Multi-phase microstructures in Anatolian Seljuks iron-steel objects: classification and production techniques

Vícefázové mikrostruktury anatolských železo-ocelových předmětů z období rúmského sultanátu: klasifikace a výrobní techniky

Ümit Güder – Cemal Cem Taşan – Alptekin Yavaş

In this paper a collection of iron objects from the Anatolian Seljuks Period, ca. 12th–13th century AD, are analysed and discussed from a metallurgical perspective. A total number of 21 iron-steel objects, small knives and flat bodied (with thin cross-section) arrowheads was examined. These objects are coming from the Seljuks' cultural layers of Eğirdir (Isparta, Central Anatolian Caravanserai), Kubad Abad (Konya, Central Anatolian Sultan's Palace Complex), and Samsat (Adıyaman, Eastern Anatolian Fortress). In the samples which were taken from iron tools, composite-like structures formed by different ferrous phases were revealed by metallography, SEM-EDX and micro hardness examinations. These structures are classified according to the production materials and techniques. The first group revealed signs of continuous forging and, in some cases, bloomery iron folding, which can lead to such composite-like structures. The second group consisted of tools which were produced from different starting materials which were forge-welded before or during shaping process. The crucible steel knives can be classified as another group, in which the composite-like structure exhibits totally different constituents leading to more homogeneous mechanical character. In modern times, composite materials have gained importance and become key engineering materials due to their outstanding specific properties. This study reveals that skilled Seljuks' blacksmiths made similar materials design choices in the production of iron or steel objects, despite limited materials and metallurgical knowledge.

Anatolian Seljuks – multiphase steel – crucible steel – arrowheads – archaeometallurgy

V příspěvku je diskutována kolekce železných předmětů z období rúmského sultanátu, ca 12.–13. stol. n. l., analyzovaná a hodnocená z metalurgického hlediska. Celkem 21 železných předmětů, menších nožů a plochých hrotů šípů (s tenkým průřezem). Předměty pocházejí z kulturních vrstev rúmského sultanátu v Eğirdiru (Isparta, středoanatolský karavanseraj), Kubad Abad (Konya, středoanatolský sultanský palácový komplex) a Samsat (Adıyaman, východoanatolská pevnost). Vzorky odebrané z železných nástrojů vykazovaly struktury podobné kompozitním, sestávající z různých strukturních fází vymezených pomocí metalografie, SEM-EDX a měřením mikrotvrdosti. Dané struktury byly kategorizovány podle užitých materiálů a techniky výroby. První skupina vykazovala známky kontinuálního kování a místy paketování svářkového kovu, které může vést k takovýmto jakoby kompozitním strukturám. Druhá skupina sestávala z nástrojů vyráběných z různých výchozích materiálů, které byly před nebo v průběhu tváření svařovány. Nože z kelímkové oceli lze klasifikovat jako další skupinu, ve které kompozitní struktura vykazuje naprosto odlišné složky, vedoucí k rovnoměrnějším mechanickým charakteristikám. V dnešní době nabyly kompozitní materiály velkého významu a díky svým výjimečným specifickým vlastnostem se staly klíčovými materiály strojírenství. Tato studie odhaluje, že zruční seldžučtí kováři volili podobnou materiálovou konstrukci při výrobě železných nebo ocelových předmětů, navzdory omezeným materiálovým a metalurgickým znalostem.

anatolští Seldžukové – vícefázová ocel – kelímková ocel – hroty šípů – archeometalurgie

1. Introduction

The presence and variety of microstructural phases results in desirable mechanical properties in structural alloys. For example, advanced high-strength steels can be produced by strengthening ductile ferrite and/or austenitic matrix with the existence of martensite, bainite and/or various carbides (*Springer – Tasan – Raabe 2015*) and titanium alloys combine beta and alpha phases (*Zhang et al. 2017*) etc. For industrial applications, rolling is one of the favourable shaping methods for bonding high carbon steel and alumina stabilized ferrite material. This technique provides better uniformity for the deformations of layers than traditional processes like forging and hammering (*Charles 1998*, 501). The concerns for production of steel objects which are easy to form, shock resistant and production of which is cost-efficient by using the available technologies, were in the Middle Ages similar to those in modern times.

In order to determine the technique and materials used by Anatolian medieval blacksmiths, a total number of 21 arrowheads and knives, dated from ca. 12th to 13th century AD was examined. Because of the domino effect created by the Mongol invasion, Central Asian artisans migrated to Anatolia especially during the 13th century (*Arık 2000*). The transitions can be seen in the architectural designs, stone working and ceramic production, though it is expected that the experienced blacksmiths worked during this period in Anatolia as well. Moreover, as Mongol invasion had reached Anatolia, the new habitants had used similar techniques for construction of buildings, production of ceramics and metals but with some major aesthetical and technical changes. Due to this fact, the archaeometallurgical studies of the finds from this period become more interesting.

Examined iron-steel objects, knives and flat bodied (with thin cross-section) arrowheads, come from the excavations at Anatolian Seljuks' cultural layers of Eğirdir (Isparta, Central Anatolian Caravanserai), Kubad Abad (Konya, Central Anatolian Sultan's Palace Complex), and Samsat (Adıyaman, Eastern Anatolian Fortress).

Samsat (known as Samosata and Sümeysat as well; *Demirkent 1979*, 235), which was submerged under the lake of Atatürk dam in 1990, was one of the biggest mounds of lower Fırat region in Southeastern Anatolia. The mound and the lower city of Samsat was an important cultural centre hosting Hittites, Assyrians, Urartians, Persians, Byzantians, Crusaders, Umayyads, Seljuks, Artuqids, Ayyubids, Mongols and Mamluks. In 1978–1989, during the excavations of medieval cultural layers, a huge set of medieval arrowheads was found. The set consisting of 12.200 arrowheads was found hidden in a medieval tower together with pottery and coins dating from the 12th–13th century (*Öney 1982*, 75; *Özgüç 1986*, 445). Because the assemblage contains also semi-finished arrowheads, knives and pieces of blooms, it is assumed that it is a hoard buried by Seljuk blacksmiths during the Mongol invasion to Samsat.

Kubad-Abad which is situated on the coast of Konya-Beyşehir lake in the Central Anatolia, is a huge city-palace consisting of dozens of buildings spread not only on the coast of the lake but also on the islands and the Anamas mountainside. It had been constructed between 1225–1230 by the order of I. Alâeddin Keykubat, the most powerful Sultan of the Anatolian Seljuks period. In the Kubad Abad city-palace complex, reflecting eastern palace models, buildings for production like smithing, pottery, glass and tile workshops were localized as well as constructions for aristocracy (*Arık 2002*, 264). Till now, 59 arrowheads with a large variety in shapes have been found during excavations. Though it is a small number for such a great complex, the hunting garden (Paradaison), where more iron objects related to hunting are expected, has not yet been excavated (*Yavaş 2012*, 125). Moreover, findings such as part-shaped arrowhead, knives, bloom fragments, smithing

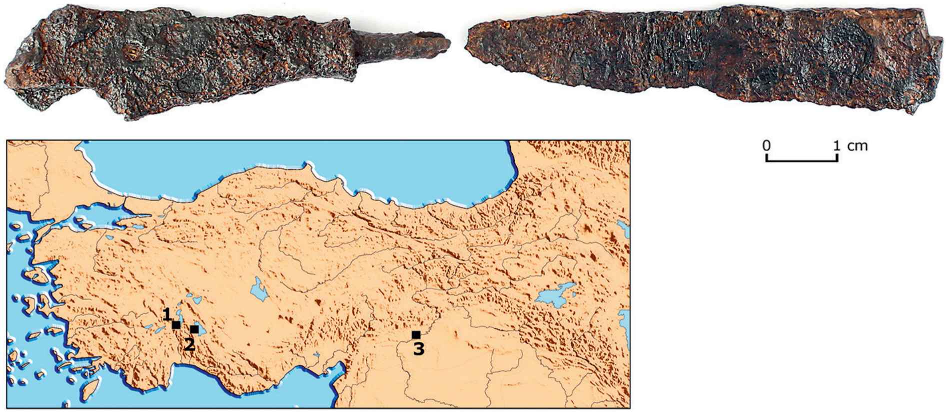

Fig. 1. Examples of the Anatolian Seljuks Iron Objects; flat bodied arrowhead KU.1 no 09 (left) and a small knife KU.1 no 11 (right) from Kubad-Abad. The locations of the sites mentioned in text: 1 – Eğirdir, 2 – Kubad Abad, 3 – Samsat. Map by Ü. Guder.
Obr. 1. Příklady anatolských železných předmětů z období rúmského sultanátu; plochý hrot šípu KU.1 no 09 (vlevo) a malý nůž KU.1 no 11 (vpravo) z Kubad-Abad. Lokality zmíněné v textu: 1 – Eğirdir, 2 – Kubad Abad, 3 – Samsat.

slags etc., proves activity or iron smithing workshop covering needs of the palace (*Güder – Yavaş – Yalçın 2015*).

Sultan II. Keyhüsrev Caravansarai which was constructed in 1237–1238, is the fourth biggest caravansarai of the Anatolian Seljuks period. It is situated on Eğirdir lake shore in the Central Anatolia, which is on the caravan route of Konya-Antalya-Denizli. It fell into ruin for unknown reasons in the second half of the century in which it was constructed (*Bozer 1994*, 98). During the excavations, 62 arrowheads and 2 knives, some of which bore traces of fire which destroyed the building, were recovered.

2. Material and technique

2.1. Samples

Fifteen of the selected objects for material analyses are iron-steel flat bodied arrowheads. Although surfaces of the arrowheads are heavily corroded, they can be classified typologically, and their cores still have solid metal enabling metallography and microhardness analysis. Almost all the arrowheads have tangs circular in cross-section, but their blades differ in shape, thus differences can be seen inside the group. Besides arrowheads with points in the form of a wide angle as seen at *fig. 1*, there are also those ending with sharp spatula-like points and willow leaf-shaped points. According to Mamluk (*Latham – Paterson 1970*, 31), Arabian (*Faris – Elmer 1945*, 107–109) and Ottoman (*Yücel 1999*, 300) treatises, the flat bodied arrowheads were used against unarmoured targets, either during military campaigns (i.e. against horses to take the cavalry down) or for hunting purposes. Contrary to arrowheads with square, round or star cross-sections, flat bodied arrowheads are inefficient for piercing armour and shields.

In total, five knives from three sites were analysed. The blade length of the knives is between 6 and 8 cm. The knives have straight back and their cutting edge rises to meet the back at the tip (*fig. 1*). No or little material remained at the tang part of four knives. Some metallic core survived in all blades, except for the knife SA no 17, which is fully corroded. Considering both the size and archaeological context of the knives[1], it can be assumed that they were used for shaving or similar purposes (*Güder – Yavaş – Yalçın 2015*, 197).

2.2. Analytical techniques

Samples for metallography were taken from the selected objects with air cooled diamond discs. The cutting process was realized with low rotational speeds and with intervals to prevent the distortion of the microstructure by the heat generated during the process. The samples were taken from both tangs and bodies of the arrowheads, and from tangs (when available) and blades of the knives. The samples were mounted in epoxy resin, ground using wet silicon carbide papers with grit sizes from 240 to 1200 and polished using diamond pastes with 6, 3 and 1 micron particle sizes.

The samples were documented at various magnifications by a light microscope before and after etching the samples with 1% Nital etchant. The fully corroded sample from knife (SA no 17) was not etched. Micro-hardness was measured with Vickers hardness tester using a 200 gram load. The micro-indenter was targeted at five different un-corroded and slag inclusion free areas for each sample. Scanning electron microscope was used in the case of the corroded sample (SA no 17) to search for remnants of original metallographic structure possibly surviving in corrosion. High-contrast images created by the Back Scatter Detector (BSD) of the SEM were preferred to detect remnant or ghost structures (*Notis 2002*, 261). Additionally, crucible steel structure elements which were difficult to identify by light microscope, were inspected with SEM and chemical compositions of crucible steel and slag inclusions in arrowheads were checked using EDX instrument attached to SEM.

3. Results and discussion

3.1. Analytical Results

As can be seen from *table 1*, metallographic examinations revealed multi-phased microstructures of the objects, except for three arrowheads. In one of the single phased samples (SA no 25) equiaxial ferrite grains and in two others (EGI no 22 and EGI no 51) elongated ferrite grains are the only structures observed. Micro-hardness tests on SA no 25 gave values corresponding to a soft iron structure, which are between 81 and 87 HV. On the other hand, the hardness values of EGI no 22 are between 160–173 HV which is higher than expected for ferritic structure. The elevated hardness is caused by the deformation of ferrite grains due to cold working (*Sherby – Wadsworth 2001*, 348). The homogeneous structures of samples provide little derivation between minimum and maximum hardness throughout the sample.

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[1] Two knives coming from Kubad-Abad were found where the palace was connected with the hamam (a Turkish bath).

No.	Sample Code	Site	Period (century)	Object Type	Steel Type[1]	Micro-structure[2]	Classification	Hardness[3]
1	SA no 13	Samsat	12th–13th	Knife	Hypereutectoid	Glob. Cementite	(III) Crucible Steel	280–401
2	SA no 17	Samsat	12th–13th	Knife	Hypereutectoid	Cementite Needles	(III)Crucible Steel	N/A
3	SA no 25	Samsat	12th–13th	Arrowhead	Iron	Equiaxial Ferrite	None	81–87
4	EGİ no 02	Eğirdir	13th	Arrowhead	Hypoeutectoid	Fer.-Pear.	(I) Forging/ Folding	128–234
5	EGİ no 22	Eğirdir	13th	Arrowhead	Hypoeutectoid	Elong. Ferrite	None	160–173
6	EGİ no 51	Eğirdir	13th	Arrowhead	Iron	Elong. Ferrite	None	N/A
7	EGİ no 54	Eğirdir	13th	Arrowhead	Hypoeutectoid	Fer.-Pear.	(II) Piled Steel	189–249
8	EGİ no 62	Eğirdir	13th	Arrowhead	Hypoeutectoid	Fer.-Pear.	(I) Forging/ Folding	145–189
9	EGİ no 44	Eğirdir	13th	Knife	Hypoeutectoid	Fer.-Pear.	(II) Piled Steel	N/A
10	KU.1 no 04	Kubad Abad	13th	Knife	Hypereutectoid	Glob. Cementite	(III) Crucible Steel	254–380
11	KU.1 no 06	Kubad Abad	13th	Arrowhead	Hypoeutectoid	Fer.-Pear.	(II) Piled Steel	171–198
12	KU.1 no 07	Kubad Abad	13th	Knife	Hypoeutectoid	Fer.-Pear.-Mar.	(II) Piled Steel	111–608
13	KU.1 no 08	Kubad Abad	13th	Arrowhead	Hypoeutectoid	Fer.-Pear.	(II) Piled Steel	102–213
14	KU.1 no 09	Kubad Abad	13th	Arrowhead	Hypoeutectoid	Fer.-Pear.	(II) Piled Steel	125–184
15	KU.1 no 10	Kubad Abad	13th	Arrowhead	Hypoeutectoid	Fer.-Pear.	(II) Piled Steel	195–271
16	KU.1 no 11	Kubad Abad	13th	Knife	Hypoeutectoid	Fer.-Pear.-Mar.	(II) Piled Steel	119–543
17	KU.2 no 01	Kubad Abad	13th	Arrowhead	Hypoeutectoid	Fer.-Pear.	(I) Forging/ Folding	189–234
18	KU.2 no 02	Kubad Abad	13th	Arrowhead	Hypoeutectoid	Fer.-Pear.	(II) Piled Steel	N/A
19	KU.2 no 03	Kubad Abad	13th	Arrowhead	Hypoeutectoid	Fer.-Pear.	(I) Forging/ Folding	N/A
20	KU.2 no 04	Kubad Abad	13th	Arrowhead	Hypoeutectoid	Fer.-Pear.	(II) Piled Steel	N/A
21	KU.2 no 08	Kubad Abad	13th	Arrowhead	Hypoeutectoid	Fer.-Pear.	(I) Forging/ Folding	184–249

Tab. 1. List of analysed objects from three archaeological sites. [1]Classification according to the carbon content; iron is zero carbon material. Hypoeutectoid steel; carbon content is lower than 0.76 %. Hypereutectoid composition has carbon higher than 0.76 %. [2]Abbreviations: Glob. Cem. Globular Cementite, Elong. Elongated, Fer. Ferrite, Pear. Pearlite, Mar. Martensite. [3]Minimum and maximum Vickers (HV 0.2) hardness values.
Tab. 1. Seznam analyzovaných předmětů ze tří archeologických lokalit. [1]Klasifikace podle obsahu uhlíku; železo je materiál s nulovým obsahem uhlíku. Hypoeutektoidní ocel; obsah uhlíku je nižší než 0,76 %. Hypereutektoidní složení má uhlík vyšší než 0,76 %. [2]Zkratky: Glob. Cem. globulární cementit, Elong. prodloužený, Fer. ferit, Pear. perlit, Mar. martenzit. [3]Minimální a maximální hodnoty tvrdosti podle Vickerse (HV 0,2).

When the existing phases were pearlite and ferrite, alignment of two or more layers parallel to the cross-section were observed. These layers in seven arrowheads and three knife samples (classified as (I)Piled Steel in *tab. 1*) can be easily noticed since they run across the whole cross section, and their borders, rich in slag inclusions, are well defined. The slag-rich lines being well visible in unetched conditions were found to be borders between different structural layers revealed by etching. As seen at *fig. 2*, these borders were also accompanied by welding lines in some examples.

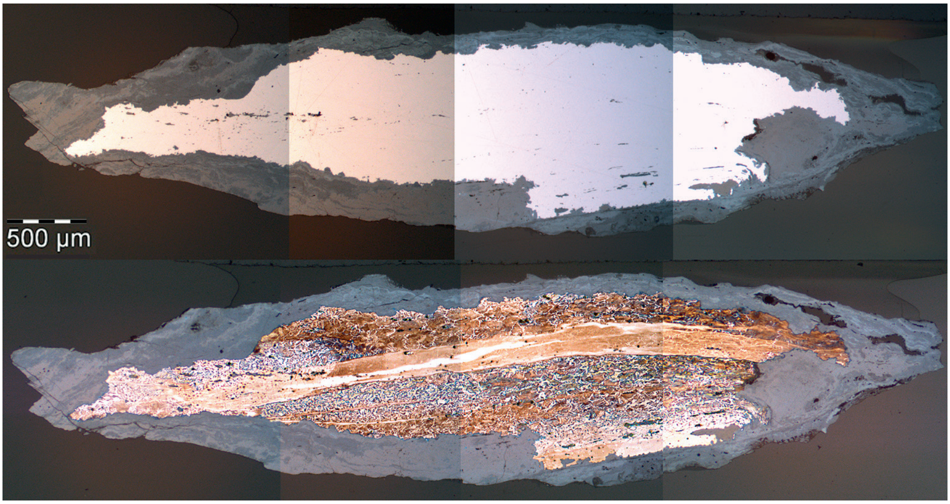

Fig. 2. Polished cross-section of an arrow-head (KU no 10) in unetched state (up) and after Nital etching that revealed two welding lines (down).
Obr. 2. Leštěný řez hrotem šípu (KU č. 10) v neleptaném stavu (nahoře) a po naleptání nitalem, které zobrazilo dvě svařovací linie (dole).

Metallography of the knives EGI no 44, and KU.1 nos. 07 and 11, revealed a sandwich construction consisting of medium- and low-carbon steel layers, with the medium-carbon steel in the centre of the blade. The blade KU.1 no 07 has a welded-on back of soft iron. The small amount of slag inclusions, except the smithing-slag inclusions, points out the use of well refined materials. The microstructure shows also traces of quenching and tempering. The distribution of martensite indicates that the whole of the blade was quenched and hardness measurements indicate slight tempering to relieve some stress and decrease the brittleness of the blade.

The concentration of slag inclusions differs from layer to layer, depending on how well refined was the material used in the particular place. The chemical compositions of slag inclusions from individual layers were measured by SEM-EDX equipment. It is expected that the line in the FeO/SiO_2 ratio graph has a characteristic slope for each material/layer, as it depends on the overall composition of the inclusions analysed (*Buchwald – Wivel 1998*, 77). Values of FeO and SiO_2 obtained by EDX analysis of the arrowhead KU no 08 were plotted in the FeO/SiO_2 graph that shows two lines with different slopes suggesting use of two different materials for the production of the object (*fig. 3* and *4*). The linear distribution of analytical ratios belonging to non-reducible impurities (i.e. Al_2O_3/ SiO_2) was observed as well.

Although layered multi-phase structures were observed also in other five arrowheads (Nos 4, 8, 17, 19, 21) the layers are somehow disordered, in some examples localized, and it is difficult to distinguish their borders. In these samples, mostly welds suggesting folding rather than deliberate construction are observed. To succeed in forge welding, the pieces to be welded must be heated at correct working (welding) temperature which depends on the carbon content, and their surfaces must be kept clean, mostly by means of fluxes

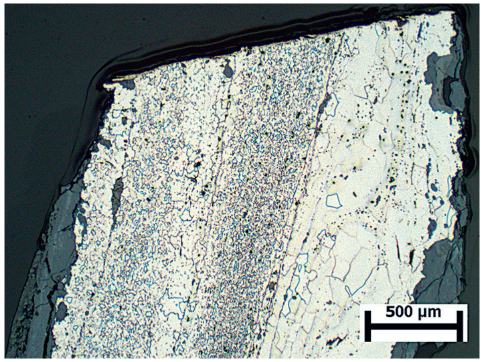

Fig. 3. Etched cross-section of an arrow-head (KU no 08) showing at least four layers.
Obr. 3. Naleptaný průřez hrotu šípu (KU č. 08) s nejméně čtyřmi viditelnými vrstvami.

(*Pleiner 2006*, 59). Welding lines associated with simple folding are thicker and mostly accompanied by corrosion products, since the working temperature was not high enough and/or the necessary flux to clean the surface had not been applied (*fig. 5*).

The micro-constituents in three knives (SA no 13, 17 and KU.1 no 04) from Samsat and Kubad Abad are different. In two of them (SA no 13 and KU.1 no 04) the carbon content can be estimated at around 2 %. In the microstructure pro-eutectoid enormous cementite particles form chains running parallel to the cross sections. In between, globular or semi-globular pearlite as very fine background could only be detected by SEM observations. For the fully corroded SA no 17, SEM images were used to detect the relics of metal, the ghost structures of cementite grain boundary network and cementite needles. A similar structure is observed in one of the Ulfberht swords and described as formed by smithing a crucible steel billet (*Williams 1977*). As a characteristic feature of these objects, EDX analysis on solid metal parts gave high manganese content values between 0.50 % and 2.5 %, which fit the crucible steel batches in historical records which mention manganese as an important ingredient since Zozimos of Panopolis 2nd century AD (*Gilmour 2009*, 139).

Both low and high hardness values, varying from 102 to 608 HV0.2, were recorded in multi-phased steel tools. The hardness of arrowheads showing ferritic and pearlitic layers varies between 30 and 100 HV0.2, depending on the character of the structure (grain size, form and amount of cementite, etc). On the other hand, high hardness values (400–500 HV) were measured in knives KU nos. 07 and 11, which were produced by iron, low carbon and tempered martensite phases. In contrast, the knives made from crucible steel (SA no 13 and KU 1. no 04) have more uniform hardness (depending on the intender targeted for globular cementite background or pro-eutectoid cementite islands) ranging between 254 and 401 HV.

3.2. Evaluation of results and classification of multi-layered steel objects

During the production of blooms consisting mostly of iron and low-carbon steel, parts with a variable carbon content were inevitably formed due to the nature of the smelting process. At the end of the primary smithing of the blooms, semi-finished products are produced with an heterogeneous carbon content, as can be seen from the inspection of medieval iron ingots (*Güder et al. 2015*). It is obvious that multi-phase layers occur when

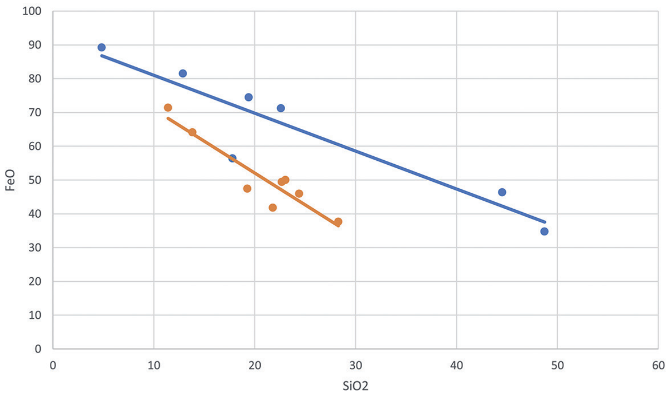

Fig. 4. FeO/SiO_2 chemical composition ratio graph created by SEM-EDX measurements on slag inclusions from two different layers in KU no 08.
Obr. 4. Graf poměrů FeO ku SiO_2 získaných SEM-EDX analýzou vměstků hutní strusky ve dvou různých vrstvách hrotu KU č. 08.

a blacksmith forms a thin sectioned object from starting material with heterogeneous character by continuous forge and folding procedure. Additionally, recycling and repairs of iron objects were common in medieval smithing since the value of the material itself was not negligible. During the recycling process, forge welding was also applied to consolidate small fragments of iron to bigger ones. This is another procedure which creates a material containing different phases. Thus, in some cases it is difficult to distinguish between accidentally or deliberately formed layers (*Lang 1984*, 62). Therefore, it is a good strategy to judge the effect of material design to the functionality of the tool. Inspection of medieval knives shows that blades with cutting edges of steel and backs of softer material, such as iron, were the standard (*Blakelock – McDonnell 2007*, 55). In this case the skill of blacksmiths determines the engagement of different materials, since the welding of mild steel and ferritic iron is difficult to apply (*Light 2000*, 335). Knives with welded-on steel cutting edges cannot function well when the steel part is worn off. So, they have to be either repaired or discarded. Therefore, a material which can combine all the most required mechanical properties, such as hardness, wear-resistance, strength and toughness would be preferred in the whole body of the tool. Crucible steel was an expensive but a very suitable material to solve the problem; this was a high-quality material in terms of mechanical properties, valued also for the possibility to reveal an attractive wavy-patterned surface. Two procedures are known how to make a crucible steel. In the first one which was described by al-Tarsusi in the 12th century, wrought iron is heated by organic matter to increase the carbon content. In the latter, cast iron is used to carburize the wrought iron, as noted by al-Biruni (973–1048) (*Williams 2007*, 234). Evaluation of the analytical study over Seljuks iron objects provide us with understanding the material and technical concerns of blacksmiths to produce the best functioning objects.

First to say; ferritic iron was not a common choice for production of thin sectioned arrowheads, although it was the case for square sectioned ones when other hardening techniques were applied (*Güder 2017*, 24). Excluding three arrowheads consisting mostly of ferritic iron, the artefacts can be divided into three main groups according to the way in which their multi-phase layered structure was formed. Objects in the first group are those whose structure was formed due to the nature of starting material, continuous forging and in some cases folding and forge-welding. The second group features forge welding of dif-

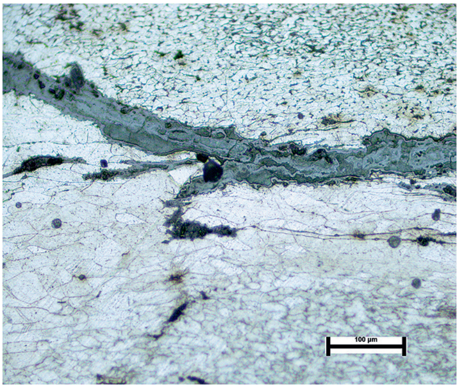

Fig. 5. Folding line and inhomogeneity of the structure in an arrowhead (EGI no 62).
Obr. 5. Překladová linie a nehomogennost struktury v hrotu šípu (EGI č. 62).

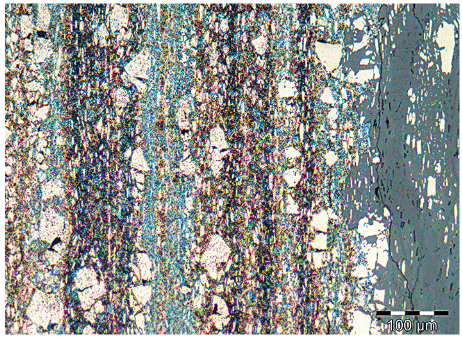

Fig. 6. Layers of large cementite particles in spheroidised pearlite matrix from a crucible steel blade (KU no 04).
Obr. 6. Vrstvy velkých cementitických částic v matrici sferoidizovaného perlitu v čepeli nože z kelímkové oceli (KU č. 04).

ferent starting materials and additional, thermo-mechanical applications such as quenching, tempering. The last group features the smithing of hypereutectoid steels in which the layered micro-structure is a result of forging and tempering cycles.

Five arrowheads, belonging to the first group, are thought to be forged from heterogenous starting material since the different phases are not well layered. Here, simple welding lines inside the structure were observed.

On the other hand, in the second group with seven arrowheads, the layers are clearly bordered with slag stringers which were formed by using fluxes during the forge welding. The stringers can also be seen clearly in the samples in unetched condition. Clear lines of layers with different characters are not a sufficient evidence for deliberate forge welding of materials with different carbon content, since bloomery steel structures can be easily misinterpreted. Further investigations, such as observations of welding lines, different concentration of slag inclusions and the chemistry of slags in different layers, are done on the micro-structures for further clarification. Layer formations caused by the use of recycled material are difficult to recognise, since similar analytical results could be reached. However, using recycled material to forge a nail or a square/round sectioned arrowhead which are consumables in military armoury or constructions, would not be a problem. But if this thin sectioned arrowhead, which needs to have more tensile strength and impact fracture than the rectangular or circular sectioned ones, will be used for Sultan's hunting (in Kubad-Abad), then it is expected that the blacksmith would not leave the success of the tool to chance and would use his experience to produce good-quality arrowheads as well.

The best examples of layered steels were observed in small knife blades of this period. Medium carbon and low carbon steel materials were observed as alternative layers, which were forged in a way that the medium carbon layer stays in the middle and forms the cutting edge. The small amount of slag inclusions shows the use of well refined blooms in the production. Traces of quenching and tempering can be seen in the microstructure as well. As seen from the distribution of martensite, the knives were fully quenched and hardness measurements show slight tempering to relieve some stress and decrease the brittleness.

The last group consists of special layered microstructures observed in the knives made of crucible steel. In the set of Anatolian Seljuks' iron finds, there are not only knives made of crucible steel which is thought to be the most precious forging material of the period, but also smithing evidences such as pieces of crucible steel ingot, high manganese bearing smithing slags and a scrap piece of knife. Skilfully applied forging and cooling cycles on the crucible steel ingots which have a homogeneous high carbon content, turns the microstructure including cementite needles to the layers created with broken cementite particles in a spheroidised pearlite matrix (*fig. 6*). This structure is also the reason of the attractive damask pattern on the surface of the knives (*Verhoeven – Jones 1987*). The chemical and mechanical features of these layered steel objects, which were detected by micro-hardness tests and SEM-EDX analysis, points out the distinctive character when compared to the other products.

4. Conclusions

As a result, this general overview of the iron products from the Anatolian Seljuks' period demonstrate the traces of the variety of the metallurgical materials and skills of the region. On the other hand, the migration of artisans from Central Asia caused the enrichment of the metallurgical knowledge and it is concluded that the production of skilful blade designs with piled steel, usage of piled steel in arrowheads and smithing of crucible steel show the interest of medieval blacksmiths to produce artefacts with composite-like structures having better mechanical properties.

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ÜMIT GÜDER, Laboratory for Archaeometric Studies, Çanakkale Onsekiz Mart University, ÇOBİLTUM, Terzioğlu Kampüsü, 17020 Çanakkale, Turkey; uguder@comu.edu.tr
CEMAL CEM TAŞAN, Department of Materials Science and Engineering, Massachusetts Institute of Technology, 77 Massachusetts Ave., 02139 Cambridge, MA, United States; tasan@mit.edu
ALPTEKIN YAVAŞ, Department of Art History, Çanakkale Onsekiz Mart University, Fen Edebiyat Fakültesi, Terzioğlu Kampüsü, 17020 Çanakkale, Turkey; alptekinyavas@hotmail.com