Slag-pit bloomery furnace of the Tarchalice type Reconstruction and experimental research

Pece se zahloubenou nístějí typu Tarchalice Rekonstrukce a experimentální výzkum

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The paper presents the results of the first stage of experimental research on reconstruction of the bloomery process in the slag-pit furnace of the Tarchalice type. The phenomenon of bloomery furnaces from the Przeworsk culture settlement in Tarchalice (Tarxdorf), Lower Silesia, Poland, has been known to the scientific community since 1903. With regard to ancient slag-pit furnaces discovered in the second half of the twentieth century in the Świętokrzyskie Mountains and Mazovia region, these features had two-times larger diameter of slag-pits and almost four-times greater weight of slag blocks. The large sizes of the slag-pits suggested dissimilarity of conditions of running the process, formation of iron bloom and block of slag in relation to quite well known from scientific experiments the bloomery process from the Świętokrzyskie Mountains.

experimental archaeology – iron smelting – Przeworsk culture – Silesia – slag-pit bloomery furnace – bloomery process

V příspěvku jsou prezentovány výsledky první fáze experimentálního výzkumu rekonstrukce procesu přímé výroby železa v pecích se zahloubenou nístějí typu Tarchalice. Fenomén železářských pecí převorské kultury v Tarchalicích v Dolním Slezsku je odborné veřejnosti znám již od roku 1903. Pokud jde o starověké pece se zahloubenou nístějí, objevené ve druhé polovině 20. století ve Svatokřížských horách a na Mazovsku, tyto objekty měly dvojnásobně větší průměr nístějí a téměř čtyřnásobně větší hmotnost struskových bloků. Velké rozměry zahloubených nístějí naznačovaly rozdílné podmínky procesu tavby, tvorby železné houby a bloku strusky oproti, z vědeckých pokusů poměrně dobře známému, procesu přímé výroby železa ve Svatokřížských horách.

experimentální archeologie – hutnictví železa – převorská kultura – Slezsko – pec se zahloubenou nístějí – přímá výroba železa

1. Introduction

Experimental research, in addition to intensive excavations at ironmaking sites, played a decisive role in explaining the essence of the bloomery process. Despite the passage of over 60 years, attempts to reconstructing furnace constructions typical for a given area and the specificity of the bloomery process, carried out in various scientific centers[1], still encounter difficulties resulting mainly from general lack in the archaeological remains

[1] In Western Europe, experimental iron smelting was initiated in the second half of the 1950s by archaeologists and metallurgists from Belgium, Germany, England and Denmark. At the same time, similar works began in Poland, and a few years later in other countries of Central and Eastern Europe: in Czechoslovakia, in the Soviet Union and Yugoslavia (see *Orzechowski – Przychodni 2014*, 249–250).

of above-ground parts of furnaces, smelting residues in the form of iron blooms and even batch materials. Although it is usually far from fulfilling the expectations of experimenters, the knowledge and experience accumulated over the years allow to approach new challenges with optimism, which is proved by this work.

The experimental research on the reconstruction of the furnace and the bloomery process undertaken in Poland was one of the first in this field. They were initiated in 1957 by the discoverers and researchers of the ancient metallurgical center in the Świętokrzyskie Mountains: the metallurgist and historian of technology, Prof. Mieczysław Radwan and the archaeologist, Prof. Kazimierz Bielenin (*Radwan 1958*). Initially, experiments were conducted in laboratory conditions at the Academy of Mining and Metallurgy in Kraków (AGH), and later at the Truck Factory *Star* in Starachowice. The Museum of Ancient Metallurgy in the Świętokrzyskie Mountains in Nowa Słupia became a permanent place of experiments of field character since 1962, and then the annual archaeological festival *Dymarki Świętokrzyskie* organized nearby. Since 2000 experimental tests have also been carried out at the Blast Furnace Complex in Starachowice as part of the *Iron Roots* educational event. Previous research has concerned almost exclusively slag-pit single use furnace, which was actually the only kind of bloomery furnace used in prehistory in Polish lands. Experimental furnaces were constructed on the basis of dimensions of slag-pits from the Świętokrzyskie Mountains, the diameter of which varied in the range of 30–50 cm, assuming the height of a shaft made of clay blocks from 80 (initially even from 25 cm) to 120 cm (see *Suliga 2006a*; *Bielenin – Suliga 2008,* 59–62; *Orzechowski – Przychodni 2014,* 250–260).

Results of the experiments referred to archaeological evidence have consolidated opinions on the general furnace construction, an air supply system, a type of batch material and its dosing into the furnace. The state of the slag-pit during the smelting was still in question (empty or filled, with charcoal or wood), and above all the form of smelting products remained unsatisfactory. Slag-iron conglomerate structures forming accretions around the blow holes was commonly obtained (*Suliga 2006a*, 173). Grainy separations, as well as iron plates and grids immersed in mass of slag could not have technical significance. Of course, the intensification of the blast led to the increase of the temperature in the furnace, liquefaction of the slag and its runoff to the pit, but reduced iron was then carburized, and even melted down, becoming pig-iron which was useless for ancient smelters.

Prof. Bielenin tried to overcome an impasse in the reconstruction of the bloomery process (*Bielenin 1978,* 60; *1985*, 187–193; *1998–1999*, 523 ff.). He drew attention to the common features of slag blocks from archaeological excavations that are typical for casting liquid material into a cold form. Since the slag was so fluid that it flowed into a pit at a certain time in the process, the iron bloom was sufficiently drained from the slag and was suitable for direct processing. The concept of Prof. Bielenin, called the 'free solidification surface' of slag blocks concept (FSS), formulated the principles of leading the process differently. At a certain point in the smelting it was necessary to devote liquefaction of the slag and its inflow into the pit, counting on draining the bloom from slag and final separation of both phases (*Bielenin 2002,* 15; *2005*; *2011*). The metallurgical verification of the correctness of the FSS concept pointed to an unknown aspect of the phenomena occurring within the slag that filled the pit – the effect of the secondary fayalite reduction leading to the formation of iron grids in slag (*Suliga 2006b*; *Suliga – Kargul 2007*; *Bielenin – Suliga*

2008). The secondary reduction effect confirmed along with other features of the crystallization of the slag block (crystal structure, segregation of phases) the FSS concept, but also indicated the possibility of such process in the slag phase earlier, during the smelting in the furnace shaft (*Suliga – Karwan 2014*, 170). It was necessary to introduce this to experiments, that was strongly encouraged by Prof. Bielenin.

At the end of the last decade, thanks to the efforts of the members of the Świętokrzyskie Association of Industrial Heritage (ŚSDP) in Kielce, significant progress has been made in experimental research. Attempts conducted by Andrzej Przychodni and Adrian Wrona contributed to this, as well as establishing cooperation with Jens Jørgen Olesen, the experienced experimenter from the museum in Thisted, Denmark. Undoubtedly, the use of definitely richer hematite ore was also important for improving the results of the experiments. Smelts carried out in 2013–2014 in accordance with the principles of the FSS concept gave the expected results. In two stages of the process, reduction of iron from ore and from slag in the furnace shaft as well as liquefaction and draining of slag into the pit, the iron bloom of 3.65 kg weight, technically pure, with ferritic structure and slag in the form of a block was obtained (*Przychodni – Suliga 2016*).

2. The phenomenon of the Tarchalice furnaces

The Silesian metallurgical region was one of three, next to the production centers in the Świętokrzyskie Mountains (*Bielenin 1992*; *Orzechowski 2007*) and in western Mazovia (*Woyda 1978*; *2002*), the main areas of the ancient iron industry in Poland. It was situated in the upper and middle Oder basin. The smelting sites were concentrated mainly in the wide zones of the Odra valley, from Racibórz to Nowa Sól, and the valleys of its larger tributaries, including Mała Panew, Nysa Kłodzka, Oława, Ślęza, Bystrzyca, Widawa and Barycz (*Madera 2002*). Metallurgical production, dated from the younger pre-Roman period to the early Migration period (1st c. BC – 5th c. AD), was associated with the Przeworsk culture. The raw material for smelting was local bog ores. The production was conducted in unorganized ironworks including usually a small number of slag-pit furnaces. It was implemented for local needs, within settlements or in their direct vicinity (*Orzechowski 2013*, 224–243).

Iron smelting site in Tarchalice (before 1945 *Tarxdorf*), district Wołów, Lower Silesian Voivodeship, site 1, is located about 50 km on the NW from the capital of the region – Wroclaw, on the right bank of the Odra valley (*fig. 1*). It was the first excavated metallurgical site in Polish lands. The archaeological research was made in 1903 and 1908 in connection with repeated finds of iron slag and fragments of pottery on the surface (*Seger 1894*; *Olshausen 1909*, 60–66; *Weiershausen 1939*, 97–104). In an area of approx. 10 × 10 m the remains of 37 bloomery furnaces in the form of pits filled with blocks of slag were then uncovered. Due to their large size and good state of preservation they aroused extraordinary interest not only among archaeologists, but also engineers-metallurgists. These studies and the accompanying discussion in *Zeitschrift für Ethnologie* (*von Luschan 1909*; *Olshausen 1909*; *Krause 1909*; *Giebeler 1909*) should be regarded as the beginning of archeometallurgy in Central Europe. The significant concentration of discovered furnaces in small trench in the presence of slag on the surface of 6 ha and finding in their context

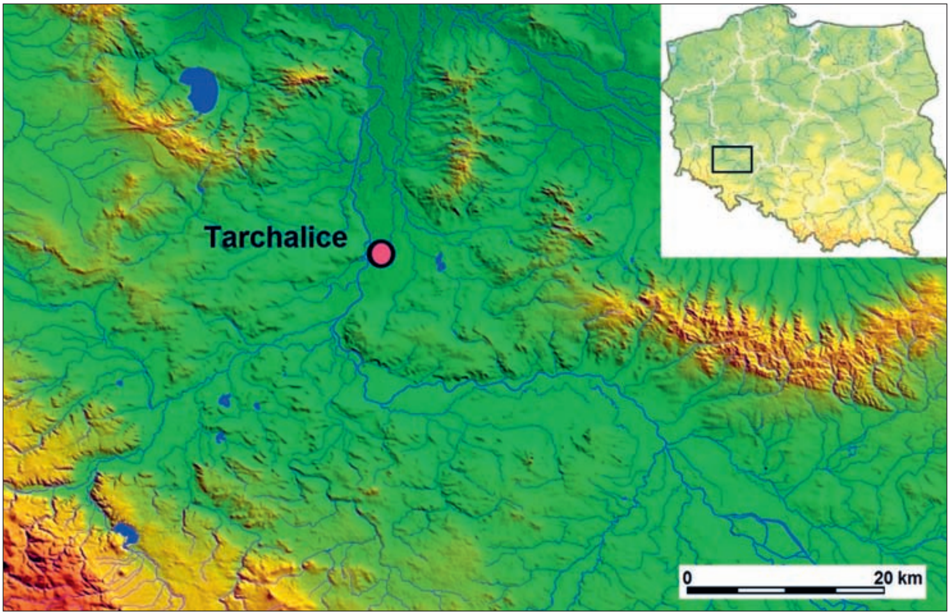

Fig. 1. Tarchalice (before 1945 *Tarxdorf*), district Wołów, Lower Silesian Voivodeship, site 1. Block of slag with widening at the top in form so-called 'cap' (there are remains of the slag-pit walls clay lining and the negatives of the wooden rods on the lateral surface of the block). Photo Kazimierz Bielenin.
Obr. 1. Tarchalice (před r. 1945 Tarxdorf), okres Wołów, Dolnoslezské vojvodství, lokalita 1. Blok strusky s rozšířením v horní části (nesoucí zbytky výmazu zahloubených nístějí a negativy dřevěných prutů na boční ploše bloku).

pottery from the Hallstatt period caused, that the site for some time was considered as the largest and one of the oldest centers of iron production north of the Alps.

After WW2 research was continued by Polish archaeologists (*Hołubowicz 1956*; *Domański 1972*; *2000*). In total, in the area of about 12 ares, relics of at least 75 furnaces located mainly in 2 clusters along the shore of the one Odra oxbow lake were discovered. While in the test-trenches established in the eastern part of the site there were remnants of the Przeworsk culture settlement in the form of residential buildings, hearths and farm pits. Thus the excavations did not confirm the previously predicted huge number of furnaces (30,000 – 40,000 units.). Due to the lack of ^{14}C analysis, the production activity is dated in a wide chronological framework of the settlement's functioning, determined on the basis of ceramic material from 1st c. BC to 3rd c. AD (*Domański 2000*).

It is significant, that until the 1970s there was no consensus on the construction of furnaces discovered over there. Initially, they were considered as sunken hearts features with a blowing canal from the surface to the bottom of the furnace (*Giebeler 1909*) or partially sunken with a conical shaft, but also with a blast to the bottom of the furnace (*Krause 1909*). After the resumption of research after the War, under the influence of *Weiershausen* (*1939*, 102), they were treated as shaft devices (*Hołubowicz 1956*, 212; *Domański 1972*, 422–433; *1975*), although this was in conflict with their stratigraphic position. A design of the slag-pit furnace was first proposed by Prof. Radomír Pleiner, but the location of the blast in the upper part of the pit still was not a satisfactory solution (*Pleiner 1965*, 32, 38). Eventually, the main interpretation problems in favor of the slag-pit furnace were settled by Prof. *Bielenin* (*1975*).

Certain features of the discussed devices allow them to be treated as a special type of slag-pit furnace named Tarchalice type (*Bielenin 1983*). It belonged to the category of furnaces with a large slag-pit (internal diameter above 50 cm). Most of the slag blocks preserved in their entirety presented an exceptional regularity of a cylindrical or conical shape crowned with a characteristic 'cap'.[2] The slag-pits were usually equipped with pit canals. Most importantly, however, they all had a unique wall construction in the form of a clay lining about 10 cm thick, reinforced with vertical wooden rods (*fig. 1*).[3]

Some of the slag-pits were distinguished by huge dimensions (maximum diameter over 80 cm, preserved depth of nearly 90 cm) and the weight of the slag blocks reaching 342 kg. This means that they had two-times larger diameter and blocks of slag had almost four-times greater weight than in typical furnaces from the *Świętokrzyski* and Mazovian metallurgical centers. This allows the inclusion of the finds from Tarchalice in the recently defined group of furnaces with 'very large' slag-pit (*Madera 2008*). Features with similar parameters are found in a large area of the European *Barbaricum*, that forms a wide arch running through the territories of Norway, Sweden, Denmark, East Germany and Poland. However, in the Silesian region their highest density (they occurred on 26 excavated sites) and dimensions (internal diameter of the pits up to approx. 1.5 m, slag weight up to 850 kg) are observed. Apart from the phenomenon of a close connection between iron production and settlement and consequently its widespread especially in the late Roman period, these furnaces undoubtedly represent the technical and technological specificity of the ancient iron industry in Silesia, not only in the area occupied by the Przeworsk culture (*Madera 2008*, 195–196).

[2] The authors have in mind here a kind of the widening occurring at the top of the slag block, usually interpreted as a result of widening of the upper part of the slag-pit. Such form is commonly found on slag blocks, but in Tarchalice on some blocks it was of extraordinary size and shape reminiscent of a 'cap' or 'hat' (*Pleiner 2000*, 260, fig. 68: 6–7, 9–12).

[3] A number of furnaces discovered in Silesia originally considered as Tarchalice type have been negatively verified and for some time the features from Tarchalice have been a unique among slag-pit devices. In 2005 traces of big size furnaces with analogous construction of slag-pit walls were located in Dębno, site 14, at a distance of about 2.5 km from the settlement in Tarchalice.

3. Reconstruction assumptions

The reconstruction of the 'legendary' furnaces and the smelting process carried out in them for several years remained in the sphere of unfulfilled plans for a group of enthusiasts who earlier led to the creation of the *Dymarki* Ecomuseum in Tarchalice. The obstacle in the implementation of experiments with a device of unprecedented size was too high for local conditions financial outlays. Therefore, the proposal to build and run the furnace of Tarchalice type on *Dymarki Świętokrzyskie* in Nowa Słupia was very much welcomed.[4]

In this first stage of the research it was decided to make significant simplifications in relation to archaeological data. The cylindrical form of the slag-pit was used, omitting the matter of the presence of the 'cap'. The lining of slag-pit walls was also abandoned because of the dry and concise loess ground. However, there was no question of using the pit canal type 1 according to Prof. *Bielenin* (*1983*, 55, fig. 8: 1) classification. Considering the limited material and time possibilities, an average size of the inner diameter of the Tarchalice slag-pits was assumed for the model.

The large dimensions of the furnace suggested using in the smelting process natural draft, which caused great problems in the case of running much smaller furnaces. When choosing the shape and height of the shaft, the experimenters were guided by the construction of furnaces, which have been functioning until recently in West Africa. Already in the context of the first discoveries in Tarchalice, the attention was drawn to the Banyeri / Bandjeli type shaft furnaces from Togo area, having a regular conical shaft structure and working without bellows (*v. Luschan 1909*, 39–43). The detailed description of this and other categories of African furnaces based on autopsy and interviews with their users was recently presented by *Łapott* (*2008*). The devices with inside diameter of the shaft of 70 cm and the height of 2.5–3 m were considered as a good starting point for experiments (*Łapott 2008*, 105, fig. 12).

Ultimately, the basic dimensions of the experimental furnace were as follows: the depth of the pit – 70 cm; its internal diameter (and the lower part of the shaft) – 65 cm; height of the shaft – 2.5 m; diameter of the shaft outlet – 45 cm. The outlet of the horizontal section of the pit canal with a diameter of 12 cm was placed at a height of 15 cm above the slag-pit bottom; the pit canal inlet at ground level had a diameter of 25 cm. 8 blow holes, initially horizontal, placed on the average height of 10 cm from the ground level were used. During the first smelt their diameter was determined experimentally[5] at 8 cm and this dimension was used in all experiments (*fig. 2a* and *3a*).

The shaft was built of hand-formed 'bricks' from loess with straw chaff admixture. The thickness of the walls erected in this way was approx. 15 cm at the bottom of the shaft and approx. 12 cm at its outlet. The considerable height of the shaft forced the use of a construction platform, which was then used for charging the furnace. In favorable weather

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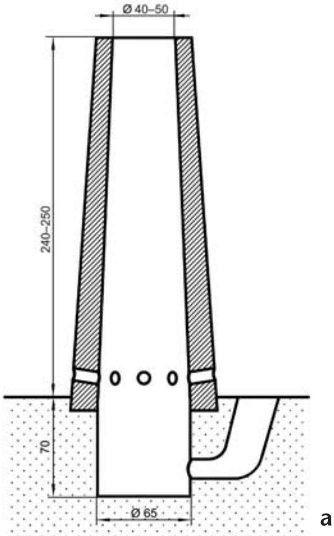
[4] The core of the team conducting experiments were: Paweł Madera, Dariusz Kik and Artur Kosmalski (District Office in Wołów, TTR *Cross*), and in the last seasons also Maciej Tomaszczyk (*Officina Ferraria*) and Maciej Fortuna (the freelance reenactor).

[5] The trial and error method was used, examining the furnace behavior (temperature) after each change of the blow holes. As a starting point a diameter of 10 cm was adopted used in Banyeri type furnaces with similar shaft parameters (*von Luschan 1909*, 40, fig. 18).

Fig. 2. Scheme of the experimental furnace (a) and its implemetation during the work (b). Dymarki Świętokrzyskie 2013, photo Kamila Brodowska.
Obr. 2. Schéma experimentální pece (a) a její realizace v průběhu prací (b). Dymarki Świętokrzyskie 2013.



conditions the construction time of the shaft with the involvement of 4–5 people, including successive drying, was 3 days. The furnace was used for single smelt and then the shaft was dismantled.

4. Characteristics of experimental smelt

The proposed experimental model was similar to the current scheme of the furnace *Świętokrzyski* type, verified by successive discoveries and experiments. However a completely different size scale and basing the furnace operation on natural draft forced the use different conditions of running the smelting process, including amount of batch materials, service principles, duration of smelting or the way of evacuation of iron. A wide knowledge concerning experimental smelts was used, as well as the experience that was gathered by experimenters working on *Dymarki Świętokrzyskie* in identical location conditions and using the same building and batch material.

The batch material was roasted hematite ore with a Fe content of approx. 59 % and a granulation of 1–4 cm and 'brown ore' with a Fe content of approx. 37 %. As fuel commercial charcoal from deciduous trees in pieces of 5–15 cm was used. The ores used differed from the potential raw material present in the area of Tarchalice, but allowed to refer the results of smelts to experiments carried out in the Świętokrzyskie Mountains (*tab. 1*).

All the experimental smelts started in evenings (*fig. 2b*). After igniting the furnace at the level of the slag-pit bottom, it was gradually loaded with charcoal to about half the


b

a

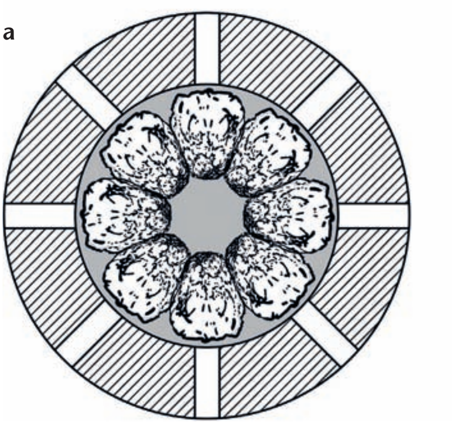


Fig. 3. Product of the experimental smelt I (Dymarki Świętokrzyskie 2013) in the form of bloom composed of 8 'segments' – view of the bottom side; below: schematic drawing of the bloom in the cross-section of the furnace shaft (a) and cross-section of one of the 'segments' (cells of the measuring grid have dimentions of 1 x 1 cm; b). Photo Kamila Brodowska (a) and Dariusz Kik (b).
Obr. 3. Produkt experimentální tavby I (Dymarki Świętokrzyskie 2013) ve formě železné houby složené z osmi segmentů; níže: schematické znázornění železné houby v průřezu šachty pece (a) a příčném řezu jednoho ze segmentů (buňky mřížky měřítka v pozadí mají rozměr 1 x 1 cm; b).

shaft height and heated up to obtain at the level of the blow holes the temperature about 1200 °C. Then the shaft was charged with equal portions of charcoal and ore in the amount of 15–20 kg. Charges were repeated at intervals of 30–130 minutes, assuming the charging level 105–110 cm above the blow holes.

Within 16–18,5 hours of smelting duration 11–14 charges were made using 200–220 kg of ore and charcoal. The furnace was opened only after 3–5 hours from the last charge. Its high temperature prevented quick demolition and removal of iron immediately after the process. Altogether, during *Dymarki Świętokrzyskie* (years 2013–2016) four experiments were carried out (smelts I–IV). The last experiment (smelt V) was made in September 2016 as part of the *ARTifacts* Archaeological Festival in Pruszków organized by the Museum of Ancient Mazovian Metallurgy (*tab. 2*).

During the first and subsequent experiments adverse phenomena appeared in the form of weakening of the chimney draft as a result of the forming bloom blocking the blow holes, 'overgrowing' the shaft with slag or changing atmospheric conditions, as well as difficulties in spontaneously draining slag into the pit. In order to improve the work of the furnace a number of modifications of its structure and way of running the smelt were made, consisting in: tilting the blow holes (up to 15°); selection of charcoal fraction also in the preheating stage; mechanical clearing of the zone of the slag flow to the pit; use additional draft from the side of pit canal; increasing the portion of the batch to 20 kg; use in the process of so-called 'cold' slag-pit; increasing the height of the shaft to more than 3 m.

Ore	Fe	SiO_2	Al_2O_3	CaO	MgO	Mn	S	P	Roasting losses
Hematite	58.72	5.87	0.39	0.3	0.32	0.54	0.11	0.017	
Hematite (roasted)	59.82	4.23	0.4	0.34	0.63	0.98	0.045	0.009	10.89
'Brown'	32.36	20.19	13.91	1.91	2.04	1.02	0.14	0.052	
'Brown' (roasted)	37.46	23.39	15.97	1.91	2.36	1.02	0.13	0.048	24.78

Tab. 1. Chemical composition of ores used in the experiments based on EDXRF analysis (Twin-X analyzer Oxford Instruments) in wt%.
Tab. 1. Chemické složení rud použitých v experimentech, ED-XRF anlaýza (analyzátor Twin-X Oxford Instruments) v hm%.

In addition, the entire arsenal of current means affecting the continuity of the process was used, such as: cleaning of blow holes; scaffolding of the shaft; periodically lowering the level of charge; use of admixture of wood in portions of fuel; blowing support with 3–4 hand bellows (smelt IV) or electric blower (smelt V).

The result of the experiments were slag-iron structures with a ring-shaped or circular form bonded to the shaft walls below the blow holes. They consisted of 8 'segments' associated with particular openings (*fig. 3a*). The 'segments' differed quite significantly with the amount of reduced iron and associated slag and other impurities (*fig. 3b*). The presence of compact metallic phases in the structures obtained in smelts I, II and V allows to define them as 'blooms'. Their weight (including impurities) ranged from about 50 to 75 kg. Assuming reduced iron content of about 50 %, 25–37.5 kg of raw material was obtained, which gives yield of iron of its available quantity on the level 20–30 %. This value is similar to that received in small experimental furnaces using artficial draft, working in recent years on *Dymarki Świętokrzyskie*.

Generally, the amount of slag produced in the proces because of use quite rich ore was relatively small, and only a part of it flowed into the pit. Even after use an admixture of poorer ore (smelts III, IV) it was not sufficient to fill the slag-pit and create such an expected regular in the shape and heavy block. Also the presence of solid structure slag, so characteristic of upper parts of prehistoric blocks, was insignificant and local. The center of the pit was dominated by porous slag with charcoal imprints. In the lower part droplets and lumps of slag in layer of charcoal were observed. In one of the experiments an exceptionally strong inflow of solid slag occurred in the sector where the outlet of the pit canal

Smelt	Shaft height	Preheating		Charging			Time of smelt (h)
		Charcoal	Time	Ore	Charcoal	Intervals	
I (2013)	2.4 m	1/2 of shaft	4 h	H/B = 5:1; 14x15 kg	14x15 kg	30–85 min	18
II (2014)	2.5 m	1/2 of shaft	5.5 h	H/B =10:1; 4x15 kg, 7x20 kg	4x15 kg, 7x20 kg	50–100 min	16
III (2015)	2.45 m	1/2 of shaft	3.5 h	H/B = 1:1; 4x15 kg, 8x20 kg	4x15 kg, 8x20 kg	35–90 min	18
IV (2016)	2.5 m	1/2 of shaft	2.5 h	H/B = 1:1; 4x15 kg, 7x20 kg	4x15 kg, 7x20 kg	40–120 min	18.5
V (2016)	3.05 m	1/2 of shaft	3 h	H only; 11x20 kg	11x20 kg	60–130 min	18

Tab. 2. Parameters of the experimental smelts I–V carried out in 2013–2016 (the abbreviation 'H/B' means the Hematite/Bog ore mixing ratio).
Tab. 2. Parametry experimentálních taveb I–V realizovaných v letech 2013–2016 (zkratka H/B znamená směsný poměr hematitu a bahenní rudy).

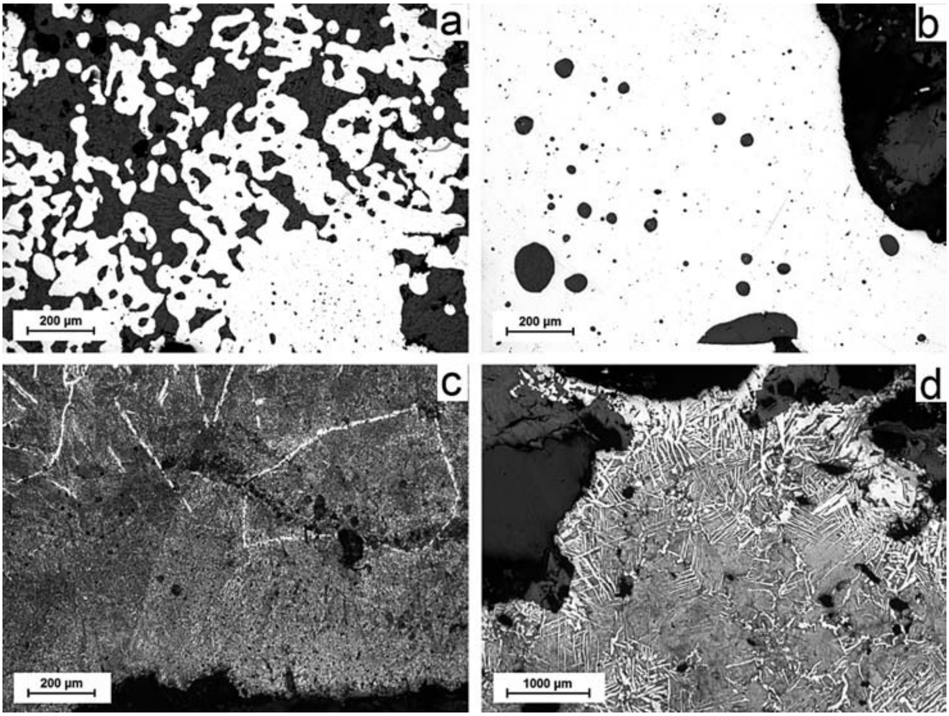


Fig. 4. Microstructure of the bloom from experimental smelt I (Dymarki Świętokrzyskie 2013). Sample before (a, b) and after (c, d) etching with 3% Nital.
Obr. 4. Mikrostruktura železné houby z experimentální tavby I (Dymarki Świętokrzyskie 2013). Vzorek před naleptáním 3% nitalem (a, b) a po něm (c, d).

was located. It may confirm its important role in the mechanism of draining this material, as long as the conditions of appropriate 'ventilation' of the slag-pit are met.

5. Bloom and slag characteristics

The microstructure of the bloom obtained in smelt I indicates the formation of iron in the form of filigree and solid zones (*fig. 4*). Solid iron was created within filigree zones probably according to the mechanisms known from the smelts carried out in furnaces *świętokrzyski* type (*Suliga – Karwan 2014*; *Przychodni – Suliga 2016*). The pieces of charcoal, on which the grids of reduced metal were emerged, also played a role in the formation of iron. The extensive solid iron zones were characterized by high purity. Only minor oxide inclusions and few slaggings were observed. However, the metallic phase appearing in the upper part of the bloom was heavily carburized to the eutectoid composition (0.77 % C) on the surface (*fig. 4c*). The observed gradient of carbon concentration indicated the diffusive nature of this carburization (*fig. 4c–d*). This was caused by too long leaving the produced bloom in the heated furnace. In the microscopically examined slag-iron structure

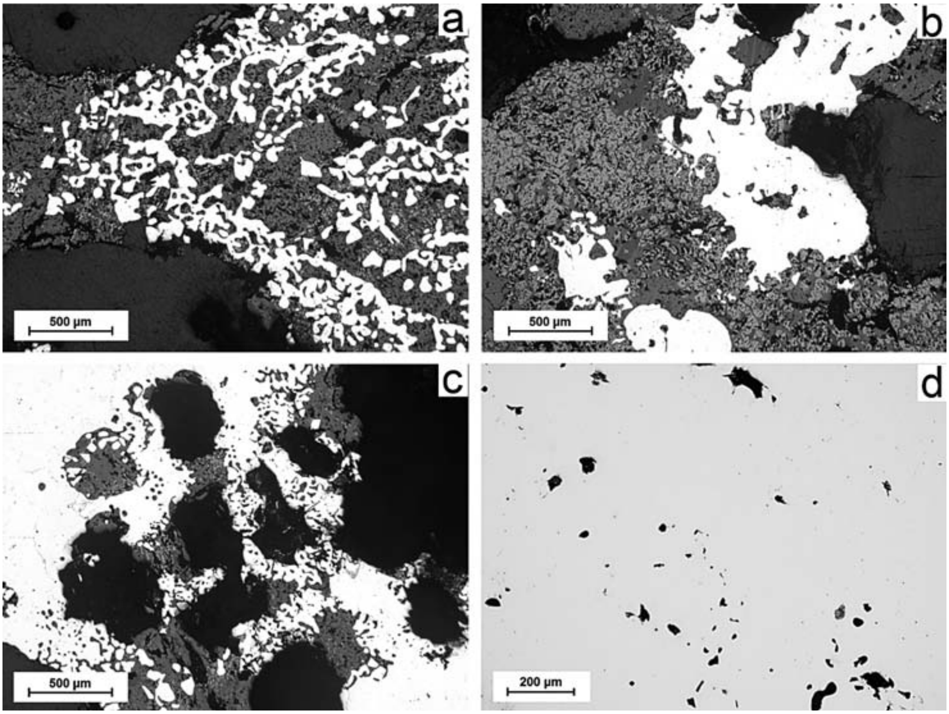


Fig. 5. Microstructure of the pseudo-bloom from the experimental smelt III (Dymarki Świętokrzyskie 2015).
Obr. 5. Mikrostruktura pseudo-železné houby z experimentální tavby III (Dymarki Świętokrzyskie 2015).

(pseudo-bloom) obtained in smelt III, iron was also formed in the form of filigree and solid zones, but these were already relatively small (*fig. 5*). Surrounded with slag and oxide phases, they were not exposed to the carburizing atmosphere in the furnace and retained ferritic structure.

The microstructures of slag samples from smelt III are typical for acid slags from iron production processes (*fig. 6*). Gangue of ores, iron oxides and ash components formed alloys from the FeO-SiO_2-Al_2O_3-K_2O system. On the background of gray fayalite Fe_2SiO_4 bright dendrites or grains of wüstite FeO can be seen. In intergranular spaces of fayalite, hercynite is probably located.[6] The presence of its may result from the reaction between slag and the material of the shaft, which was heavy melted in the area of the blow holes. This material contained clay, which could be a source of Al_2O_3. At the same time, the component in question does not show the features of the intergranular glass phase, typical for nearly all bloomery slags, because it did not shine in the 'dark field of view'.

The fine-crystalline structure of clots of slag indicates their rapid crystallisation in the potentially small volume of the slag phase, and the structural composition testifies to the higher FeO content than in solid slag. The bright bands in the structure of both clots of

[6] It was identified using the diffraction method on the EDS microanalyzer and confirmed by computer simulation in the FactSage program.

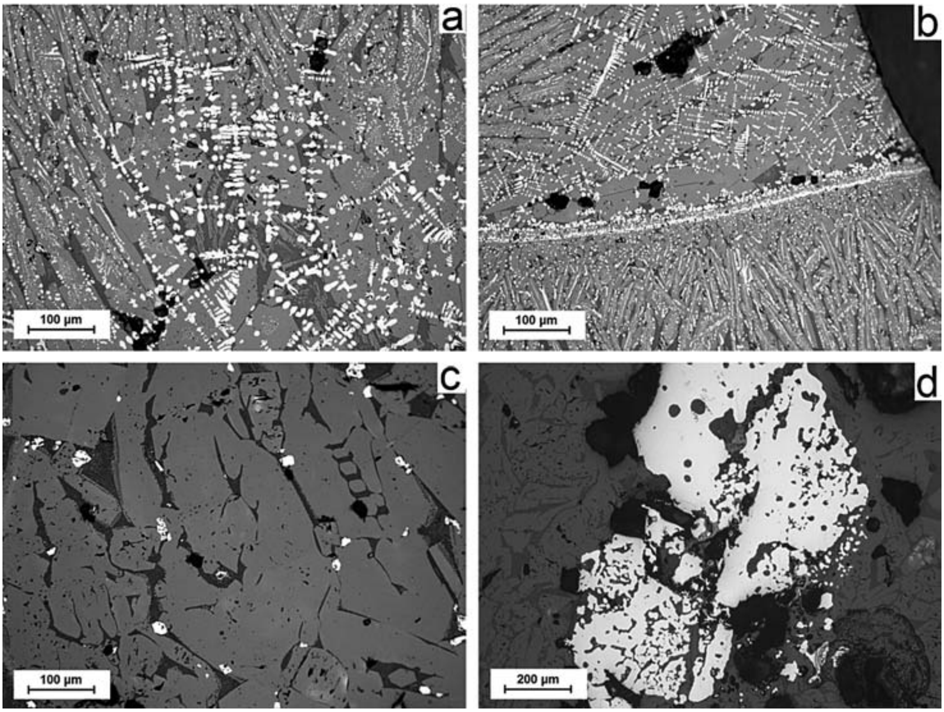


Fig. 6. Microstructure of clots of slag (a, b) and solid slag (c, d) from experimental smelt III (Dymarki Świętokrzyskie 2015).
Obr. 6. Mikrostruktura strusky s vysráženinami (a, b) a strusky monolitické (c, d) z experimentální tavby III (Dymarki Świętokrzyskie 2015).

slag and solid slag are boundaries of consecutive portions of slag inflowing over each other (*fig. 6b*). In the absence of the possibility of melting together (low temperature, low thermal capacity), these layers are separated by wüstite zones, resulting from the surface oxidation of fayalite. Particular layers of clots of slag have a different volume, they crystallize at different speeds and consequently differ in the size of crystallites. Solid slag has a coarse-grained structure indicating the slow crystallization of its large portions. The microstructure also marks the bright boundaries of the inflow layers. Generally, it is characterized by a lower FeO content than in clots of slag, it comes from a different phase of iron smelting, and also contains phases associated with K_2O (leucite $K_2O{\cdot}Al_2O_3{\cdot}6SiO_2$; $K_2O{\cdot}4SiO_4$; *fig. 6c*). Locally, separations of metallic iron with identical morphology as in the bloom were observed (*fig. 6d*).

6. Conclusion

The first stage of the presented experimental research, aiming to better understand metallurgical aspects of the Tarchalice type furnace operation, allow the following conclusions to be made.

Since the only evidence for the functioning of this kind devices were slag-pits filled with slag blocks, archaeological and ethnographic data, as well as scientific interpretations and reconstruction results from other metallurgical centers, mainly from the Świętokrzyskie Mountains, appeared to be useful for the presented research.

Conducted experimental smelts yielded metallic iron separated from slag to a greater or lesser extent. In the process natural draft was used, aided by bellows or a blower in extreme cases of 'freezing' of the furnace. Regarding the genuine slag blocks, the experimental smelts did not meet expectations. No regular and heavy block of slag with 'cap' and 'free solidification surface' was obtained. The phase and structural composition of slags obtained was identical to archaeological and experimental slags from the Świętokrzyskie Mountains (there is the lack of metallographic analysis of slags from the Tarchalice site). In the FeO-SiO_2 system the resulting slags were alloys on the SiO_2 side and had traces of a large share in their formation of ash components from charcoal (K_2O-Al_2O_3-SiO_2 alloys).

The iron was obtained in the form of slag-iron structures composed of 'segments' associated with blow holes. In the case of using hematite with possibly a small admixture of poorer 'brown ore' they had features of iron bloom. This kind of smelting product can not be referred to non-existent archaeological evidence, but their internal structures are analogous to the above quoted experimental blooms from the Świętokrzyskie Mountains. One can see there stages of forming of solid metal from filigree and grid forms to dense metallic areas contaminated with slaggings and non-metallic inclusions. Iron originally had probably a ferritic structure, but remaining necessarily for a long time in the cooling furnace was carburized into the pearlitic composition on the surface.

An unquestionable success of the experiments was the demonstration that in the determined construction parameters of the furnace and in favorable weather conditions (especially in the presence of constant blow of wind) it was possible to conduct the bloomery process only thanks to natural draft (smelts I–III), which according to the available source material was the basic air supply system to bloomeries in Polish lands in antiquity (*Orzechowski 2013*, 130). This problem regarding the Tarchalice type furnaces is, of course, still open, but even if we assume that artificial draft was in use at that time, it should be taken into consideration, that the lack of the necessity of blowing e.g. 4 bellows for over a dozen hours could compensate for the effort put into construction of a higher shaft.

In turn, the main drawback of the discussed research was the composition of the batch material. Rich hematite ore favored the yield of iron and enabled smelting results to be compared to other experiments, but it differed from the potential raw material for production site in Tarchalice. The sign of this was among others a small degree of use of the slag-pit capacity in comparison with the original furnaces. In correct experiments one should work on good quality local bog ore, which unfortunately has not been found yet.

Further research should concern optimization of a fraction of batch material and a method of its loading into the furnace, determination of a role of a filling the slag-pit and verification of views on the importance of the pit canal. However, these tests can not be carried out on such large furnace units due to the high costs and inertia of the devices. The building material of the furnace shafts also requires experimental testing. The lack of evidence of a relatively large amount of demolition material in the form of highly burnt or vitrified fragments of shafts on ironmaking sites with 'big' furnaces should be explained experimentally by specialists in ceramics. Similar research should relate to a reaction between liquid slag and the shaft casing or material forming the slag-pit walls, which could solve the problem of creating of the slag ‘caps’and other widenings at the top of slag blocks.

Admittedly the results of experiments should be considered correct in terms of the quality description of the furnace and the process itself (such is the character of observations, associations and general thoughts that emerged during tests), however further work must be directed towards the quantitative description, creation of a thermal and thermodynamic model as well as material balance, what requires the instrumentation of experimental furnace and taking measurements of temperature, air consumption and exhaust gas composition.

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