Reconstruction of the Świętokrzyskie Metallurgical Process of the Przeworsk Culture.

Lech Budaj – text and photos
Marianna Fogtman-Budaj - figures.
Poznań 2022

Abstract
The aim of the paper is to show the method of achieving the right results in the process of reconstructing old technologies on the example of the smelting process. The method used is an adaptation to the smelting process of the method developed in the 1930s by the Heck brothers. Using this method, many experiments based on both ancient and current ferrous metallurgy technologies in various cultural areas were conducted. The results obtained fully correspond to the archaeological finds, which have not been achieved by other researchers so far. In this study, I focus solely on the technological aspects of the bloomery process related to one type of furnace, which in my opinion is the key achievement in this field. It is a hearth furnace with a side hearth channel.

Keywords: Przeworsk culture, bloomery process, hearth furnace, iron slate, bloomery

Introduction
Attempts to reconstruct the smelting process were undertaken by many researchers, starting with the work of prof. M. Radwan in 1958 and then prof. K. Bielenin, in the 1960s. Experimental works carried out in Nowa Słupia lasted until 1968. As a result of these studies, in 1974 prof. K. Bielenin published a study containing, among other things, a diagram of the furnace which, after slight changes, is still valid in the literature to this day. Experimental research was resumed in the 1980s on the initiative of W. Różański as part of student camps. As a result of this work, a hypothesis was formulated about two independent stages of the process. (Różański 1984, 65) This hypothesis probably derives from the analysis of the blast furnace process but unfortunately it was rejected because it could not be proved experimentally. In the years 2000 to 2005 the team led by I. Suliga conducted research during "Dymarki Świętokrzyskie" and "Iron Roots". In the experiments, attempts were made to perform a single tapping of the slag and to use fluxes (fern ash) to liquefy the slag (Suliga 2006 167-172). Further experimental research was strongly influenced by laboratory observations, which concluded with the statement that in the last phase the slag surface was completely separated from the iron shale (Bielenin; 2005, 189-198). Experimental proof so far has not occurred. In 2008, during the "Iron Roots" and during the archaeological festival in Biskupin, J. Jansen from Norway presented his experiences. We could see the way of carburizing by melting iron in a small furnace. J. Jansen also conducted a smelting process with a hollow filled with coal dust. I had the opportunity to meet J. Jansen a few more times during smelting shows, which was a great opportunity to exchange experiences. In Poland, Adrian Wrona is working on J. Jansen's concept. In 2010, M. Marciniewski published his interpretation of the smelting process under the name "Projekt Hutnia" by M. Marciniewski (http://www.hutnia.pl/pl/s,2,Projekt_HUTNIA.html). This concept was based on the imprints of wood grain found in the remains of ancient kilns on the inside of the kiln lining. On this basis, M. Marciniewski drew the conclusion that hollow trunks covered with clay paste were used for the smelting process. He experimentally presented his concept in Biskupin in 2012 and in Nowa Słupia during Iron Smelting Days in 2014. This concept did not bring the expected results. However, the analysis of the problem

made by M. Marciniewski allowed the drawing of very interesting conclusions. The most important is the need to use wood as fuel instead of charcoal. Such a conclusion, according to M. Marciniewski, results from too small numbers of found measurers in relation to the number of furnaces. In addition, remnants of various species of deciduous and coniferous wood were found in the kilns, and coniferous species, mainly pine, are always found in the furnace hollows. However, I cannot agree with his interpretation of wood grain prints. The grain of the wood is visible on the cross-section of the trunk, not on its perimeter. Rather, I think the wood grain impressions were left by the internal wooden formwork used to build the kiln shaft. Maciej Tomaszczyk's experiments should also be mentioned, which I also had the opportunity to observe in 2017 and 2018. M. Tomaszczyk began his experiments in this field in 2008 during the festival of Slavs and Vikings in Wolin. I have seen successful processes for obtaining malleable iron, where no additional smelting processes were required. At that time, M. Tomaszczyk used a furnace with a side slag discharge without a hollow.

Since 2013, A. Wrona, in his undoubtedly interesting experiments, has focused, it seems, mainly on filling the hollow with slag. For this purpose, he tried to keep the forming iron shale above the blowholes together with the slag based on the so-called bottom carbon cushion. When a large amount of slag was formed under the forming iron shale, he opened the valley channel, thus leading to the combustion of the charcoal in the valley, and thus to the liquefaction of the slag and its flow down the valley. This procedure was repeated many times until the light of the hollow canal was flooded with slag. This process seems very complicated, and therefore it is reasonable to ask what advantage such complexity could have brought to the ancient ironworkers? A. Wrona points out that such an advantage is the possibility of using poor-quality ores commonly found in the area. (A. Wrona 2020, 11-14). This conclusion is also reached due to the fact that the use of ores with a high iron content in these experiments gave a small amount of slag but a lot of iron, while weak ores, on the contrary, gave little iron, but a lot of slag filling the hollow. It seems that this conclusion is also supported by the belief that the ancient metallurgists were not able to carry out the ore enrichment process and did not know the fluxes that would allow them to liquify the slag from high-grade ores. However, it is difficult for me to accept such reasoning when at the same time there is a widespread belief in the high skills of ancient metallurgists. The smelting process carried out according to A. Wrona's method, it seems, requires a relatively low temperature in the furnace itself, so that the iron slate does not flow into the hollow together with the slag. Only firing up the hollow increases the temperature to that needed for the slag to flow down. However, this is contradicted by the condition of the preserved fragments of ancient furnaces, which indicate a temperature above 1400 degrees in the vicinity of the blast channels. In addition, the slag block itself obtained in the experiments of A. Wrona (2020) does not indicate that it was separated from the iron shale as it is visible in ancient slags.

I have briefly presented the most interesting, in my opinion, achievements in the reconstruction of the smelting process, because the summary of achievements in this area has been dealt with much more extensively by other researchers in their publications (Suliga; 2006, Orzechowski 2013; Przychodni, Suliga 2016).

It would seem that over 60 years of research conducted by excellent research centres should result in a comprehensive study of the problem. However, that did not happen. To date, despite significant progress, this process has not been reconstructed with all its elements and, moreover, no research method has been developed that would allow for an orderly conduct of the research process. Most of the time was spent obtaining the iron by trial and error, claiming a success each time some reduced iron was found in the slag. On the other hand, the analysis of available materials was not used, even though there are more than 100 contemporary patents based on the direct reduction of iron in low-temperature processes. Not used either were known methods from other cultural areas - which became the basis for the research of the author of this study. Failures also resulted from the use of the wrong kiln model, which continues to this day. This model was probably proposed as a working hypothesis by K. Bielenin (1974). This hypothesis was not rejected in the course of research despite its obvious flaws. During the smelting process, the mixture of fuel and ore sinks downwards as the coal burns out, reducing its volume at the same time, so the furnace chamber should narrow in order to evenly reduce the ore and liquefy the slag. However, when the chamber expands downwards, free space is created as the charge shrinks, allowing unreduced ore to fall to the bottom of the furnace chamber, which causes dense fluidity of the slag and, as a result, failure of the process (drawing according to K. Bielenin 2006)(Fig. 1).

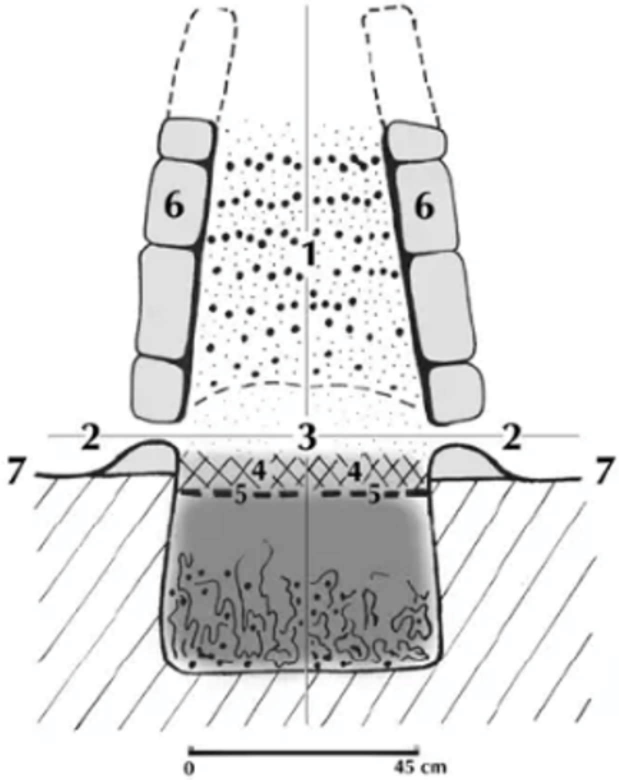


Fig. 1 Theoretical model of a slag-pit furnace from the Świętokrzyskie Mountains, after K.Bielenin 2006, 26; Fig. 10. 1 – Input: charcoaland iron ore, 2 – Ventilation aperturę, 3 – Reduction zone, 4 – Bloom formation zone, 5. Top part of slag (free solification Surface), 6 – Shaft, 7. Ground level.

Research method

In attempting to recreate the extinct animal that was the aurochs the Heck brothers, German biologists, were looking for cattle breeds that had the characteristics of their wild ancestor. For this purpose, they brought animals from various parts of the world to the Berlin Zoo and thence a special breeding centre in order to be able to use their scattered original features. Spanish bulls with a massive physique, Scottish and Hungarian cows with appropriate horns and Argentine cattle were used for crossbreeding, on the assumption that all these breeds come from a common ancestor. I also assumed that both the raw materials and the physical and chemical processes used in the production of iron are common, regardless of the culture in which they are used. Therefore, the analysis of methods of iron production in other cultures may help to find the missing elements of the bloomery process used in Poland during the Przeworsk culture. In addition, I assumed that the currently used blast furnace process is derived from the bloomery process, so it is important to know its evolution. Also, a lot of information was gained by getting acquainted with the currently used low-temperature technology of the Swedish company Höganäs producing powder steels.

Research process

I started my research on the bloomery process in 2008 in Biskupin, where I was invited as a participant in a historical festival presenting Japanese culture. As part of this festival, my task was to show the process of making steel using the traditional "Tartara Buki" method. For this project, I invited three more colleagues from the community centred around the Internet forum "Rei Dojo", dealing with the promotion of Japanese culture. They were Wojciech Kuśnierz, Sebastian Olszak and Krzysztof Arendt. Since the construction of this furnace requires a lot of time, we divided it into 2 stages. The first - the construction of the underground part carried out a month before the festival and the second - the above-ground part during the festival. Traditionally, we allocated 3 days for the "smelting" process.

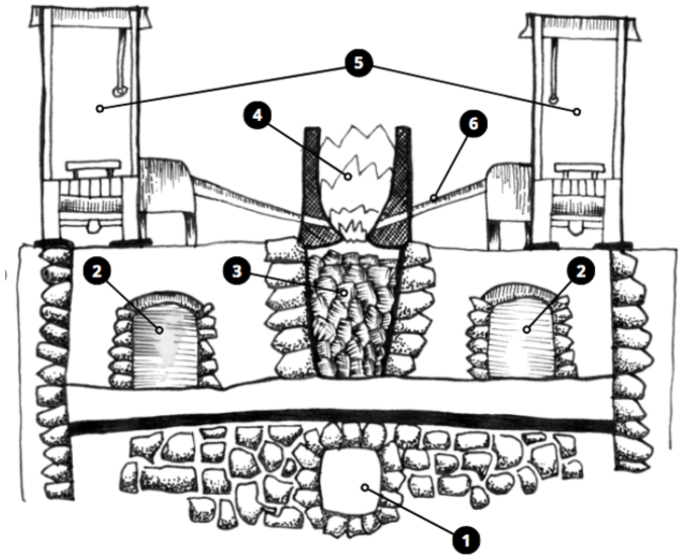


Fig. 2. Cross section of Tatara furnace. 1 - Drainage channel, 2 - Air ducts around the furnace, 3 - Subfurnace chamber filled with burnt charcoal, 4 - Furnace shaft, 5 - Leg bellows, 6 – Nozzles

A full-size kiln was usually about 2 m wide and about 4 m long. Our kiln had to be reduced to 1 m by 1.5 m and 1.2 m high, respectively. Along the kiln there are nozzles for injecting air into the lower part of the chamber, and on one of the short sides at the base of the kiln chamber there are two slag drain holes. These openings are closed with wooden plugs. The process itself is not only alternately pouring coal and ore into the furnace, it also has its own dynamics. Bog iron with a low iron content is first fed into the kiln to form a "slag pond" and then the ore with the correct iron content is poured. The airflow is maintained at a medium level so that a reducing atmosphere prevails in the furnace. Only at the end of the process, the charcoal itself is poured with maximum blowing in order to increase the temperature as much as possible. The slag formed contributes to the welding of iron particles into a larger lump called "kera" and protects it from decarburization. After about 24 hours of the process, the wooden plugs closing the drain channels are removed, which makes it possible to get rid of the excess accumulated slag. From now on, the tapping holes are covered only with charcoal, which protects against heat loss and at the same time allows free flow of slag as the process is carried out. In the last stage, the temperature is raised, allowing for maximum cleaning of the kera from slag. In our furnace, we reached a temperature of 1480 degrees Celsius at the end of the process, previously the temperature was between 1420 and 1450 degrees. Despite temporary difficulties with blowing, we obtained over 120 kg of steel with carburization from 0.9 to 1.1% of carbon.

As a result of this experience, apart from steel, I obtained a lot of interesting information, most of which I could not interpret at the time, and which in the future allowed me to avoid many mistakes.

During the first part of the kiln's construction, the "Iron Smelting Days" smelting workshops were held in the same place. Several teams from different countries tried to obtain iron in bloomery furnaces. Meanwhile, lectures and presentations were held during this event, from which I learned, among other things, that no one in Poland had ever managed to obtain iron in a bloomery furnace. During the festival itself, I had the opportunity to meet J. Jansen, who, as it turned out, also modelled his research on traditional Japanese metallurgy.

From the following year, I began regular work on the smelting process, mainly in Biskupin, which became the most important area of my experience. I also conducted demonstrations during other events and from 2010 to 2013 I focused mainly on the enrichment of bog ore needed for the so-called Pruszkow process. This is a very interesting topic, but so extensive that it requires a separate study. During the experience as the basis of the smelting process, I developed my own scheme of the furnace. The figure below shows its cross-section in the phase of slag flow into the hollow, after burning through the wooden tenon (Fig. 2).

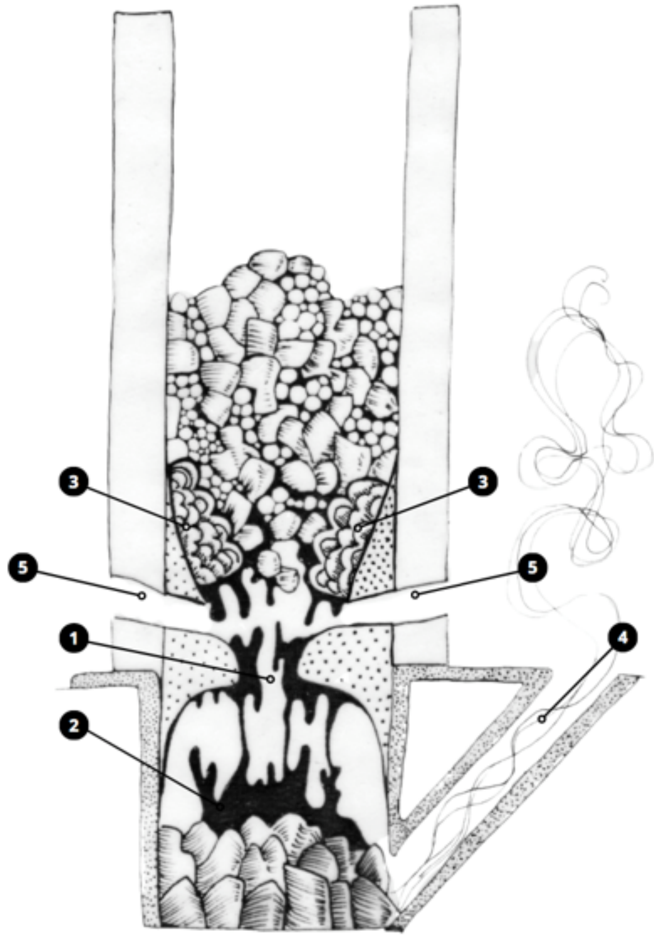


Fig. 3 Cross section of the furnace. 1 - Slag runoff after burning out a wooden tenon, 2 - Forming a slag block, 3 - Iron slate, 4 - Valley channel, 5 - blowholes (one of them in the "moving brick" installed after heating the furnace)

The hollow is walled with a mixture of clay and chaff. After bricking it, I light a fire at the bottom, leading to the evaporation of water from the vicinity of the stove and the formation of a layer of embers. Then, I put split logs with a diameter of about 5 cm into the hollow and put a heat-resistant mass on them, as shown in the picture. This mass consists of about 90 percent of quartz sand and about 10 percent of clay or clay and a small amount of water. I also put the same mass on the lower inner part of the furnace shaft.

The cross-section of this furnace is similar to the cross-section of the narrower side of the Tatara furnace. In a similar furnace, but with a side slag drain and a bricked-up hollow without an air duct, I have made many successful melts since 2009. In 2013, a team of Japanese masters making traditional melee weapons came to Poland. I had the opportunity to take part in workshops, shows and lectures. One of the Japanese instructors was Takanori Mikami, a Mukansa master who, in addition to crafting melee weapons, is also a participant in the annual steel smelting for Japanese swordsmen. Through him and courtesy of the Bizen Osafune museum, I was able to see the film documentation of various traditional metallurgical techniques. The most useful for my experiments was getting acquainted with the technology of iron smelting used in Burma (Fig. 3).

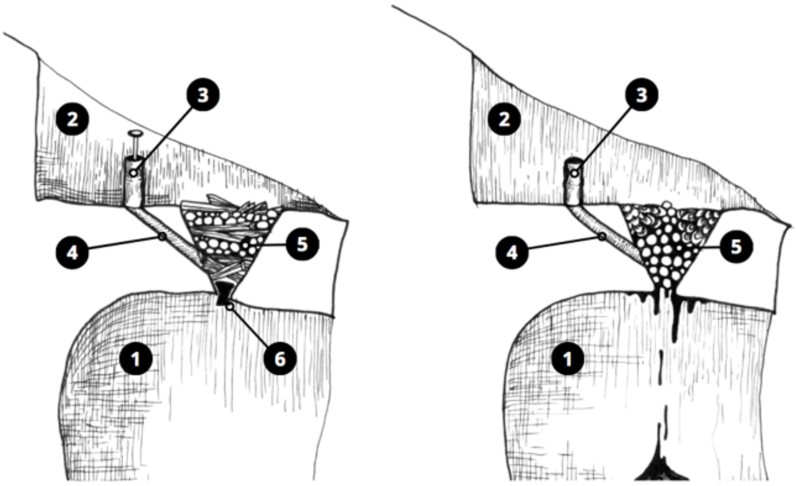


Fig. 4. Cross-section of a furnace from Burma. 1 - kiln pit, 2 - removed overburden, 3 - set of piston bellows, 4 - air ducts, 5 - furnace shaft, 6 - wooden tenon

A furnace pit is dug in the slope of the mountain, a conical depression is dug above the pit, which is lined with a layer of clay. Air ducts connecting with piston bellows made of bamboo are led into the cavity. The bottom of the depression forming the furnace shaft is pierced into the cavity under the furnace so that a round hole with a diameter of about 10 cm is formed, which is closed with a wooden plug. The subsequent process proceeds similarly to bloomery furnaces. After heating the furnace, charcoal and ore are poured alternately. Slag is discharged into the cavity under the furnace after spontaneous burnout of the wooden plug. During the subsequent process, the slag flows freely into the cavity under the furnace. I tested this technology the following year, as usual in Biskupin. I made a tapping hole in the bottom of the furnace and closed it with a pine plug. Unfortunately, the plug did not burn out and I had to push it into the hollow with an iron rod. This allowed the hollow to be filled with slag. In the next experiments, I made a special hole in the furnace wall at the right angle to make pushing the spigot easier, but I knew that this was not a good solution. I thought that the plug did not burn out because the process temperature was too low, so I focused on this problem. In Japan, pine charcoal is traditionally used as having the highest energy value. In Poland, such charcoal turned out to be unavailable, so I took care of burning it myself. Using this fuel, I managed to get a higher temperature, but the end result was not satisfactory. The plug was not burned through and I got less iron than usual, moreover the slag was thick and I had to remove it through the side drain hole. It turned out that the process was too fast to allow for proper ore reduction. Since I have not found a model of slag formation in a slag furnace in the literature, I decided to investigate it. I managed to do it only in 2017 during the picnic in Biskupin. It was very important to me, because this year I received a proposal to lead the smelting process during "Dymarki Świętokrzyskie in Nowa Słupia". I built the kiln a little higher than usual and in its side wall I made a series of holes for taking samples (Photo 1).

Photo. 1. – Furnace built as part of the conducted experiments, Biskupin 2017.

My priority was not about getting a slate iron therefore I could work with a lower temperature. It was also important to slow down the process in order to identify the different phases of slag formation. As fuel, I decided to use pine wood and the process was carried out without the use of bellows. Instead, I left a brick-sized hole and a series of smaller air holes at the base of the shaft.
After heating the furnace, I started to pour ore and wood alternately - they were split logs about 20 cm long. The process was quite fast at first and then slowed down significantly. Initially, the unheated ore fell to the bottom of the furnace, so I had to pour it again, but then it stopped. After some time, I began to take samples and describe from what height in the furnace they came. It was supposed to be accompanied by temperature measurement, but this failed. The temperature meters I had at my disposal were not suitable for such measurements. The products falling to the bottom of the furnace turned out to be sintered lumps of reduced ore and charcoal. The wood used for the process did not burn completely, but only charred. The temperature at the bottom of the kiln was slightly above 900 degrees Celsius, although the highest temperature was just above the air vents. I had learned about the effect of half-burning wood before, when I was working on the enrichment of bog ore, but now the context of my experience gave me an idea to apply this phenomenon. The next day I built a small kiln with an internal diameter of 15 cm and a height of about 40 cm, and then restarted the process in the larger kiln. I poured the hot material into a small furnace, in which air was fed by means of a bellows. Sparks coming out of the blow hole testified to the high temperature of the process. After passing through the experimental furnace, the ore particles formed conglomerates of sintered reduced iron lumps surrounded by a slag coating, which could be easily crushed. In the small furnace, however, the process led to liquefaction of the slag and obtaining a small iron shale.
Description of the process carried out on the basis of the above experiences in 2018 during "Dymarki Świętokrzyskie" in Nowa Słupia.

Furnace construction
Analyzing my experience so far, I concluded that the burning of a wooden tenon requires air access from the side of the hollow, similarly to the furnace from Burma, which is why I decided to use the

hollow air duct known from archaeological material. Previously, I was not convinced of the need for its use (Fig. 4).

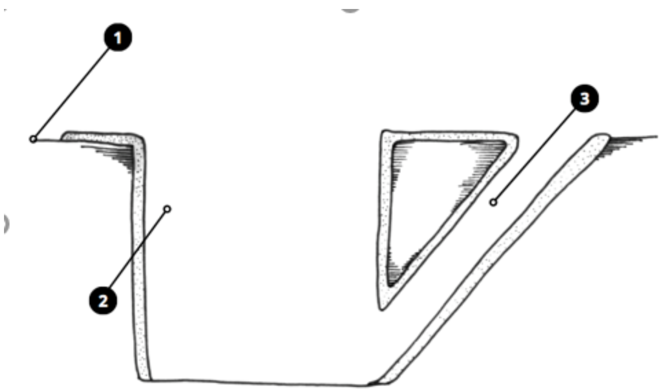


Fig. 5. Cross-section of the hollow. 1 - ground level, 2 - hollow, 3 - air duct

The hollow, as before, was bricked up and heated well, and a layer of embers was formed at the bottom, on which I put wood parallel to the walls of the hollow. Then, a vault made of heat-resistant sand-clay mass was put on. I put the mass directly on the wood, which was properly arranged and I closed the centre of the vault with a wooden tenon. It is important to use a minimum amount of clay or sand. Too much of these materials and water can cause the vault to crack. (Fig.5)
Then the furnace shaft was built. For this purpose, I used an internal formwork made of wooden staves. It is similar to a bucket with the difference that the staves are perpendicular to the base and their joints are on the inside. The lower part of the kiln shaft is also lined with a heat-resistant mass and its walls narrow downwards (Fig. 6a and 6b).

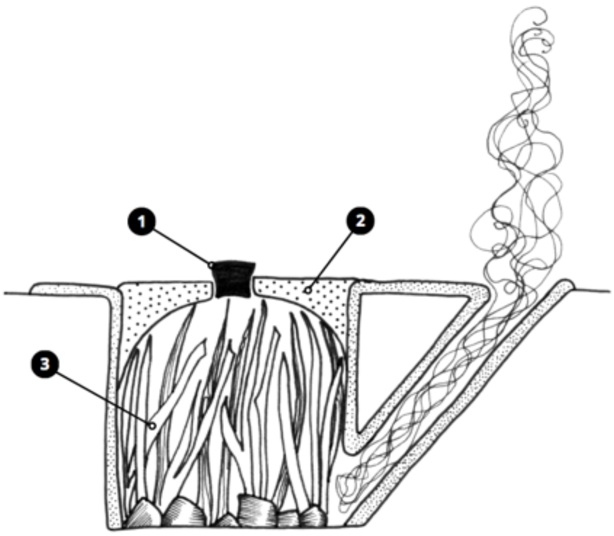


Fig. 6. Cross-section of the hearth during wood burning. 1 - wooden tenon, 2 - vault made of heat-resistant mass, 3 - burnt wood

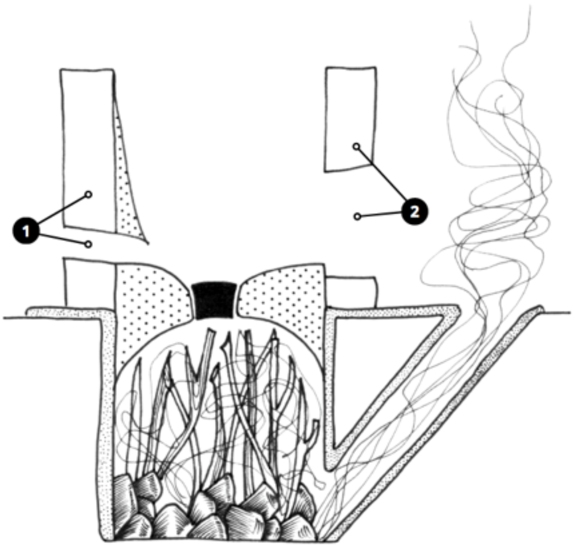


Fig. 7a. Cross-section of the furnace in the first phase of construction. 1 - a wall with an air inlet, 2 - a wall where the air inlet is in a "moving" brick.

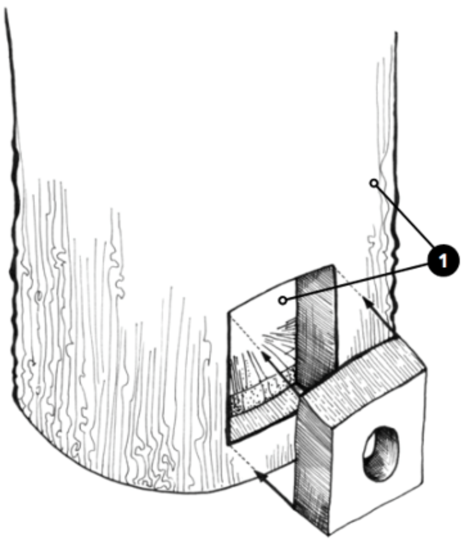


Fig. 7b The furnace from the outside in the first phase of construction, a "pull-out" brick with an air inlet is visible.

After laying 2 layers of bricks, I start heating the kiln shaft. When the first batch of wood burns out, I cover the lower inner part of the stove with a heat-resistant mass and then add the remaining layers of bricks up to a height of about 120 - 130 cm and then I resume heating the stove (Fig. 7).

In 2018, during "Dymarki Świętokrzyskie" in Nowa Słupia, we built 3 furnaces according to the construction described above and lit them at the same time. Two furnaces had previously burnt hollows, but only after they had cooled down were they filled with wood shavings at the bottom and wood above. They worked on natural air flow with a closed valley channel. After they were heated, we began to pour pine wood and ore alternately (Fig. 8).

The third furnace was designed to work with bellows, and for the time being, until two furnaces began to extract reduced ore along with charcoal, this furnace only burned wood. The furnace, unlike the others, had an open-hearth channel from which smoke was coming out. Full work began when we were able to pour the hot batch into its interior (Fig.9a).

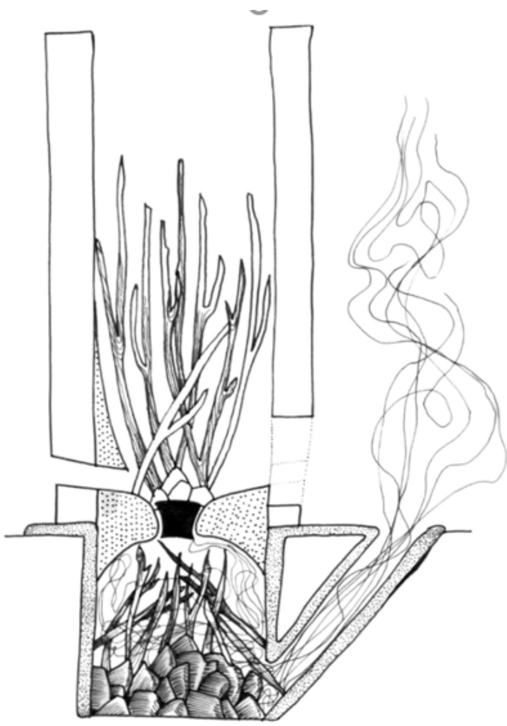


Fig. Fig. 8 Cross-section of the kiln during the firing of the kiln shaft

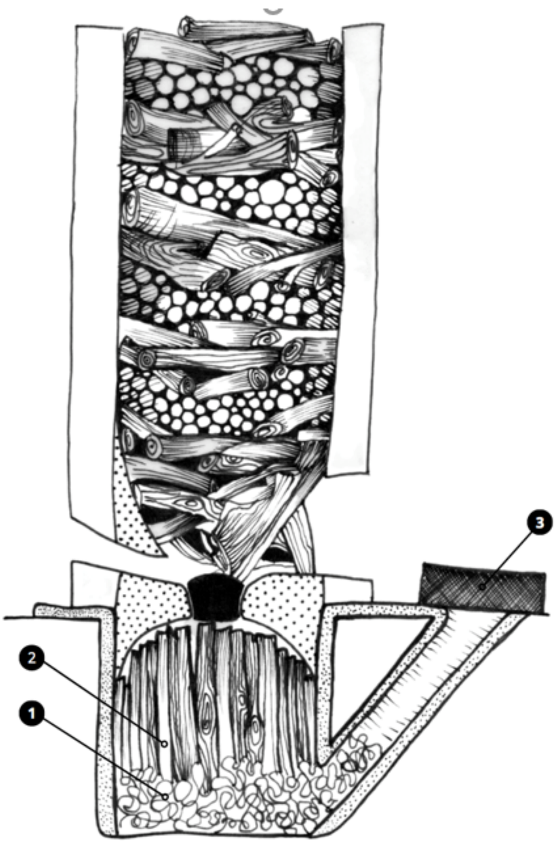


Fig. 9 Cross-section of the smelting furnace during operation, 1 - wood shavings, 2 - Wood, 3 - closing the outlet of the hollow channel.

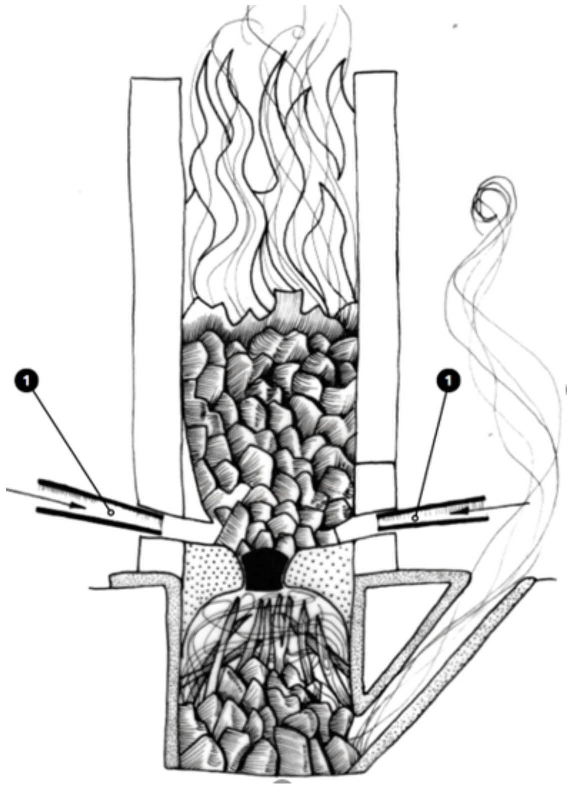


Fig. 10a. Cross-section of the smelting furnace during operation, 1 - air blowing

The temperature of the charge at the bottom of the "reducing" furnaces was around 950 degrees, but the transfer and cooling of the feeder lowered this temperature to around 700 degrees before the charge entered the smelting furnace. It quickly became apparent that the furnace should not be filled to the top, because the charge was subject to further cooling. The optimal height turned out to be filling the furnace slightly more than half. Also, the operation of the 2 reduction furnaces turned out to be too slow to keep up with the rapid combustion in the smelting furnace. Unfortunately, we filled the gaps with cold charcoal. After a little more than 2 hours, the wooden plug closing the hollow burned out, which could be concluded from the flame coming out of the hollow channel in the rhythm of the bellows. Then I closed the hollow channel (Fig. 9b).

The furnace worked for several more hours and all the time the slag was flowing into the hollow. After breaking the bloomery, we took out the iron slate, and the next day I dug up a block of slag, which I left at the disposal of the Museum in Nowa Słupia. Photos below (Photos 2-7).

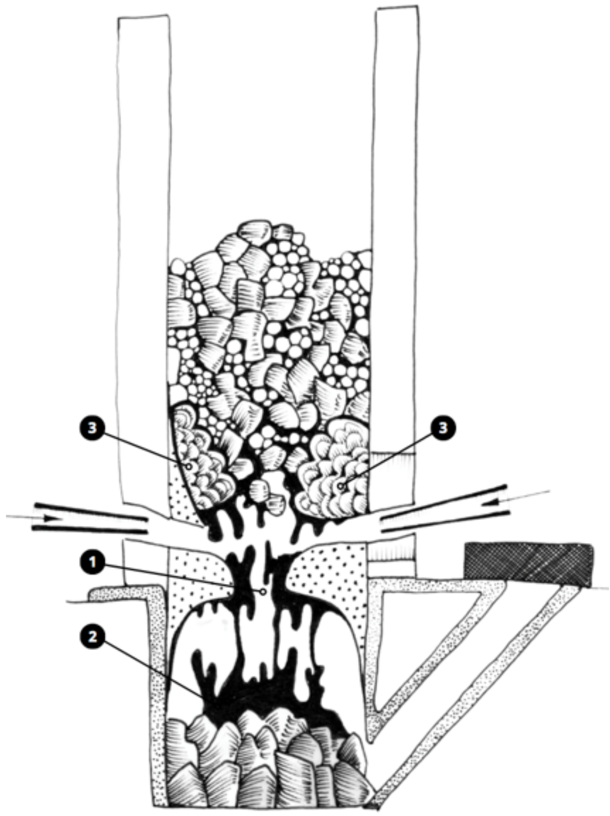
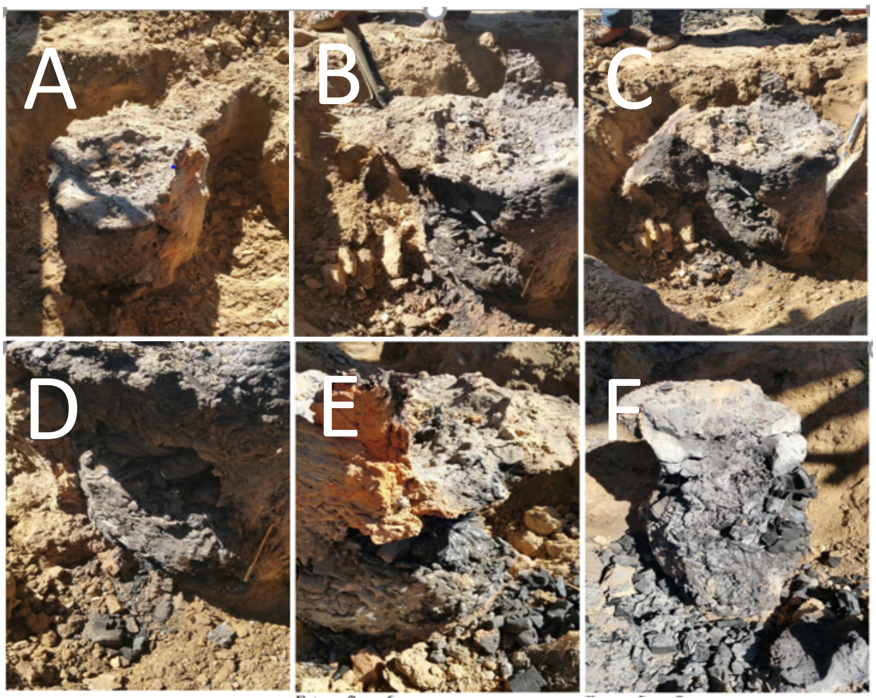


Fig. 10b. Cross-section of the smelting furnace after burning through the plug, 1 - slag sewer, 2 - forming slag block, 3. growing iron shale



Phot. 2-5. Phases of excavating a cinder block (A-F). Photo D additionally shows a fragment of the side pudding. In photo 6, in the upper part, you can see a fragment of the vault of the pit with the bottom of the furnace, which are insulation from the slag block. At the bottom and on the side, you can see the hollow filled with infiltrates of slag and the remains of charcoal.

The experiment undoubtedly proved the correctness of the assumptions of this technology. The hollow was filled in a manner analogous to the finds, the wood was used as fuel and the process was carried out in two stages. This resulted in much better fuel utilization than when using charcoal. The temperature of the process easily reached 1400 degrees (maybe more, but a meter for higher temperatures was not available), which had previously proved to be unattainable because adding cold ingredients to the furnace caused continuous cooling of the furnace from the top, while preheating the charge radically changed this situation. Unfortunately, the need to use an additional amount of charcoal did not allow the maintenance of the temperature during the entire process. Nevertheless, the resulting iron shale contained less slag than usual, which made it much easier to reforge. In addition, the hot slag in the hollow increased the energy efficiency of the entire system but, above all, the construction of the furnace was completely different from the one used so far. The whole process has been simplified, because the element of obtaining charcoal has been eliminated, and the energy lost in this process has supplied the first phase of melting for free. However, not everything was successful. The plan was to use another furnace, in the same configuration. It was enough to build one more furnace in place of the one already used for smelting and we were ready for that, but we could not afford to build 2 furnaces due to the schedule of the smoke event.

Finally, I would like to share my reflections on the structure known as foamed slag. What is this phenomenon? In 2014 I had the opportunity to participate in the iron smelting days workshop in Nowa Słupia. There I could see cinder blocks having this structure extracted from the earth. This is something I also found at the bottom of the Tatara furnace from 2008 in Biskupin. At that time, it was just a curiosity of no importance to me. This "pumice stone" formed on the bottom and sides of the lower part of the kiln chamber. This chamber, where the highest temperature is, was lined with a heat-resistant mass composed of a mixture of quartz sand and a small amount of clay. The clay from this mixture melted and flowed down with the slag, and the sand glued together with glass created at the border of its grains created this openwork structure. In the case of ancient traces, this structure was probably additionally mineralized. During the workshop in Nowa Słupia, we also melted tartare, but due to the lack of time, its underground part was made only of a layer of charcoal, so tartare was barely heated to 1380 degrees. As it turned out, it was too low a temperature to create a "pumice" structure.

In this study, more than the process of obtaining iron, I wanted to present how I came to solve the problem, which for me was to find the "essence of the issue". That is, the answer to the question why former steelworkers made efforts that resulted in these and no other technological solutions.

References

Kapp Leon and Hiroko; Yoshihara Yoshindo 1987 The craft of the japanese sword

Bielenin K. 1974 Starożytne górnictwo i hutnictwo żelaza w Górach Świętokrzyskich, Warszawa – Kraków

Bielenin K. 2005. Kloc żużla dymarskiego z Boleszyna: uwagi o znaczeniu badań powierzchni kloców żużla Dymarskiego, MA 35, 189- 198

Różański W. 1984 Sprawozdanie z doświadczalnych wytopów żelaza przeprowadzonych podczas obozu naukowego w Nowej Słupi w czasie od 12 do 24 IX 1983 r. „informator Towarzystwa Przyjaciół Górnictwa, Hutnictwa i Przemysłu Staropolskiego” s. 58- 67

Przychodni A. Suliga I. 2016 Charakterystyka łupki żelaznej i kloca żużlowego z doświadczalnego procesu dymarskiego, Wiadomości Archeologiczne 67, 2016, s.147-174

Orzechowski. S 2013 Region żelaza. Centra hutnicze kultury przeworskiej, Kielce 2013

Suliga I.; Orzechowski S. 2006 50 Lat badań nad starożytnym hutnictwem świętokrzyskim, Kielce

Wrona A. 2020 Nowe i najnowsze badania nad rekonstrukcją procesu dymarskiego w piecu kotlinkowym, A.E