HOW EXPERIMENTAL ARCHAEOLOGY CAN ANSWER QUESTIONS ARCHAEOLOGICAL ARTEFACTS CANNOT. IRON SMELTING EXPERIMENTS WITH USE OF SLAG-TAPPING BLOOMERY FURNACES

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Rezumat. Este în general acceptat faptul că metoda directă de producere a fierului este o tehnică folosită din Epoca Fierului până în epoca modernă şi, înainte de inventarea furnalului, a fost singura metodă de obţinere a fierului. Folosind această tehnologie fierul este adus în stare solidă ca urmare a reducerii minereului în interiorul cuptorului de redus minereu de fier.

Producerea fierului este un proces complex care implică mai multe etape. În siturile arheologice legate de industria timpurie a producerii fierului se găsesc o gamă largă de artefacte care ilustrează astfel de etape. Aceste rămăşiţe, după producerea fierului, au o poveste importantă de spus, dar nu pot oferi răspunsuri la toate întrebările care apar atunci când un arheolog cercetează un sit unde se producea fier.

Arheologia experimentală poate fi folosită pentru a recrea spaţiul atelierului antic şi modul cum a fost folosit. Permite investigarea modelului reconstituit al cuptorului şi verificarea ingredientelor care au fost utilizate în timpul topirii (testarea diferitelor surse de minereu şi argilă). De asemenea, este utilă în cuantificarea cantităţii de fier care a fost produsă pe locul respectiv. În cele din urmă, aceasta oferă informaţii despre echipa care a lucrat: numărul, funcţia şi competenţele acestora.

Experimentele arheologice care se axează pe reconstituirea procesului de reducere a fierului contribuie cu adevărat la înţelegerea mecanismului de producere a acestuia. Compararea artefactelor arheologice cu materiale experimentale îmbunătăţesc semnificativ înţelegerea întregului proces de producţie, care are loc la locul de producere a fierului.

Cuvinte cheie: Arheologie experimentală, minereu de fier, metalurgie, cuptor de redus, lupă din fier, zgură, producerea fierului, cuptor de tip "cu zgura derivată".

1. Introduction to Early Iron Production

In general, there are two main techniques of iron making: 'direct method' and 'indirect method'[1]. When using the first technique, iron is made in a solid state directly as a result of reduction of iron ore inside the bloomery furnace. The end product of the direct iron smelting process (single-stage process) is a spongy mass of reduced iron particles full of slag and un-burnt charcoal known as a bloom ('smelted bloom'[2]; or

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[1] Bayley *et alii*, 2008, p. 57; Radwan, 1963, p. 9.

[2] Tylecote, 1987, p. 248.

‘raw bloom’[3]).

Using the second technique, wrought iron is made through a conversion process, such as fining or puddling of cast iron (commonly known as ‘pig iron’), which is a product of smelting iron in a blast furnace. Because two or more steps are involved in this process it came to be known as the indirect method of iron production[4].

It is generally accepted that the direct method of iron smelting is a technique used from Iron Age to modern times and, before the invention of the blast furnace, it was the only way of producing iron. Based on the way in which bloomery furnaces operate they can be divided into two main types: non slag tapping (‘slag-pit’ or ‘non-tapping’ furnace) and slag tapping (‘tapping’ furnace). The first type “*retains the slag produced during smelting within the lower part of the furnace or in a purpose-build pit below*”[5]. Construction of the second type of the furnace, slag-tapping furnace, allowed for withdrawing slag during the smelt via an opening in the bottom[6].

A single smelt in a bloomery furnace required economically viable iron ore (capable of making iron), fuel (charcoal to run the furnaces for hours at temperatures between 1150–1250°C)[7] and clay to build furnace walls and tuyères (which is a tube through which air is blown into the furnace), and to repair or alter the furnace during the smelt. Also, smelting requires a team of people who will operate the furnace on the site and a team of people who will deliver all required materials to the site.

2. What can be found on early iron production sites?

Iron production is a complex process which involves several stages and requires some social organisation, even specialisation of particular groups of people in certain tasks (like making charcoal). It is an integrated process from the searching and mining of the raw materials (like iron ore and clay) to the forging of bloomery iron. It comprises of ore searching and its extraction, production of charcoal, preparation of the ore for the smelt (roasting, crushing, sometimes even washing), building the furnace and smelting, consolidation of the bloom and forging it into currency bars/billets (primary smithing) or the production of iron tools from half products (secondary smithing).

At the archaeological sites related to the early iron making industry a wide range of artefacts and features can be found, which are the remains of some of these phases. The technological debris after iron production can be divided into four groups: raw materials (iron ores, charcoal and clay), structural evidence (remains of ore roasting beds, furnaces and sometimes smithing hearths), waste products (smelting slags, sometimes primary and secondary smithing slags if metal is worked on the site) and the metal itself (blooms, gromps, currency bars, billets and iron scraps). These unattractive iron production debris offer complex data and have an important story to tell.

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[3] Scott, 1990, p. 9.

[4] Tylecote, 1976, p. 82; Radwan, 1963, p. 10; Suliga, 2006, p. 163.

[5] Bayley *at alli*, 2008, p. 43.

[6] Cleere, 1972, p. 8; Cleland, 1981, p. 166.

[7] Morton, Wingrove, 1969, p. 1556; Tylecote, 1987, p. XIX.

3. Questions asked by archaeologists working on the early iron production sites

Although nowadays we are able to collect more data from the archaeological materials found on the iron production site, it is still really difficult to find answers to some general questions, which appear during an excavation. Questions like: What part of the iron production process is represented by materials found at the particular archaeological site? When was this activity taking place? And how long it was carried out for?

Off course, careful examination of other artefacts recovered from the site, like pottery, will deliver partial answers to these questions, but will not answer them completely. And there is much more we could ask about the particular smelting site. Questions like: What was the furnace's design? What kind of an air blast was used to operate the furnace? How ore was selected and processed before being added to the furnace? What type of charcoal was used during the smelt? What was the number of smelts carried out in the furnace? How efficient was a single smelt? How was the space at the smelting site organised? And finally, who were the people making iron? These questions can be answered by studying ancient technology through experimental archaeology.

3.1. Investigation of furnace design

The first question you might be able to answer involves the interpretation of the furnace remains on the site. Unfortunately, furnaces do not preserve very well if at all, because they were destroyed during the last smelting campaign and/or left exposed to severe atmospheric conditions. Nobody has ever found a complete bloomery furnace shaft and usually only bottom part of the furnace with some slag are the only clues left by ancient smelters.

Reconstructing particular bloomery slag-tapping furnace we need to estimate diameter, height, wall thickness, location of tapping channel and blowhole/tuyère. The furnace diameter can be established by careful examination of the furnace wall remains or furnace bottoms (also called 'furnaces slag cakes') as well as the location of the tapping channel and even the space into which the slag was tapped. More problems arise when trying to establish the side where the bellows were attached to the furnace, because fragments of blowholes or tuyère are only sporadically found on the sites. Also, it is difficult is estimate the thickness of the furnace as usually vitrify or melted and slagged parts of walls are found scattered across the smelting site.

As mentioned earlier, no complete furnace ever was found, so the shaft height must be estimated. Decades of less or more successful smelting experiments taught us that reduction of ore to metallic iron requires certain conditions in the furnace: the right amount of time and the right temperature. Ore slowly drops down in the shaft reducing to metallic iron and this can't be obtained in a furnace with the shaft lower than 80 cm, but most of the smelters prefer 100 cm high shafts. However, it is possible to smelt successfully even in the furnace with slightly lower shaft. During Furnace Festival in Woodford 2018 (Ireland) I completed successful smelt in a furnace with 75 cm tall shaft (**Fig. 1**).

Fig. 1. Small slag-tapping bloomery furnace with artificial air blast. Note other furnaces remains (top left). Furnace Festival 2018 in Woodford, Ireland.

We know that the furnace base must be seated on the flat ground. Even when some smelting sites are located on slopes is doesn't mean that the slag tapping furnace had a steep bottom. A bowl-shaped or flat furnace base allows the bloom to sit in the liquid slag bath during the smelt. An uneven or inclined furnace bottom will cause the slag to collect in the lower part of it and freeze there making withdrawing trickier from this point. Also, frozen slag will not take part in the formation of the bloom. The bloom needs space to grow with constant temperature distribution and it forms near the tuyère or in the most powerful point of air jet pumped into the furnace through a blowhole. It grows in size and eventually it anchors itself to the furnace walls. Therefore the tuyère or strong air jet determines the position of the bloom and must be placed 25–30 cm above the furnace bottom to give the bloom enough of space to grow[8]. It is possible to make the furnace with smaller space (like 20 cm, experimental smelt in Woodford), but it will affect the size of the bloom and amount of slag hold within the furnace. The slag gathers in this area and must be occasionally tapped out when its level is too high and starts blocking the air flow. So the smaller the space the more frequently you will have to withdraw the slag.

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[8] Metz, Bohr, 2018, p. 14.

3.2. Recreating the ancient workshop and how this space was used

What did the smelting workshop look like? Without doubt smelting is an outdoor activity. The amount of poisonous gasses coming out of the furnace is huge and they are deadly. You simply can't do anything breathing in carbon monoxide. Also, there is a large amount of sparks coming out of the furnace and a high flame, therefore you can't have a low roof above it. It is possible to have a high-roofed pavilion above the furnace, however it is not necessary. You can smelt in light rain, but off course it makes the whole experience less pleasant.

Because iron smelting is time consuming process it is much more desirable and safer to have a shelter from the sun or rain built nearby. Just a simple pavilion to rest in for a while, a place from where you can keep a watchful eye on what is going on around and with the furnace. In such place you can also keep raw materials out of the rain if necessary.

The furnace needs some space around it, at least a 2 m radius of working room (**Fig. 1**). Off course having more space is better, as you can stock up components for the smelt close by and you will have space to avoid toxic gasses or painful sparks coming out of the chimney. The charcoal pile should be not located too close to the furnace to avoid the liquid hot slag or sparks setting it on fire. Also, there must be a space for the ore, water, and some emergency wet clay to repair the furnace.

It is extremely unlikely to find any tools or equipment left by ancient smelters on the site. But thanks to experiments we know exactly what people who worked there needed. The tools and equipment required to build and operate the furnace comprises of some digging tool like a shovel (used to dig a pit or a channel to tap the slag); poker (to remove slag drops which occasionally block the air flow); containers of various size (like buckets or scoops used for holding an ore and charcoal, water bucket required to wash and cool down the tools or to rescue bellows from burning down); pointed iron rod (to pierce through the slag to withdraw it from the furnace while liquid); bloom tongues (to take out the raw iron); wooden mallets and iron hammers (to compact the bloom); anvil (to forge the raw iron) and bellows, which will pump considerable amount of air into the furnace. Above tool list is quite basic and very similar to the equipment used by blacksmiths. I made the above list after smelting in Woodford, where I turned up empty handed and had to borrow everything from a blacksmith working nearby or other smelters. Some of this equipment you can make by improvising, for example poker (long enough wooden stick) or wooden mallet (15–30 cm thick tree trunk or branch), anvil (tree trunk or stone). But majority of the tools are specialist equipment and are not easy to get.

The most important tool in a smelter's workshop are bellows. They have to be located at a safe distance away from the furnace, so they will not catch fire. They need to be powerful to achieve the right temperature and they have to be easy to operate. The air must be pumped into the furnace under some pressure, so it will penetrate the whole furnace bottom, not only the small area in front of the tuyère or blowhole. The easiest way to recognise that the bellow pressure is right is to observe how the charcoal drops in the furnace. Charcoal should descend through the shaft evenly and not just at the one side. If that does happen it could be a sign that the air flow is not correctly directed and is not reaching the middle of the furnace hearth or your bellows are too week to provide enough air.

3.3. Testing and verifying properties of iron ore

Limonite, hematite, goethite and various ‘bog iron’ are types of ore used in the past for the production of iron in a bloomery furnace. Experiments with various types of ore proved that ancient smelters could make this metal from almost everything containing a sufficient amount of iron. We know that the ore properties affects how the smelt was done and how ore was prepared before adding it to the furnace.

It is very difficult or impossible to recognise properties the specific type of iron ore has. Of course, the original colour of the ore, the place where it was found, as well as its colour after roasting give us some clues about its iron and other minerals content, but will never reveal much about the ore behaviour in the furnace during a smelt. To learn if ore is likely to produce iron while smelting in a bloomery furnace, there are ways of testing it, for example Lee SAUDER’s ‘Iron dumpling’ test[9]. But we have no proof that ancient smelters tested ore in this way.

Besides the obvious link between iron content in the particular ore and the amount of metal yielded from it, the ore composition affects also the slag viscosity, slag amount, slag melting point, reducibility and retention time[10]. In the bloomery furnace iron is in the solid state but slag is permanently liquid. The success of the smelt depends on the slag separation from the metal, because only low-viscosity slag allows the small native iron particles to accumulate to form the bloom[11]. Viscosity of the slag is affected by presence of certain oxides. Some decrease it (like K2O, CaO, MgO, MnO and FeO), while others (like SiO2, Al2O3) have an increasing effect[12]. For example low iron content in the ore increases slag viscosity and how quick it freezes in the furnace[13].

I believe the ancient smelters could read iron ore as well as slag behaviour during the smelt. Through these observations they were able to select and prepare particular ore in such a way that it smelted easy and produced iron of desired properties (carbon content). Dense iron ores (like hematite and limonite) were roasted to become more brittle, easier to crush into small particles. Content of sulphur within the ore was lowered by 85–90% thanks to roasting[14]. Bog ores, which were very porous and naturally brittle, did not need to be roasted and could be naturally dried to remove majority of water (like local bog ores used during Furnace Festival 2018 in Woodford).

Without doubt the way how ore was prepared for a smelt depended on iron and gangue content within it, but also the impurities determined how the ancient smelters were operating the furnace. Bog ores often contain quarts, oxides and hydrates of magnesium or manganese, siderite (FeCo3), phosphor in form of apatite Ca5(PO4)3(F,Cl,OH)

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[9] Sauder, 2018, p. 1-2.

[10] Metz, Bohr, 2018, p. 2.

[11] Metz, Bohr, 2018, p. 2.

[12] Metz, Bohr, 2018, p. 3.

[13] Sauder, Williams, 2002, p. 125.

[14] Radwan, 1966, p. 29.

Fig. 2. Bloom (bright) and furnace slag cake (dark). Furnace Festival 2018 in Woodford, Ireland.

or vivianite ($Fe3(PO4)2\cdot 8H20$)[15]. Thanks to the results of various iron smelting experiments, we know that very rich iron ores will produce a small amount of slag (**Fig. 2**), so you do not need to tap the slag so often or at all in some cases. Also, the ores rich in manganese require higher blowing rates[16] to maintain the temperature required, about 1250°C. The melting point of Mg is about 1246°C. Above this temperature it goes into the slag and lowers the amount of Fe within it, allowing more iron particles to form the bloom. Furthermore, increasing proportions of charcoal to ore during last hour of smelt increase the carbon content of the bloom.

3.4. Quantifying the amount of iron produced on the site

The appearance of the slag indicates the type of ironworking taking place on the site. Estimating the amount of waste products might suggest the scale of the production, how much raw iron was made on the site. Of course we must be aware, that the slag was often reused as a building material and more recently it was smelted in blast furnaces. Therefore the amount of slag waste discovered on the particular smelting site might not represent a complete scale of metal production.

Nonetheless being able to smelt iron successfully and obtaining similar looking slags (the same appearance and size) to these found on the site we might try to quantify the amount of iron produced there. To do this we will measure how much material

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[15] Werońska, 2009, p. 31-32.

[16] Crew, 2013, p. 42.

goes in to one furnace during the smelt and how much material comes out. We will calculate the amount of ore and charcoal used during the smelt with the amount of produced iron and slag. Next, we will compare amount of the experimental slag and produced iron with slag recovered from the archaeological site to estimate approximate amount of iron made there.

3.5. Team of people who worked on the site

Experimental smelting with the use of a particular furnace type can deliver information about the team of people who had to work on the site (their number, function and skills). You need people who will build and operate the furnace for hours and who will deliver the materials necessary to run the smelt, people with sophisticated technological knowledge of how to reduce the iron stone to workable metal and people who know how to work obtain metal.

A furnace can be build by one person, but more people involved in this activity the quicker job will be completed. It took me about 30 hours to build one small furnace (35 cm diameter and 75 cm tall shaft) including preparation of the clay, which was the most time consuming and exhausting task. Obviously skilled craftsmen would complete the building of the furnace quicker, but they would still have to spend a proportional amount of time on preparation of all required building materials. After completing the furnace it must be dried. It is an easy one person task, which just requires keeping a fire in the furnace for a few hours, so the majority of water within walls evaporates. This requires nothing but wood and natural draft will do the rest of the job.

To smelt in a small furnace powered with one bellow, you need a master, who will be in charge and control of the whole smelting process (he would be loading the furnace, tapping out the slag when necessary and making decision when it is the right time to take out the bloom); minimum two bellow operators (who would take turns in operating the bellows) and one smelting assistant (person whose task would be to help the master preparing portions of ore and charcoal before adding it to the furnace and assist him taking over his duties when necessary). So ideally you need a team of four people to run one smelting campaign. Next, you would need a minimum two people to compact the bloom (one person who will pull it out of the furnace and hold it while the second person bits it with a hammer to remove slag) and at least three men to split the bloom (**Fig. 3**).

People working beside the furnace will not be the only people required on the smelting site. There is a need for people to take care of the smelters, who will make food and drinks for them and to take their places ploughing fields, picking up fruits etc. The simple fact of discovering an iron smelting site gives us a clue how complex was the society of which they were members.

4. Conclusion

Experimental archaeology can be used to recreate the ancient smelting workshop and how its space had been used. Also, it allows to investigate reconstructed furnace design and to verify the ingredients which had been used during the smelt (test of different ore sources, charcoal made out of different types of wood and properties of clay used to build the furnace).

Fig. 3. Splitting the bloom. This activity has two purposes: to test quality of the raw iron and to cut it into easier to work pieces. Furnace Festival 2018 in Woodford, Ireland.

Archaeological experiments focusing on reconstructing the bloomery process truly help to understand the mechanism of the iron production. The comparison of archaeological artefacts with experimental materials significantly improve our understanding of the whole manufacturing process taking place at the iron smelting site. Thanks to information obtained through the experiments we might try to estimate impact of particular iron production site on the social organisation (groups of people specialising in certain activities), environment and even local economy.

It also allows us literally to feel the past and to see iron production from a very different perspective. It brings up problems and difficulties which ancient iron smelters had to deal with. Also, it gives impressions and ideas of emotions, desires, even sentiments connected with smelting. Some feelings, like the excitement and fear in the very moment of taking out the bloom, cannot be learned in any other way than through the smelting experiment. In other words, archaeological experiments open our minds and eyes to a large amount of issues connected with iron production in the past.

5. Acknowledgements

I would like to thank the organisers of the Furnace Festival 2018 in Woodford, Ireland and all participants for inspiration and help in my smelt.

Fig. 4. Daria and her 4.3 kg of iron smelted from 23,4 kg of wet Irish bog ore.
The bloom had been compacted and split into three pieces.
Furnace Festival 2018 in Woodford, Ireland.

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