IRON IN ARCHAEOLOGY
THE EUROPEAN BLOOMERY SMELTERS

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years, the form of these experiments has undergone a certain development. The goal of the first trials was simply to obtain some metallic iron in the slag produced under primitive conditions and to test reconstructions of some types of furnace. In recent years, since metallurgists have began to participate more systematically, so the experiments tended to diverge along two main lines of approach.

First, there are attempts to keep as close as possible the original conditions, with furnaces built strictly according to remains identified during excavation, using traditional structural materials and bellows worked by hand. These operation have quite often been turned into very succesful public shows, in addition to the original goal of controlled experimentation. The second, metallurgically driven approach stresses examination of the theoretical principles of the process itself, omitting those external parameters such as the structural furnace materials (clays), mode of construction and the location of the trial in the field. Furnace replicas in laboratories and halls, blown by mechanically driven air supplies, are widely applied and chemical and physical measurements including gas analysis and thermocouple readings, levels of ore and charcoal consumption and time recording as the basis for metallurgical evaluation. Combined trials, which are useful when properly documented, are also being carried out.

Another trend in experimental smelting has seen researchers using furnaces of types recovered from excavations with the aim of obtaining slag and product equivalent in appearance and composition to archaeological residues. The goals are a more precise reconstruction of installation and the evaluation of metallurgical results obtained under known conditions.

The literature on smelting experiments, as published since the 1950's, is so voluminous and ever-increasing annually, that its compilation is a task which we have left to others, quoting and citing in the bibliography only those works directly relevant here.

The working of the bloomery furnace

In the light of what has been said above, and being conscious of some uncertainties, it is possible to present in rough outlines the reduction of iron ore in a low bloomery furnace as reflected by the theory of physical metallurgy and the results of experimental smelts conducted in reconstructed installations.

Let us imagine a cylindrical shaft furnace of 100cm height and 35cm – 40cm in diameter, charged with charcoal and preheated several hours under a mild air flow. Oxygen combines at heat with the carbon to form carbon dioxide ($C + O_2 \rightarrow CO_2$) and subsequently, carbon monoxide ($CO_2 + C \rightarrow 2CO$) which is the principal reducing agent. This rises through the charcoal column to the furnace throat where the gas mixture contains only 1 – 4 % of CO_2 (Tylecote et al. 1971, 348). This proportion changes after the addition of the first charges of ore and charcoal which were in varying ratios (expressed by weight — very often 1 : 1). Then, oxygen is removed from the ore so that carbon dioxide is regularly produced:

$$3Fe_2O_3 + CO = 2Fe_3O_4 + CO_2 \uparrow$$
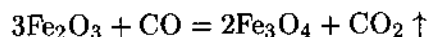
After several charges of ore and fuel, the atmosphere in the upper part of the shaft contains much CO_2 which, at low temperatures around 500°C, acts as a reducing agent (Schürmann 1958, 1300). With the first charges in the furnace, taken into account its dimensions as above, under a forced draught, the intensity of blowing was usually raised to feed the interior with about 200 to 300 litres of air per minute (Tylecote et al. 1971, 340; Crew 1991a; Crew and Salter 1991). We have to bear in mind that during the full process, the temperatures in the furnace are distributed extremely heterogeneously, with the isotherms not being level but in zones shaped like a candle flame, as a result of the flow of the air and gas (Fig. 33). While in the combustion zone at the tuyere mouth, temperatures could reach over 1400°C, indeed as high as around 1600°C (Morton and Windgrove 1970, 6; Tholander and Blomgren 1985, 417;
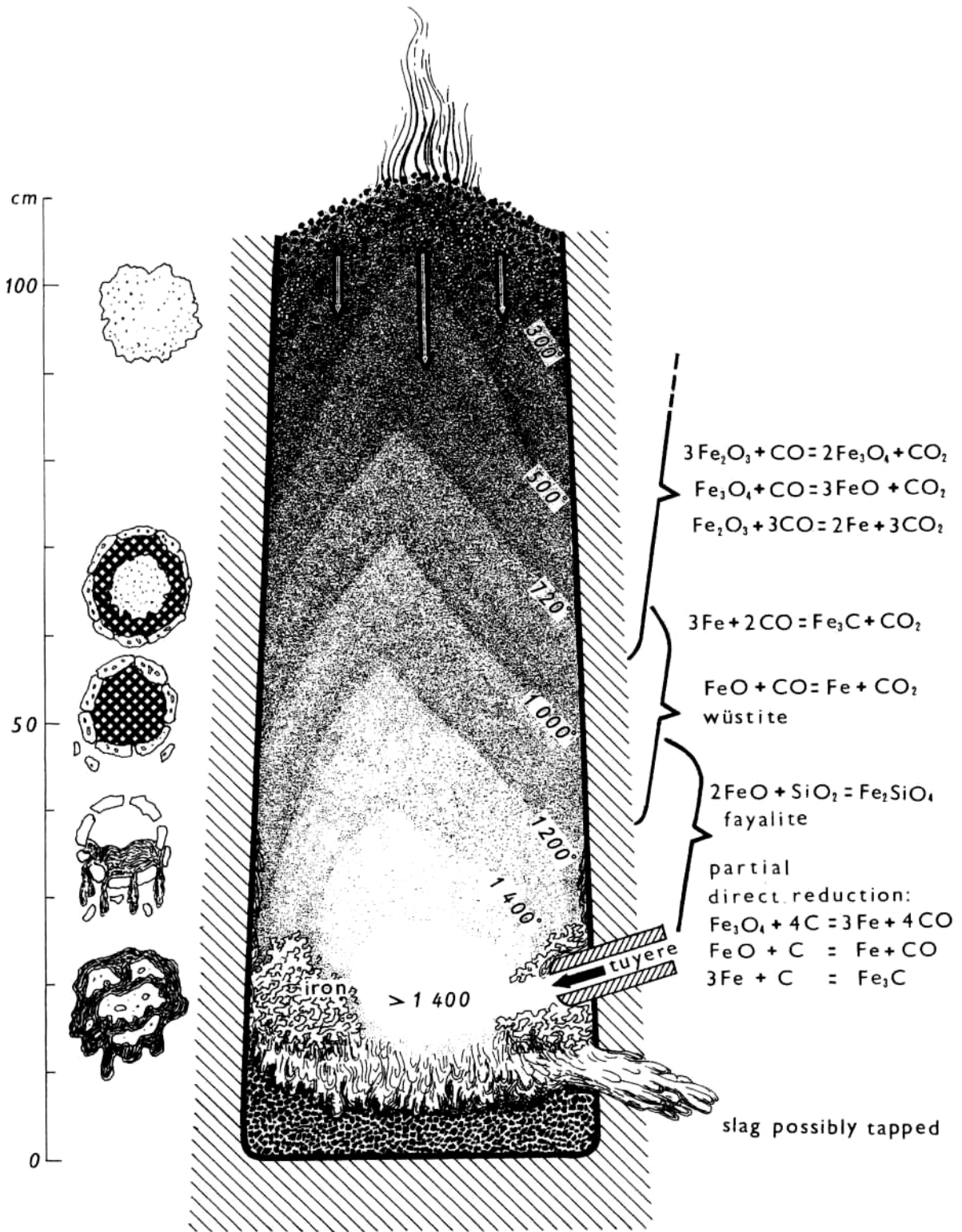
$$3Fe_2O_3 + CO = 2Fe_3O_4 + CO_2$$
$$Fe_3O_4 + CO = 3FeO + CO_2$$
$$Fe_2O_3 + 3CO = 2Fe + 3CO_2$$

$$3Fe + 2CO = Fe_3C + CO_2$$

$$FeO + CO = Fe + CO_2$$
wüstite

$$2FeO + SiO_2 = Fe_2SiO_4$$
fayalite

partial
direct reduction:
$$Fe_3O_4 + 4C = 3Fe + 4CO$$
$$FeO + C = Fe + CO$$
$$3Fe + C = Fe_3C$$

tuyere

iron $> 1\,400$

slag possibly tapped

Fig. 33.   The principle of the bloomery process. The position of iron sponge in the furnace hearth is marked at the tuyere level. Liquid slag penetrates the pores down and may be tapped. On the left there is schematically sketched the behaviour of individual ore fractions: formation of wüstite, coating with iron shell, slagging, and destruction of the shell (based on Tholander 1987).

Rehder 1986), a few centimeters away, they decreased to around 1200 – 1300°C and higher up the furnace to 1000 – 700°C, falling to around 500 – 350°C in the throat of the shaft.

Let us now follow a grain of a pre-roasted haematite, consisting of the ore mineral and siliceous gangue particles, on its way down the shaft with the charge, against the current of the CO-containing reducing gases. In the upper zone, at 500 – 550 °C, it becomes totally dry and porous, especially when calcined before. Up to ca 700 – 750°C, a great deal of the ore will be reduced to magnetite Fe_3O_4 and partly to the lower oxide FeO, wüstite:

$$3Fe_2O_3 + CO = 2Fe_3O_4 + CO_2 \uparrow$$

$$Fe_3O_4 + CO = 3FeO + CO_2 \uparrow$$
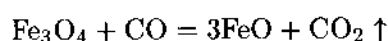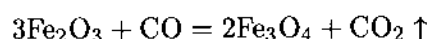
On the surface of the ore grain, an outer layer of wüstite is formed which may be just covered by a thin pellice or skin of metallic iron:

$$FeO + CO = Fe + CO_2 \uparrow$$

$$Fe_2O_3 + 3CO = 2Fe + 3CO_2 \uparrow$$
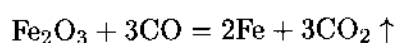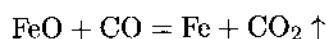
This metallic skin is visible in many samples of bloomery slag, both from archaeological finds and experimental smelts (Pleiner 1969b, fig. 16: 6 – 7; Morton and Windgrove 1970, figs 1 and 15; Tholander and Blomgren 1985, 418 – 420; Clough 1986, 29; Blomgren and Tholander 1986; Tholander 1987, 153, fig. 8; Leroy 1997, 165, fig 89). Under strongly reducing conditions, after all wüstite having been consumed, it may start to be carburized (Straube 1986, 23; 1996, 52; Morton and Windgrove 1970, 6 – 7), a process which occurs principally in the temperature range over 900°C. The γ-iron absorbs carbon from the gas:

$$3Fe + 2CO = Fe_3C + CO_2 \uparrow$$
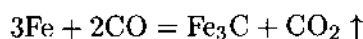
Inside the ore grains which contain residual mineral, gangue and wüstite, carbon from the CO ($2CO \rightarrow C + CO_2$) impregnates the fissures and surfaces and the gas pressure developed is powerful enough to perforate the iron envelope, the smallest particles of which can absorb much energy resulting in their being strongly carburized and even melted to pig iron (Tholander and Blomgren 1985, 417 – 418).

Meanwhile, the ore-wüstite-iron conglomerate sinks to lower levels where, at temperatures roughly 1100 – 1200°C, a further reaction takes place. The gangue particles of the ore grains combine with wüstite to form fayalite $2FeO.SiO_2$ or Fe_2SiO_4, the main constituent of slag, which melts and flows out of perforated iron cage. Parts of the iron envelope scatter and sinter together with other iron grains, forming a sort of iron sponge (Pl. XXIV: 2 and 3) adhering to the walls of the hearth, roughly at the level of the tuyere and its mouth, leaving the slag to sink through the pores to the bottom, where it collects and can, in some cases, be tapped out. As the smelt continues, many ore pieces descend still in unreduced state. If they are enveloped by slag, then the reduction by CO-rich gases is interrupted and, for this reason, premature slag formation diminishes the yield.

Nevertheless, in zones with temperatures over 1000°C, another reaction, direct reduction by solid carbon takes place. Ore in contact with charcoal produces further carbon monoxide:

$$Fe_3O_4 + 4C = 3Fe + 4CO \uparrow$$

$$FeO + C = Fe + CO \uparrow$$
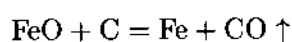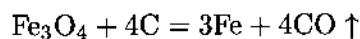
Reduced iron particles can be carburized in the same way:

$$3Fe + C = Fe_3C$$
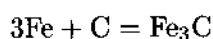
The smelt is rich in antithetic reactions which develop during the movements of the charge, exposing the pieces of iron ore which have passed through various stages of reduction, to different conditions. Slag influences the process in two ways. On the one hand, it tends to decarburize iron which has been already carburized, while on the other, it protects the metal against the strongly oxidizing air stream in the combustion zone. The formation and removal of slag allows the restoration of the reduction of iron oxides and carburization of the reduced metal. However, the direct impact of oxygen at temperatures in the range of 1400 – 1600° despite affecting only a limited space, converts much iron into ferruginous slag. Again, under specific circumstances, it is possible, at high temperatures, for iron to be reduced from fayalite (Hauptmann 1986, 11).

Silicon dioxide SiO_2 is significantly active within the bloomery process, but its role, however, is ambiguous. It not only binds FeO but also other oxides of the gangue and governs the formation of slag. When fayalite is formed too soon, the further access of CO is blocked and the reduction of iron hindered (Tylecote et al. 1971, 360; Osann 1971, 71 – 79). This may happen especially when the ore gangue contains only small amounts of other oxides such as MnO, CaO, MgO, Al_2O_3 and P_2O_5. In cases where the silica content of the ore is too low (2 – 3 %), and there is no sand added and no SiO_2 is available from the furnace lining, the reduction of iron takes place on only a limited scale, with isolated and dispersed iron particles occurring within the cinder mass. Nevertheless, if a high-grade ore with low silica content can be slagged, then the slag will be very viscous and only in small amounts so that there is the possibility of obtaining a significant amount of carburized iron (Osann 1971, I, 71 – 79; Clough 1986, 35).

Molten fayalite-wüstite slag, containing some glass, absorbs MnO, CaO, Al_2O_3, P_2O_5 and other oxides which cristallize as various mineralogical phases (Pl. XXIII; Chapter XIII). However, they lower the melting point of slag only in the limited range of 1150 – 1300°C. Manganese passes into the slag, substituting for some of the iron and combining with SiO_2, thus making the reduction of iron and its carburization easier. Phosphorus pentoxide P_2O_5 (which is found at especially high levels in some bog-ores, and in charcoal ash) plays a positive role in slag formation, but tends, on the other hand, to block the absorbtion of carbon by iron.

Lime is often considered in the archaeological literature to have been added as slag former and limestones and lime kilns discovered in the vicinity of bloomeries are usually explained as being connected with the bloomery technology. In fact, lime content only influences the fusibility of iron-rich bloomery slag to a limited degree, and has a negative effect under the conditions of the direct method. The use of limestone as a flux was usual in the blast furnace process and acted principally in the range of 1300 - 1400°C (Tylecote 1987, 329 – 330). In early fining processes lime played a role in moderating the influence of high phosphorus contents (Horstmann 1996). In any case, CaO contents in the bloomery slags usually vary from 3 to 6 % and higher proportions (16 – 17 %) are exceptional, resulting perhaps from local interaction between the slag and calciferous furnace lining rather than from intentional addition of limestone as flux. Where fluxes were used in the bloomery process, they probably would have consisted of old FeO rich slags.

The particles, sintered-together fibres and nodules of iron finally form an iron-and-slag conglomerate which is concentrated around the tuyere level, leaving the bulk of slag to flow through the pores to the furnace hearth. Under favourable conditions, more compact or consolidated masses (compact blooms) could be created. To prevent unwanted reoxidation of the product in the liquid or viscous slag and to avoid unnecessary losses, the smelter usually removed the iron from the furnace when hot and cooled it rapidly in water (Pl. XXIV).

Most bloomeries produced soft, malleable iron, which was wanted by their customers as an easily workable material for structural parts, sheet and wire. However, a portion of the metal produced could be, as shown, considerably carburized, and used for hard steel cutting-edges and points. Cast or pig iron, if produced by chance in bloomeries, was usually not used for castings but treated as a waste product, possibly being added, together with fresh ore, charcoal and old

slag (as a flux), to new furnace charges.

The making of steel

On the basis of results achieved in reconstructions of primitive bloomery furnaces, the most favourable conditions would seem to be provided by the use of pre-roasted high-grade ore (at least 60% iron oxide), mixing charcoal and ore together in individual charges, more moderate blowing rates (according to the ore properties), a prolonged stay for the bloom in the furnace which is fed at the end only with charcoal and blown after the last charge. Abundant slag, when tapped, promotes the formation of carbon-free or low carbon malleable iron.

In the light of our present knowledge, the manufacture of primary steel requires high-grade iron ore (a high Mn content is especially favourable) with a fuel-to-ore ratio higher than 1:1 (e.g. 1.5:1), while the iron should be protected against secondary re-oxidation by suitable systems of air-ducts (Pleiner 1969a; Pelet 1992). Again, a prolonged residence under the conditions described above is extremely important.

The need for such optimum conditions was known in the past and the extent to which smelters were able to achieve them in their furnaces depended on their experience, working skills within their own traditions. There were individual groups of ironmakers who understood how to make steeled blooms.

Good homogeneous steel was a valuable material, circulating in limited quantities and was an item of trade although at some times and in some places, it was not easily obtainable. On the other hand, hard steel was not always preferred by early smiths. It was good for cutting-edges, but for the bodies of implements, or for making wire and iron sheet, soft and ductile wrought iron was required. Therefore, we may assume that some bloomeries directed their smelting specifically towards the production of malleable iron. Their operators would have accepted that yields would be lower as a result of higher blowing rates, of giving the charges shorter residence times in the furnace shaft and of holding the bloom for longer at high temperatures in the oxidizing zone to obtain an iron-rich, but tappable slag.

The ancient smelter proceeded empirically and the smelting furnace was for him a magical cauldron. As we know from the ethonological record, smelters sought to harness its magic by performing complicated rites throughout their campaigns, incorporating the weight of observations made during successful work. Their criteria of control over the yield were, in the last analysis, the quantity and quality of the product.

Post-mediaeval bloomery survivals

Late examples of the bloomery process were described by authors for several countries in Europe. Thus, in Italy, Vanoccio Biringuccio (1540) devoted brief remarks to iron in books I.6 and III.3 of his *Pirotechnia*, while in Bohemia and Saxony, Georgius Agricola wrote about two models of bloomery furnace, open hearths and shaft furnaces (book IX of the *De re metallica libri XII*, 1556). In 1589, Thomas Payne included in his *Description of Ireland* a reference to what may have been bloomery smelting by smiths using bog ores (Scott 1990, 152). For Poland, a remarkable account of the bloomery ironmaking was given by Rożdzieński in his *Officina ferraria*, published in 1612. Schultze (1732), Swedenborg (1734), Evenstad (1790) and Bush (1851) presented descriptions of stone-walled and timber-clad furnaces of funnel-shaped internal profile, bellows-blown by man power, fed with bog ore and, exceptionally, with wood. Evenstad gives the duration of one smelt as 4 hours and mentions a yield of 8 – 10kg of iron (Espelund 1991a, b).

A very peculiar iron smelting was practised in Corsica from the mid-16th century and ceased in the period around 1830 – 1840. The process took place in an open fireplace with a stone wall pierced by obliquely positioned tuyere and blown by a *trompe* in which the air pressure is supplied by a flow of water falling through a vertical shaft. Heaps of pre-packed fuel and ore