

### Introduction

The manufacture of iron from its ores can be carried out using a variety of smelting technologies. These can be broadly divided into the direct and indirect processes. The indirect process uses a blast furnace to create cast iron which is then refined into malleable iron. The direct or bloomery process produces malleable iron in a single furnace. The bloomery process took place below the melting point of the iron and bloomery iron had to be refined by forging before it could be used. All these processes generated slags and residues as by-products. The exact configuration of raw materials, furnace architecture, and other factors means that there are many variations within bloomery smelting and this may be reflected in the nature of the slags and residues.

### Iron ores and ore processing

Iron (Fe) is the fourth most abundant element in the earth's crust and many geological processes concentrated iron compounds to form ore bodies. The commonest ores are limonites, carbonates and hematites. They occur as bedded or vein deposits and as nodules within other deposits such as clays. A significant ore source in antiquity was bog iron ore, which formed by the precipitation of iron compounds in lakes and bogs. Iron smelting sites are therefore not restricted to specific geological regions; early (pre-16th-century) sites have been found in most counties in Britain. It was essential that the ore charged to the furnace was as rich as possible, usually over 70% iron oxide. Too much gangue (the non-metallic component of the ore, for example silica) would cause large quantities of slag to form at the expense of metal.

Bog ores could easily be worked by digging, but for other ores deeper open cast pits, bell pits and deep mining were used. All iron ores benefit from processing, which may include washing, roasting and crushing. Roasting was most important since it broke down compounds and caused micro-cracking in the ore lumps. This facilitated reduction in the furnace, by allowing the reducing gases to penetrate the ore lumps. Raw ores can be difficult to recognise: they are not necessarily dense or brightly coloured. Roasted ores are more obvious, being usually a red or purple colour, or more rarely grey-black. They are most commonly found on site as small particles of ore fines which can occur either where the ore was roasted, crushed or stored, or in smaller concentrations in or around the furnace structures.

### Furnace structure and materials

Bloomery furnaces provide an enclosed space for the production of iron which will allow a sufficiently high temperature and reducing atmosphere to be maintained. Most furnaces had an internal diameter of 0.3m but larger examples are known (including some more than 1m diameter). Furnaces usually had walls which could be cylindrical or domed. The identification of the overall size and shape of furnaces is complicated by the fact that few furnaces survive intact. In most cases, much of the superstructure of a furnace will have been lost and in extreme cases all that survives is a small patch of burnt clay or earth. The walls of the furnace were normally over 0.2m

thick to reduce heat loss from the furnace. The furnaces would have air inlets, called tuyères or blowing holes, usually 0.3-0.5m from the base. In many cases an arch through the wall of the furnace enabled slag to be removed, either cold or as tapped slag. Some furnaces were partly built into banks of clay, which can result in a substantial proportion of the furnace surviving. The size of a furnace should be recorded as an internal diameter, with an estimate of the likely wall thickness. All furnace structure potentially *in situ* can provide good material for archaeomagnetic dating.

The preferred material for the construction of furnaces was usually clay. The clay was often heavily tempered with sand and small stones. Stone and tile could also be used as part of the furnace structure. The high temperature in a furnace produces vitrified clay lining, though heavy vitrification is usually limited to a zone above the tuyère and elsewhere in the furnace the clay will be baked to a greater or lesser degree. The inner surface can be vitrified for 10mm or more and it usually has a surviving backing of baked clay, either oxidised red or reduced to a grey colour, depending on its original position in the furnace. Indications of furnace repair are often found as multiple layers of vitrification. The clay can also be coated with slag and it can react with the slag to form thicker accumulations of furnace lining reaction products.

Broken fragments of furnaces are often found in secondary contexts. The fragility of furnace fragments means that larger pieces are often only found close to the original site of the furnace. The shape of surviving furnace fragments can provide clues as to the form of the furnace, especially on the method of introducing the air. On early sites this is usually through a simple circular blowing hole in the wall of the furnace, but this would normally only survive as a fragment of vitrified clay with a distinctive curved shape. Some Roman sites have produced evidence for clay tuyères, and in the Roman and medieval periods there is some evidence for the use of replaceable block tuyères. These are separate circular or rectangular blocks of clay, with a blowing hole, which are set in place in a prepared cavity in the furnace wall.

### Fuel

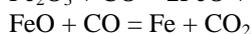
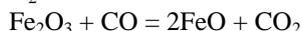
The commonest form of fuel was charcoal. Its availability was probably the most important factor in determining the location of furnaces, since large quantities were needed and it could not easily be transported great distances. There has been little archaeological investigation of charcoal production sites.

Charcoal is not always found in abundance on smelting sites but samples can be used for dating and to identify the species used, as well as indicate any woodland management (e.g. coppicing; see HMS Datasheet 305). Charcoal has a small percentage content of inorganic material, which can make a significant contribution to the chemistry of the other slags formed in a furnace.

### Smelting

The furnace was charged with fuel and preheated. When hot, mixtures of ore and charcoal would then be fed into the furnace from the top, and bellows used to pump air into it. The temperature inside a bloomery furnace will vary from as little as 500°C at the top to 1300°C at the base where the air enters the furnace.

Two important reactions occur during smelting; the reduction of iron oxide to metallic iron, and the formation of a liquid slag. Carbon monoxide (CO) is formed by reaction between oxygen in the air and carbon present in the fuel. This gas reacts with the oxygen atoms in the iron ore, reducing it to metallic iron:



As pieces of ore pass through the furnace they become reduced progressively to particles of iron surrounded by envelopes of slag. When they enter the hot zone above the blowing area, the iron particles begin to coalesce and eventually they become welded together to form the bloom. As the melting temperature of iron is 1538°C, the iron forms as a solid rather than a liquid. The bloom forms just below the blowing hole and is usually attached to the furnace wall, slowly subsiding under its increasing weight. The bloom would often be heterogeneous, varying in composition ranging from ferritic iron (no alloying elements), phosphoric iron (containing up to 1% phosphorus) to carbon steels (containing up to 0.8 % carbon). The phosphorus would derive from the ore (although not all ores contain phosphorus) and the carbon could derive from the charcoal. The bloom grew until it started to interfere with the air blast, at which stage it had to be removed.

The second reaction in the furnace is the formation of a slag from some of the iron oxide (FeO) and the gangue oxides (silica, alumina, etc) in the ore. The slag has a lower melting temperature (typically in the range 1100-1200°C) and so is more liquid and will continue to descend into the lower part of the furnace, though a significant proportion of it remains attached to and trapped in the bloom.

Different bloomery technologies used different methods of slag removal. With very rich ores, little slag was produced and it could remain within the furnace., often forming relatively small, irregularly-shaped masses, e.g. prills. For leaner ores the slag needed to be removed from the furnace. In some cases, slag could be allowed to accumulate in a pit at the base of the furnace. These are usually large accumulations of dense slag, weighing from about 2kg upwards and they can retain the shape of the furnace base, sometimes with part of the baked clay structure still attached.

The commonest method of removing slag from a furnace was by tapping: opening the arch and allowing the slag to run out of the furnace. Tap slag is easily recognised even as rather small fragments. The upper surface is usually smooth but with pronounced ripples, the lower surface has an impression of the ground over which the tap slag flowed.

A range of other residues can sometimes be found in the base of a furnace including partially reacted ore, prills and shells. As furnaces were frequently reused, it is rare for slag to be found *in situ*. Most slags are found mixed together, often in a dump outside the building in which the smelting was carried out.

### Bloom smithing

Raw blooms have not been found on archaeological sites, as the first stage of refining would normally be carried out at the smelting site, while the bloom was still hot. The bloom had to be refined to remove excess slag, to consolidate the iron and to either homogenise the bloom or separate the different alloys. The refined bloom could be in a variety of forms, such as a sub-circular cake or as a rough cuboid. The refining would also result in slags which may vary from prills to plano-convex cakes

### Other related evidence

There are no known tools specific to the smelting process which survive in the archaeological record. Neither is there any direct evidence for the form of the bellows, except in some later literary sources. Some prehistoric sites have produced evidence which may be related to bellows, such as low-angle stakeholes (which would have held flexible stakes giving the return action for foot operated bellows) and shallow hemispherical pits with large stakeholes, which may be related to the bellows design. Some iron-working sites have produced evidence for fire-lighting, either as lumps of iron-pyrites used to produce sparks, or fire-drill stones, with cup-shaped hollows, which would have been used as bearings for a fire drill.

Perhaps the most important evidence related to smelting are the buildings or structures in which the work would have been carried out. Shelter would have been essential for the storage of both ore and charcoal and for protecting the furnaces, which would have represented a considerable investment of time and materials. Examples of round stakewall smelting huts have been found on prehistoric sites and large square post-built shelters on medieval sites. If a site has not been ploughed, it should be possible to re-construct the layout of such installations with some confidence.

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