefact (marked with 1 in Figure 2).
2. A lined section in Figure 2 (B-B), was sampled by cutting.
3. The surface of the artefact was polished (C-C) from the rounded end up to the mentioned line and examined in point 2.

Besides identification of the several metals (which the artefact was made of) and analysing its microstructure, an additional goal of the analysis was to reconstruct the steps of the production process of these exclusive belt ornaments.

Results and discussion

Iron axes

Detailed and complex metallographic studies on such kind of special Avar axes and war hammers are relatively rare; however, some extensive surveys provide information for essential characteristics of medieval axes and outline the general results of the examinations (Pleiner 1967; Piaskowski 1989). There is only one axe from the Avar Period which has been analysed until now; an L-shaped cleaver from Grave 125 of Környe. Jerzy Piaskowski was an individual who established that it had been made from low-phosphorous and low-carbonic iron (Piaskowski, 1974: 128). It was later case-hardened which means that it had been covered with charcoal and then heated to temper the blade (Piaskowski, 1974: 122–123). Thus, the cleaver could be used as a heavy duty working tool and a weapon as well.

There are some interesting samples of the Norwegian and Danish axes from the 10-12th centuries AD are demonstrated by Buchwald (2005. 307-310). These axes are a common Norwegian type derives from the late Viking Age (Rygh 1885: Fig. 561). The structure of the examined samples is perlilitic-ferritic with 0.3-0.6% carbon. Inside this structure, there are fayalite laths in a glass matrix as slag inclusions could have been examined. No phosphorus has been detected (Buchwald 2005: 308-309).

In the medieval times, general techniques have been used to be applied in making axes, adzes, picks, etc. which are demonstrated by Pleiner (2006: 208-209). These technologies of manufacturing e.g. Slavic battle-axes in the 9th century meant overlapping or punching the shaft-hole and scarf-welding the cutting-edge.

Double headed war hammer (DHW, Figure 1/1, A-A, B-B)

Two samples have been taken from the double headed war hammer. The mosaic image which was taken from the whole section (A-A) revealed an extremely inhomogeneous microstructure (Figure 3). The centre area of the section consists large (170 µm) uniaxial ferrite grains. Towards to the edge of the cross-section, the size of the ferrite grains decreasing (28 µm) additionally small pearlitic colonies appears. It can be observed that an increase of carbon content causes a large change of the grain size. High carbon content could be found in both sides of the examined section. Near the surface a fully pearlitic and a ferritic-pearlitic microstructure could be observed, moreover, seconder cementite could be detected in the fully pearlitic area.

Figure 2. The examined belt accessory is on the left side, the studied parts are marked.
The carbon content varies in a large range (~0-1.1 wt %) between the fully ferritic area and the parts of secondary cementite and pearlite. However, a suddenly change of carbon cannot be observed on adjacent areas. The ferritic-pearlitic regions are showing a continuous transition. This assumes that the raw material was inhomogeneous, mainly with a carburised surface. During the forging process more or less banded structure has been formed. The micrographs show a transformed structure without any trace of plastic deformation. This indicates that the structure was formed from austenite. Hot forging was performed in a high temperature while the full cross-section was in the austenitic region of the iron-carbon system. Based on the micrographs, after the forging a moderate cooling of the war hammer was also concluded.

Near the surface of the A-A section a series of inclusions was observed. The microstructure and the chemical composition, examined by SEM-EDS, suggest that these inclusions arose from the smelting process, although a relatively high amount of Ca was also detected (Figure 4, Table 1). The microstructure of the slag shows a typical glassy matrix in which fayalite (2FeO·SiO₂) particles are embedded. Based on the chemical composition and micrographs, the amount of glassy phase is too small that all Ca present in the glassy phase so the particles are a complex olivine instead. Buchwald & Wivel demonstrated a similar microstructure of a fayalite-glass slag inclusion in a ferritic-pearlitic iron (1998: 75, Fig. 2). Pearlitic-ferritic iron has a fayalite-glass inclusion where the more the ferritic part in the structure of the metal, the less the ratio of the glassy phase in the inclusion as it was demonstrated by Buchwald (2005: 162-163, Fig. 160). The microstructures of the inclusions fit with Buchwald’s observation within the examined section. Fig. 4 shows a SEM-EDS micrograph of an inclusion in the A-A section of double headed warhammer. Light grey particles (probably fayalite based complex olivine) are embedded in dark grey glassy matrix.

Other sample was taken from the material around the shaft-hole (B-B point 1). The mosaic OM-image reveals a similar banded, heterogeneous microstructure (Figure 5) The shaft-hole is also strongly corroded; however, a pearlitic band can be examined in the centre.

Figure 3. A mosaic OM-image was taken from the A-A section of the double headed war hammer. The microstructure is extremely inhomogeneous. The bright areas are fully ferritic areas with low carbon content. The dark areas are mainly pearlitic areas with higher carbon content.

200 µm
of the sample with high carbon content. Small grained (10 µm) and ferritic-pearlitic areas are situated next to this band. The small grain size suggests a higher cooling rate after hot-forging, than is supposable on the basis of the examination on the cross-section which has been demonstrated above. The transition from the pearlitic band to the other area is also smooth due to the carbon diffusion. This also proves that the war hammer was made from a piece of single bloom.

There were inclusion analyses carried out during the SEM-EDS examination of the sample from the metal around the shaft-hole. These inclusions also have similar microstructure and chemical compositions (Table 1) as those that examined in the sample taken from the cross-section of the war hammer.

**T-shaped cleaver (TSC, Figure 1, C-C, D-D)**

There are also two samples were taken from the T-shaped cleaver (C, D). Figure 6 shows the C-C section of the artefact (see Figure 1). In the OM-image, mainly small grained ferrite and pearlite can be seen. The assumed carbon content is 0.3-0.35 wt% based on the ratio of the ferrite and perlite. C-C section is almost homogeneous, but series of inclusions and a thin pearlitic band can be observed.

The thin pearlite band, which was mentioned above, is not a characteristic feature of the microstructure. The existence of this band could be accidental. The nature of the structure is similar as it can be seen in the shaft hole of the double headed war hammer. There are more bands can be observed in the section. The bands revealed by either the microstructure (the ration of ferrite and perlite, so the carbon content changes a bit) or a series of elongated inclusions. The dimensions of the inclusions show the direction of the plastic deformation. This shows that the material was hammered at top-bottom direction (to see C-C section). To see the dimensions of the object it could be concluded the same.

Two kinds of inclusions can be identified by SEM-EDS examination (Figure 7). One type is an iron-silicate slag (Figure 7, Point 1), probably originated from the smelting, with high Al-content and just slightly higher K- and Mn-content than in cases of the inclusions from the double headed war hammer could be detected. However, the microstructure of this type of inclusion is similar to the other ones within the material of the war hammer. There are also assumed fayalite type olivines particles can be found in a glassy matrix. The inclusions of other type (Figure 7,

Table 1. There are SEM-EDS analyses of some inclusions in the examined iron artefacts. The table shows the chemical composition of the inclusions.

| Samples                  | O   | Mg | Al | Si  | Cl  | K   | Ca  | Ti  | Mn | Fe   |
|--------------------------|-----|----|----|-----|-----|-----|-----|-----|----|------|
| DHW, A-A, point 1 (Fig. 4)| 35.39 | 1.85 | 2.94 | 20.97 | 0.74 | 15.58 | 1.57 | 20.96 |
| DHW, B-B                 | 30.02 | 2.08 | 3.59 | 26.19 | 0.92 | 23.73 | 1.08 | 12.39 |
| TSC, C-C, point 1 (Fig. 7)| 26.51 | 0.68 | 8.22 | 25.44 | 3.42 | 1.41  | 0.62 | 2.26 | 31.44 |
| TSC, C-C, point 2 (Fig. 7)| 29.00 | 0.91 | 7.80 | 28.20 | 2.90 | 1.47  | 0.66 | 2.16 | 26.90 |
| TSC, D-D                 | 30.32 | 0.94 | 10.37 | 36.34 | 4.95 | 2.17  | 0.98 | 2.69 | 11.24 |
| HA, E-E, point 1 (Fig. 10)| 20.54 | 1.61 | 6.02 | 17.15 | 1.38 | 2.02  | 4.81 | 7.08 | 39.39 |
| HA, E-E                  | 17.41 | 1.66 | 6.80 | 17.35 | 2.61 | 4.87  | 7.17 | 42.13 |

* Figure 4. SEM-EDS micrograph of an inclusion in the A-A section of double headed war hammer.*
**Figure 5.** A mosaic OM-image was taken from the sample around the shaft-hole B-B, point 1.

**Figure 6.** Mosaic OM-image was taken from the C-C section of the T-shaped cleaver.

**Figure 7.** SEM-EDS micrograph of the inclusions of the C-C section from T-shaped cleaver. 1 – Inclusion with heterogeneous structure, 2 – Single phased inclusion.
Point 2) have a relatively homogeneous structure and slightly lower Fe-content, but it’s higher in Si-content. This type of inclusion mostly appears near the surface arranged in line in the direction of formation (see Fig. 6), while the heterogeneous inclusions can be observed in widely dispersed state in the material. Based on this observation, it is possible that this kind of homogeneous inclusions could originate from smithing. However, it is not possible to conclude this question definitively by using only an optical microscope and SEM-EDS.

The observed microstructure confirms that in this case a hot forging process had been applied as well. However, small grain size of the ferrite suggests that it has an enhanced cooling. Also, a normal air cooling is assumed as in the case of war hammer, but the lower thickness of the object can cause the enhanced cooling.

Figure 8 shows a mosaic OM-image which was taken from the D-D section of the T-shaped cleaver. A similar banded structure can be observed as in the case of the double headed war hammer. The upper part of the cross-section is mainly built up by ferrite; however, the lower part consists of a ferrite-perlite and fully pearlitic material. A small grained ferritic structure (10-12,5 µm), as a product of the phase transformation from austenite, is the result of an enhanced cooling.
cooling too. This was also shown through by the Widmanstätten ferrite in the ferritic-pearlitic band. In this case, diffusion zones between the bands with different carbon content are more clearly visible. This assumes that the whole cleaver has been made from a piece of a single bloom as in the case of the war hammer. In this section, there are single phased inclusions can be found arranged in a line. The chemical compositions of these inclusions are similar to those that are examined in section C-C. The Al content is slightly higher, but the Fe/Si ratio is more lower (0.31) than in the cases of the inclusions from section C-C (0.95 and 1.23).

**Hammer axe (HA Figure 1 E-E)**

E-E section of the hammer axe has also been studied. **Figure 9.** In the mosaic OM-image of the all microstructural parts can be observed as in the case of the double headed war hammer. In the upper left corner a large grained (100-150 µm) ferritic area can be discovered, in the lower left corner the dark area is mainly a pearlitic area. In another separated area, a small grained ferritic-pearlitic (ferrite grain size 25 µm) structure can be seen as well in the micrograph. This large difference originated to the large difference in carbon content. The microstructure also suggests a hot-forging technology applied at the austenitic

**Figure 11.** SEM-analysis was taken from the spot on the narrow side of the belt accessory. SEM-micrograph shows the iron-rich area and the copper-based alloy area

**Figure 12.** SEM-micrograph of the tin-iron-tin layers
temperature range. The strong similarity between the examined artefacts shows a general technological method of their production. Another evidence for the similar processing is the banded like structure. It is also suggested that the whole artefact is made from one bloom and from one smelting process.

Series of inclusion can also be discovered in this cross-section. In the fully ferritic area a large group of inclusions can be seen. Microstructure and chemical composition of a typical inclusion, examined by SEM-EDS, demonstrated in Figure 10. The morphology, the position and the microstructure show that the inclusions of this artefact are also related to the smelting process. Similar distorted slag inclusion with fragmented fayalite laths is demonstrated by Buchwald (2005: 121, Fig. 120) The relatively high Mn-content of these inclusions (7-8 wt%) is similar characteristic.

**Table 2.** Local SEM-EDS analyses of the points in Fig. 14

| Points in Fig. 14 | O  | Pb  | Ag  | Sn  | Fe  | Cu  | Zn  |
|-------------------|----|-----|-----|-----|-----|-----|-----|
| 1                 | 17.91 | 76.64 | 5.45 |
| 2                 | 0.40 | 2.44 | 1.81 | 89.51 | 5.84 |
| 3                 | 6.79 | 1.02 | 12.57 | 1.78 | 75.75 | 2.09 |
| 4                 | 10.32 | 0.17 | 0.24 | 21.47 | 67.06 | 0.74 |
| 5                 | 20.33 | 5.50 | 0.08 | 0.22 | 71.07 | 1.19 | 1.61 |
| 6                 | 18.67 | 2.72 | 73.79 | 3.73 | 1.09 |
that we detected by the examination of Avar Age slag samples from a neighbouring Transdanubian county (Somogy) (Török et al. 2015: 232).

**Belt accessory (Figure 2, on the left side)**

Three examinations, as they are listed above, were performed on this artefact using SEM-EDS.

The examination (1) practically was a local analysis without polishing. An iron-rich area with more than 6 wt% copper and lead and with 1.54 wt% zinc, a copper-based alloy area (a spot) with 5.11 wt% zinc and 3.91 wt% tin is distinguished. The Figure 11 shows a SEM-micrograph which was taken from the spot on the narrow side of the artefact – (marked with point 1 in Figure 2). This preliminary study reveals that the belt accessory basically contains two different kind of metallic materials: an iron based and a copper based alloy.

The SEM-micrographs were made during the examination (2), of the cross-section (marked with B-B line in Figure 2) which shows the belt accessory actually consists of several layers and metals:

- The base material is an iron sheet, plated with Sn, like sandwich-type tin-iron-tin tapes (Figure 12). The thickness of the iron sheet, between the thin Sn layers, is relatively stable (350-400 µm).
In the Figures 13 and 15 U- and L-cross-sections 2-3 mm high formations can be observed. The material of these formations is copper-based alloy, brass with low Zn-content (Figure 14, Point 2) and near the former tin layer with higher Sn-content (Figure 14, Point 3).

The material of the large space, between the brass formations, is iron-oxide in a specific structure containing 3-4 wt% copper and 2-3 wt% lead (Figure 14, Point 6). The material of the tin gaps, between the brass columns, is also an iron-oxide with a number of Cu- and Pb-inclusions. (Figure 14, Point 4)

Figure 13 and 14 show the sizes of the brass formations and the distances between the formations and between the brass columns (thin gap with squared corners), as well. The examination of the cross-section of the belt accessory implied a varied and detailed material structure, which encouraged us to make further investigations.

Before the examination (3) the surface of the artefact was polished from the rounded end (C-C) up to the line marked point 2 in Figure 2. A specific structure has been found. Largely corroded rings made of a thin iron wire and additional straight iron wires laid between the rings can be seen. Traces of brazing with brass are visible along the iron wires and rings (the light grey areas). (Figures 15 and 16)

Conclusions

Iron axes

The examined Avar axes have similar metallographic characteristic, made of non-alloyed iron with inhomogeneous structure and have a relatively low average carbon content (0.1-0.5 wt%). The centres of the examined cross-sections have a mainly ferrite structure with a relatively large grain size. The amount of the lamellar pearlite phase is increasing towards to the sides. However, for the cleaver with T-shaped blade we did not find exactly the same structure as in the case of the other two examined artefacts. It could be the result of the inhomogeneity of the iron bloom.

All examined axes were supposedly forged from a piece of inhomogeneous iron without folding. Those were kept on high temperature (in austenitic region) and forged the edges multiple times but not with extreme intensely. The forging process ended with moderate air cooling. The EDS analysis of the examined inclusions implied iron-silicate based slag without phosphorus content worth mentioning. Most of the examined inclusions may originate from the smelting process of the bloomery furnace. There were some special characteristic in the chemical compositions. The analysed inclusions of each artefacts could be detected: DHW - high Ca-content; TSC – high Al-content, slightly higher K-content and detectable Ti-content; HA – high Mn-content, medium Al-content and the highest Fe/Si ratio.

There were two ways of getting the shape, as it was mentioned above: bending method or punching method. In the course of the bending method, the long narrow metal-sheet was bent at the middle to encompass a roundish metal rod. The socket was formed from the loop obtained by this way. The bended metal-sheet was hammered and shaped to a blade (Pleiner 2006: 209; Szabó, 1954: 139). In the course of the punching method, the smith formed the raw material into a suitable shape and size and then he punched it at the place of the eye. After the socket has been shaped, he formed the blade and the butt (Pleiner, 1962: 229, Fig. 45; Pleiner 2006: 209). The advantage of this method was that there were not any jumped segments on the axe which could split later in the use. The results of the metallographic examinations proved that the hammer axe, the T shaped cleaver and the double headed war hammer investigated in our study, were made by the second method.
**Belt accessory**

The results of the SEM-EDS examination, carried out on multidirectional sections, on a piece of the Avar belt set which revealed that these ornaments were made of various kind of metals. This multi-phase production process, which is a unique among not only the Avars’, but also the early medieval methods, was quite complicated method, in spite of the relatively small size of these artefacts.

The assumed technology of the production:

1. A 1.5-2 cm wide iron sheet was formed which was plated by tin afterwards (Figure 17.a).
2. On the iron sheet surface, iron rings were placed in three lines. Thin straight iron wires were laid between the lines. The tin plating made it easier to braze the iron wires to the surface (Figure 17.b).
3. Thin brass sheets were fitted along the iron rings and between the straight iron wires (Figure 17.c).
4. During the heating, these brass sheets were melted and functioned as an ornament and also as a braze material which has a good adhesion to the iron. A part of the tin flowed away and the other part fused in the material of the brass -or- remained on the iron sheet as a very thin layer. Of course, the centuries of corrosion modified the original structure (Figure 17.d).

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