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First Archaeometrical Approach of the Examinations of Iron Age Ferrous Fragments from Regöly and Bükkábrány (Hungary) – The Inception of Iron Working in the Carpathian Basin?

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ABSTRACT

The emergence, spread and development of iron working in the Carpathian Basin is an essential and interdisciplinary research field, an important stage of which being the results of the archaeometallurgical-archaeomaterial examinations presented in this article. The excavation site of Regöly (Hungary) represents a special source from the earliest Iron culture of the Carpathian Basin, and using the results of metallographic analysis our aim is to place the examined objects in their proper context with regard to the process of iron working. One fragment found in the tumulus of Regöly during the excavation 2011–2012 has been presumed part of an iron bloom; this may be the earliest example of iron working in the Carpathian Basin (630–600 BC). From both an historical and technological point of view this raises several questions. One aim of our study is to characterise the fragments in order to figure out what kind of processing has been applied and ultimately see how the 'iron bloom' fragment can be connected in any way to the other iron objects found at the site. Examinations were carried out by optical microscopy (OM) and scanning electron microscopy (SEM-EDS) on both the iron objects and the bloom fragment. Metallographic analysis revealed a very specific microstructure, indicating that the bloom fragment is not a direct product that came directly from the bloomery furnace; it could be a secondary or even tertiary product (prefabricated) instead. However, regarding the bloom fragment, there is evidence of a forging method. During the tests, slag inclusions were also examined. The results from Regöly were also compared with other finds from a Celtic workshop-type site (Bükkábrány, 320–200 BC). Although a direct connection between the examined iron objects and the iron bloom fragment (as possible raw material) cannot be confirmed, the iron artefacts and fragments of Regöly might easily have been made from some basic material as represented by the fragment of an iron bloom or bar. Even though the find from Regöly does not definitively provide the earliest evidence for iron smelting technology in the Carpathian Basin area, it does give evidence for some form of iron forging from a semi-finished product.

1. Introduction

In carrying out archaeological research of iron cultures in the greater regions of Europe, one must consider that the required knowledge to process iron – as a raw material, its production from iron ores through deliberate reduction with different pyrometallurgical methods, and the manufacturing practices of iron objects generally – have appeared in distinct separate periods in different regions (Pleiner, 2000, pp.28–31). As such, this is equally true for the research into iron cultures of the Carpathian Basin.

The peoples of Asia Minor acquired iron metallurgy technology around 2000 BC, during the Bronze Age, being closely connected with copper alloy metallurgy (Tylecote, 1992, p.47). Subsequently such technology spread through Europe between 1500 and 600 BC (Pleiner, 2000, p.268). In addition to the early European copper alloy metallurgical sites found in the Mediterranean (Tylecote, 1992, p.54), the beginning of the Iron Age in Central Europe can also be traced back to between 750 and 700 BC, one of the

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best examples being the Austrian Hallstatt-Culture sites (Habashi, 1994, p.62; Pleiner, 2000, p.269). The impact of the Iron Age can be clearly seen as it was introduced along the Danube River (Tylecote, 1992, p.54). Buchwald (2005, p.74) describes the spread of the handling of iron and its metallurgy in Europe as a process that spanned from 1200 to 300 BC, from the Anatolian "cradle of technology" through the Mediterranean and Caucasus to the North, and through to Egypt in the South. The formation of the Central European iron culture is connected to the Hallstatt cultures, the prime age being related to the Celtic tribes of the 5th century BC (Buchwald, 2005, Chapter 5).

With regard to the Carpathian Basin, another significant influence of note is that originating from Western Siberia, a continuation of the northbound spread of the iron metallurgy from Asia Minor. According to Gömöri (2000, p.219), the ancient technology was brought to the Carpathian Basin by the Scythians who moved westward from the Sarmatians. However, despite the intensive Celtic iron-working activity and Pannonian Roman forges in the surrounding area, the earliest traces of furnaces which were sufficient for the bloomery process had only been found on sites in Hungary that related to the Avar culture (7th–8th century AD) (Gömöri, 2000). The oldest iron slag found within the territory of modern Hungary belongs to the findings of a pre-Scythian tomb (Patek, 1984).

Iron blooms – the primary products of ancient iron metallurgy – are sporadically known from the Late Bronze Age. One of the oldest blooms found in the Carpathian Basin (Torna'la, South-Slovakia, Hallstatt B3) weighs 2.5 kilograms and is considered to be unique. From this raw material alone, it would be possible to make 3 longswords, 6–8 axe heads, or a hundred smaller knives (Furmánek, 1988). In addition, numerous blooms weighing 1–2 kg have been found in modern Slovakia that originated from the Hallstatt culture (particularly from the south-western foothills of the Carpathians), although a great portion of these belong to objects identified as forges. These low-phosphorus-content blooms were heterogeneous in quality, with a composition ranging from pure ferrite to pearlite and a carbon content of between 0.02% and 0.7% (Pleiner, 2000, p.231).

The artefacts excavated in 2011–2012 at the site of Regöly (located between Lake Balaton and the Danube in Hungary, see Figure 1) can play a key role in the research of the Early Iron Age in Europe. Almost seven thousand pieces of metal, ceramics, bones, and lithic finds have been excavated from the central part of a mound (tumulus). Based on the structure of the mound and archaeological examination of the pottery sherds, the metal objects can be assumed to have connections both to the east (Scythian culture) and west (Hallstatt culture) (Fekete-Szabó, 2015 and 2017). According to our current knowledge, the fragment of a presumed iron bloom (Figure 4a) from the Regöly site may be the earliest example of iron working in the Carpathian Basin (630–600 BC) This then raises several questions from both historical and technological points of view.

From 630 BC, in the southwest area of present-day Hungary, Croatia, and Slovenia, and the area alongside the Danube to the Adriatic Sea, there were several archaeological groups that related to the material cultures of eastern Asia (Regöly, Kaptol and Martijanec). According to Herodotus, these can be identified with various tribes of the Sigynnae (Szabó and Fekete, 2014; Szabó, 2020). As far as their origins are concerned, they were probably of the Medes,

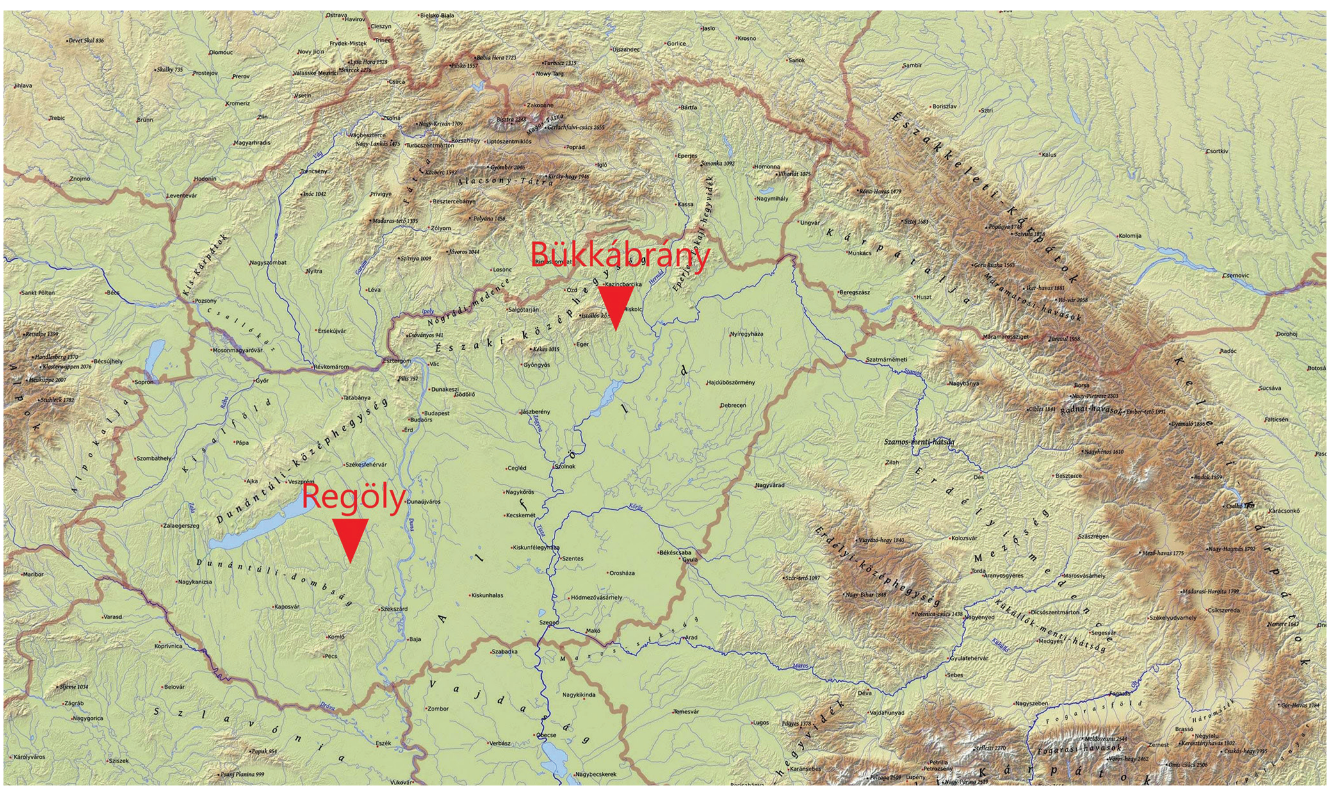

Figure 1. Map showing the locations of Regöly and Bükkábrány in Hungary.

later known as Illyrians and Pannonians. It also raises the possibility that the iron arrowheads and fragments of scaled armour from Regöly and similar scales from Jalžabet (620–600 BC) were brought to the Transdanubian region, but not by the Scythians (Horváth and Szabó, 2015). One of the most interesting properties of the finds from Regöly are not directly related to the Scythian culture (Kürthy *et al.*, 2018; Gyöngyösi *et al.*, 2019), despite most of them being clearly of eastern origin and also Scythian in date. The analysis of the archaeological, historical background and pottery finds clearly defines a group of people who, although in their roots of steppe origin, crossed the Caucasus and came directly to the Carpathian Basin from Asia Minor. The discovery of the Regöly bloom (or bar) fragment also raises another possibility: that the most ancient iron metallurgy and iron working technology was brought directly to the Carpathian Basin from Asia Minor with this migrating population.

For this reason, it is extremely interesting to compare the results of the Regöly study with another Iron Age site, namely, Bükkábrány (Hungary, La Tène B2–C1, Figure 1), where Scythian and Celtic cultural elements have been mixed. Agricultural and economic remains (pottery kilns, bronze crucibles, iron tools, textile remains) have been unearthed at this site; however, except for two iron artefact deposits, no bloomery furnace has been identified and no metal working tools found. On the other hand, iron slag pieces can be found in the fillings of all the Iron Age features (pits and workshop-type buildings).

There is a further example of the mixing of archaeological artefacts by the aforementioned two cultures within the same site. In this case, the time period is set according to the archaeometallurgical examination of the iron objects. A grave of a highly-ranked person with a burial assemblage has been unearthed at Bátmonostor, Hungary, being dated to 600–400 BC (Gyucha *et al.*, 2015). While the grave construction and most of the ceramic, antler, bronze and iron findings revealed from the burial assemblage fit well in the Scythian Period of the Great Hungarian Plain, there is also a quantity of grave goods and several iron weapons, such as a long axe, a shaft-hole axe and a trunnion axe, which bear resemblance to the Transdanubian Hallstatt Culture. The archaeometrical investigations clearly indicate that they could choose from among different manufacturing processes (Török *et al.*, 2016). However, no finds suggesting the existence of an iron production process (*e.g.*, iron slags, fragments of a bloom or bar) were found at this site.

According to our existing knowledge, finds from the Iron Age, which are not parts of an iron artefact, but represent intermediate results of the iron's production process (*e.g.*, bloom or bar), have only been found in the previously mentioned sites of Regöly and Bükkábrány.

The main goals of this case study were the characterisation of the iron finds and the presumed iron bloom fragment (microstructure and chemical composition) from Regöly. In addition, a study of the slag inclusions and search for possible traces of compacting and purification by hammering

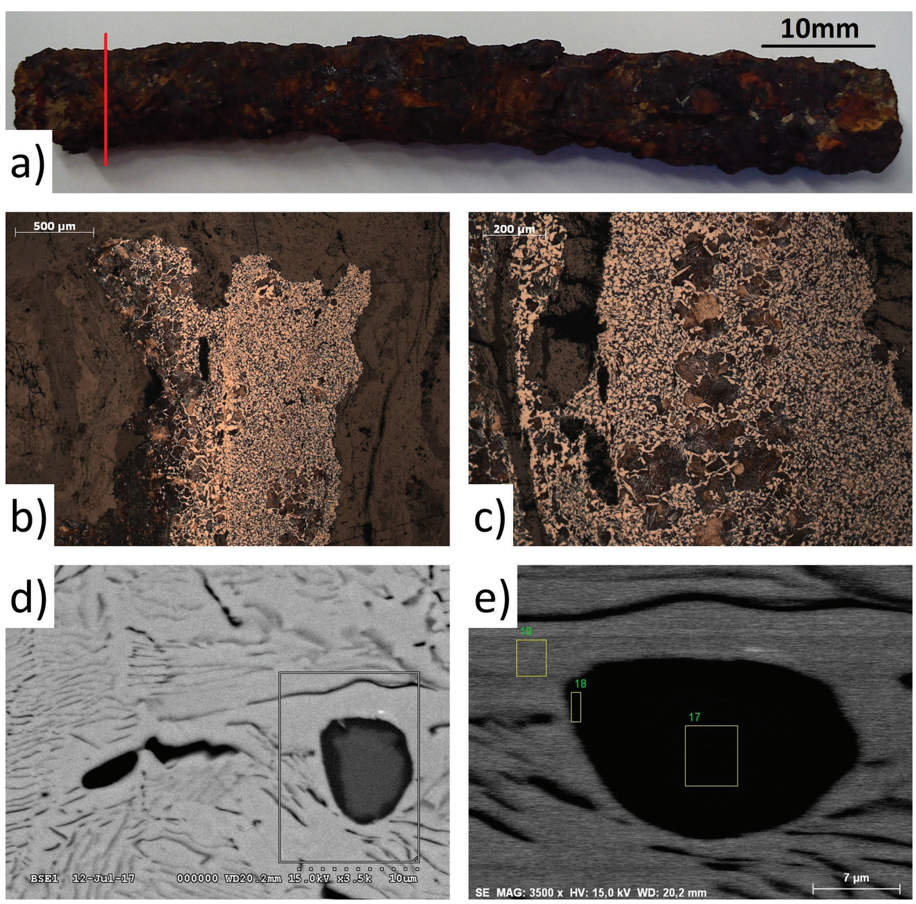

Figure 2. a) Object R1: Needle or awl fragment from Regöly. Red line shows the examined section; b) and c) optical microscopic images; d) and e) SEM images of inclusions and their immediate surroundings.

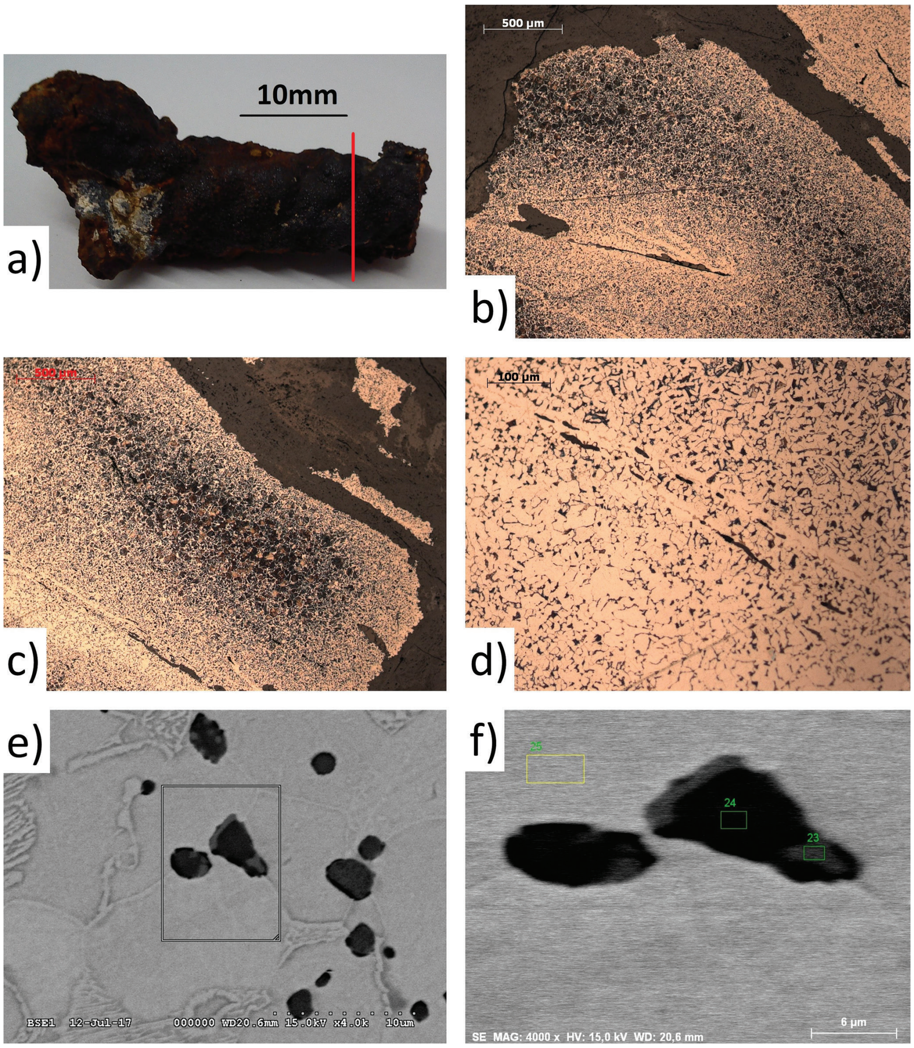

Figure 3. a) Object R2: Needle fragment from Regöly. Red line shows the examined section; b), c) and d) optical microscopic images; e) and f) SEM images of inclusions and their immediate surroundings.

were made. Lastly, a close comparison was made with the microstructures of similar fragments found in the Late Iron Age workshop-type site of Bükkábrány. Primarily, we sought answers to the following questions: what kind of iron process are we dealing with? Can the aforementioned possible bloom fragment be linked in any way to an iron object found at the Regöly site?

We would like to highlight the fact that the focus of this study is not so much on the presentation and comparison of the archaeological aspects of the two sites based on the examined samples, but rather a determination of the role and place of production of these rare finds in the technology of the iron-production cycle, using metallography as the archaeometric method.

2. Materials and methods

During the examinations, samples were taken from five iron objects from the Regöly assemblage (R1–R5), and two from the finds of Bükkábrány (S-73, S-551). The primary goal in every case was to obtain microstructural and compositional information. The description of microstructure establishes the state of manufacturing, as well as the most probable methodology. Composition analysis concentrates on the examination of inclusions to reveal their origin and quality.

2.1 Objects from Regöly

The archaeological aspect of the tumulus site from Regöly has been already discussed in the introduction. Five iron objects were selected from this site. In the case of four of them, their function could be deduced from their shape: a fragment of a needle or an awl (R1, Figure 2a), a fragment of a needle (R2, Figure 3a), a fragment of a nail (R3, Figure 4a), and a plate fragment from scale armour (R4, Figure 5a). These objects were thus well suited for investigation, but one object was different from the rest. The purpose of the object sample R5 (Figure 6a) could not be identified based on its shape; according to its nature and shape it was assumed to be a piece of raw material (iron bloom) or of some preproduction (*e.g.*, a bar).

2.2 Objects from Bükkábrány

Archaeological aspects of the site of the Late Iron Age at Bükkábrány have already been described in the Introduction. Metallic fragments (Figure 8) were found among the slag

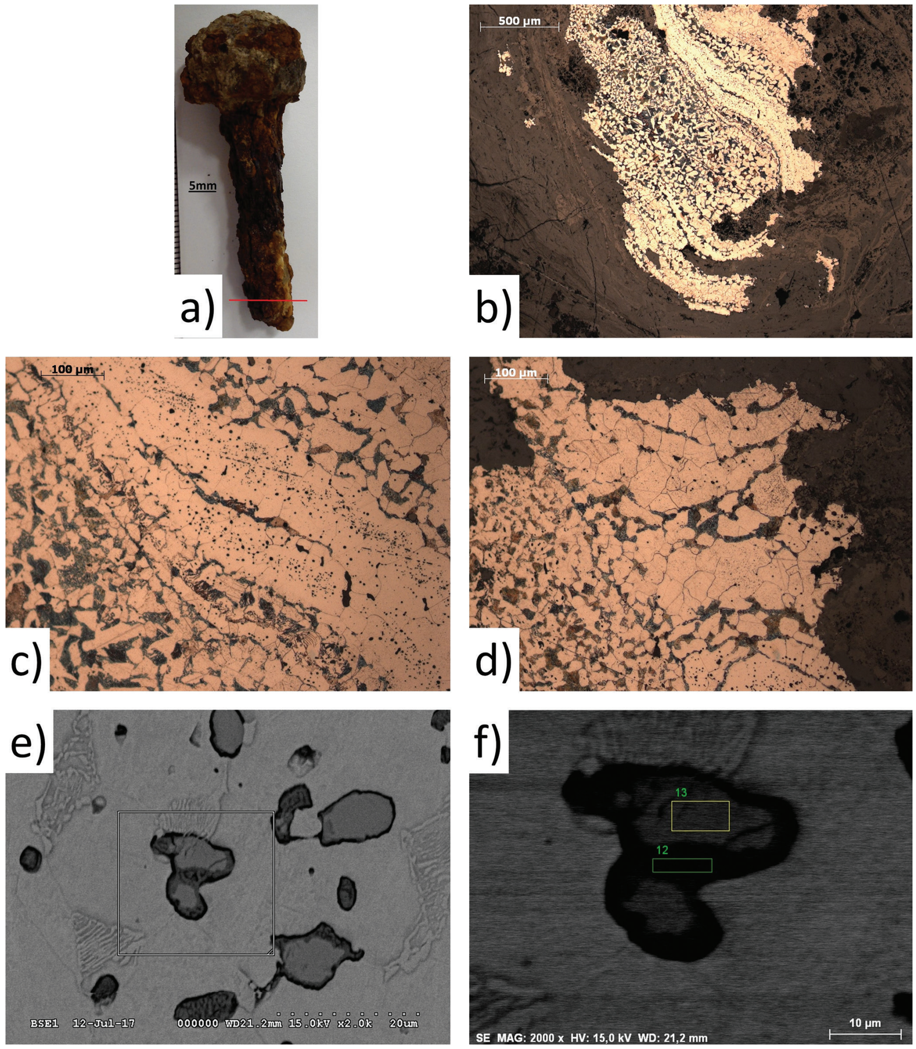

Figure 4. a) Object R3: Nail from Regöly. Red line shows the examined section; b), c) and d) optical microscopic images; e) and f) SEM images of inclusions and their immediate surroundings.

finds and were selected for archaeometallurgical analysis. The two iron fragments from Bükkábrány shared similarities with the R5 sample find from Regöly – not being parts of a complete iron artefact and coming from a site where a mixture of both Celtic and Scythian cultures was observed – thus indicating the comparability of the objects.

2.3 Optical microscopic examinations

The essential aim of the optical microscopic investigations was to study the microstructure in detail: the different phases, their fraction and characteristic size, making it possible to determine the state of the metal in the technological process. Hence their manufacture and its main parameters can be estimated based on a knowledge of the effects of deformation, and the temperature by the phase transformation processes (Mehofer, 2006; Mihok and Kotygoroshko, 2009; Hošek and Meduna, 2011; Stránský, 2011; Košta and Hošek, 2014, Chapter 3). The carbon content (local or average), which has a fundamental influence on the structure and mechanical properties of the object, also can be estimated. This is based on the volume fraction of different phases (Buchwald, 2005; Muňoz *et al.*, 2006; Blakelock and McDonnell, 2011; Larreina García and Quirós Castillo, 2018). Samples were cut from the objects for metallographic study by sawing with great care. The cut surface was subjected to mechanical grinding and polishing, followed by etching via immersion in nital solution (2%). Optical imaging was performed using a Zeiss Axio Imager M1m optical microscope in bright field. Inclusions and slags were also observed and selected for further testing.

2.4 SEM-EDS analysis

The main goal of the SEM-EDS examinations was to reveal the microstructure of the inclusions and to determine the local chemical composition in oxide forms, and different phases of the inclusions. The analysis was carried out on each above-mentioned sample. Shape, microstructure and composition of the inclusions, as the remainders of slag created during the smelting and/or forging, can provide useful information about the several stages of processes (Schwab *et al.*, 2006; Dillmann and L'Héritier, 2007; Blackelock *et al.*, 2009; Żabiński *et al.*, 2016). Furthermore, SEM allows us to examine the phases, morphology and microstructure of the sample in higher magnification than in the cases of OM examination. SEM-EDS analysis of the samples of Regöly finds involved a Hitachi S4300 CFE electron microscope, equipped with a Bruker energy dispersive spectroscope. In the case of the

Bükkábrány samples, further imaging was done with a Zeiss EVO MA10 scanning electron microscope equipped with an EDAX energy dispersive spectroscope.

3. Results

Five objects were sampled from the Regöly assemblage for preliminary examinations. All objects were fragmentary while the original function of two of the objects were unidentifiable. The rest included a plate and a nail, and another one may have been a fragment from a metallurgical product, possibly a bloom or bar. One of the main goals of this study was to identify the state of manufacture of this fragment (R5). The other objects were analysed to reveal whether they were produced from the material of this R5 fragment. Besides the metallographic analyses, an examination of inclusions was also carried out. The following paragraphs provide the details of the results. Table 1 shows the compositions – in wt%, calculated on the oxide constituents based on the metallic element concentrations – of the inclusions that were measured by EDS.

3.1 Sample R1, a fragment of a needle or an awl

The images of the sample of R1 (fragment of a needle or an awl, Figure 2a) show a ferrite-pearlitic structure in equilibrium (Figures 2b and 2c). Although the ferrite fraction is not homogenous in the studied cross-section (Figure 2c), the carbon content is estimated to be 0.6% based on the phase ratio of the structure. The most probable manufacturing method is the so-called "bulk hot forging" with no folding. The cross-section shows a few small, spherical inclusions. The typical inclusion visible on Figure 2d has a two-phase microstructure. EDS analysis was carried out on the areas marked with yellow on Figure 2e. The results are compiled in Table 1. Area 17 is aluminium-silicate with a high potassium content (most likely leucite and perhaps kalsite, though it was not confirmed by mineralogical investigation). A high amount of the potassium content comes from the ashes of charcoal (Török *et al.*, 2018). In some other inclusions of the sample, Ca-Mg-silicate was typically found instead of Al-silicate. Potassium oxide is also relatively high in these cases (>3%), and the iron-oxide content is much higher than in the case of area 17, but it is still lower than 37%. In area 18, iron-oxide is the dominant component, but the 13% of SiO_2 reveals the presence of fayalite ($2FeO \cdot SiO_2$) as well. This micromorphology could form during a fabrication step – for example hot forging – at high temperature. Area 19 is the base material (metallic iron) with a minimal content of excited slag inclusion. The inclusions have most likely originated from the forging process because of the relatively high amount of potassium and the lack of a considerable amount of manganese and phosphorus (Selskienė, 2007).

3.2 Sample R2, a fragment of a needle

The microstructure of object R2 (fragment of a needle, Figure 3a) has a similarly ferrite-pearlitic structure (Figures 3b and c) to that of R1. The ferrite distribution along the cross-section is similarly not homogeneous (Figure 3c). Based on the phase ratio, the carbon content is estimated to be 0.4%. The ferrite-rich areas contain larger ferrite grains (Figure 3d). The overall structure clearly shows that the material was folded during forging. Boundaries between two layers are visible in Figures 3c and 3d. Long and fragmented inclusions can be seen along the boundaries (Figure 3d). The object has a significant extent of corrosion and hence the number of folds cannot be precisely established. However, it is certain that there had been more than one folding. The microstructure is close to equilibrium, thus indicating the most probable manufacturing technique is hot forging and slow cooling, including folding in the process. This suggests that the inclusions were most likely formed on the surface or interphases during the forging process. Analysis shows that these inclusions also have two-phase microstructures (Figure 3f and Table 1). Area 25 is the base metal with a similarly minimal content of excited slag inclusion as in the case of R1. In the inclusion, silicate phases with very high silicon content are visible. Each one contains potassium, but in lower quantities compared to the first sample R1. Considering all the results, it is not obvious whether the inclusions originate from the bloomery process or forging process.

3.3 Sample R3, a fragment of a nail

The traces of folding are also identifiable in the microstructure of object R3 (a nail, Figure 4a). In the cross-section, multiple layers are visible; however, the exact number cannot be determined due to strong corrosion (Figure 4b). The structure mainly consists of ferrite-pearlite (Figure 4c). Its heterogeneous distribution is a result of forging the layers together (Figure 4d). Ferrite grain size greatly differs in the purely ferritic areas (20–30mm) compared to the ferrite-pearlite layers (50–70mm), this being a result of the behavioural differences of the material during plastic deformation and secondary phase formation. It can be observed that higher ferrite content leads to a larger grain size. Inside the layers an equilibrium microstructure is found; the presumed manufacturing method is hot forging with folding. The last forming step was also performed at high temperature, followed by slow cooling. The estimated carbon content based on the structure is approximately 0.4%. SEM-EDS analyses of the two-phase inclusions show that the iron content is significantly high in both phases (Figures 4e and 4f, Table 1). In area 13, an extremely high iron content was measured. This was because metallic iron was also excited there during measurement. When repeating the analysis at several other inclusions of the sample, in addition to iron oxide, high silica (~20%) and moderate amounts of aluminium, magnesium and calcium oxide were observed (2–4%). Iron-rich complex oxides were also identified, which suggest that the final composition and structure of these inclusions were formed during the forging process.

Regarding the general microstructure, carbon content and inclusions of the examined samples, the three objects can

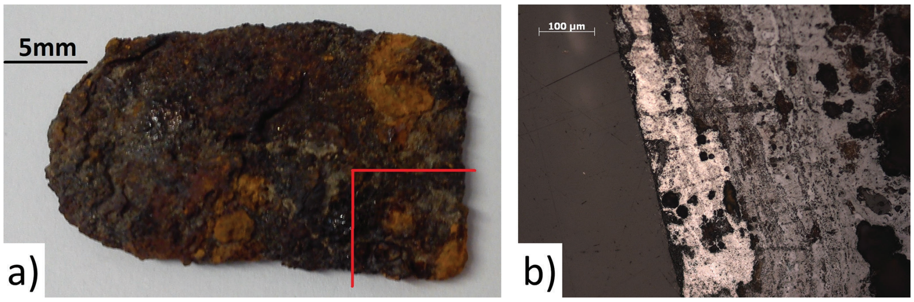

Figure 5. a) Object R4: Armour plate fragment from Regöly; b) OM image of the sample of object R4.

be considered similar. The manufacturing technology is also similar in the case of R2 and R3. Object R1 shows no traces of folding; however, the similarities in material composition are evident. Comparing these results, it can be determined that the objects could have been made from the same type of raw material or prefabrication.

3.4 Sample R4, a plate fragment from scale armour

Object R4, a plate fragment from scale armour, was corroded to such an extent that only a small amount of metallic area was visible on the cross-section (Figure 5). This metallic area was not suitable for metallographic and chemical analysis due to the strong effect of the corrosion. It is not possible to deduce the manufacturing technique or the raw material. The only thing which can be seen is that the carbon content of the iron was low. Inclusions did not identify clearly in the section, but the corrosion could also modify the composition of the inclusions.

3.5 Sample R5 fragment

The purpose of the original object (Figure 6a) of sample R5 cannot be identified based on its shape. Nevertheless, it has become a central element of our case study from a metallurgical point of view, since its nature and shape, is pre-assumed to be a piece of raw material (bloom) or of preproduction (bar). This preliminary assumption is also

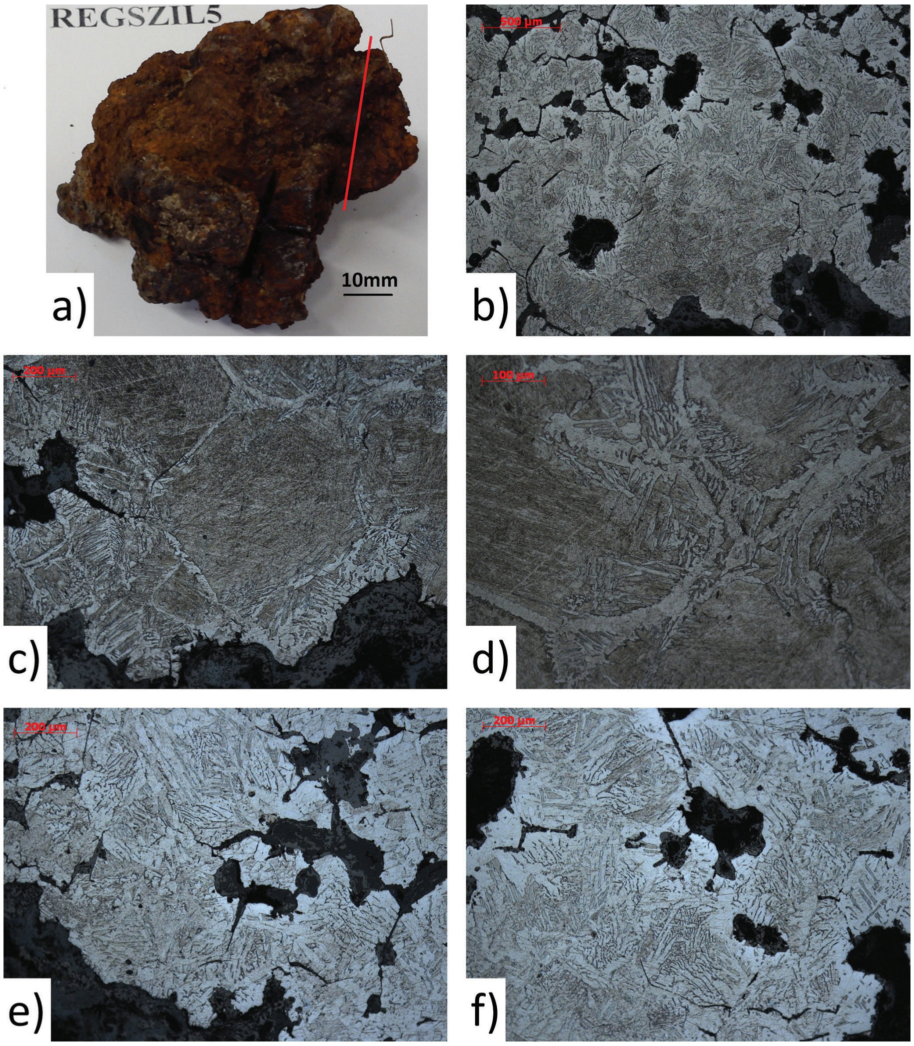

Figure 6. a) Object R5: presumed fragment of bloom or bar from Regöly; b), c) and d) optical microscopic images of the sample R5. A strong Widmanstätten character can be seen in the ferrite-pearlitic structure.

Table 1. Results of EDS analysis of inclusions and adhered slags from the samples from Regöly and a slag sample from Bükkábrány (in wt%).

Area	Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	K_2O	CaO	TiO_2	MnO	FeO
Fig.2e/17	0.22	0.06	14.60	68.21		14.13	0.41	0.21	0.08	2.07
Fig.2e/18	0.14	0.57	1.60	13.06	0.14	0.30	3.61		0.23	80.36
Fig.3f/23	0.27	2.88	1.68	32.91	0.44	0.80	4.47		3.30	53.25
Fig.3f/24	0.46	0.58	2.74	29.99	0.52	1.50	7.45	0.25	1.33	55.17
Fig.4f/12		0.64	0.88	14.17	0.07	0.47	2.48	0.16	0.85	80.28
Fig.4f/13			0.96	2.55	0.08		1.06			95.36*
Fig.7b/30		0.07	0.42	0.17		0.06	0.38	0.48		98.43
Fig.7b/31		0.80	1.94	24.64	0.60		4.13	0.40	0.80	66.70
Fig.7d/32	0.13	0.31	6.56	21.51	0.45	0.34	2.61	0.35	0.33	67.40
Fig.7d/33		1.71	1.50	25.12	0.30	0.07	5.87	0.28	0.97	64.18
Fig.10d/1		1.68	0.16	1.00	0.56	0.18	0.48	0.53	1.28	94.14
Fig.10d/2	0.25	1.16	3.99	49.10	0.64	2.62	16.81	0.83	0.82	23.78
Fig.10d/3	0.10	0.47	6.53	62.79	1.03	0.17	2.30	0.63	0.40	25.59

* Metallic iron is also an excited state (see section 3.3).

supported by the microstructure analysis (Figure 6b–f). The cross-section contains a network of grain boundary ferrite, Widmanstätten-type ferrite, and bainitic (Figure 6f), but in some places with pearlitic parts (Figure 6d). The Widmanstätten character is significantly strong (Figures 6c and 6e). The microstructure leads to the conclusion that the object was rapidly cooled from high temperature, but not fully as in a quenching method.

The ferrite net displays the austenite grains from which it developed. These large grains range between 500–600 mm approximately (Figure 6c). The object was kept at a high temperature for an extended period in an austenitic state. The microstructure along the cross-section is compact and more homogenous than is the case for objects R1–R3. Only pores and cracks from corrosion are visible (Figures 6b and 6e). The metal was subjected to hammering and compacting. Only a few but large-sized slag adhesives were visible at the surface of the sample, which differentiates the fragment from the previous objects. These slag pieces consist of multiple phases with dendritic structures (Figures 7a and 7c), which are most characteristic of inclusions that form during smelting. EDS analysis was performed on the sample. It can be seen at higher magnifications in Figures 7b and 7d, and the compositions are presented in Table 1. Complex silicates are visible, while the dark matrix material has a higher iron content. The dendrites contain more silicon and less iron. The composition

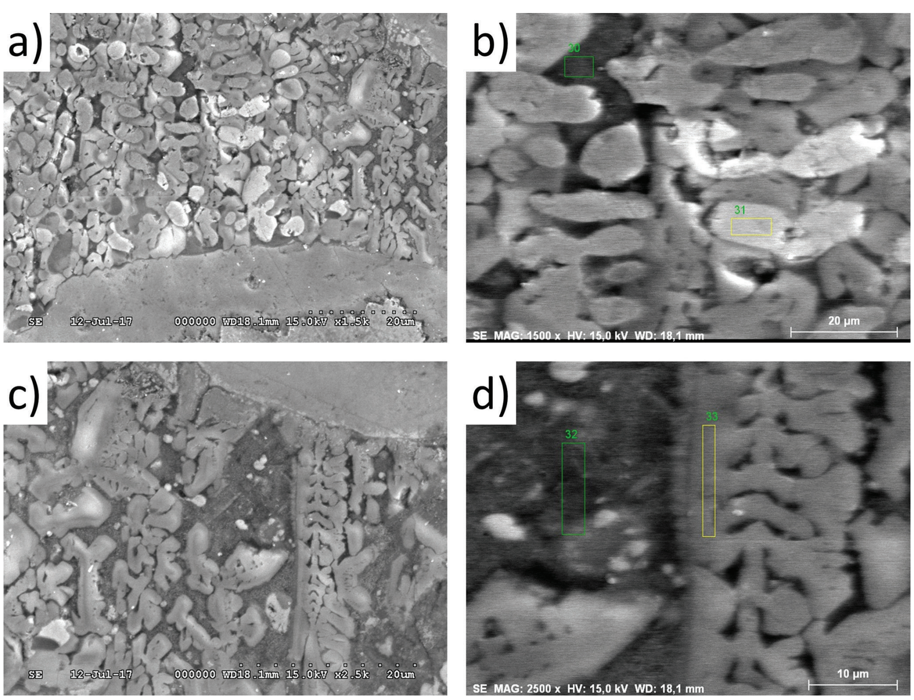

Figure 7. SEM images of slag adhesives from object R5.

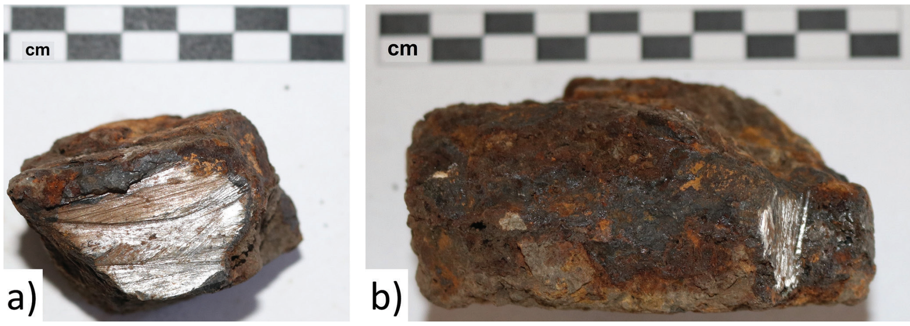

Figure 8. The examined objects from Bükkábrány. a) S-73 and b) S-551.

characteristics also suggest the slag pieces originated from smelting. The quality, size and appearance of the adhered slag are vastly different from the previous samples (R1–R4), which leads to the conclusion that this fragment is not a part of a finished product; instead, it is a raw material that could have been used for manufacturing other objects.

The microstructure of object R5 can be considered more homogeneous while the objects R1–R3 contain inhomogeneous structures. The question then arises of how the presented objects or similar could have been made from this material. It must be taken into consideration that the object R5 is relatively small compared to the other objects, and the sample taken from it is also small.

3.6 Sample S-73 from Bükkábrány

Two metallic iron fragments (S-73 and S-551) found at the aforementioned Iron Age site in Bükkábrány were also examined. The S-73 sample was approximately a 5-cm-long solid piece of iron with a very thin layer of slag on the surface. The S-551 sample was an embedded metallic part of a piece of slag (Figure 8). The examined slag pieces and the previously mentioned two samples showed typical characteristics of forging slags (Török and Kristály, 2020).

The microstructure of sample S-73 varies greatly due to the inhomogeneous carbon distribution (Figure 9). Most of the sampled area was pearlitic (Figure 9a), but it included large areas of ferrite as well (Figure 9b). A secondary carbide net could be found with carbide particles in carbon-rich areas (Figures 9c and 9d), thus creating brittle spots in the material. In areas with a higher carbon content, even precipitated carbide grains were observed along with the pearlite. The structure shows that the object was subjected to hammering, with hot forging at an austenitic temperature range completing the final step of the process. If the temperature had been sufficiently high enough, then the carbide could dissolve into the austenite and this effect was not realised. The cooling from the austenitic range is not considered to have been fast. The Widmanstätten characteristic can be observed on the ferritic area (Figure 9b); however, this is not as significant as in the case of object 5. The inhomogeneous structure of this sample is considerably closer to the objects R1, R2 and R3 than is the case for sample R5.

3.7 Sample S-551 from Bükkábrány

The sample S-551 has a heterogeneous microstructure. Ferritic, ferrite-pearlitic (Figure 10a) and purely pearlitic

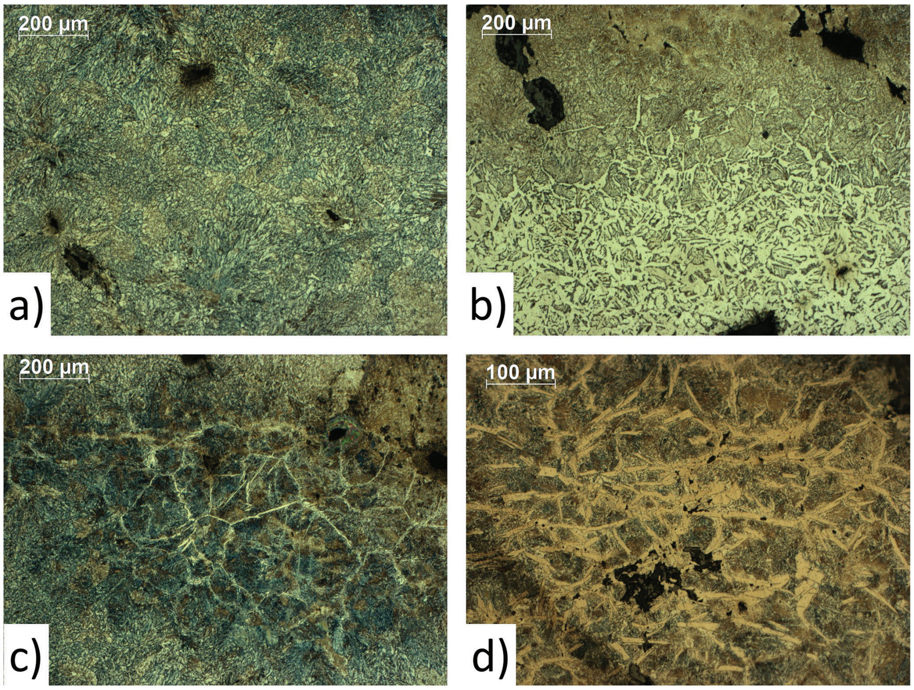

Figure 9. Optical microscopic images of sample S-73.

(Figure 10b) areas can be observed with a secondary cementite net forming around the pearlite. In one area the carbon content is high enough to form carbide grains within the austenite, while in another area eutectic ledeburite is also visible (Figure 10c, upper right corner). A kind of localised melting has occurred, the resulting ledeburite and the surrounding cementite network producing a brittle material difficult to forge. Figures 10d and 10e show the microstructure of this ledeburite grain at higher magnifications. The overall structure shows a greater extent of heterogeneity compared to S-73.

The metallic piece of object S-551 is embedded in slag. The 'slaggy' part of the sample has also been examined. A SEM micrograph of a slag sample belonging to this bloom fragment shows the typical structure of slag that has originated from the bloomery process (Figure 10f) with wüstite (FeO) dendrites (1) and CaO-rich spots (3) in a fayalite matrix (2). The composition of the examined areas can be seen in Table 1. A similar microstructure of slag samples from several Late Iron Age Celtic forge sites have been found by SEM-EDS analysis (Török and Kristály, 2020). In this case, the iron oxide dendrites are deformed, which may have been caused by the forging process, and the silicate particles do not appear in well-defined shapes. Furthermore, the fayalite is not observed in the lath form that is common in metallurgical slags (Kristály and Török, 2020).

4. Discussion

At the Regöly site, where traces of intensive bronze working were also found, several iron objects were excavated from the Early Iron Age, which leads to the question of whether any kind of iron processing was also part of the metal working activity here. A positive answer to this question is supported by the fact that an iron fragment, that cannot be identified as an object of any kind but may instead have been part of an iron bloom, was unearthed. A major aim of this study was to examine this fragment and determine its manufacturing state. Furthermore, additional iron objects were analysed to understand the structure of a so-called 'finished' product, and to achieve our goal of determining if these objects could have been made from the material of this 'bloom' fragment.

The examination of the objects revealed that their structure is very inhomogeneous, with pearlitic and ferrite-pearlitic areas next to each other. All have been made by hot forging

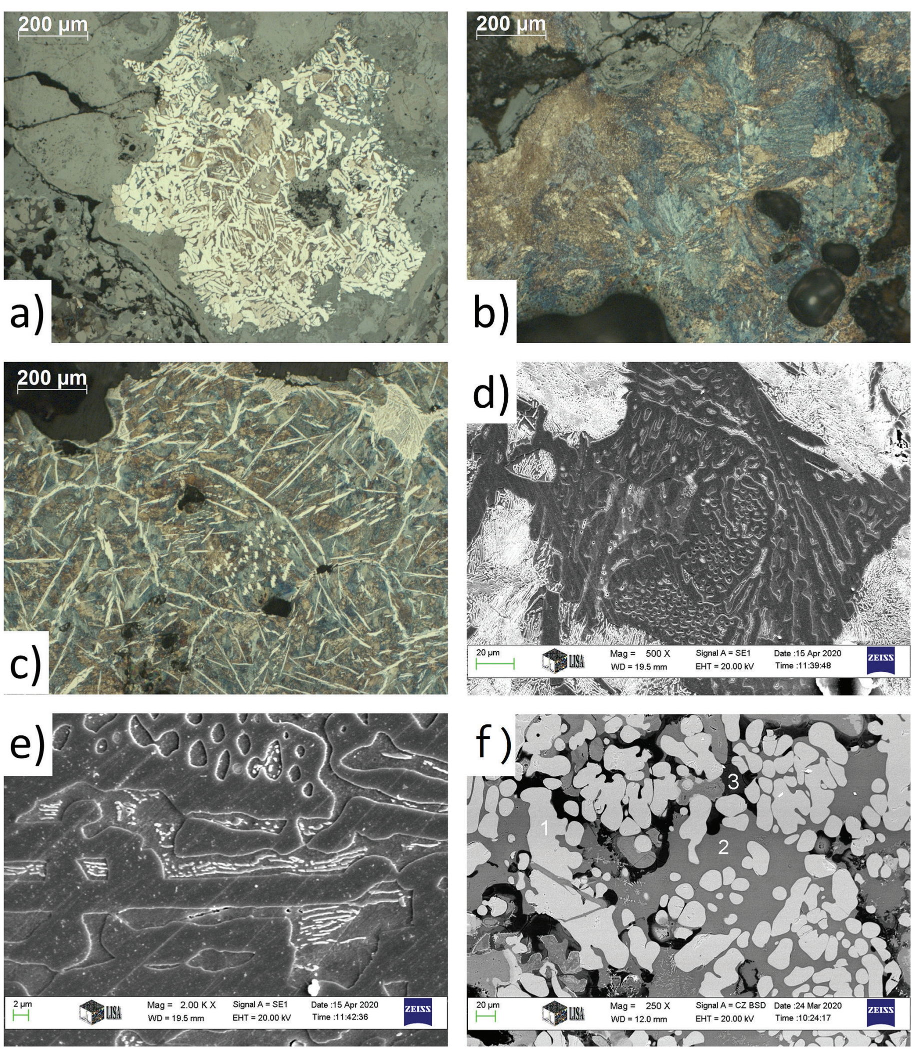

Figure 10. OM and SEM images of sample S-551.

and signs of folding can be observed in two cases. Small spherical inclusions can be found in the base metal as a result of this technique.

However, object R5 is different both in microstructure and inclusion characteristics and this leads to an important and complex question which was the main focus of this study: what element of the whole iron working process can be identified? Is it raw material, prefabrication, or more probably a semi-finished product? Another question is whether there is a manufacturing connection between the fragment and the excavated iron objects? Products of different stages of iron making and iron working – from bloom, through the blacksmith's starting stocks, to manufactured objects – have been discussed in several comprehensive works in the literature (*e.g.*, Tylecote, 1992, pp.48–49; Buchwald, 2005, pp.151–157; Pleiner, 2006, Chapter 4).

Although the microstructure of object R5 is mainly ferrite-bainitic and pearlitic and the average carbon content is close to that of the objects, it also contains a significant amount of Widmanstätten ferrite, which is in good agreement with the microstructure. This suggests that the object R5 might have cooled faster and from a higher temperature than the other objects. The slag adhesives of this fragment are large with a dendritic microstructure. Based on their composition and structure, the origin of the slag adhesives can be most connected to the smelting process. The structure of object R5 also shows signs of compacting (hammering), which might have led to the modification of the slag adhesives. The first assumption is that this fragment is from an intermediate product that is more closely related to smelting than forging. However, the general characteristic of the base metal of the fragment does not show the obvious traces of primary smelting; it could rather be a product from a low degree of processing. The comparison is made more difficult by the fact that the small sample taken from the R5 fragment shows an almost homogeneous microstructure, which leads us to the conclusion that the examined objects are not related to the fragment. However, it is well known that iron blooms have an extremely inhomogeneous structure (Buchwald, 2005, pp.101–105; Pleiner, 2000, pp.230–244; Török *et al.*, 2018); but usually, heterogeneity can also be seen in pre-products. The change in the typical microstructure, due to the inhomogeneity of the carbon content, may be on a much larger scale over a much larger area than the examined surface of our sample. In other words, a material that is homogeneous on a smaller scale can be otherwise distinctly heterogeneous over a larger area; hence our first assumption cannot be certain.

4. Conclusion

According to our knowledge there are only two Iron Age sites in Hungary where an iron piece has been found that is not a part of a well-fabricated iron object, rather it being in a primer, or bloom or bar, state of the production process. Several fragmented iron objects from the Early Iron Age have been found at the site of Regöly. However, one fragment cannot be identified as an object of any kind, and instead may have been part of an iron bloom or bar. The results of the metallographic examination of this (R5) iron fragment were compared with samples of fragments of some artefacts from Regöly, as well as samples of pieces of pre-products of a slightly later period from the site of Bükkábrány. In the case of the samples from Bükkábrány, an intermediate step of metal working procedure was surely identified, which helps us to identify the role of the R5 fragment from Regöly within the whole iron-manufacturing process. In both samples from Bükkábrány a similar ferrite-pearlitic area can be seen, even to a similar extent, but we can also find areas of pure pearlite and even a few areas of secondary cementite and pearlite. Such a nature as found in these pre-products is a result of the technical characteristics of the smelting process. Most likely, areas with similar properties to that mentioned could also be found in the object R5 by further more extensive sampling. However, in that case, the whole R5 sample would be completely ruined, which is clearly not permitted. In view of this, the R5 fragment might even be connected indirectly to the other iron objects examined. Unfortunately, a direct connection between the examined iron objects and the iron bloom or bar fragment as a possible raw material cannot be confirmed. However, the iron artefacts found at Regöly might have been made from some basic material represented by the R5 fragment from an iron bloom or bar.

Although object R5 from Regöly does not provide the earliest evidence for the technology of iron smelting in the Carpathian Basin, it does give evidence of iron forging from a pre-product. At the same time, however, it can be assumed that the local production of iron objects was not made from locally smelted material, but rather from foreign pre-products.

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