

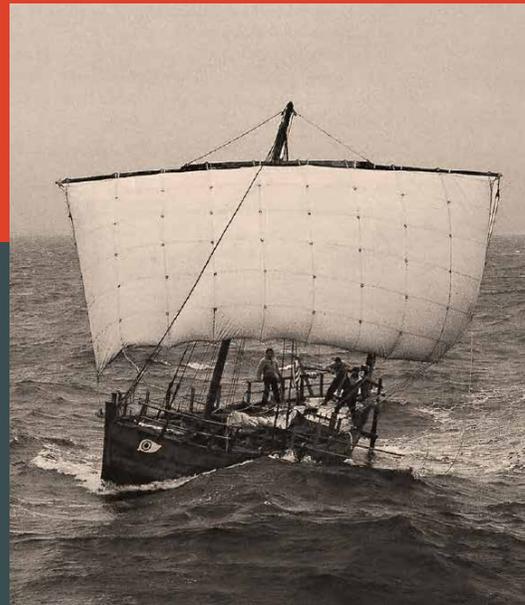


# EXPERIMENTS PAST

## HISTORIES OF EXPERIMENTAL ARCHAEOLOGY

EDITED BY

JODI REEVES FLORES & ROELAND PAARDEKOOPER



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## Contents

<b>Histories of Experimental Archaeology. Documenting the Past for the Future</b>	7
<i>Roeland Paardekooper &amp; Jodi Reeves Flores</i>	
<b>The History of Experimental Archaeology in Croatia</b>	15
<i>Andrea Jerkušić</i>	
<b>History of Experimental Archaeology in Latvia</b>	35
<i>Artūrs Tomsons</i>	
<b>Experimental Archaeology in Ireland. Its Past and Potential for the Future</b>	47
<i>Triona Sørensen &amp; Aidan O'Sullivan</i>	
<b>Experimental Archaeology in France. A History of the Discipline</b>	67
<i>Guillaume Reich &amp; Damien Linder</i>	
<b>Experimental Archaeology in Spain</b>	85
<i>Javier Baena Preysler, Concepción Torres, Antoni Palomo, Millán Mozota &amp; Ignacio Clemente</i>	
<b>The Developmental Steps of Experimental Archaeology in Greece Through Key Historical Replicative Experiments and Reconstructions</b>	97
<i>Nikolaos Kleisiaris, Spyridon Bakas &amp; Stefanos Skarmintzos</i>	
<b>The Role of Experimental Archaeology in (West) German Universities from 1946 Onwards – Initial Remarks</b>	117
<i>Martin Schmidt</i>	
<b>Ruminating on the Past. A History of Digestive Taphonomy in Experimental Archaeology</b>	131
<i>Don P. O'Meara</i>	
<b>The History and Development of Archaeological Open-Air Museums in Europe</b>	147
<i>Roeland Paardekooper</i>	

<b>Experience and Experiment</b>	<b>167</b>
<i>Hans-Ole Hansen</i>	
<b>Erfaring og Eksperiment</b>	<b>182</b>
<i>Hans-Ole Hansen</i>	
<b>Experimental Archaeology in Denmark 1960-1980 – As Seen Through the Letters of Robert Thomsen</b>	<b>189</b>
<i>Henriette Lyngstrøm</i>	
<b>The Origins of Experimental Archaeology in Catalonia. The Experimental Area of L'Esquerda</b>	<b>205</b>
<i>Imma Ollich-Castanyer, Montserrat Rocafiguera-Espona &amp; David Serrat</i>	
<b>Building, Burning, Digging and Imagining: Trying to Approach the Prehistoric Dwelling. Experiments Conducted by the National University of Arts in Romania</b>	<b>215</b>
<i>Dragoş Gheorghiu</i>	
<b>From Ship-Find to Sea-Going Reconstruction. Experimental Maritime Archaeology at the Viking Ship Museum in Roskilde</b>	<b>233</b>
<i>Vibeke Bischoff, Anton Englert, Søren Nielsen &amp; Morten Ravn</i>	
<b>Experimental Iron Smelting in the Research on Reconstruction of the Bloomery Process in the Świętokrzyskie (Holy Cross) Mountains, Poland</b>	<b>249</b>
<i>Szymon Orzechowski &amp; Andrzej Przychodni</i>	
<b>Engaging Experiments. From Silent Cultural Heritage to Active Social Memory</b>	<b>269</b>
<i>Lars Holten</i>	

# Experimental Iron Smelting in the Research on Reconstruction of the Bloomery Process in the Świętokrzyskie (Holy Cross) Mountains, Poland

*Szymon Orzechowski & Andrzej Przychodni*

## **Introduction**

It should be surmised that because of specialist knowledge, high technical requirements and a complex set of tools, the skill of iron smelting must have been a sort of taboo and was restricted only to members of the professional groups participating in the process (Orzechowski 2012, 308-309). In the following cultural systems that technology underwent many transformations, and original solutions, treated as secrets of the trade, fell into total oblivion. The only way to recreate them is experimental research. Although a full reconstruction of technological processes connected with obtaining iron in the antiquity turned out to be very difficult, observations collected in the course of experimental smelting yielded a lot of significant information, allowing for understanding the nature of the technique. Without that knowledge it is difficult to imagine carrying out excavation research on production sites or correct interpretation of its results.

## **Difficult beginnings**

Experimental research on reconstruction of the bloomery process has a long history and dates back to the end of the nineteenth century (see Wurmbrandt 1877), but only numerous discoveries of sites of prehistoric metallurgy made in the 1950s and 1960s in many regions of Europe, and problems connected with their interpretation, enforced undertaking that research trend. Initially it was conducted in laboratory conditions, and after working out model solutions of the bloomery process tests were made in reconstructed objects. Archaeologists and metallurgists from Western Europe were regarded as precursors in this field: in Belgium, Jean Sadzot (1956, 564); in Germany, Joseph-Wilhelm Gilles (1958; 1960, 943-948) and Eberhard Schürmann (1958, 1299); in England, E. J. Wynne and Ronald Frank Tylecote (1958, 338-348); and in Denmark, Olfert Voss (1962, 7-8) and Robert Thomsen (1963, 60-74). Almost at the same time, already in 1957, they

were joined by scientists from Central and Eastern Europe – in Poland Mieczysław Radwan, Kazimierz Bielenin and Waclaw Różański, and a few years later in the Soviet Union, Borys Aleksandrowicz Kołczin, O. Krug (1965, 1966 and n.) and the former Yugoslavia, Harald Straube, Bruno Tarmann and Erwin Plöckinger (1964, 7-44). Results of their work were presented at the international symposium in Schaffhausen, Switzerland in 1970 (Tylecote 1971, 77).

Research on reconstructing the bloomery process in Poland was undertaken following the discovery of a huge metallurgical centre in the Świętokrzyskie Mountains (see Bielenin 1992; Orzechowski 2007). Lack of knowledge concerning construction and the functioning principles of bloomery furnaces used in that region obliged researchers to seek explanations of those problems by means of experiments. They had to be started practically from scratch and many technical challenges had to be dealt with as well as a lack of similar research. A Polish team conducted the first experimental smelting in 1957. The previously mentioned J. W. Gilles started his research a year earlier, however, because of unfavourable weather conditions the smelting had to be put off twice and successful experiments were carried out only in 1958 and 1959 (Gilles 1958, 1960 and n.). The smelting carried out by the English team of E. J. Wynn and R. F. Tylecote preceded the Polish experiments only by a few months. Attempting to realise their experimental programme, the Poles did not know the results of foreign research and independently reached certain findings.

The initiator of experimental research, their manager and animator was an eminent expert on the history of metallurgical techniques – a metallurgist, Professor Mieczysław Radwan. From the very beginning representatives of various disciplines of sciences and humanities actively participated in it. Among them were metallurgists, archaeologists, metal scientists and chemists representing mainly two scientific institutions from Kraków – the Academy of Mining and Engineering (AGH) and the Archaeological Museum (Bielenin 1974a, 46). They obtained organisational support from the History of Polish Metallurgical and Casting Technique Unit at the Polish Academy of Science, which had been established in 1957. Vast knowledge and personal commitment of such people as Mieczysław Radwan, Kazimierz Bielenin, Waclaw Różański, Adam Mazur, Elżbieta Nosek, Tadeusz Stopka, Jerzy Zimny, Stefan Knapik, and Ferdynand Szwagrzyk have caused the results of research conducted then to still be regarded as a basis for any attempts undertaken in this field.

Basic assumptions and postulates concerning the reconstruction of metallurgical objects, recreated technique and technology of iron production were formulated during the first phase of the experiments. Solving them helped to correctly interpret structures discovered in the course of archaeological excavations, as well as to understand the complex physical-chemical phenomena associated with the so-called 'direct process' occurring in slag pit furnaces. The knowledge gained was also indispensable for presenting the ancient Świętokrzyskie Mountains metallurgy as a historic and cultural phenomenon. In reference to technical issues, the scientists' attention focused on a few fundamental elements:

1. reconstruction of a bloomery furnace and functions performed by its elements during the smelting process;
2. learning the principles of iron reduction in such objects and generally the technology of bloomery production;
3. determining type of raw materials needed for smelting, ways of preparing them and proportion and method of feeding in the charge;
4. establishing the type of air blast used;
5. and determining the time the process took and the form and structure of the obtained iron.

It would be difficult to overestimate the immense role of experimental research in building a vast cultural and technological image of ancient metallurgy in the Świętokrzyskie Mountains region. Although excavation research conducted on a large scale by K. Bielenin systematically yielded new source materials, their vestigial character – only lower parts of furnaces remained – made impossible a full reconstruction of those objects, which undoubtedly made recreating the complex technological processes connected with obtaining iron more difficult. When there was no source data available, attempts were made to allude to discoveries known from the same cultural and chronological circles or ethnographic analogies. It was, however, impossible to avoid making errors. According to the state of knowledge at that time, a bloomery furnace found in the Świętokrzyskie Mountains was a one-part object in the form of a shallow pit – sunk into the earth – without a shaft casing. The first smelting experiments were conducted within similar constructions. Initially, they were conducted in laboratory conditions and only after acquiring necessary experience was real smelting carried out.

The first field attempt supervised by S. Holewiński, in the presence of M. Radwan, W. Różański and K. Bielenin, was carried out in Starachowice in 1957 and did not yield expected results. In a simple pit without a casing, measuring 40 cm in diameter and 50 cm deep, the temperature of only 500<sup>0</sup>C was obtained. The temperature rose to approximately 800<sup>0</sup>C after a small shaft approximately 25 cm tall was built, but still the iron compounds the ore contained did not undergo the reduction process. Only adding artificial draft allowed for obtaining some small iron sponge badly contaminated with slag (Radwan 1958, 496-497).

Similar experiments were continued in the years 1958-1960 in the grounds of the AGH in Kraków. The pit used had size similar to real parameters of discovered furnaces (initially 45 cm, later 35 cm in diameter) without shaft casing. Even though a kind of loose brick wall was built on the edge of the pit, which slightly improved the furnace functioning, providing a strong artificial air blast was necessary to obtain suitable temperatures. Only a discovery, made by K. Bielenin, of clay walls of a shaft casing of a furnace, which had been preserved in less damaged sites in the Łysa Góra range, resulted in building small shafts 40-45 cm tall in experimental objects. However, with such a low superstructure, artificial draft had to be used forcing the air in through two, and then four, symmetrically spaced draft openings (Bielenin 2011, 83).

The first attempts showed that ores with a high content of silica were not suitable for smelting. Only Fe content at the level of 40-60% and SiO<sub>2</sub> within 10-20% allowed for obtaining iron at the level of 18-20%. It was also established that smelting 1.8-2 kg of iron ore yielded approximately 1 kg of slag, and fuel consumption for 1 kg of iron exceeded 12 kg (Radwan 1959, 388). Moreover, it was discovered that ore calcination, particularly in case of carbonate (siderite), advantageously influenced its properties during smelting.

An important moment in realising the project was concluding an agreement in 1959 with *Archeologickym Ustavem* of the Czech Academy of Science and ensuring the cooperation of a Czech archaeologist, Radomir Pleiner. In 1960 in the grounds of the AGH in Kraków a series of joint Polish-Czechoslovakian smelting processes was carried out. Two different types of furnaces were being tested – a single smelting furnace of the Świętokrzyska pit type, and a multiple-use furnace of the Lodenice type (Pleiner and Radwan 1962; 1963). That time local hematite ore from the mine in Rudki was used, which potentially might have been used in ancient furnaces (50.56% Fe, 15.5% SiO<sub>2</sub>). During the work, the proportion of the charge ore and charcoal was also tested, as was the size of fed raw material fractions. In the next experiments the proportion of 1 kg of ore to 1.5 kg of coal, or 1:1 was used. As far as ore granulation was concerned, it was decided that there was no point in crushing it too much because even larger lumps (30-40 mm) fell apart by themselves in the furnace under the influence of the heat from escaping gases. On the other hand, of great importance was appropriate breaking up of coal (25-30 mm), due to which a high concentration of carbon oxide could be maintained (Radwan 1962, 270-280).

Particularly interesting were the results of temperature measurements. It was found out that they were greatly varied, both in the horizontal and vertical cross-section. By applying one tuyère, temperatures above 1500° C could be reached. However, even at the distance of merely 25 mm it fell to approximately 570° C. With two tuyères the temperature became more even but it still was quite varied (Radwan 1960, 561).

## Field smelting

Experience and knowledge gained during the first stage of research conducted mostly in the grounds of the AGH in Kraków, in semi-laboratory conditions, allowed for starting regular field smelting already at the beginning of the 1960s. The area at the Museum of Ancient Metallurgy in the Świętokrzyskie Mountains in Nowa Słupia, turned out to be a perfect site for conducting the process, so in 1962 the research testing ground was moved there (Figure 1). Apart from a convenient location that ensured conditions close to natural, the team acquired a laboratory and storage base, as well as accommodation. In the years 1962-67 eight smelting tests were carried out here. Furnaces with low (approximately 50 cm) shafts were built, and artificial draft was applied (Radwan 1963; 1964; 1967; 1968).

Special care was taken to carry out the smelting experiments in conditions as close to natural as possible, and the charge was obtained from local deposits. Pits were dug into the ground and shafts were made from local loess clay. The



Figure 1: Professor M. Radwan supervising one of the first smelting experiments carried out at the beginning of the 1960s in Nowa Stupia

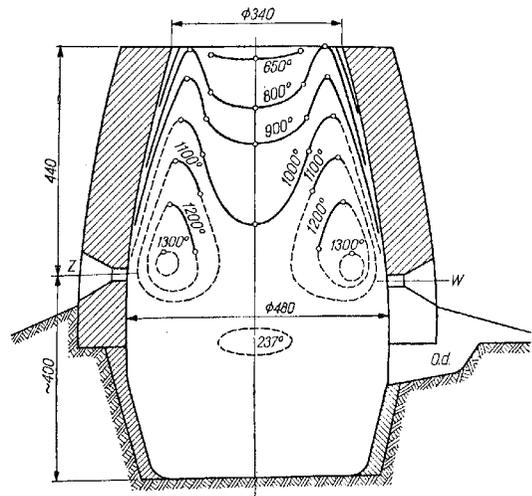


Figure 2: Isothermal diagram prepared on the basis of temperature measurements in the experimental furnace. Measurements are given in millimetres (Legend: z, w – tuyère openings; od – slag pit canal)

experimenters even produced their own charcoal. Various kinds of wood (beech, pine), corresponding to the species used by ancient metallurgists, were charred in charcoal pits. In order to improve the process an additional opening was introduced beneath the tuyère, modelled on the so-called pit canals found in some furnaces (see Orzechowski 2011). Even the air blast produced by mechanical devices was rejected, in favour of manual bellows which provided a less regular draft but closer to the one that might have been applied by smelters in the antiquity. Raw materials used for smelting were analysed in detail, while obtained materials were subjected to chemical and structural testing. Multi-spot and very precise temperature measurements allowed for drawing isotherms which explained phenomena such as the so-called edge run (Figure 2). It is worth emphasising that, in contrast to

previous experiments in which it was only possible to smelt from few to several, rarely several dozen kilograms of ore, in the course of new research attempts made to increase the amount of charge materials were successful, and the said amount was closer to that used in the antiquity. In one of the furnaces a block of slag merged with iron sponge weighing approximately 80 kg was obtained (Mazur and Nosek 1966, 28).

Various kinds of ores (limonite, siderite, hematite) found in the nearby mine in Rudki were used at that time. Let us remember, that the deposit is characterised by a very low content of phosphorus (0.09 to 0.14 P<sub>2</sub>O<sub>5</sub>) which, according to a metal expert J. Piaskowski, was to determine the character of iron produced in this region (Piaskowski 1984). In order to verify that hypothesis, attempts were made to check the distribution of phosphorus in iron and slag by carrying out a few smelting tests with high-phosphorus ore (above 1.5% P) imported from Grodzisko near Częstochowa – beyond the Świętokrzyskie Mountains region (Radwan 1964, 369; 1965, 228). The problem was not explicitly solved, although in the general conclusion it was stated that during the bloomery process phosphorus was transferred mainly to slag (Holewiński 1963, 105-106). One of the last experiments in the series took place on 15 September 1967, in the presence of spectators, thus initiating the open-air festival known as *Dymarki Świętokrzyskie* (Bielenin 1974b, 123-129; Radwan 1968).

That first but crucial stage of research was closed in 1968 with the tragic death of its initiator and manager, M. Radwan. Immense knowledge and experience of that scientists, as well as passion and persistence with which he ran the project has constituted a model both unique and impossible to imitate. The team he created, though later partially reactivated, never again operated so dynamically and comprehensively. Experiments organised throughout the next decade, carried out mostly during the *Dymarki Świętokrzyskie* festival, were primarily a form of scientific presentations for the general public, geared towards popularising technical knowledge among wide audiences.

A new stage of research was initiated at the end of the 1970s by a previous co-worker of M. Radwan, Prof. Waław Rózański, who carried out a series of smelting experiments within scientific camps for students of the AGH in Kraków, *Officina Ferraria*. They were organised in Nowa Słupia in the years 1978, 1979, 1982 and 1983 (Rózański 1980; 1982; 1982-1985; 1984). At that time there occurred a radical change in opinions concerning the applied draft, and artificial draft was rejected in favour of natural. It required significant heightening of the above-ground section of the furnace, first to 80 cm, and later to the height of 120 cm. From two to six draft openings located just above the pit were used during various phases of the programme. Owing to the heightened shaft a better concentration of carbon monoxide was obtained, and therefore more advantageous conditions for the reduction process as well as an opportunity for better carburization of iron. Temperatures obtained at the level of draft openings reached 1100-1280°C, and in case of a larger number of openings even 1320°C (Rózański 1980, 37-38).

Various kinds of ore were used, from limonite from the Skarżysko-Kamienna region to hematite and siderite from Rudki. Proportions of charge materials and their granulation-ore from 10-30mm and charcoal from 10-40 mm – worked out during the first period of research were maintained (Róžański 1982, 55).

One of the more interesting research hypotheses formulated in the course of the work was the idea of running the smelting in two independent stages. In the first phase – the author did not indicate where it might have taken place – the goal was to obtain a slag-iron conglomerate, which was then melted again in the bloomery furnaces, traces of which we have found during archaeological excavations in the so-called slag pit furnace clusters. The aim of the second stage was complete separation of slag from iron sponge. Although an experiment carried out in 1983 to verify this hypothesis led to obtaining well-liquefied slag that made a compact block resembling its prehistoric counterpart, it appeared impossible to separate it from metallic iron (Róžański 1984, 65) (Figure 3). Though from the technological viewpoint, the idea of this two stage process seemed a fairly reasonable solution, it was not acceptable because of lack of archaeological evidence of earlier production of the above mentioned conglomerate.

Theses concerning the construction, shape and height of the shaft, formulated in the course of scientific student camps, and confirming the possibility of applying natural draft influenced subsequent smelting attempts, from then on conducted mainly during the open-air event known as *Dymarki Świętokrzyskie*. Although



*Figure 3: Scientific camp of a students' group Officina ferraria in Nowa Słupia in 1970; Profile of an experimental furnace after smelting*



*Figure 4: Dymarki Świętokrzyskie in the 1970s: in the centre from the left Prof. Kazimierz Bielenin and Prof. Wacław Róžański*

each of the experiments carried out during the festival served to verify a research hypothesis, they were primarily aimed at popularisation and education (Figure 4).

Summarising that period of research, one has to emphasise very clearly that thanks to the many years of experimental smelting it was possible, at least partially, to clarify many controversial issues concerning the construction of the bloomery furnaces used in the Świętokrzyskie Mountains region, and principles of their function. Verifying the model assumptions in the process of so-called direct reduction would not have been possible without testing them in practice by means of experimental smelting. After confronting those results with archaeological materials, some basic assumptions were made which, in the most credible way, allow for recreating the appearance of bloomery furnaces and the manner in which smelting had been conducted (see Figure 5):

1. Smelting was carried out in a single-use furnace that was destroyed after iron had been extracted from it.
2. The furnace consisted of two fundamental parts; a small hollow called the pit, dug into the ground to the depth of approximately 50-80 cm, and a clay shaft of unknown height. Depending on the kind of applied draft it might have measured between 80 to 120 cm.

3. Clay blocks in the form of *quasi* bricks, unknown anywhere else, were used for building the above-ground part of the furnace in the Świętokrzyskie Mountains.
4. Best conditions of ‘releasing’ the charge were observed in shafts resembling a truncated cone, so it should be surmised that it was what the above-ground section of the furnace looked like.
5. Raw material for smelting was properly prepared – calcinated iron ore and charcoal obtained from deciduous and coniferous trees. The ore and coal were suitably crushed and fed in proportions 1:1.5, which ensures appropriate ventilation of the charge. No fluxes were found to have been added.
6. Bloomery furnaces could operate both by artificial and natural draft. In both cases temperature above 1200° C was obtained, in which it was possible to reduce iron oxides and to obtain liquid fayalite. With natural draft the shaft height ought to exceed 100-120 cm.
7. Draft openings located in the ground section of the shaft approximately indicated the level where formed iron sponge contaminated with slag.
8. Various types of the pit widened sections-so-called pit canals facilitated the process, allowing for better ventilation of the furnace.

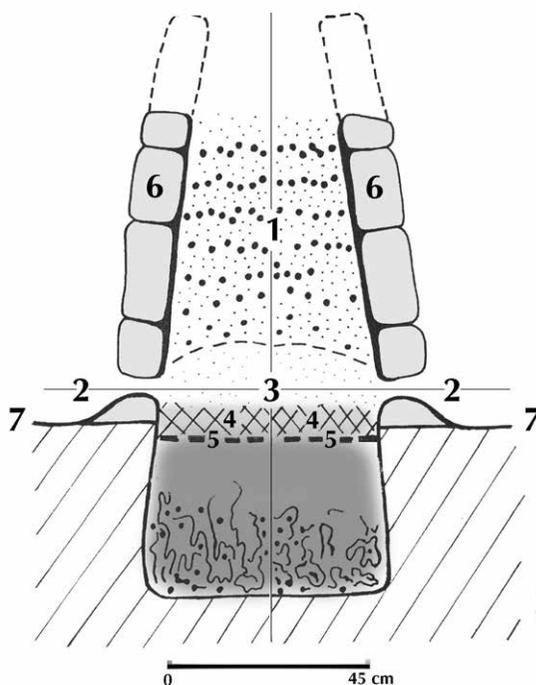


Figure 5: Theoretical model of a slag pit bloomery furnace from the Świętokrzyskie Mountains according to K. Bielenin (2006, 26, fig. 10) (Legend: 1 – input: charcoal and iron ore. 2 – tuyère opening. 3 – reduction zone. 4 – iron sponge zone. 5 – upper section of a slag block – so-called free solidification surface. 6 – shaft. 7 – soil surface. 8 – ‘calec’ undisturbed soil)

## Experimental smelting during the *Dymarki Świętokrzyskie* festival

The next stage of experimental research on the reconstruction of the bloomery process in the Świętokrzyskie Mountains is associated with the open-air event called *Dymarki Świętokrzyskie*, which has been held every year in Nowa Słupia since 1967 (Bielenin 1974b). As mentioned before, the event originated from the research carried out at the Museum of Ancient Metallurgy in the Świętokrzyskie Mountains and expressed the understanding of the scientific community for the need to popularise the knowledge among a wider audience. Immense media success of the idea undoubtedly contributed to the further development of the event. Thus began its heyday and a period of extreme popularity of the *Dymarki* festival, which lasted till the beginning of the 1990s. A breakthrough came with founding Society of Friends of Mining, Metallurgy and Old Polish Industry in Kielce (TPGHiPS), which has taken care of its organisation and promotion since 1970. Owing to the perfect location of the Furnace Cluster along a pilgrimage and tourist route to Mount Holy Cross (Święty Krzyż), an attractive artistic programme, and especially an interestingly arranged show of ancient smelting, *Dymarki Świętokrzyskie* entered the canon of tourist attractions of the Świętokrzyskie Voivodeship and became one of the best known open-air events in Poland (Orzechowski 2012, 320-323).

The 1990s were a period of a gradual decline of the event in which it came down to being a populist folk festival, where iron smelting merely constituted a background for various entertaining activities. Only in 1999 after establishing the Świętokrzyskie Association of Industrial Heritage in Kielce (ŚSDP), a new educational project entitled *Man and Iron During the First Centuries AD* was prepared, due to which the archaeological aspect regained its proper place. Iron smelting was enriched with new elements alluding to a wider technological and cultural context. An independent version of the programme addressed to school students was also prepared under the title *Iron Roots* (*Żelazne Korzenie*), which has been organised on and off since 2002 (Przychodni 2006, 206-210).

The change in the *Dymarki Świętokrzyskie* formula, whose programme was enriched with new, carefully prepared archaeological presentations, commenced another series of experimental research. Smelting was carried out within an extensively reconstructed bloomery furnace cluster where, besides the furnaces, its whole auxiliary infrastructure was recreated in the form of places where raw materials were prepared and stored, various types of hearths and a blacksmith's workshop (Figure 6). The archaeological festival that accompanied it was to present the Świętokrzyskie Mountains metallurgy against a wider background of the Roman period in the Polish territories and its references to the political situation in Europe at the time of the Roman Empire (Orzechowski, Przychodni and Czernek 2008, 85-87).

A new research team was quickly established whose aim was to continue a strictly scientific programme of research on iron smelting. In the years 2000, 2002 and 2005 the team supervised by I. Suliga, from the Faculty of Metallurgy and Material Engineering at the AGH in Kraków, consisting of Mirosław



Figure 6: Reconstruction of a bloomery workshop during the Dymarki Świętokrzyskie Festival in 2006

Karbowniczek, Szymon Orzechowski, Andrzej Przychodni and Daniel Czernek, conducted a few smelting experiments during *Dymarki Świętokrzyskie* and *Iron Roots*. Tested elements included: the impact of potassium on the degree of slag liquefaction, functioning of pit canals with natural draft were tested, and attempts to make a single draining of slag into the pit with the help of a wooden grate (see Karbowniczek and Suliga 2002; Bielenin, Dąbrowski, Orzechowski and Suliga 2004, 68-69, 80-81, Fig. 13, 14; Suliga 2006, 167-172). New types of ore were used for testing, such as siderite from Majówka deposit near Starachowice, and so-called 'down' ores from the vicinity of Tychów.

At that time an extensive programme of further experimental research on reconstructing a complete technological process in slag pit furnaces was prepared, which was sent to the Scientific Research Committee within a ministerial grant. However, no funds for financing the project were acquired. In such a situation, the appointed team temporarily suspended their activity and abandoned further experiments, concentrating on carrying out laboratory research (see Suliga 2006; Suliga and Kargul 2007; Bielenin and Suliga 2008, 65-73).

After years of stable progress, there occurred a certain impasse in experimental research. The technological scheme, repeated over and over again for half a century, did not fulfil the hopes pinned upon it. Its fundamental drawback was primarily lack of iron sponge free from slag. In contrast, upper surfaces of prehistoric slag blocks clearly indicate the sponge being distinctly separate from slag. That

observation became known in the literature of the subject as ‘free solidification surface’ (Bielenin 1998-1999, 525-527, Abb.4; 2002, 16 and n; 2005,189-190). Iron sponge that formed below draft openings, at least during the final stage of the process, did not have direct contact with slag that was drained from the reduction zone and stored in the pit. On the other hand, the half-finished product obtained until recently in the course of experimental research alluded to the iron smelting technology used by modern-day peoples of Africa and Asia, but differed radically from what ancient smelters had been able to produce (see Łapott 2008, 131-133).

Drawing attention to the ‘free solidification surface’ led to new research perspectives, interrupting the long-lasting impasse in experimental research. In recent years it has been additionally supported with results of metallurgical analyses. They revealed segregation of elements and phases in cross-sections of genuine blocks, which proves that the latter crystallized from a huge volume of liquid slag. In practice, the possibility of a single inflow of a large amount of slag into the pit at the final stage of the process is assumed (see Suliga 2006, 268; Bielenin and Suliga 2008, 68-72). According to that concept, there may have existed two stages of the smelting process – in the first ores were reduced and gangue rock was slagged, in the second a single ‘run-off’ of slag into the pit took place.

This extremely interesting hypothesis is acceptable only when we assume that at least some of the liquefied gangue rock flowed freely to the pit during the smelting, creating a kind of openwork structure constituting a basis for the forming iron sponge. Only during the final stage of the process, the slag still remaining in the reduction zone was liquefied and tapped to the pit at one go, making causing the top portion to have a solid and regular surface – so characteristic for the upper and perimeter section of the slag block (Orzechowski 2013, 78-81).

## Recent years

Regardless of the above mentioned problems, recent years have also brought many interesting initiatives and innovative solutions spearheaded primarily by scientists associated with the Świętokrzyskie Association of Industrial Heritage in Kielce. It has also been mentioned how much the organisation contributed to altering the formula of *Dymarki Świętokrzyskie*, which, thanks to it, has grown into the largest archaeological festival in Poland devoted to the issues of ancient metallurgy and the period of Roman influence. However, requirements and restrictions connected with such a huge open-air event began to negatively influence the presented programme of experimental research. Both during *Dymarki Świętokrzyskie* and *Iron Roots* an essential part of the programme is dismantling the bloomery furnace and presenting the effects of the conducted smelting. It has to take place at a specific time and, therefore, it is difficult to suit the research programme to the audience expectations. In the majority of cases the process was either interrupted before its real completion, or the amount of charge materials was adapted to the time the presentation took, ignoring the actual working possibilities of particular objects recreated for this purpose. Naturally, the need for introducing change in

this respect had been perceived before. It seemed that the best and most effective solution would be separating the experimental part from educational and scientific shows for the general public (Orzechowski 2012, 323). The former should take the form of an independently realised scientific programme of significantly wider nature – involving also archaeological research, specialist analyses of materials from production sites, settlements and burial grounds of the Przeworsk culture, as well as prospecting for ore deposits that might have been mined by ancient smelters from the Świętokrzyskie Mountains region. The project has not been realised yet – mainly because of difficulties in obtaining suitable funds.

In such a situation, members of the association undertook various attempts of combining experiments with different forms of presentations connected with educational activity of the ŚSDP aimed at popularising the issue. In the years 2000–2011, several dozen of smelting processes were carried out during all kinds of workshops, archaeological festivals and numerous open-air events throughout the whole country. They were mostly of educational character, and their purpose was popularising knowledge concerning prehistoric iron metallurgy. One of the more interesting initiatives was inviting Jens Jørgen Olesen from the museum in Thisted, Denmark, to cooperate and experiment during the *Iron Roots* event in Starachowice. In 2008, he conducted a successful smelting process in a reconstructed furnace of the Świętokrzyskie Mountains type with a pit canal, on the basis of hematite and limonite ores from spoil heaps in Starachowice. The method he used involved filling in the pit with wood before starting the process and feeding in larger portions of iron ore, and was later applied in preparing projects of further experiments within presentations prepared by the ŚSDP in Otrębusy, Warszawa and Łódź in the years 2009–2010.

Subsequent stages of cooperation with Olesen were connected with furnaces with side outflow of slag, known from Scandinavia and recreated by him during the festival of *Dymarki Świętokrzyskie* in the years 2009 and 2010. The iron bloom obtained from them was also worked on initially during the presentation (Figure 7). It has to be added, that the above mentioned work was carried out based on ores brought from Denmark. Thus, the fundamental problem that made it impossible to fully transfer his experience onto the Świętokrzyski region grounds turned out to be ignorance of local ore deposits.

Exchange of professional experience with Olesen, and in following years also with the team from the Museum of Ancient Metallurgy in Mazovia in Pruszków<sup>1</sup> and colleagues from the City Museum in Wrocław, Archaeological Museum Branch<sup>2</sup>,

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1 Curator of the Museum of Ancient Metallurgy in Mazovia, Dorota Słowińska, with Wojciech Sławiński, Krystyna Koza, Maciej Aust, Piotr Holub, Bogdan Zając, Kamila Brodowska and Robert Wereda, prepared the project *Campaign of Fire*, which, besides promotional issues, involved crucial experimental research postulates realised by the museum team since 2010, also during *Dymarki Świętokrzyskie* in cooperation with ŚSDP.

2 On the basis of previous experiments conducted in Tarchalice, Wołów district, Lower Silesia Voivodeship, and material obtained from the site located in that village, Dr Paweł Madera, Dariusz Kik and Artur Kosmański prepared an experimental reconstruction of a bloomery furnace with a 'large' pit whose building was realised during the years 2011–2012. In 2013, during the *Dymarki Świętokrzyskie* festival a smelting experiment was carried out in the yet again recreated furnace of the Tarchalice type, which proved to be a successful bloomery process.



*Figure 7: Slag run-off in the furnace operated by Jens Jørgen Olesen during Dymarki Świętokrzyskie in 2010*



*Figure 8: Iron sponge obtained during the smelting in Starachowice in 2013*

contributed to significant progress in experimental work. However, participation in the project of a young member of the ŚSDP, Adrian Wrona, turned out to be of key importance for further research. Within his research work, he showed interest in the issue of obtaining carburized steel in a bloomery furnace (Wrona 2013). He based his inquiries on sources such as findings of American experimenters (Sauder and Williams 2002). Their result was working out an author's method of obtaining iron in a slag pit furnace, fully in keeping with archaeological sources. Observations connected with the phase of reduction and re-melting of iron sponge

allowed for obtaining bloomery iron fairly well separated from a slag block, during a seminar in Starachowice in 2013 (Figure 8). It was an additional confirmation of the previous, successful attempts conducted by Adrian Wrona in surface furnaces and a furnace with a side outflow of slag. Similar results were achieved within joint experiments carried out by the ŚSDP team with Jens Jørgen and Andreas Olesen in 2013, during the *Dymarki Świętokrzyskie* event. Results of recently conducted experimental work also carried out near Kielce in November 2013, have been waiting for analyses that will be carried out in cooperation with the AGH University of Science and Technology in Kraków.

Most recent experiments have been carried out in small-pit furnaces (approximately 30 cm in diameter) defined in literature as the Kunów type (see Bielenin 1992, 75-77). Some of them were fitted with 'pit canal', which, to a certain extent, facilitated controlling the process. Still, however, deposits of iron ore that might have been used by ancient smelters from the Świętokrzyskie Mountains cannot be identified. Nowadays, iron ore from Bosnia-Herzegovina, acquired by the courtesy of the Arcelor Mittal Company from Katowice, is used for the purpose of experimental smelting. Its mixture with ores from slag heaps at the Blast Furnace Unit in Starachowice is used during testing.

### **Some remarks to conclude**

In the general conclusion it should be emphasised that, regardless of the described interpretation and raw-material problems, experimental research conducted for over half a century revealed a certain helplessness of experimenters who appeared unable to cope with numerous problems decisive for the success of the process. Until recently, in experimental furnaces ore was reduced to metallic iron but its molecules were highly dispersed and did not form iron sponge distinctly separate from slag. The majority of smelting ended in obtaining a more or less compact ferrous-slag conglomerate merged with proper slag. Another problem was the inability to obtain suitably liquid slag, which usually ended up suspended in the upper part of the pit instead of flowing down to its bottom (see Bielenin and Suliga 2008, 62).

The fact, that previously conducted experimental processes differed radically from their prototypes is also confirmed by results of testing the chemical content of prehistoric slag and that obtained during experiments, which are significantly different. Prehistoric slag was almost completely devoid of metallic iron – which confirms that iron in the form of sponge-like mass was formed above the pit, without direct contact to the slag block. Metallic precipitation, occurring sporadically in some ancient blocks, resulted from the process of secondary oxidation that took place outside the reduction zone – mostly on the surface of larger pieces of charcoal (Suliga and Kargul 2007, 621). It cannot be ruled out that at least a part of iron obtained in the course of modern-day experiments underwent secondary oxidation due to too high a temperature and strong air blast. One cannot help but get the impression that in the attempts conducted so far the main focus was on liquefying slag and formation of a block, while forgetting about the main aim of the process,

namely iron reduction. So far, a low degree of iron ore reduction has been found in experimental slag.

Recent experiments have indicated the possibility of practically recreating the direct process in the slag pit furnaces, although those positive results are partially based on a raw material of foreign origin (Bosnian ore). The key problem the solution of which seems indispensable is obtaining iron ore which might have been used in the Świętokrzyskie Mountains region by ancient smelters. The latest, successful experiments still require thorough studies based on specialist analyses. Experiments carried out on various kinds of ore bring us closer, at least theoretically, to that target, and without their continuation it is difficult to imagine further progress in this area. Though we may never achieve the proficiency of prehistoric smelters at running the bloomery process, it seems that after almost 60 years of research on the Świętokrzyskie Mountains metallurgy, new perspectives are now opening as far as experimental work is concerned.

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