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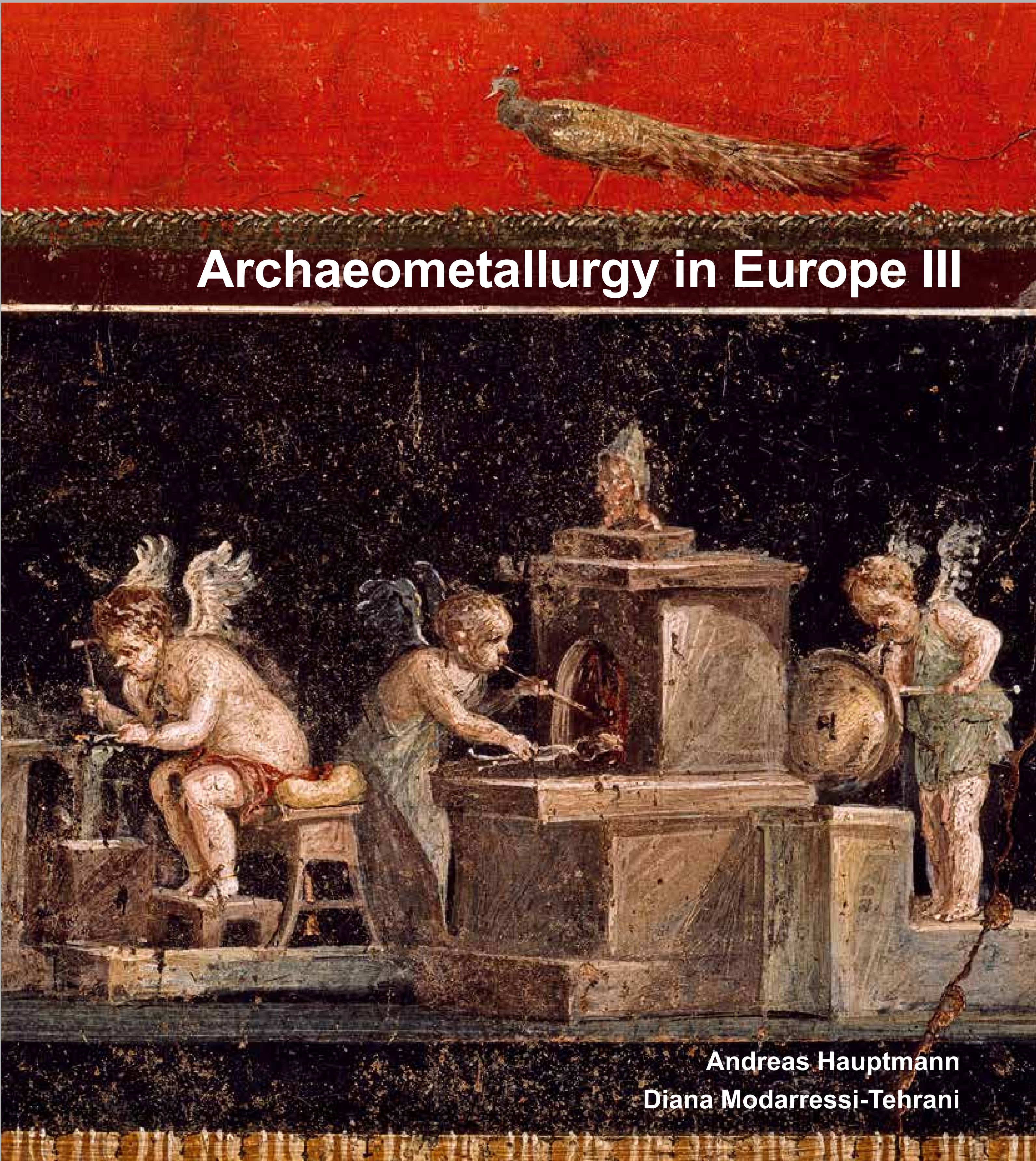

Archaeometallurgy in Europe III

Andreas Hauptmann
Diana Modarressi-Tehrani

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Domus Vettiorum / Casa dei Vettii, Pompeii (Campania, Italy, 63-79 BC), which was excavated in 1894. Section of a Pompeii-style scenic fresco showing Erotes and Psyches in a gold assay laboratory. In the left corner, scales for weighing gold are put on a table. Next to it, one of the Erotes is working with a small hammer on an anvil. On the right side, an assay furnace is shown. Another of the Erotes is holding a small crucible with pincers with the right hand while using a blowpipe with his left hand, supplying the fire with air. The large bellow for the assay furnace is driven by the third of the Erotes.

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Editorial

This volume comprises a range of articles, which were submitted and selected from all the presentations given on the International Conference ”Archaeometallurgy in Europe III”, held from the 29th of June to 1st of July 2011 at the Deutsches Bergbau-Museum Bochum, Germany.

The present volume is the third in the series “Archaeometallurgy in Europe” , capturing the spirit of the successful series of international conferences on this special theme of research. The first conference “Archaeometallurgy in Europe” had been organized by the Associazione Italiana di Metallurgia and took place in Milano, Italy, from the 24th to the 26th of September 2003. The second conference was held in Aquileia, Italy, from the 17th to the 21st of June 2007. It was also organized by the Associazione Italiana di Metallurgia.

The splendid idea to launch this conference series, a scientific series of meetings limited to the countries of Europe, came from the late Prof. Dr. Walter Nicodemi, formerly President of the Assoziazione Metallurgia di Italia. Thanks to the efforts of Dr. Alessandra Giumlia-Mair, Merano, these conferences have developed into increasingly productive events with a high scholarly quality. Since then three conferences have taken place and the fourth meeting is at an advanced stage of preparation and will take place in Madrid, Spain, from the 1st to the 3rd June 2015.

The title of the conference series covers a research field which is a distinctive part of archaeometry, and which so far was usually included as one of the topics in the program of the “International Symposium on Archaeometry” (ISA), organized every third year at different locations in Europe and in the United States. However it is our opinion, that in the last decade archaeometallurgy has developed as a very important research field, and we are observing a large number of scholarly activities all over the world. We are convinced that such an important topic needs to be organised and presented in conferences specifically dedicated to this field. Therefore the topic of this conference is the history of metals and metallurgy primarily in Europe, but it also includes other regions of the Old World.

The future prospects of the conference series are promising, especially because “Archaeometallurgy in Europe” constitutes an extremely useful broadening and a regional counterpoint to the well-established and successful conference series “The Beginnings of the Use of Metals and Alloys” (BUMA), which was launched in 1981 by Professors Tsun Ko, Beijing, China, and Robert Maddin, then Philadelphia, USA. The focus of the eight BUMA conferences held so far (the last one was held in Nara, Japan, in 2013) lays on the development of metallurgy in South-East Asia and the Pacific Rim. We firmly belief that the two conferences complement each other very effectively and should therefore continue to exist side by side.

With this special volume of *Der Anschnitt*, we are delighted to publish a selection of the lectures presented at the conference at the Deutsches Bergbau-Museum Bochum in 2011. Many of the authors contributed with very instructive and informative papers, which finally resulted in this volume.

We are very much obliged to all these authors who, with patience and persistence, cooperated with us and helped to shape this volume. We would also like to thank the reviewers who decisively contributed in the improvement of the scientific level of this volume.

Our thanks go first to all those colleagues and friends who helped to organize the conference in 2011. The former director of the Deutsches Bergbau-Museum, Prof. Dr. Rainer Slotta, and the present director, Prof. Dr. Stefan Brüggerhoff encouraged and promoted our efforts to organize this scholarly meeting. Dr. Michael Bode, Dr. Michael Prange, and Prof. Dr. Ünsal Yalçın supported the conference planning and realization in every aspect. Many colleagues of the staff of the Deutsches Bergbau-Museum, and many of the students working in our research laboratory offered their assistance and help.

Finally, our thanks go to Mrs. Karina Schwunk and Mrs. Angelika Wiebe-Friedrich who performed the editorial work, design, and layout for this volume.

Andreas Hauptmann
Diana Modarressi-Tehrani

Contemporaneously to the conference in 2011 a volume with abstracts on every lecture given and every poster presented was published:

2011 HAUPTMANN, Andreas, MODARRESSI-TEHRANI, Diana & PRANGE, Michael (eds.), Archaeometallurgy in Europe III. Abstracts. METALLA, Sonderheft 4, 2011.

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Béla Török, Árpád Kovács & Zsolt Gallina

Iron metallurgy of the Pannonian Avars of the 7th - 9th century based on excavations and material examinations

Summary

The technologies of iron metallurgy of Pannonian Avars in the Carpathian Basin of the 7th - 9th century is described by means of archaeometallurgical investigations of ore, slag, furnace wall-fragment and iron finds.

All the technological processes (burning of charcoal, roasting of ore, smelting, compacting of bloom and smithing) were performed in the same area of workshops having a high volume and productivity as compared to the early medieval circumstances in this area. The local roasted bog ore having a relatively low Fe-content was smelt in a so-called Avar-type clay bloomery which were standing partly free and were equipped with breast-wall and tuyères. The iron-loss and the quantity of slag were relatively high during smelting. On the basis of the morphology, composition and microstructure of slags it can be stated that two different sorts of slags were formed: tap-slag flowing out of the furnace and cinder remaining in the bloomery up to the end of smelting. The relatively high MnO-content of ores and slags is a characteristic local feature.

The bloom made in this way was reheated after smelting and packed on the site and was probably used soon. The smithies were mainly built outside of houses but there are indications for smithing activities within buildings.

Though quickly cooled microstructures in iron artefacts without any traces of forming could be found, the investigation of most of the iron tools denotes basically the technology of a free-form forging without heat treatment. However, it can be supposed that a conscious technology was used, which is shown by the overlapping of soft ferritic structures and relatively harder ferritic-pearlitic structures. Using this feature, the surfaces, edges and pins exposed to higher strain were always harder even at the pieces having a very thin cross section.

Introduction

The Avars represented among others the early medieval iron metallurgy in the Carpathian Basin. Metal finds found in Avar graves are signs of remarkable bronze and/or iron cultures.
Pannonian workshop sites from the second half of the Avar period prove that a considerable iron metallurgy activity was carried out in the Avar Empire. In Western-Hungary and in the area of today Somogy County larger bloomery furnace workshops have come to light from the 7 - 9th centuries AD. A part of these workshops must have survived the fall of the Avar Empire and their technology heredity reached as far as the end of 9th century as well as for the Hungarian Conquest.

Two important excavations were carried out at Kaposvár-Fészerlak in South-West Hungary in 2001 and near Zamárdi at the south coast of the Lake Balaton in 2005. The distance between the two excavation sites of Kaposvár and Zamárdi are only 70 km. The excavation at Kaposvár-Fészerlak was extremely important from the industrial-archaeological point of view, because an Avar ferrous metallurgical centre of the 7th - 8th century was discovered in 2001. An area of 17.500 m^2 of the total area of 110.000 m^2 was explored. It nicely represented the Avar workshops with 425 objects and remains of more than 20 bloomery smelting furnaces (Gallina 2002).

The four sites of Zamárdi are even more important. 1.421 objects were found in the area of more than 27.000 m^2 in 2005. A supposedly multi-periodic Avar settlement of the 7 - 9th century with remains of carriage-roads, about 20 houses with stone furnaces and more than 100 open air furnaces were found at the sites. Artefacts from the Neolithic period were made, copper artefacts from the Early and Late Bronze Age, and from the Celtic and Roman periods as well. A complex ferrous metallurgical centre was also found. Probable remains of charcoal kilns, about 100 ore burning pits, 19 - 20 bloomeries, reheating fireplaces and a smithy workshop were found (Gallina et al. 2007). The remains of bloomeries fit into the series of furnaces of the 7th - 8th century found earlier in excavation sites in the Pannonian area (Gömöri

2000: 102-111, 185-196, 210-216). The metallurgical importance of this area was recognized by previous excavations, but the excavation at Zamárdi can be designated as one of the largest archaeometallurgical site of the early middle ages of Europe.

Technical examination of the finds

Between 2009 and 2011, the archaeometallurgical finds were investigated using the following methods: chemical analysis were performed by using a Varian 710-ES ICP-Spectrometer and a LECO Carbon- and Sulphur-Analyser, moreover by using a wet chemical method (titration) for separating the bivalent and trivalent iron. For mineralogical investigations a Bruker D8 Advance powder diffractometer was used. Microstructures were investigated by an Amray 1830i Scanning Electron Microscope in the Complex Laboratory of Image and Structure Analysis at the University of Miskolc. This is also true for the measurements of the Vickers hardness tests (HV1). Similar examinations were carried out in 2006 and 2007, when chemical analysis and SEM-EDS investigation of slag-samples were performed (Török & Kovács 2010).

We analysed 15 samples of iron ore (3 from Kaposvár, 12 from Zamárdi) and 70 of slag (10 from Kaposvár, 60 from Zamárdi) and 3 pieces of wall-fragments of a bloomery (from Zamárdi).

The samples have the following codes:

Kaposvár site:	K19
Zamárdi sites:	Z56, Z58A, Z58B, Z89.

Moreover, 14 iron tools (knives, needles, nails, chain, ring, slipper of wooden spade, iron stick with a loop, other not identified artefacts) were investigated metallographically.

Results and discussion

Iron ore, slag and wall-fragments of bloomery

The size of each of the investigated ores was ca. 3 - 5 cm. Their colour was basically reddish-brown with a more or less porous structure that could be crumbled a bit. During the study of the ore samples, we took into consideration that the surroundings of sedimentary chutes in the vicinity of both excavation sites were reasons for the formation of limonitic above-ground meadow and bog ore.

A great number of ore-roasting pits could be found at the sites. Moreover, a relatively high quantity of more or less roasted ore was excavated. As a consequence, the following fundamental question arises: Which of the ore-pieces found in the vicinity of furnaces and ore-roasting pits were used and which ones were considered inappropriate for metallurgical operation? We assume that the Avar metallurgists should have had special empirical knowledge to characterize ores on the basis of their colour and consistency.

Some characteristic compositions of the investigated ores are compiled in Table 1. A great number of ore-pieces containing Fe in a quantity similar to or less than the Fe-content of samples # Z58B/I and #Z58B/II (both are excavated from the infilled area of the same object). They show sometimes extraordinary high quantities of CaO with moderate concentrations of SiO_2 (e. g., #Z89/III). The results of possible metallurgical operations using such ores containing only 25 – 40 wt.% Fe (recalculated from the total concentration of Fe-oxide in the ore) are uncertain. Because of the high CaO-content serious difficulties would arise during the slag formation and concerning the slag viscosity. Other examples of

No.	SiO_2	FeO	Fe_2O_3	Al_2O_3	CaO	MgO	MnO	Na_2O	K_2O	TiO_2	P_2O_5	S	H_2O
Z56/I	5,60	1,03	87,03	1,16	0,29	0,92	0,67	0,05	0,093	0,059	0,011	0,010	3,01
Z58B/I	4,05	2,05	57,78	1,05	27,02	1,22	1,79	0,08	0,097	0,313	0,124	0,005	2,18
Z58B/II	10,80	0,26	35,98	1,91	48,16	0,84	0,30	0,24	0,091	0,002	0,125	0,004	1,18
Z58B/III	5,51	0,01	74,76	0,66	8,48	1,21	5,50	0,07	0,095	0,024	0,033	0,012	3,61
Z89/I	5,03	0,51	84,43	1,02	0,39	0,87	5,37	0,04	0,112	0,042	0,028	0,010	1,95
Z89/II	6,30	0,51	81,15	0,80	0,85	0,87	6,06	0,05	0,068	0,033	0,019	0,005	2,86
Z89/III	33,21	0,51	52,17	1,03	3,15	0,41	7,31	0,09	0,060	0,040	0,012	0,020	0,25
K19/I	9,82	0,51	79,51	2,96	0,18	0,89	2,67	0,06	0,505	0,060	0,013	0,010	2,83
K19/II	7,80	3,08	80,63	1,14	0,26	0,81	3,51	0,04	0,119	0,032	0,012	0,012	2,51

Table 1: Chemical composition of some meadow and bog ores from the excavations of the sites of Kaposvár (K19) and Zamárdi (Z 56, 58, 89). Values given in weight percent.

ores shown in Table 1 indicate that they could have been well utilized for a successful metallurgical operation. This was supported by our smelting experiments (unpublished results).

The raw material used for the bloomery smelting processes in the two sites discussed consisted of meadow and bog ores having a low basicity (CaO/SiO_2 = 0.01 - 0.05) and an Fe-content of 55 - 60 wt.% . This is less than the Fe-content of ores used in other regions of medieval Europe, especially in Scandinavia (Kronz 2004; Buchwald 2005: 135, 145). There are strong indications that the ores from Kaposvár and Zamárdi sites were roasted before smelting. The high H_2O-content in Table 1 is caused by physical humidity, partly it is hydrate water bonded to the iron-oxide in crystalline phase (the preliminary ignition was carried out in 450 °C).

The relative high MnO-concentrations can be considered a regional speciality as compared to the MnO-content of early medieval iron ore finds found in the Carpathian Basin and examined by us earlier (Gömöri & Török 2002). Similar high MnO-contents were also detected at the investigations of slags.

The microstructure of some ore samples was investigated by SEM-EDS. The experienced characteristic structure can be seen in Fig. 1. A lighter lattice richer in iron surrounds the dark particles consisting practically of SiO_2 (a Si-content of 63.3 % could be detected at point 1) with a Fe-content of about 1 - 5 %. In this lighter lattice, the Fe-concentration is between 30 % and 85 % but the average value is about 50 - 60 %. In some places Mn- and Ca-concentration can also be observed; e. g., in point 2, the probability of prevalence of Mn is 12.4 %, of Ca is 11 % in addition to the Fe of a quantity of 31.2 %.

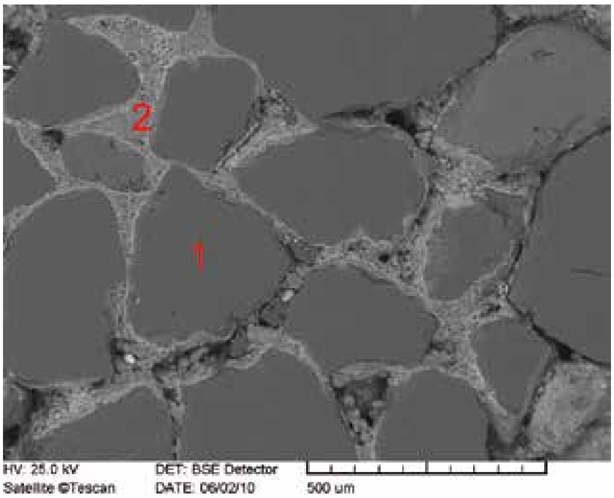


Fig. 1: Characteristic microstructure on a SEM image of iron ore sample (#Z58B/III).

During a metallurgical operation, the silicate-particles and surrounding oxides are liquified and form slag. This is separated and mostly flow away by bonding a significant quantity of iron-oxide (FeO) as oxides or silicates, along with Mn-, Ca- and Al-silicate complexes. FeO bonded in such a way causes considerable losses in iron from the point of view of the metallurgical operation, but it is the basis for a slag with low viscosity and relatively low melting points. Grains and lumps of iron metal were formed after the last reduction step of the residual iron oxide.

The results of mineralogical examination of four ore samples show a relatively high volume of an amorphous fraction. This and crystalline components can be seen in Table 2.

The measured crystallite sizes of hematite (9 - 19 nanometer) and goethite (19 - 23 nanometer) were relatively small. The lepidocrocite in sample Z58B/III is a distinct feature, it may be a primary mineral of sedimentary or oxidation zone iron ores (Szakáll et al. 2000). It is noteworthy that the color of ore samples reflected the differences in composition: the goethite dominant Z56/I is of light yellowish brown while the lepidocrocite containing Z58B/III is already of darker brown with shades of red. Samples Z89/I and K19/I have the characteristic hematite color. It is most likely that the samples Z89/I and K19/I are pre-roasted ores, but the samples Z56/I and Z58B/III are not pre-roasted raw materials.

Component	**Z89/I**	**K19/I**	**Z56/I**	**Z58B/III**
Hematite α-Fe_2O_3	50,81	51,68		
Quartz SiO_2	5,31	9,18	14,32	5,49
Muscovite $2M_1$ $KAl_2(Si_3Al)O_{10}(OH)_2$	0,12	0,17		
Goethite α-FeO.OH			38,28	37,61
Calcite $CaCO_3$				7,54
Lepidocrocite γ-FeO.OH				4,25
amorphous	43,76	38,97	47,39	45,12

Table 2: Mineralogical composition of ores. Values given in weight percent (Downs & Hall-Wallace 2003)

Both the macro- and microstructure of slag found in a high quantity in the workshops is highly inhomogeneous. Most of the slags can be identified as the primary result of the metallurgical process. Slag resulting clearly from the process of reheating or smithing was not found though some samples seemed to be very suspicious. Nevertheless, most of the slag-pieces could be divided into two groups from morphological point of view.

The characteristic representatives of slags of the bloomery processes are tap-slags. They usually are very heavy, relatively compact, completely melted pieces with shining black surface and flowing structures; minor gas bubbles can be found in their dark-grey fractures – otherwise their structure is relatively homogeneous.

The so-called cinder belongs to the other group of slag which does not flow into a slag-pit in front of the bloomery furnace, but it remains inside of the furnace. Cinders are large, strongly indented, sponge-like slag-blocks with a lot of gas-shrink holes and sometimes calcareous and charcoal gathering-ups and inclusions, having a less density, more heterogeneous structure than that of the tap-slags. Slag pieces of a similar type, sintered and adhered to a furnace wall fragment, can often be found as well.

At the same time, there are some pieces of slag of a special kind of transition type which bear the properties of both sorts. Although the morphology of the transition slag is closed to the morphology of the cinder, these are entirely melted and compact pieces. Often these are frozen in the shape of plano-convex (like the bottom of the hearth or slag pit).

Table 3 shows the chemical composition of a dozen of characteristic slag samples out of the investigated 70 slag fragments excavated from the two sites. The C-content arises from sticked and embedded charcoal grains.

The typical composition of tap-slags is indicated in the first four lines (three samples from Zamárdi (Z) and one from Kaposvár-Fészerlak). The high SiO_2- and FeO-contents are due to the main component of the iron silicate fayalite ($2FeO \cdot SiO_2$, or more familiar Fe_2SiO_4) that was easily detected by mineralogical investigations (Gömöri & Török 2002). The iron-loss of method is basically caused by it. The following four samples (#Z58A/1-2 and #Z89/3-4) show the characteristic composition of cinders found in the bloomery furnace. The basic characteristic feature of this group is that the proportion of oxide formed by the trivalent iron (Fe^{3+}; Fe_2O_3) (this value was calculated from bivalent iron (Fe^{2+}) and from the total quantity of iron) is much higher than in case of the tap-slags.

The reason for that is that the greater part of metallic iron grains in the slag have a relatively loose textual bonding to the bloom during the metallurgical operation. They became rusty in progress of a long time period, and iron-hydroxide developed in this way were transformed into reddish-brown Fe_2O_3 after losing water. Higher Fe_2O_3 concentrations were only rarely be found in tap-slag. It will be formed perhaps at the end of the metallurgical operation. Otherwise, the silicate slag is in equilibrium with metallic iron. Slightly higher CaO-contents than at the tap-slags (average about 4 wt.%) were found in most of the cinders (average about 8 wt.%), but the higher MnO-content mentioned as a local characteristic feature of the ores can also be observed in this type of slag.

There is a relatively great number of slag samples that are called “transient slags” for lack of a better classification. The composition of these slags is shown in the

No.	SiO_2	FeO	Fe_2O_3	Al_2O_3	CaO	MgO	MnO	Na_2O	K_2O	TiO_2	P_2O_5	C	S
Z89/1	27,81	38,67	18,36	3,63	4,97	2,19	2,18	0,20	0,85	0,15	0,05	0,38	0,001
Z89/2	28,58	47,49	5,57	4,97	5,94	2,62	2,38	0,25	1,06	0,23	0,11	0,49	< 0,001
Z58B/1	32,03	54,94	0,90	1,24	3,58	1,24	3,58	0,69	0,90	0,24	0,072	0,51	< 0,001
K19/1	28,67	46,29	7,89	5,09	1,87	1,43	3,61	2,41	0,67	1,10	0,163	0,26	< 0,001
Z58A/1	18,70	23,11	28,24	3,52	13,20	2,86	8,04	0,23	0,91	0,17	0,092	0,16	0,002
Z58A/2	16,30	30,66	27,96	3,19	7,01	3,46	8,35	0,16	0,72	0,12	0,142	1,33	0,003
Z89/3	40,10	24,78	23,51	2,88	3,08	0,94	1,64	0,14	0,88	0,13	0,034	0,21	0,002
Z89/4	20,66	35,15	19,44	3,10	7,98	2,82	8,67	0,15	0,80	0,15	0,06	0,31	0,003
Z89/5	21,00	39,10	13,10	2,59	9,71	1,71	0,22	0,21	1,13	0,15	0,042	0,43	0,001
Z89/6	43,74	18,32	0,65	2,87	30,60	0,52	0,64	0,28	0,23	0,12	0,091	0,25	0,001
Z89/7	29,70	30,16	20,80	3,47	2,49	3,72	6,61	0,21	1,05	0,16	0,048	0,13	0,001
K19/2	15,58	30,34	41,79	1,45	4,74	0,39	2,66	1,14	0,73	0,05	0,153	0,47	< 0,001

Table 3: Chemical composition of characteristic slag samples from the excavations of the sites of Kaposvár (K19) and Zamárdi (Z 56, 58, 89). Values given in weight percent.

last four lines of table 3. There are some samples here that consist basically of siliceous lime (#Z89/6), having a lower iron-oxide content as compared to the other samples, and another sample having a very high iron-oxide content can also be found here (#K19/2).

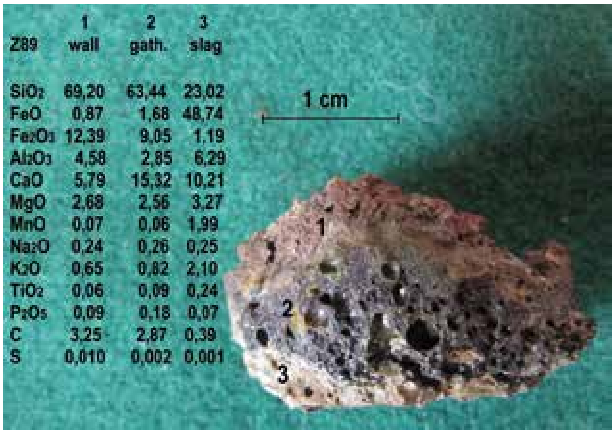
Interesting information can be obtained by investigating slag pieces which stuck to the side of a furnace wall. Fig. 2 shows one of these special pieces. The sample consists of three layers with different chemical composition of the individual layers. The first layer is the material of inner side of furnace wall (perhaps near ar tuyère) which consists mainly of alumo-silicates. Other samples of furnace wall fragments provided prills of metallic iron grains embedded in the slagged (ceramic) matrix; the long-time reoxidation of similar iron grains can also play a role in forming the Fe_2O_3 content of the first layer of the sample in Fig. 2. The second, grey layer of the sample, a very porous layer, consists of Ca-silicate. It is similar to the #Z89/6 sample with the exception that the quantity of Fe_2O_3 is higher than that of FeO. The third layer is a slag layer of fayalite, wüstite and Ca-silicates. The slightly higher K_2O-content as well as a part of CaO can be caused by the ash of charcoal.

A characteristic SEM image of the surface of a furnace wall facing the furnace chamber can be seen in Fig. 3. The material having a homogeneous structure and uniform grain-size and burnt like a brick (point 1 - Si: 44.40 %, Al: 10.34 %, Fe: 8.18 %) is covered by a layer of iron silicates containing metallic iron grains as well (point 2 - Si: 16.30 %, Al: 5.40 %, Fe: 49.95 %).

The characteristic SEM image of tap-slag showing a spectacular dendritic structure is demonstrated in Fig. 4. The dendrites consist of almost pure iron oxide and solidified sometimes in tertiary arms (point 1). They are surrounded by complex composed Al-Si-Ca-K-phases and glass (point 2) and the middle-gray larger areas consist of fayalite crystals (point 3). The smaller black areas show gas bubbles. A similar dendritic solidification was observed in slag samples published by Buchwald (2005: 97). However, in some cases their structure was very fine with small dendrite arms.

An eutectic structure of a silicate slag crystallized in a panelled form could be observed in a slag sample from a slag pit excavated in Zamárdi (Török & Kovács 2010: 457).

A very similar crystallization can also be observed in the SEM image of a cinder having quite a different morphological character but here the dendrite arms are usually not so distinct and sharp, moreover more gas bubbles can be seen. At the same time, special microstructures could sometimes be found in the sample of cinders. It is a columnar tubular form of silicate phases and oxides (Fig. 5). The shell of tubes has a very high Mn-content



Z89	1 wall	2 gath.	3 slag
SiO_2	69,20	63,44	23,02
FeO	0,87	1,68	48,74
Fe_2O_3	12,39	9,05	1,19
Al_2O_3	4,58	2,85	6,29
CaO	5,79	15,32	10,21
MgO	2,68	2,56	3,27
MnO	0,07	0,06	1,99
Na_2O	0,24	0,26	0,25
K_2O	0,65	0,82	2,10
TiO_2	0,06	0,09	0,24
P_2O_5	0,09	0,18	0,07
C	3,25	2,87	0,39
S	0,010	0,002	0,001

Fig. 2: Slag with a layered structure adhered to the wall of bloomery and the chemical compositions of the layers.

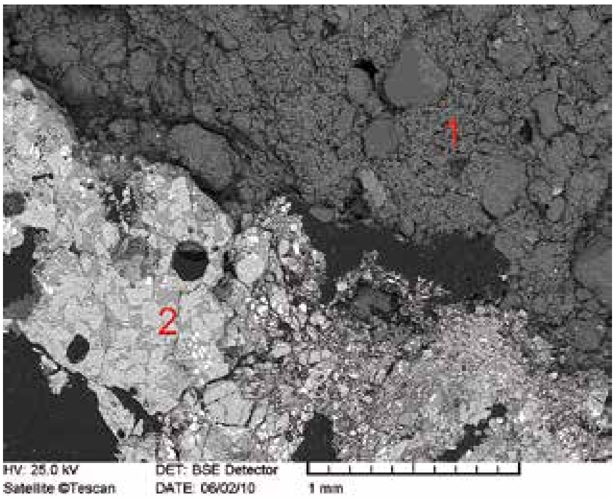


Fig. 3: Homogeneous burnt microstructure with iron silicate layer on a SEM image of a sample from the internal surface of furnace wall-fragment. For explanation of numbers see text.

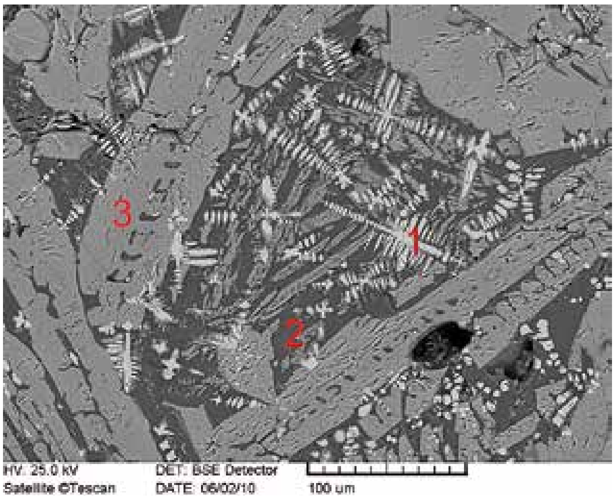


Fig. 4 Characteristic FeO-dendritic and fayalitic microstructure on a SEM image of tap slag (#Z58B/1). For explanation of numbers see text.

(Mn 43.68 wt.%, Fe 13.79 wt.% at point 1) but the direct parts among the tubes (point 2) have also relatively high Mn-content (18.60 %) and the Fe-content is higher here (30.31 %). Non-corroded metallic iron grains can also be found in the images of larger magnification.

Iron artefacts

All the iron artefacts investigated were excavated at the site 58B in Zamárdi. In addition to determine the microstructural properties of each artefact, our purpose was to describe the general material quality and the characteristic technologies of smithing and metal treatment.

The characteristic material of the iron artefacts made presumably in the same workshop or in workshops being near each other is ferritic iron showing in parts only a pearlitic-ferritic structure. The majority of tools has a low – in some cases very low – carbon content (ca. 0.4 - 0.6 wt.%). The largest piece of the collection, an iron slipper of a wooden spade consisted of coarse-grained pearlite with a C-content of 0.8 - 1.0 wt.% and secondary cementite lattices surrounding it. It was a very interesting observation that in this sample a very high Cl-concentration (14.32 wt.%) could be detected on one side of the edge in the element-spectrum, but other mineral components could not be observed. The absence of martensitic or bainitic structure differing from the matrix excludes the heat treatment by using a salt bath; instead it could point to the use of a whetstone having a high Cl-content on one side of the spade-edge only. A relatively large grain-size could be observed at the majority of artefacts, even at those spots with very thin cross-sections. For instance, ferrite grains of 40 - 60 µm could be found in a long needle. During investigating the mainly heterogeneous microstructures, important information could be obtained by examining the proportion and location of pearlitic parts. In knives, nails and needles, these parts were concentrated on edges and points. Unfortunately, the greatest part of the surfaces of tools became rusted during the last 1300 - 1400 years.

The traces and direction of shaping could well be identified in many artefacts both by grain-deformation and by the deformation of slag inclusions, the number of which increased towards the narrower cross section. These inclusions are complex oxides containing 15 - 20 wt.% of Si and 10 - 15 wt.% of Ca and Al, around 5 wt.% of Mg and 2 - 3 wt.% of K. In addition, they contained about 1 wt.% of Mn despite the relatively high MnO-concentrations the ores and metallurgical slags have. There are variations in the Fe content which reached in some cases 15 wt.%.

Nevertheless, some different microstructures were found which correspond to individual forging technologies. For example, in case of two similar size knives originated

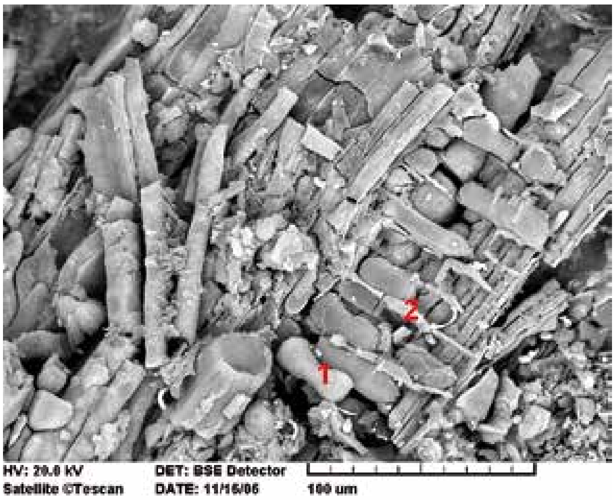


Fig. 5: Special columnar tubular microstructure on a SEM image of cinder. For explanation of numbers see text.

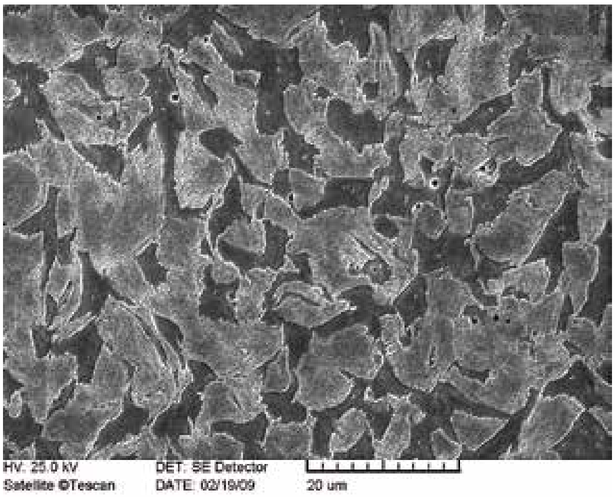


Fig. 6: Quickly cooled microstructure without traces of forging on a SEM image of an examined knife.

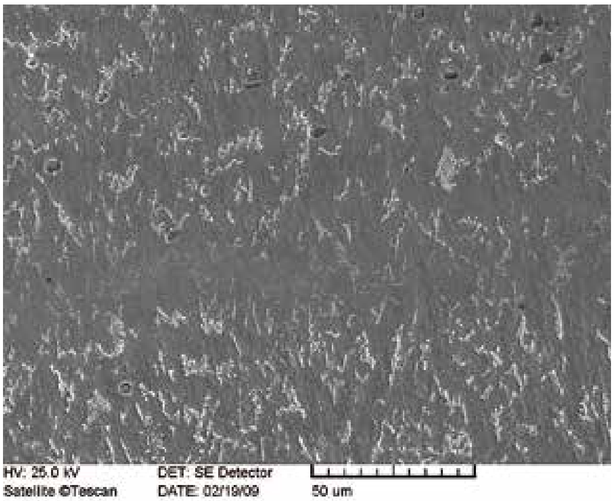


Fig. 7: Slowly cooled and formed microstructure on a SEM image of another knife.

from the same object different microstructures can be observed. In one case beside of ferrite particles fine grained bainite-martensite-degenerated perlite structure with immature bainite needles can be found which originated quick cooling. There is no trace of forming (Fig. 6). In the other case the slow cooling and the forged structure is well observed. Heterogeneous microstructure with coarse grain perlite, somewhere else poor in cementite can be found in the examined sample (Fig. 7).

At the examination of a ring of chain a spheroidite (this is a microstructure found in iron and steel alloys consisting of sphere-like cementite particles within an α-ferrite matrix.) microstructure denoting multiple heating below A_1 temperature (723 °C) in the Fe-C system, slow cooling and re-forging. This structure is called annealed structure by which the metal becomes suitable for the further formation, in our case for the shaping of a ring (Fig. 8).

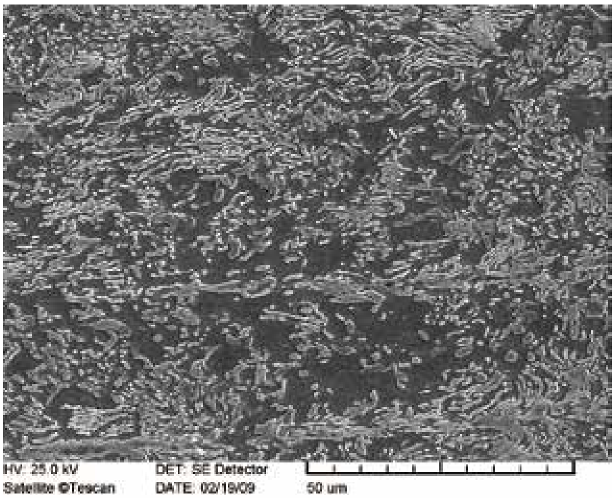


Fig. 8: Spheroidite structure on a SEM image of the ring of chain.

In spite of the heterogeneity, probably one kind of basic material was used for making each artefact. Exception is a forged, recrystallized needle-like nail where characteristic areas separated by sharp boundary line could be found in the longitudinal cross section – a softer ferritic structure could be observed towards the thickening part while a mainly harder pearlitic structure could be observed towards the pin of artefact. In addition, slag inclusions arranged parallel to the direction of formation can be seen at the boundary of the two characteristic areas (Fig. 9).

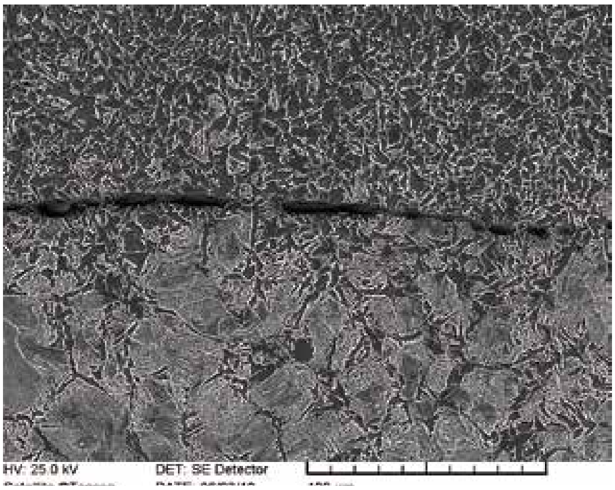


Fig. 9: Distributed structure on a SEM image of an examined needle-like nail.

The investigated Avar tools were made of relatively mild (wrought) iron (it is not steel in today's technological sense. The basic materials of early medieval iron artefacts were wrought iron with low C-content, steel and sometimes phosphoric iron). The HV1-tests resulted values between 100 - 140 in the ferritic internal zones while maximum values of 210 - 250 in the stainless parts of needle- and nail pins containing more proportion of pearlite.

Avar-type furnaces, workshops and processes

Numerous traces of the developed iron metallurgy of the Avars have already been found in Pannonia and it shall be taken into consideration that the workshops were often established in the place of a former Roman villa or vicus (Gömöri 2000: 223). Both the area and productivity of the two excavation sites, especially Zamárdi, mentioned in this paper are the largest ones of the sites known up to now. The Pannonian Avars seem to have performed all the stages of iron production and metal formation in one place so to say a complex verticum operated in the workshops from the roasting of ores, through the smelting, reheating and bloom-hammering, until the final smithing in the vicinity of living-houses (Fig. 10).

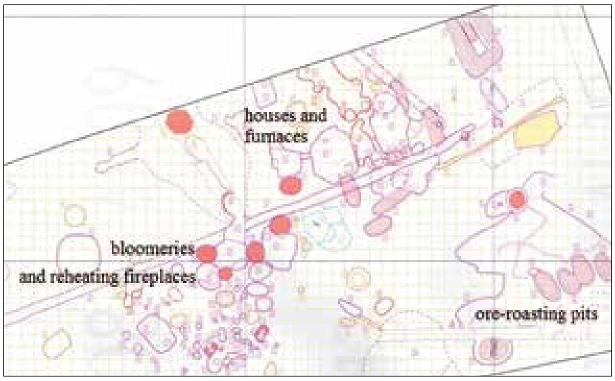


Fig. 10: Part of a workshop of iron metallurgy on the excavation map of Zamárdi site No. 89.

The remains of operational processes preceding the smelting are the round holes with a diameter of 2 - 3 m and a depth of 20 - 35 cm. They remember the charcoal kilns and the oval ore-roasting pits with a length of 2 - 3 m and a width of 1 – 1.5 m described by Gallina (2002: 77). They can be founded in a relatively small area in a great number in groups.

The characteristic features of the bloomery furnaces called „Avar-type" in the Carpathian Basin are the round or oval cross sections narrowing upward. It may reach a height of 70 -80 cm. Their round, oval or U-shape coffered basin was 30 - 40 cm in diameter, it was dug in the ground only for 30 - 40 cm (Fig. 11).

At the same time we can not exclude that a second type of bloomery furnaces was dug in the earth. There was a 30 - 40 cm wide and high oval hatch at the bottom of the front side of the furnace that was closed with a fitting clay layer. The air-blasting was performed by using probably one windbag through a clay tuyere embedded in the middle of the front wall. It is interesting to note that though a large number of finds of front walls and tuyères were excavated, e. g., in Kaposvár-Fészerlak but only a very limited number were found at Zamárdi.

There is no unequivocal prescription concerning the metallurgical processes in the Avar-type bloomery.

However, on the basis of the features available from the excavations, from the investigation of archaeometallurgical finds, and finally from the smelting experiments it can be stated that ore and charcoal were broken to a grain-size of 1 - 2 cm, were charged in portions of 200 - 300 g into the bloomery furnace. This was dried before firing with wood and charcoal, then it was heated to a constant high-temperature-profile. The quantity of ore for one smelting process reached 10 - 20 kg.

During the continuous air-blasting, the charcoal was further burdened in order to maintain the furnace temperature and reducing atmosphere. The use of slag forming materials (sand, limestone) could not be detected but it cannot be excluded. The relatively high quantity of slag is a characteristic feature of the Avar-type furnaces. A great number of very large pieces of tap-slags flowing into the slag-pit in front of the open tap hole on the bottom of breast wall and of cinders taken out of the furnace at the end of smelting could be found. It was necessary to ensure continuously a temperature of 1150 - 1300^{o} C in the furnace chamber during the 10 - 12 hour long metallurgical operation, though a result could sometimes be obtained during a shorter time in the course of reconstructed smelting experiments. After completing the metallurgical process, the bloom of a weight of 1 - 3 kg drawn through the opened breast-wall was heated on the round mildly dished reheating fireplaces of a diameter of 40 - 50 cm near the furnaces and compacted by hammering out the slag inclusions and gathering ups by using a wooden hammer.

Fig. 11: Remains of an Avar-type bloomery and reheating fireplace of Zamárdi site No. 89.

It was found on both sites that the bloomery furnace and reheating fireplace were protected by oval roofs. The packed blooms were probably processed in the smithy workshops having a pile-construction on the site, but very few traces of this processing was found. But a fireplace and flue found in each near building and the traces of a stone furnace opened on the upper part point to smithing activity as well (Gallina et al. 2007, 160).

Some different technological methods were used for smithing the tools made of only one kind of iron generally but the traces of using the free-form forging method for the multiple heated material cooled on open air can be found most frequently, even at the thin needle-like pieces where the drawing and stretching would have seemed to be more logical processes – instead the material was formed by fine, careful forging. No intended heat-treatment technology was used in case of the investigated artefacts. The traces of quick cooling – probably quenching – could be discovered once, but at the same time the hammering of the harder pearlitic parts having a relatively higher C-content of originally inhomogeneous bloom towards the edges and pins denotes a conscious forming technology. The effect of this technology is that the slag inclusions deformed flat according to the direction of forming are more frequent in these parts mainly in case of the nails.

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