ARCHAEOMETALLURGY – EXPERIMENTAL FERROUS METALLURGY

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Abstract

Iron metallurgy is one of the most iconic achievements of early human history. It surely forged the future. Metal that is used mostly in the world is still iron. The demand for it was and still is increasing significantly. And it is for sure that in its earliest times iron was crucial for everybody that could afford it.

The paper presents the basic and historical adaptation of iron making. This is a method known and used by smiths since the 4th century B.C. the La Tène period and used until at least the 18th century. This paper rounds down the basics of the historical iron making and supplies of materials that are needed to do so. One part of the paper will talk about the actual making of bloomer iron. Another one about processing the bloomer lump into a more workable piece of wrought iron. The last part will be focused on ceramic pipes used for air distribution in La Téne furnaces.

In conclusion, the paper will be focused on the actual real-life experiments that were made to correspond with the historical and archaeological findings. As the name suggests, archaeometallurgy is the metallurgy of the ages long forgotten.

Keywords: Ferrous metallurgy, wrought iron, history, archaeometallurgy, technologies

1. INTRODUCTION

The furnaces made in the La Tène period weren´t able to reach high enough temperature to melt iron. The method used was a high-temperature iron reduction. This did not melt iron and it didn´t make smelted ingots. At the end of the process, at the foundation of the furnace, the bloomer lump of caked pure iron is found. This lump was composed of pure iron and impurities. The main impurity is slag, which was a combination mainly of calcium and silicate oxides. There was other unwanted content like unburned charcoal and other metals, like copper or lead, in various forms. The chemical composition of the bloomer lump was strongly dependent on the ore that was used for the metallurgical process. This method of iron making was lengthy and tiring and it could take up to 16 hours of hard work. In this time the amount of the iron made was around 5 kilograms. Which is not a lot for the given period.

Even the fact that this technology is very old and not used in these days it is of most importance to know how our ancestors did something we now hold as something common and mass-produced. As we know it iron was made in the late 19th century. Smelted and made into steel to build from. The iron of the La Tène period is called wrought iron. It is steel with low to high carbon content. And it was made by countless welds of the iron made in the furnace. The main goal of this paper is to show real experiments of iron making in a copy of the La Tène period furnace.

2. ARCHAEOMETALLURGY

Archaeometallurgy studies the historical means of metal-making. In this paper, the main focus will be on ferrous metallurgy. And the actual ferrous metallurgy of iron reduction and its further processing. Iron ores were used as very potent minerals for crafting tools and weapons [1]. And this even before our ancestors started to use it for metallurgy purposes. Meaning reduction in older furnaces a then smelting in blast furnaces. These ancestors of the early iron age used actual iron minerals from space. They shaped around 250 t of meteoritic stones into weapons and other useful tools [2]. This shows the potency of iron-based minerals and also the potency of materials made from them.

2.1. Iron

The main source of iron for the La Tène furnace was iron ore. The surface cover of soil and rock was shallow, and the deposits easily exploited, probably as open casts. Most of the deposits were even in the open on the surface. Even now one can walk the field and find iron ore. The most common iron ores are listed in **Table 1** below. These are mostly probable ores that could be found.

Table 1 Iron ores

Mineral	**Formula**	**Iron weight percentage**
Hematite	Fe_2O_3	70
Magnetite	Fe_3O_4	72.4
Limonite	$2Fe_2O_3.3H_2O$	59.8
Siderite	$FeCO_3$	48.2

It is very important to properly dry up the ore to remove excess not chemically bonded water. Normally it´s done above an open fire in the specially made furnace. Ore is then roasted to remove chemically bounded water. This was done in an open fire there is a needed at least a temperature of 300 °C and higher. The last preparation step is grinding. Ore is ground to small fraction about 3 millimeters so it can fit in cavities formed by the charcoal grain. This step is very important because it allows for proper reduction.

2.2. Charcoal

The main source of carbon is charcoal. This commodity holds more than one function. It brings carbon as a reducing agent into the process. Charcoal also fulfills the role of the physical frame in the furnace. This frame consists of small cavities between actual grains of charcoal. These enable a proper reduction.

The Source of charcoal in the early periods was a charcoal pile. A charcoal pile is a carefully arranged pile of wood. And every possible cranny, cavity, and space is filled with additional wood to utilize the space designated for the pile. The erected pile is covered by dirt and straw to form kind of an anaerobic layer. Turf can be used as well. This thick outer layer ensured the lack of oxygen that was introduced to the burning process. In the center of the pile is a shaft formed by several long sticks plunged in the ground. This shaft is named King. The shaft is filled with short pieces of wood and lit. The king is stuffed repeatedly to ensure no cavity is created. The pile is tended mostly by two charcoal burners. Wood support is added around the outer perimeter of the pile. This betters structural integrity of the outer cover layer. This support was also used as ladder for easier access of the top part of the pile.

The basic chemistry behind charcoal making is the carbonization of wood. The intent is to remove unwanted water and other chemicals like CxHy from wood and make charcoal made of mostly pure carbon. The historical charcoal pile is shown in **Figure 1**. The denser wood makes for better and denser charcoal. Denser charcoal will provide longer burning time which should accommodate a better result of the reduction. Some of the best wood is oak, cedar or even hazel.

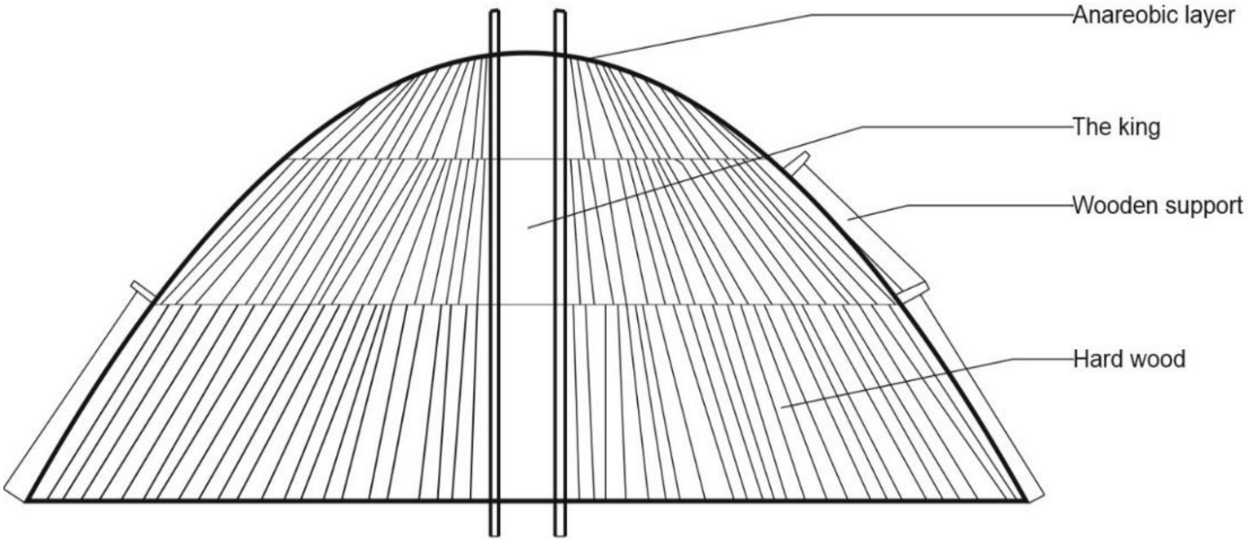

Figure 1 Charcoal pile

2.3. Iron reduction

The process of reduction is quite lengthy, and it takes some preparation time. First, the furnace is built. It is about 1 meter high; bottom diameter is about 40 centimeters and the top diameter is about 20 centimeters and it does have an opening at the bottom about 30 centimeters wide and high. This furnace is used often more than one time, as long as it holds up.

The bottom opening of the furnace is then covered with clay forming tag. Through tag goes clay or ceramic pipe, also called tuyere, that allows air to be blown inside the furnace with a bellow. Under tuyere is located tap hole for the slag to be poured out if needed.

At the start, the cold furnace is filled up with wood. This step allows wet tag and ceramic pipe to dry up. The whole furnace slowly heats up. After this step charcoal is introduced to the furnace. Bellows are blown to heat furnace even further. After the working temperature of around 1 350 °C is reached iron ore is started to be fed. There is always used a mixed batch of half a kilogram of charcoal and half a kilogram of iron ore. The furnace is fed as long as reduction goes on and is possible to do so.

At the end of the reduction process, the entrance of the furnace breaks open and bloomer lump of iron is removed from the furnace. Removing the lump is done very carefully so that the actual furnace is damaged as less as possible for further use. But sometimes the iron lump is so broad that the whole furnace must be torn apart to remove the bloomer. While still hot, the iron lump is taken to a wooden log and beaten down into a denser piece of iron with wooden mauls. The mauling step is crucial because it unites various rifts that are present in the bloomer iron lump [3].

The productivity of this process is about 20 to 40 % meaning that from 12 kilograms at the end genuine iron lump measures around 3 to 4 kilograms. And it takes about 16 hours to complete. While still hot after one reduction process furnace can be used again right after iron bloomer is removed. This method saves a lot of energy and fuel that would be normally used to heat the furnace. At this time furnace can still have around 300 °C. In **Figure 2** it´s illustrated the whole process of iron reduction in the La Tène furnace. The top right part shows the end of the charcoal making process. The top left shows the preparation of ore by roasting and grinding. The rest of the picture shows chemical processes that are present in the furnace [4].

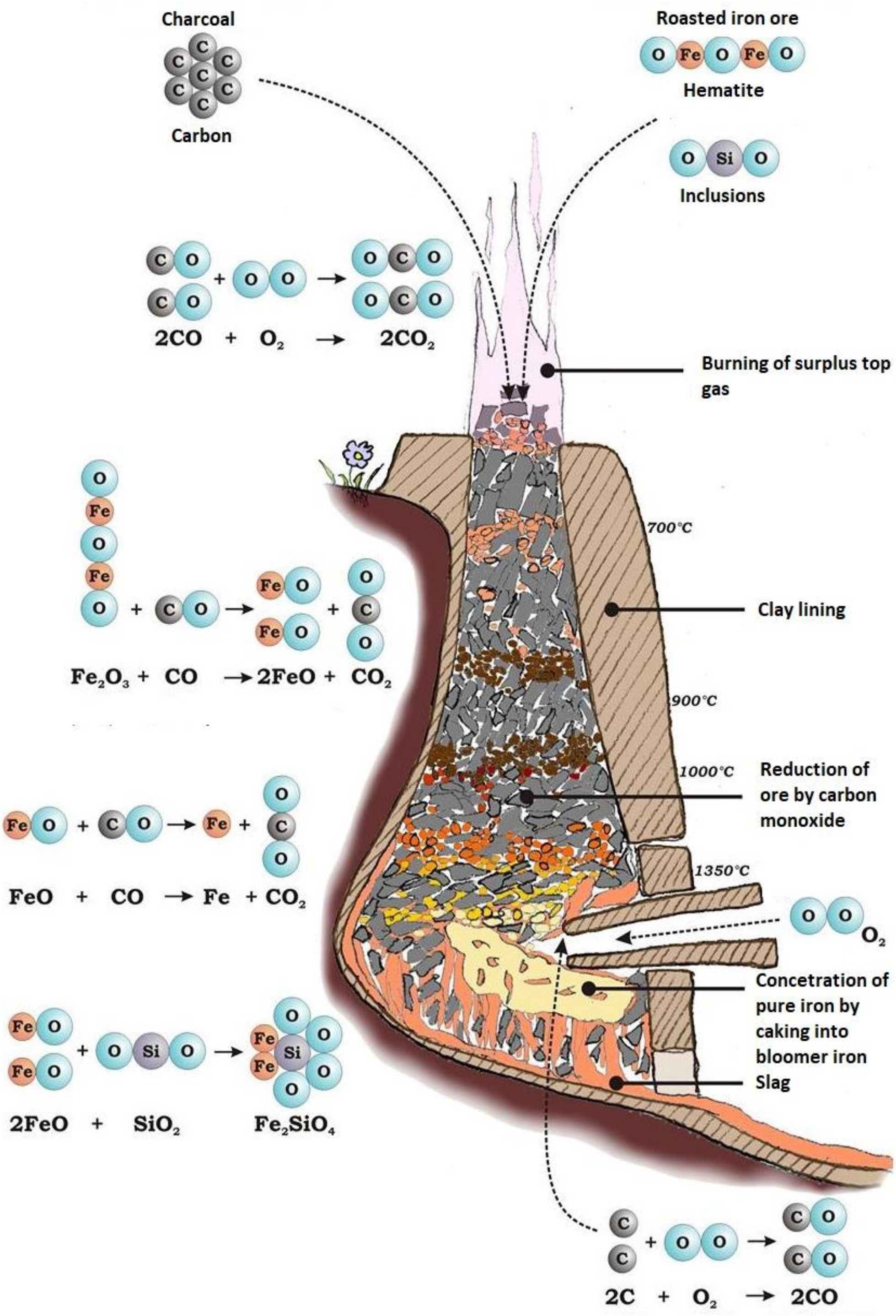

Figure 2 Reconstruction of La Tène period furnace [4]

After initial mauling is bloomer taken to specific type of forge. The lump is repeatedly heated and forged into more manageable piece. This process welds and homogenizes bloomer lump into iron billet. These billets were commonly sold for the further use by blacksmiths. Billets are forged with borax to combine the iron and to get rid of all unwanted inclusions. Iron is worked with hammers and drawn out into flat bars. These bars are stack up on each other heated up and dusted with borax then heated up once more and forge welded together. After few more repetitions the bar of wrought iron is made. But even from raw iron bloomer a tool can be forge. This tool will be of bad quality but with proper care it can be a great addition for some basic tasks [5].

2.4. Tuyere

The reason behind using the ceramic tuyere is to the provide oxygen for the heart of the furnace. It is basically to get the oxygen inside the main body of reduction. If there is no tuyere the wind that is blown into the furnace by the bellows will go by the easiest way and climb the near wall of the furnace, this phenomenon is called the wall effect. The tuyere than solves this problem. To cancel the wall, effect the tuyere has to be at least x millimeters outside the inner wall, where x is 10% of the actual diameter of the furnace at its bottom. So practically speaking there is at least 30 - 40 millimeters of the tuyere needed to ensure good reduction.

Best results are also achieved by adding some portion of the pipe on the outer part of the wall. From practical examples was found out that the best length of the tuyere is about 20 cm if we use standard La Téne furnace with the bottom diameter of 40 cm, so half of it.

The degree of the tuyere plays some role too. It is one of the main parameters of actual success. From practical experiments was found out the best results are yielded when tuyere is angled down slightly at the 10 to 30 degrees. The tuyere could be put in horizontally, but this is going to shorten the reduction column and it is overall unpractical. In the most practical experiments is the angle somewhat random, but there is always a strong emphasis on the fact that the tuyere is pointing just slightly down [6].

3. EXPERIMENT

Experimental furnaces were built in several locations. From scratch, a basic La Tène period furnace was built in Ostrava. This furnace is 80 cm high and 40/20 cm wide. In **Figure 3** we can see the process of building. The basic groove is dug out as in **Figure 3a**. Next, the arc of the entrance is erected and the base of the furnace is made, as shown in **Figure 3b**. The furnace is built just a bit higher than the groove as in **Figure 3c**.

Figure 3 From left to right: **a** – Dug out groove, **b** – the arc of the entrance, **c** – finished furnace.

This furnace was used for several experimental reductions. These reductions were all successful and yielding at least 30 % iron. One reduction batch is in the next **Table 2**. This reduction process had two taps which is somewhat unusual but still within the standard. The process always starts and ends with 3 batches of pure charcoal. Ore is added with charcoal simultaneously, half a kilo each. The outgoing bloomer had approximately

32 % of iron and weighed around 4 kg. This adds up to 1.28 kg of pure iron and the process of reduction took almost 4 hours. Data from this particular reduction are noted in the **Table 2**.

Table 2 Table of reduction; n as the amount of ore added (combined with charcoal), C as charcoal (when added solely), T as the tap

t	n/C/T	t	n/C/T	t	n/C/T	t	n/C/T	t	n/C/T
13:36	C	14:07	1.5	14:51	4	15.26	6	16:04	8
13:43	C	14:14	2	14:59	4.5	15:34	6.5	16:10	C
13:52	C	14:18	2.5	15:09	5	15:40	7	16:17	C
13:53	0.5	14:26	3	15:09	T	15:42	T	16:25	C
13:57	1	14:37	3.5	15:19	5.5	15:55	7.5	17:20	Fin

Further experiments are going to be done. Best way to do so is to use different types of ores. When still using the same furnace. But this can be tricky because a furnace can manage to hold up for about 10 to 30 reduction processes. In the future new and different types of furnaces are going to be built. One which is going to be chimney furnace. This type of furnace that is high enough so manual blowing is not required.

4. CONCLUSION

There is still a lot what can be found and known about ferrous archaeometallurgy. This paper sums up the basics of iron making and shows the proper way to make reduction ready charcoal. Experiment shown presents the normal way of furnace making and basic method behind ironmaking itself. Process can be very long and unforgiving. Several experiments were disastrous and didn´t yield any success. The reason mostly being tuyere. Right tuyere is extremely important and easily most crucial part of the whole reduction process.

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