Historic England

Archaeometallurgy

Guidelines for Best Practice

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The Historical Metallurgy Society

Summary

This guidance document provides an introduction to the ways that the archaeological evidence for metalworking is studied. Archaeometallurgical evidence can include whole landscapes, buildings, features, artefacts and waste materials (eg slag and crucibles). Archaeometallurgy includes fieldwork investigations (survey and excavation) and the subsequent study of these data as well as any artefacts and residues recovered. Scientific approaches provide insights into the techniques used to produce different metals and how these were fabricated into artefacts.

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- *Science for Historic Industries. Guidelines for the investigation of 17th- to 19th-centuries industries;*
- *Archaeological Evidence for Glassworking. Guidelines for best practice; and*
- *Guidance for Archaeological and Historic Pottery Production Sites.*

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Cover images

Left: 16th-century blacksmithing (Agricola) and
Right: Modern experimental blacksmithing.
[photo © David Starley]

Contents

Introduction

Archaeometallurgy is the study of metalworking structures, tools, waste products and finished metal artefacts, from the Bronze Age to the recent past. It can be used in the field and during the post-fieldwork phases to identify and interpret metalworking structures and waste products, such as slags, crucibles and moulds. The nature of technologies used in the past (as well as their social and economic impact) can be reconstructed from the archaeological evidence. Scientific techniques can provide information about the manufacture and consumption of a range of metals.

Archaeometallurgical investigations can provide evidence for both the nature and scale of mining, smelting, refining and metalworking trades, and aid understanding of other structural and artefactual evidence. They can be crucial in understanding the economy of a site, the nature of the occupation, the technological capabilities of its occupants and their cultural affinities. In order that such evidence is used to its fullest, it is essential that archaeometallurgy is considered from their outset and at all subsequent stages of an archaeological project. Technological and functional aspects of metalworking should be understood within wider socio-economic contexts which can include symbolic and/or magical qualities (Giles 2007).

These Guidelines aim to strengthen the retrieval of information about all aspects of metalworking from archaeological investigations. They are written mainly for curators and contractors within archaeology in the UK and will help them to produce project briefs, project designs, assessments and reports.

The Guidelines are divided into a number of sections. First is a summary of the sort of metallurgical finds to expect on sites of all dates (p 2). This is followed by a section entitled ‘Standards and good practice for archaeometallurgy’, outlining its relationship with other aspects of archaeological projects (p 7). Then come the fully illustrated sections describing archaeometallurgical processes and finds: for iron (p 16), copper and its alloys (p 40), lead (p 49), silver and gold (p 53), tin (p 56) and zinc (p 58). A shorter section on non-metallurgical high temperature processes illustrates finds that are often confused with metalworking debris (p 59). A section is provided introducing some of the scientific techniques commonly used in archaeometallurgy (p 62). Finally, sources of additional information (p 67) and a glossary of common metallurgical terms is provided (p 69).

1 What to Expect

It is useful to know what sort of archaeometallurgical evidence to expect from a particular site. This depends on a number of factors, such as the location of the site, its date and the nature of the occupation. For example, archaeological evidence for mining tin will usually only be observed in areas where tin ores are found, iron working evidence is unusual before the beginning of the Iron Age, and precious metalworking is more likely to be concentrated at high status and/or urban sites.

The following chronological summary of the archaeometallurgical record for the UK indicates the types of evidence that are likely to be found.

1.1 Bronze Age

Copper alloy and gold artefacts of this period show that these metals were worked. Some evidence exists for copper mining (Timberlake and Marshall 2013), while other evidence demonstrates working, mostly casting, of copper alloys. There is almost no direct evidence for how other metals used during the Bronze Age were obtained. It is generally accepted that the tin ores in south-west England were exploited from the Bronze Age onwards but there is little direct evidence for this (Penhallurick 1997).

Evidence for mining can only be expected in regions where ores are found. In England, copper ores are known in Cornwall, Devon, Shropshire, Staffordshire, Cheshire (Timberlake and Prag 2005), North Yorkshire and Cumbria, and other sources are known in mid and north Wales (Timberlake 2003) and Scotland. Old workings and hammer stones (Pickin 1990) have been discovered during more recent mining and similar evidence has been recovered during archaeological excavation of Bronze Age mining sites (Lewis 1990). Early working made use of stone tools or fire to weaken the rock (Craddock 1995, 31–7) and this can be distinguished from later working where iron tools or explosives were used. The palaeoenvironmental record confirms that copper (and lead) mining took place (Mighall *et al* 2009)

Little is known about how ores were transformed into metals in Bronze Age Britain. No smelting furnaces have been identified (Craddock 1990; 1994), although some slag has recently been found on the Great Orme in North Wales (Jones 1999; Williams 2013). Some useful ideas, however, have been gained from recent experimental archaeological work (Timberlake 2007).

The earliest copper-based metals (fairly pure copper, sometimes containing small amounts of arsenic) appear in the third quarter of the third millennium BC, ie the late Neolithic or

Figure 1

Experimental iron working at Plas Tan y Bwlch, Gwynedd: removing a bloom from a furnace. [photo © David Starley]

Chalcolithic (Allen *et al* 2012). Bronze (an alloy of copper and tin) appears with the early Bronze Age in the final quarter of the third millennium BC. Copper alloy artefacts were produced by casting and smithing. Fragments of clay moulds and crucibles have been found on many Bronze Age occupation sites and a few have produced large quantities of these objects, for example Dainton, Devon (Needham 1980), Jarlshof, Shetland (Hamilton 1956) and Springfield Lyons, Essex (Brown and Medlycott 2013), however, finds of this type are rare in early Bronze Age contexts. The main evidence for bronze smithing can be found in the microstructure of finished tools and weapons (Allen *et al* 1970).

Some evidence for iron working has been found in contexts that are culturally assigned to the Late Bronze Age (Collard *et al* 2006).

1.2 Iron Age

Iron Age settlement sites generally provide more evidence for metalworking, and for a wider range of metals, than Bronze Age sites.

Iron ores, unlike copper ores, are found in many areas and iron mining and smelting could be carried out on a small scale almost anywhere in Britain. No Iron Age iron mines are known, but bog ores and other surface outcrops were probably exploited. Several sites have yielded furnaces and large quantities of iron smelting slag, for example Brooklands, Surrey (Hanworth and Tomlin 1977), Welham Bridge, Yorkshire (Halkon and Millett 1999) and Bryn y Castell and Crawcwellt, Gwynedd (Crew 1986; 1998b).

Evidence for iron smithing is much more widespread, as at Dragonby, Lincolnshire (May 1996) and Scalloway, Shetland (Sharples 1999). Iron smithing can also be indicated by cut fragments of iron stock and hoards of blacksmiths' tools – for example at Waltham Abbey, Essex (Manning 1991) – while the microstructure of finished objects provides information about the smiths' techniques (Salter and Ehrenreich 1984). Important information on the use and trade of different types of iron stock can be obtained from currency bars, for example the hoard found at Danebury, Hampshire (Cunliffe 1984), and from more rare smithed blooms and billets.

Many Iron Age settlement sites have yielded some clay mould or crucible fragments for casting copper alloys but a few sites, including Gussage All Saints, Dorset (Wainwright 1979) and Grimsby, Lincolnshire (Foster 1995), have produced large assemblages. Coin manufacture can be demonstrated at a number of *oppidum* sites, such as Verulamium (St Albans), Hertfordshire (Frere 1983), and there was possible silver production at Hengistbury Head, Dorset (Northover 1987).

Those parts of Britain that were not within the Roman Empire kept Iron Age traditions of metalworking although some also incorporated elements of 'Roman' techniques.

1.3 Roman

A great variety of evidence for Roman metalworking has been found throughout Britain. Any substantial excavation of a Roman period site is likely to recover some evidence.

Roman sites with large numbers of furnaces and huge quantities of iron smelting slag have been discovered in the Weald of Kent and Sussex (Hodgkinson 2008). Other major iron smelting centres existed in the Forest of Dean (Jackson 2012), Northamptonshire and Lincolnshire (Schrüfer-Kolb 2004) but iron smelting evidence occurs in many other areas (Fyfe *et al* 2013; Griffith and Weddell 1996; Paynter 2006). Iron smithing slags are routinely discovered on almost all Roman sites, and occasionally blacksmiths' workshops are found (Buxton and Howard-Davis 2000; Hammer 2003).

A number of large, circular, stamped copper ingots have been found, particularly in Wales (Kelly 1976), although no evidence of contemporary copper mines, furnaces or slag involved in their production has yet been discovered. Specialised crucibles for brass production have been identified on a few urban sites (Bayley 1984). Clay moulds and crucible fragments are relatively common finds on many Roman sites and occasionally the evidence is particularly abundant, for example at Castleford (Bayley and Budd 1998). Stone and metal moulds (Bayley *et al* 2001) are also known, but are far

Figure 2

Reconstruction of a Roman workshop, based on excavated features and finds from Verulamium.
[illustration © Michael Bayley]

less common. A number of workshops have been discovered in which a variety of structures and occupation layers have been preserved, for example at Caerleon (Zienkiewicz 1993). Where workshop remains are well preserved there is often evidence for a range of both ferrous and non-ferrous metalworking.

The best known evidence for Roman lead production consists of large inscribed lead ingots although some smelting sites have been identified (Page 2005). Large litharge cakes, showing that silver was extracted from lead, have also been found in the Mendips (Dunster and Dungworth 2013) and Welsh borders (Bayley and Eckstein 1998). Small litharge cakes, produced during the extraction of silver from debased alloys, are also often found on urban sites.

The only evidence for tin mining in the Roman period is the occasional inscribed ingot. Tin smelting slag has been recovered (Lawson-Jones 2013) but no furnaces have yet been identified. Palaeo-environmental evidence suggests tin exploitation from the late 1st century AD to the end of the Roman period (Meharg *et al* 2012). The casting of pewter is fairly well known from stone moulds that have been recovered from both urban and rural sites (eg Lee 2009).

Roman-period gold mining is known from Dolaucothi, Dyfed (Burnham and Burnham 2004). Parting vessels, for separating silver from gold, have been found on a few urban sites (Bayley 1991a).

1.4 Early medieval

Both urban and rural settlements produce a great variety of evidence for the working of many different metals. The finds are not all the same in the different cultural areas of the British Isles.

A variety of iron smelting technologies, which produced distinctive types of slag, were in use. Large slag blocks have been found at a number of sites, including Mucking, Essex and Aylesham, Norfolk (Tylecote 1986, Fig 81), while at Ramsbury, Wiltshire (Haslam 1980) both non-tapping and tapping furnaces were found. Virtually every settlement site will produce at least small quantities of iron smithing slag and larger amounts are not uncommon, for example at Deer Park Farms, Antrim (Lynn and McDowell 1988) and Coppergate, York (Ottaway 1992). Metalworking tools are found, both in burials, for example at Tattershall Thorpe (Hinton 2000), and on settlements, such as Coppergate (Ottaway 1992). The variety of manufacturing techniques employed by smiths increased and a much wider range of structures, including pattern-welding, are commonly seen in metallographic studies of iron artefacts (Blakelock and McDonnell 2007; Gilmour and Salter 1998).

A range of non-ferrous metals was widely used (Bayley 1991b) and evidence for refining, casting and smithing is common on many types of sites. Examples include urban sites, such as Coppergate, York (Bayley 1992) and Armagh (Gaskell Brown and Harper 1984), monastic sites, such as Hartlepool, Tyne and Wear (Daniels 1988), and some other high status centres, for example Dinas Powys (Alcock 1963) and Dunadd (Youngs 1989). Typical finds are small crucibles, cupels, litharge cakes, bar ingots, scrap and waste metal. Ingot- and object-moulds were made from stone, clay and antler. Crucibles, scrap metal and clay moulds for small objects are common.

1.5 Medieval

From the medieval period onwards there was an increasing tendency for some metal industries to be concentrated in towns, and often in particular areas of towns, although iron smithing also took place in many rural settlements. Bell-casting was often, although not always, carried out where the bell was to be used (Dungworth and Maclean 2011). Metal smelting was still carried out near the ore sources (Pickin 2010).

An important development of this period was the introduction of water power to operate bellows or trip hammers; however, this is poorly understood.

Water power was used for at least some bloomery smelting (Mott 1961; Young and Poyner 2012) and it was an essential component of the blast furnace and related fineries and forges introduced at the end of the 15th century.

Urban excavations frequently recover evidence for secondary working of a range of metals (Bayley 1996). The scale of metalworking increases in this period and the size of assemblages is often larger, although the range of finds is similar to that of earlier periods. This change in scale is particularly noticeable in crucibles whose size increases (Fig 36), and large clay moulds for castings such as cauldrons and bells became common (Richards 1993) Mass-production also led to changes in mould technology. Multi-part clay moulds for casting dozens of objects at one time were developed (Armitage *et al* 1981) and reusable limestone piece moulds were made for casting pewter trinkets (eg Margeson 1993, Fig 127).

1.6 Post-medieval

During this period a wide range of both ferrous and non-ferrous metalworking took place, and technologies evolved rapidly, often with several complete changes in practice within the period (Crossley 1990; Day and Tylecote 1991). With the increasing separation of 'industry' from agricultural and domestic life, many sites and field monuments become primarily industrial in function and can be immediately identified as such. This situation is less true, however, of craft workshops, small-scale urban industry, and experimental laboratories and workshops. Throughout the period their archaeology remains poorly understood, even into the 20th century (Brooks 2000; Hull 2003; Martinón-Torres 2012). Documentary sources, including maps and plans, form an increasingly useful tool for studying the archaeology of recent metallurgical industries.

Physical evidence of post-medieval metal mining is frequently on a large scale. These sites will often comprise large heaps of waste rock as well as extensive washing floors. From the 17th century onwards mining sites are often accompanied by engine houses used to provide water pumps and lifting gear.

In the iron industry, blast furnaces, both charcoal-fuelled and (later) coke-fuelled, are well known archaeologically (Crossley 1990). Most is known about charcoal-fuelled furnaces as these have often been preserved in remote woodland areas. The coke-fuelled furnaces were situated in areas that remained intensively used into the 20th century and so are less well preserved. The processes and monuments connected with the conversion of cast iron into malleable iron (finery, chafery, puddling, etc) are less often identified and are incompletely understood. Excavation has identified cementation (Belford and Ross 2007) and crucible steel furnaces and a few upstanding monuments are known (Cranstone 1997). Bloomery smelting declined in importance but continued into the 17th century and the best surviving examples tend to be those in rather remote locations (Photos-Jones *et al* 1998).

Non-ferrous smelting was initially concentrated in areas with good access to suitable ore sources, however, with the development of the coal-fuelled reverberatory furnace in the late 17th century these industries increasingly moved to locations with good access to fuel (especially the coal fields).

The archaeological investigation of post-medieval metalworking sites can face significant obstacles. The scale at which earth and rock was moved and slag produced could be enormous. This usually resulted in strategies to manage and dispose of such waste which need to be considered in any excavation. Waste material would often be removed from the production site which would otherwise be swamped, leaving relatively little material for the archaeologist. Heaps of waste can be located some distance from the original production site (especially after the introduction of the railways). Nevertheless, such waste heaps can provide useful metallurgical evidence (which might be largely absent from the production site) but might also bury and preserve earlier metalworking features and structures.

2 Standards and Good Practice for Archaeometallurgy

This section sets out the relationship between archaeometallurgy and other aspects of archaeological projects. The resources provided for archaeometallurgical remains should reflect the importance of such evidence. This is most effectively achieved by the appointment of a suitably qualified/experienced archaeometallurgical specialist.

Summary		
Stage	**Archaeological Action**	**Archaeometallurgical Action**
Initiation	Curator identifies need for project and produces brief	Respond to any request for input to brief
Planning	Contractor contacts specialist	Provide input to Written Scheme of Investigation or Project Design. Plan excavation and sampling strategy for metalworking features
Fieldwork	Survey	Identify features located and estimate scale of activity
	Excavation	Advise on identification of metalworking features. Suggest sampling strategies. Advise on cleaning and packaging
Assessment	Provide information on metalworking features and debris (spatial distribution and phasing)	Assess all (or a sub-set) of the finds in an assemblage in the light of the archaeological information. Write assessment report, which should include recommendations for further work (including a methods statement and estimate of time/cost for analysis phase)
Analysis	Liaise with specialist(s)	Undertake the work identified at the assessment stage. Identify metalworking processes. Quantify debris by context, phase, area, etc
Dissemination	Incorporate archaeometallurgical reports into excavation report	Write archaeometallurgical report(s) which place the activity in a wider social and economic context, for inclusion in excavation report and/or specialist publication

Archaeological projects might be initiated for many different reasons and the main drivers are some threat to the archaeology and a desire to better understand that archaeology. While research will be an essential part of any archaeological project, many are initiated because the archaeological resource might be at risk due to change in land use and especially if this involves some construction work. In this case the damage to the archaeological record is mitigated by recording it. Archaeological projects are also carried out by higher education bodies and community groups and in these cases the main driver is usually an improved understanding of the archaeology.

Many archaeological projects are initiated as part of the planning process: the development of a site for new uses is assessed to determine whether it will potentially impact archaeological remains. If the archaeology is deemed sufficiently important then the recording of the affected archaeology will be made a condition of the planning permission. The principles are laid out in the National Planning Policy Framework and are implemented at the level of local government. Having decided that a site needs some level of recording, the curator produces a brief for the work (or sometimes an information section within the planning condition). Developer appointed archaeological practices then respond with a written scheme of investigation. Excavations which are not driven by threats to the archaeological record also need project documentation (eg project design).

The successful completion of archaeological projects depends on careful planning and implementation. This applies whether the main driver is threat or research and for both large and small projects. The relevant principles are set out in the Management of Research Projects in the Historic Environment (MoRPHE). MoRPHE provides a flexible structure which can be adapted to particular situations:

- Start-up (Project Proposal)
- Review 1
- Initiation (Project Design, Risk Log)
- Review 2
- Execution Stage(s)
  - Data Collection (Survey, Excavation, etc)
  - Assessment of potential
  - Data Analysis and production of Publication Report
- Review 3 (Updated Project Design)
- Closure (End of Project Report)

The tasks to be undertaken as part of the Project Execution will vary depending on the nature of the project. Each phase of a project should have clear objectives, and these should be regularly reviewed. Archaeometallurgy is an integral part of archaeological investigations and plans should be made for its inclusion, even in small-scale evaluations, where sites have archaeometallurgical potential. An experienced specialist can provide invaluable advice.

2.1 Project planning and the formulation of research designs

Before any fieldwork is undertaken the archaeometallurgical potential of a particular site can be anticipated to some extent from a consideration of the general nature of the site (see Section 1). Previous work in the locality will be recorded in the Historic Environment Records held by the Local Authority and will provide additional information on the nature of any archaeometallurgical evidence. Regional Research Frameworks will also contain information on the range of metalworking that might be expected (see Section 9). Slags and other archaeometallurgical finds are frequently discovered and contractors should approach appropriate specialists at the project planning stages (Start-up and Initiation). Suitable specialists can contribute to the project proposal and project design and can help to prepare excavation strategies. If the site is thought to have been primarily metallurgical in function, then archaeometallurgy should be a major aim of the project design.

2.2 Fieldwork: survey

Much can be learnt about metal working sites prior to, or in the absence of, excavation. Information is sometimes gained about the types of processes carried out and the scale of the craft or industry. The survey methodologies employed will depend, to a large extent, on the current land use.

Aerial photography is a relatively inexpensive means of characterising well-preserved industrial landscapes, such as mining and smelting features in upland regions that are now under pasture (Gerrard 2000).

Metric surveys can determine the extent of metalworking debris that survives as earthworks, and so indicate the scale of metalworking activity (Fig 3). The interpretation of upstanding metalworking remains from either aerial photography or from metric survey requires input from a specialist (Bowden 2000; Cranstone 1994).

Geophysical survey, especially using magnetic techniques, is often well suited to detecting the remains of archaeometallurgical processes. Many slags (in particular iron smithing slags) have higher magnetic susceptibilities than topsoil. Both primary (smelting) and secondary (smithing) sites will have fired structures such as furnaces and hearths that can produce strong magnetic anomalies (see p 62-63 for further details). Geochemical surveys (especially using portable instruments) have considerable potential to identify and characterise many metalworking sites (Dungworth *et al* 2013).

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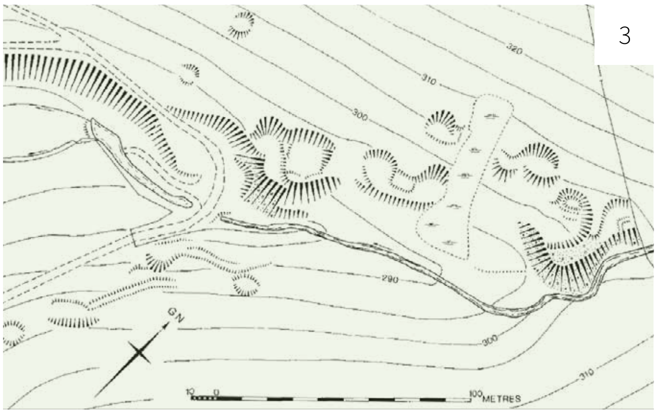

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Figures 3 and 4

3 Earthwork survey of the Iron Age slag dumps at Sherracombe, Devon.

4 Iron Age bloomery furnace at Crawcwellt West, Gwynedd.
[photo © Peter Crew]

2.3 Fieldwork: excavation

Many kinds of metalworking structures and debris are distinctive in appearance, and with experience or training these can be recognised in the field (Fig 4). Early consultation with a metalworking specialist and a site visit will enable the evidence to be better understood. The specialist can provide training, sampling strategies, put together a site reference collection, and advise on cleaning and packaging procedures. Some knowledge of the relevant metalworking processes is greatly advantageous.

The three metalworking processes most frequently encountered by archaeologists during fieldwork are iron smithing, iron smelting and the casting of non-ferrous metals (copper alloys, silver and gold).

Metalworking evidence can be divided into structures and finds. Structures (and archaeological features) include mines, pits, water channels, dams, buildings, furnaces, and hearths. Finds can include slags, ceramic materials, tools, stock metal and metal residues. The excavation of metalworking sites should include the examination of associated features, such as domestic dwellings, in order to place the technology in its social and economic context.

2.3.1 Structures and context

Mine sites will display a range of structures, features and deposits depending on the type of ore being sought and the methods employed in its extraction. Some of the earliest evidence for early mining is contained in historic records of mining in the 18th and 19th century and their references to 'Old Men's Workings' (Timberlake 2003a). The excavation of such sites and the recovery of evidence for early mining requires a range of specialist skills (Cranstone 1994; Dutton and Fasham 1994; Timberlake 2003b; Timberlake and Prag 2005).

Some of the most useful contexts are those within buildings or areas where metalworking was practised (primary deposits). More frequently, however, metalworking debris is recovered from secondary deposits such as dumps, middens, pits and ditches, or from where it was used for surfacing paths (the scale of dumping will depend on the nature of the metalworking, for example iron smelting will produce much more waste than iron smithing). The excavation of the two types of deposit needs to be approached in slightly different ways, since the type of evidence recovered and its interpretation is different.

In primary deposits, metalworking structures (furnaces, hearths and pits) might be encountered, and the distribution of the residues within a building can be crucial in identifying

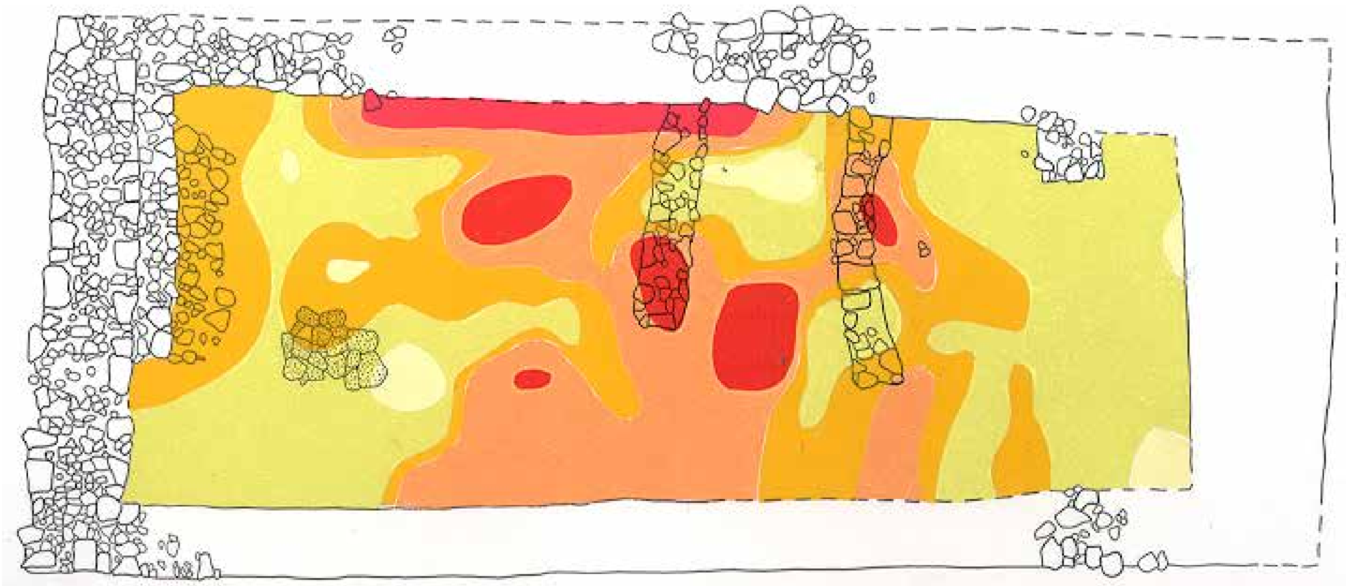

Figure 5

Plot of magnetic susceptibility readings, with darker tones indicating higher values (corresponding to higher concentrations of hammerscale), within the medieval smithy at Burton Dasssett, Warwickshire. The building is 12m long.

and separating different activities. For example, on an iron-smelting site, charcoal production, ore roasting and bloom smithing might also have been carried out. The excavation of areas where metalworking was done requires gridding and careful sampling, both for hand recovered material and soil samples for micro-residues, in particular hammerscale (see p 36).

The dimensions and layout (plans and sections) of structures should be recorded. Sometimes it might be necessary to 'unpeel' them layer by layer to understand how they were repaired or modified during use. The relationships between furnaces or hearths and other features (buildings, pits, etc) should also be carefully recorded. It is possible that waist-high or above-ground hearths existed but do not survive. It is sometimes possible, however, to reconstruct their positions from an examination of the distribution of metalworking debris (Fig 5).

Secondary deposits are contemporary with or later than the metalworking activity that produced the debris. Careful recording of the residues can indicate the direction from which the material was dumped, and so suggest where the metalworking activity was located. Large features often contain larger, and therefore more representative, deposits of metalworking debris. Where a process produced large quantities of slag this might have all have been dumped some distance from the hearths or furnaces. The proportion of features left unexcavated should be recorded to provide a means to estimate the total quantity of slag.

2.3.2 Finds and sampling

Finds include ores, slags, fragments of hearth or furnace structure, crucibles, moulds, metal stock, scrap and waste, and iron or stone metalworking tools (hammers, tongs, etc). Three-dimensional recording of bulk finds, such as slags, is not usually feasible or desirable, but crucibles, scrap metal, etc should be treated as 'registered finds'. Sampling strategies should be tailored to the size and nature of the debris recovered. Best practice is to initially retain all excavated bulk finds and soil samples. Where circumstances permit, a site reference collection should be established by the metalworking specialist. This will form the basis on which all slags and residues will be classified.

Slag, ores, crucible and furnace fragments are usually large enough to be easily recognised; some residues, however, are so small that they appear only as coloured 'soil' deposits. An example is hammerscale (Figs 5 and 30) which is so small that it can easily be missed during trowelling. Nevertheless it can be detected using a magnet. Soil samples should be taken from contexts containing hammerscale, particularly primary contexts. A workshop floor surface comprising a single context should be sampled throughout (at 0.1–0.5m intervals) in order to examine the distribution of hammerscale. A 0.2 litre sample is adequate for magnetic susceptibility screening and quantification of hammerscale, as at Burton Dassett (Fig 5; Mills and McDonnell 1992). Samples should also be taken from contexts spatially and chronologically removed from the iron-working areas, for comparison.

All charcoal associated with metalworking features and debris should be collected for species identification and tree age – this can provide important evidence on the management and exploitation of wood resources for metalworking. Radiocarbon samples should be processed in the usual manner to avoid contamination (Historic England 2015a).

The identification of metalworking finds and debris usually requires that they are cleaned. Some materials, however, are delicate and can be damaged; any cleaning procedures must be agreed with the metalworking specialist and/or conservator (English Heritage 2008b). Materials that should not be washed (except by, or under the supervision of, the metalworking specialist) include crucibles, moulds, hearth and furnace linings.

Some minerals and metal production waste are toxic; those handling or cleaning these materials should complete risk assessments and/or COSHH assessments.

Bulk finds, such as slag, should be packaged in tubs or heavy-grade plastic bags. Woven polythene bags can provide a useful alternative to conventional plastic bags. In most cases bulk finds are extremely robust and do not require specialised storage conditions. Slags with a high metallic iron content (test by magnet), however, should be treated as metal finds, ie stored under conditions of low relative humidity (English Heritage 2013). Debris recorded as 'registered finds' should be packaged individually and particular care should be taken with delicate materials, such as ceramic moulds. All debris must be kept, for examination by a metalworking specialist.

2.3.3 Dating

The date of the archaeometallurgical activity on a particular site will affect its significance. It is not currently possible to date slag directly. Metallurgical processes, and the debris they produced, often remained virtually unchanged for very long periods. Therefore dating is most commonly achieved by using associated material culture, radiocarbon dating, dendrochronology and archaeomagnetic dating. Mining and smelting sites have often yield very little datable material culture, although this might, in part, be due to a focus on the obviously 'technological' aspects of such sites (hearths, furnaces, slags heaps, etc). The excavation of ancillary areas should increase the recovery of datable artefacts. Most metalworking activities made use of charcoal fuel that can be radiocarbon dated. Samples should be of clean, short-lived charcoal (Historic England 2015a). Waterlogged metalworking sites (especially mines and sites that used water-power) can yield timbers that can be dated using dendrochronology (English Heritage 1998). The final use of fired clay structures, such as hearths and furnaces, can be dated archaeomagnetically (see p 63).

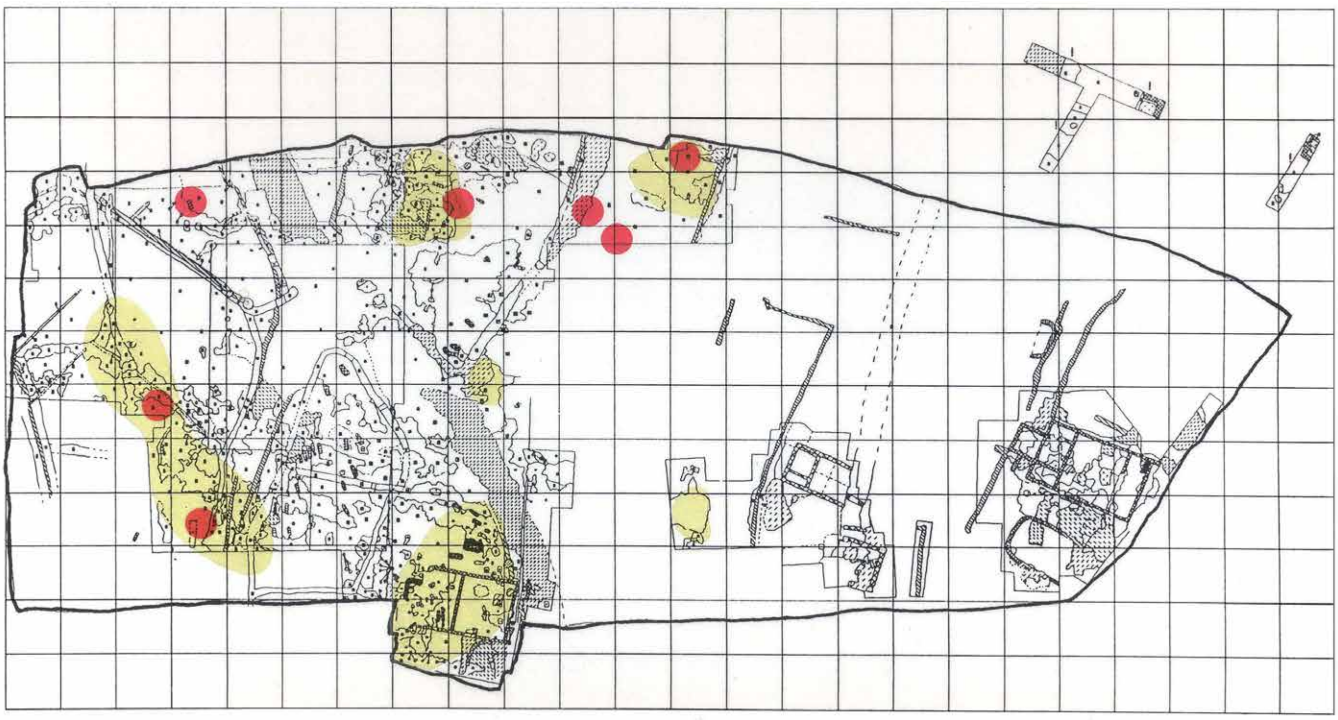

Figure 6

Plan of the excavated features at the Roman site of Shepton Mallet, Somerset where iron smelting (yellow) and smithing (red) were taking place. Note the partial spatial separation of the two activities.

2.3.4 Site archive

The product of the fieldwork phase of the project is the site archive, which should include all the fieldwork data and a brief statement of the nature of the stratigraphic, artefactual and environmental record and finds (Brown 2007; Cool *et al* 1993).

2.4 Assessment of potential for analysis

Detailed analysis of the records and materials recovered during archaeological fieldwork must be preceded by an assessment. An assessment report contains a summary of the data and a statement of the potential for that data to address the original project aims and objectives. It should contain specific recommendations for further work, storage and curation. This phase is also an opportunity to update the project design in the light of the discoveries made. It is important that all the evidence for metalworking is considered as a whole and where possible all relevant material remains should be seen by a single specialist (where this is not possible provision should be made for different specialists to share data and results).

The metalworking specialist will classify the debris into different types depending on relatively simple characteristics (colour, density, size, shape, surface morphology, etc – see Sections 3-6). Many of the recognisable types of debris are diagnostic of particular processes. In addition, the total quantity of debris should be determined. For large assemblages of metalworking debris, the assessment can be carried out on a sub-sample of the available material. The sub-sample should include examples of all the different types of artefacts, and debris, recovered, and should also reflect the full range of contexts excavated. The selection of a sub-sample should be agreed with the metalworking specialist.

It is extremely important that the metalworking specialist is provided with a brief summary of the site, including stratigraphic and contextual data. Information on related features and finds assessed by other specialists should be made available. Metal and fired clay objects – such as ingots, billets, bar stock, scrap, waste, unfinished artefacts, metalworking tools, crucibles and moulds – are particularly important.

The metalworking specialist will make an assessment of the archaeological value of the metalworking evidence, which is dependent on a number of factors. The most important is the current state of knowledge of that metalworking process (eg Bayley *et al* 2008). For example, evidence for medieval or earlier copper smelting in England is extremely limited, so any early smelting is important. At some periods, some processes are relatively well known and such sites would be particularly important only where primary deposits survive in good condition. The specialist will note any important or unique features of the excavation record and recovered finds and debris. The site should be compared with other broadly contemporary sites locally, regionally and nationally.

This information will enable an assessment to be made of the significance of the evidence and of the requirements for the analysis phase. The assessment report should set out the procedures for further work and specify any scientific analysis required (chemical analysis, micro-structural examination, etc). The specialist will also be able to advise where the evidence for metalworking does not justify further work.

2.5 Analysis and report preparation

The analysis phase consists of the examination of the records and materials identified during the assessment phase, and the production of a publication text that reflects the importance of the results. The analysis phase can provide information on the range of metals worked, the technologies used, the social and economic importance of these activities, trade and exchange, and cultural affinities.

The metalworking specialist will provide reports on features and/or groups of material that have been identified as having potential for analysis and that are linked to specific objectives in the updated project design. All metalworking debris must be made available to the specialist for study during the analysis phase of a project. The entire assemblage should be visually examined, classified and identified as far as is possible (see Sections 3-6). The finds should be weighed and/ or counted and recorded by context. Dimensions should be recorded where appropriate – for example diameters and depths of furnace or hearth cakes, size of crucibles, diameter of hole in tuyère mouths or blowing holes. The evidence should be compared with the stratigraphic record in order to examine spatial and chronological patterns in metalworking activities (see Figs 6 and 7).

2.5.1 Quantification

It is essential that the metalworking evidence is quantified by type and archaeological context. It might in some cases be appropriate to record the material by numbers of fragments, eg large fragments of ceramic mould, metal off-cuts, and moderately complete examples of crucibles (or when the total quantity of material is very small). In most cases, however, weight provides a more practical and useful quantification of

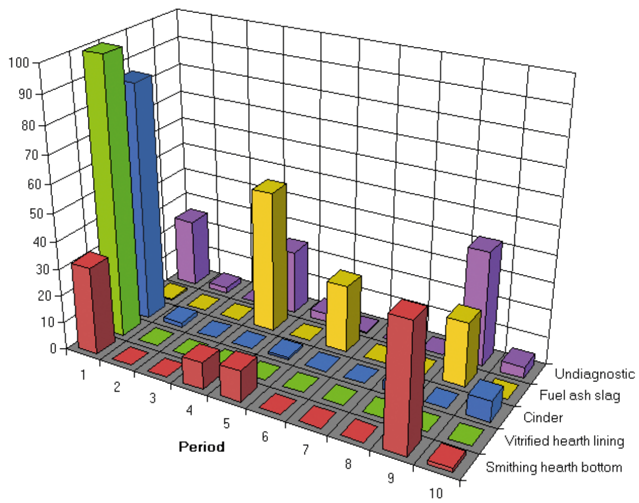

Figure 7

The histogram shows the proportions of different types of slag for each phase of occupation at medieval Wigmore Castle, Hereford and Worcester.

metalworking waste. The number of fragments of waste will often be influenced by taphonomic factors (and the method of excavation) which will reveal little about the metalworking process or its social and economic importance.

Achieving a reliable estimate of the total quantity of debris present in any partly excavated, or unexcavated large feature (such as a slag heap) is difficult, but can indicate the scale of activity on the site. The volume of the features should be estimated and the proportion of slag determined. The proportion of slag within a context might vary considerably between different features and sites and can best be determined by excavating a section. The total volume of the context/feature (in cubic metres) should be multiplied by the bulk density of the slag (varies depending on the nature of the slag and context) to give the total weight in tonnes.

The quantity of metalworking evidence recovered can be used to provide data on resource exploitation, such as labour required for charcoal production and woodland management. Assessing resource implications depends on the accurate quantification of diagnostic debris, a full understanding of the metallurgical process and the precise nature of debris (ore, slag, charcoal, etc). Bloomery iron working is currently the only process that is sufficiently well understood for such analyses to be possible. The ratios of ore, charcoal, slag and bloom have been explored through experimental reconstructions of iron smelting and smithing (eg Crew 1991; Sauder and Williams 2002). In one experiment (XP27, smelting a phosphorous-rich bog ore in a low, non-slag tapping shaft furnace, Crew 1991), 7.6kg of bog ore was smelted and yielded a 1.7kg bloom of iron. This was then smithed into a 0.45kg bar and the whole process required 61kg of charcoal and produced 6.1kg of slag. Sauder and Williams (2002) have succeeded in producing blooms of ~13kg from ~40kg of ore (and ~90kg of charcoal) and the forging of these blooms has yielded bars of ~5kg. The ratios of raw materials, waste and finished product are likely to vary considerably depending on the type and quality of ore, the technology used and the skills of the metalworkers (Crew 2013). A certain amount of information on these variables can be gained from chemical and mineralogical analyses of representative samples of ore, slag and charcoal. Such analyses can be integrated with an examination of the wider landscape and its use (eg Fyfe *et al* 2013; Mighall and Chambers 1997; Crew and Mighall 2013).

2.5.2 Scientific techniques

In order to fully understand the available metalworking residues a specialist might employ a range of scientific techniques, including physical and chemical analytical methods to determine a range of properties, such as chemical or mineralogical composition, melting point, density, etc (see p 62–68). This should only be carried out, however, where there is a specific archaeological question that has been identified in the updated project design that is likely to be answered by scientific techniques.

The scientific techniques to be employed depend on the nature of the material to be analysed and the questions that have been asked. In some cases there might only be one technique which can address a particular question while in others several techniques might be available. Understanding the fabrication of metal artefacts usually requires some understanding of the metal's microstructure (metallography). Metallography has been applied to a range of artefacts to show the wide variety of techniques used by early metalworkers (eg Allen *et al* 1970; Ottaway 1992; Tylecote and Gilmour 1986; Wilthew 1987).

Chemical analysis of metals and metalworking debris are frequently used to understand the nature of the metals and the processes which produced them. Before chemical analysis is undertaken a consideration needs to be made of the nature of the question being asked, aspects of the analytical techniques (including cost) and the damage (if any) to the artefact or waste material to be analysed. Analytical techniques vary widely in terms of the degree of quantification, accuracy, precision, detection limits and the range of elements that can be detected. Some types of chemical analysis are quantitative, providing precise information about composition in percentages or parts per million; others give qualitative results, identifying the main elements or compounds present, and provide a rough idea of relative concentrations. Some methods require small samples that will be destroyed by the analysis, but in other cases surface analysis can be performed without damage to the artefact.

Analysis contributes to an understanding of potential sources of metal (Paynter 2006; Wilson and Pollard 2001), and the prevalence of recycling (Bray and Pollard 2012; Caple 2010). It has been used to revise typological classifications of artefacts (Bayley and Butcher 2004), and has shed light on the ways in which copper alloys reflect wider processes in society such as Romanisation (Dungworth 1997).

2.6 Dissemination

The dissemination of the results of analytical work should reflect the importance of those results. In many cases the results should be integrated into the excavation report. The format and approximate length of reports should be agreed before work is started. In some circumstances it might be appropriate to publish archaeometallurgical data separately (with a summary in the excavation report). In some projects, dissemination can also be through temporary or permanent displays in a museum.

Strategies for the storage of metalworking debris need to be flexible and take into account the size and significance of the assemblage. Deposition of the material evidence should pose no problems if the excavation and sampling strategies have been agreed in advance by the excavator, the specialist and the museum. A full copy of all data produced must be supplied for inclusion in the site research archive (Brown 2007; Museums and Galleries Commission 1992; Society of Museum Archaeologists 1993).

3 Archaeometallurgical Processes and Finds: Iron and its alloys

3.1 Background

Iron (Fe) is the fourth most abundant element in the earth's crust. Iron ore suitable for smelting occurs in many locations, so archaeological evidence for smelting is geographically widespread. The methods of producing iron and its alloys, and the extent to which the alloys were used, changed with time. Several different alloys of iron have been used and these have distinct properties.

Plain iron is very pure: it contains less than 0.1% of other elements. It is often described as ferritic iron because structurally it is made up of many crystals of a type known as ferrite. Its melting temperature is extremely high, about 1545°C, so rather than being melted it was forged into shape. Alloys of iron melt at lower temperatures than plain or ferritic iron and have different properties. Early plain iron was made using the bloomery process. During smelting the metal never melted and so it is typically heterogeneous and a mixture of alloys can be present in one object. Plain iron was also the product of conversion processes (fining or puddling) which accompany the blast furnace and was traditionally known as wrought iron. These two types of plain iron (bloomery and wrought) can be distinguished from each other using scientific techniques to characterise the tiny fragments of slag trapped in the metal (slag inclusions).

The presence of small amounts of carbon in iron can produce a range of different alloys. Steel is an alloy of iron which contains moderate levels of carbon (typically 0.3–1% carbon). Nevertheless, the distinction between plain iron and low-carbon steels is not clear, especially for bloomery iron/steel. Steel is an ideal material for cutting edges on tools and weapons because its strength and hardness can be manipulated by a combination of quenching and tempering. Steel can be produced during smelting, owing to the presence of the carbon-rich fuel, or afterwards, by heating the iron in the presence of a carbon-rich material, such as charcoal. Higher levels of carbon (2–5%) give rise to an alloy (cast iron) which has a much lower melting temperature (1150–1300°C) but is brittle when solid making it unsuitable for forging in a blacksmith's workshop. Iron and steel can be obtained by melting cast iron and removing some or all of the carbon.

Phosphoric iron contains up to 1% phosphorus, which makes it harder than plain iron. The phosphorus enters the metal from the ore during smelting. Due to the nature of most British iron ores, phosphoric iron is abundant in most periods before the 19th century. The presence of phosphorus in iron influences the uptake and distribution of carbon, and phosphoric iron and ores were sometimes selected or avoided for specific applications.

Iron in summary

Plain iron contains less than 0.1% of other elements and is often known as ferritic iron and sometimes as wrought iron. It has a melting temperature of 1545°C. Alloys include steel (~ 0.3 to just over 1% carbon), phosphoric iron (up to1% phosphorous), low carbon iron (up to 0.3% carbon), and pig or cast iron (~ 2 to 5% carbon). Cast iron describes a carbon-rich iron alloy which has a relatively low melting temperature (~ 1150–1300°C); cast iron straight from the blast furnace was usually called pig iron.

Process	Description	Archaeological debris
Bloomery smelting (8th C BC – 16th C AD and later in some areas)	An inhomogeneous solid bloom of metal was produced, as the metal did not melt during the process. The main product of these furnaces was plain or ferritic iron but other alloys were commonly produced as well. The impurities present in the ore reacted with some of the iron oxide to form iron-rich slags.	Fuel, ore, vitrified furnace lining and slag. Usually large amounts of slag will be recovered, including tap slag or large slag blocks. The bases of furnaces and tapping pits sometimes survive. Hammerscale can also be found if the iron bloom was consolidated on the smelting site. There is sometimes later evidence for waterpower.
Blast furnace smelting (15th C AD onwards)	These furnaces operated at higher temperatures and produced a form of liquid iron. The iron was cast on a bed of sand to produce bars of pig iron or ingots. The slag is silica rich and contains little iron.	Ore and fuel. Large quantities of blast furnace slag were produced. The furnace rarely survives to its full height. Remains of associated buildings, possibly with casting pits or mould fragments. Evidence of waterpower should be expected.
Finery forge (end 15th to early 19th C AD)	Pig iron from a blast furnace was fined in a finery forge, commonly with two finery hearths, a chafery hearth (for reheating) and a helve hammer. The product was plain bar iron (wrought iron).	Rarely pig iron feedstock, but more commonly waste slag which is iron rich and can closely resemble many forms of bloomery iron smelting slag. Hammerscale may be found.
Puddling (1790s to 1960s)	Pig iron from a blast furnace was melted in a running out furnace to make refined iron (or finers metal). This was remelted in a (reverberatory) puddling furnace. A hammer was then used to shingle (consolidate) the puddled ball. A rolling mill then rolled it into wrought iron bars.	Rarely pig iron feedstock, but more commonly waste slag which is iron rich and can closely resemble some forms of bloomery iron smelting slag (especially tap slag). Hammerscale (millscale) may also be found.
Smithing	Most iron alloys were shaped, by smithing or forging, while solid. The metal was heated and then shaped or welded.	Smithing hearth cakes, hammerscale and vitrified hearth lining. Ground level hearths might survive. Evidence of waterpower might be found on later sites.
Steel	Steel could be made in several different ways. Bloomery furnaces could be used to produce blooms of steel. Plain or wrought iron could be converted into steel by carburisation. The steel bars were often welded together and forged to improve the quality. From the 1740s, some blister steel was melted in crucible furnaces to make homogenous crucible steel.	Evidence of early steel production is in the form of objects, bars, billets or blooms containing steel.
Casting	Pig iron could be tapped straight from the blast furnace into moulds to produce objects. Cast iron could also be re-melted in purpose built furnaces (reverberatory furnaces or cupolas).	The most commonly used moulding material was sand and this is rarely recognised as such. Cupolas were often designed in sections to make them moveable.

3.2 Smelting

The bloomery and blast furnace processes were the two main methods of smelting iron. In England bloomery iron smelting was probably introduced in the 8th century BC (there is some evidence for earlier smithing (Collard *et al* 2006), but not yet for smelting of this date) and continued in use until the 16th century AD – and later in some areas – when it was superseded by the blast furnace process. The temperatures achieved during the bloomery process did not usually exceed 1250°C, which is well below the melting point of plain iron (and low carbon and phosphorus alloys). Therefore the metal does not melt during the process. The bloomery process is sometimes referred to as the Direct Method of forgeable iron production because it produced, in a single process, iron alloys (possibly including steel) that could be forged by a smith.

In contrast, blast furnaces, introduced to Britain *c*1500AD, produced cast iron. The lower melting temperature of this alloy meant that the furnace produced molten metal, which was cast to shape. Cast iron was brittle, however, and not suitable for all applications. Refining processes had to be used to convert it into tougher, forgeable iron alloys when this was required. For this reason blast furnace smelting, and the subsequent refining, is sometimes referred to as an Indirect Method of forgeable iron production.

Bog ore was probably a major source of iron ore, especially for the bloomery process. It is formed by the precipitation of iron compounds, in lakes, bogs and other poorly drained locations, and could simply be dug out. Other recognised sources of high quality iron ore include limonite (hydrated iron oxide), siderite (iron carbonate) and haematite (iron oxide), and these were extracted by mining. From the medieval period onwards, the iron ores found in the Coal Measures became increasingly important (Challis 2002; Dungworth 2010). Raw, or untreated, ores rarely occur in any quantity on archaeological sites. Iron ores would usually have been roasted before being smelted. Roasting makes the ore easier to smelt and changes the colour of the ore (Fig 8). Ores could also be sorted, washed and broken up to reduce the proportion of impurities, collectively known as gangue, which entered the furnace. Crushing the ore would increase its surface area and hence the rate of reaction, although if ore is crushed too finely the particles could clog the furnace. Small particles, known as ore fines, are found in areas where the ore was roasted, crushed or stored, and sometimes in and around furnace structures.

3.2.1 The bloomery process

Although the historical evidence for early iron smelting in Britain is strongest for just a few areas (eg the Forest of Dean and the Weald of Surrey and Sussex), archaeology has frequently shown

Figure 8

Iron ores vary in colour and can be difficult to spot, particularly if they have not been roasted, as they do not necessarily have a strong colour or high density. Unroasted ores can be black, red, brown or orange while roasted ores are commonly red, purple or orange, because they are oxidised. Ore fines are small particles of roasted ore that sometimes respond to a magnet and have high magnetic susceptibility. Pieces of reduced ore, sometimes partially slagged, are sometimes found among the debris from the bottom of the furnace, and these are commonly grey. The minerals present in iron ores can be determined using X-ray diffraction, and the iron content can be determined by chemical analysis (p 66). The ores recovered during archaeological fieldwork need not be representative of the ores smelted because, for example, they might have been discarded because they were of poor quality.

that bloomery iron smelting was widespread (Crew 1986; 1998b; Dungworth 2011; Dungworth and Mepham 2012; Halkon and Millet 1999; Paynter 2007a). The bloomery process required the production of a fluid slag (typically at temperatures around 1200°C) and so the slag is usually iron-rich (there is no evidence that any additional fluxes were used in bloomery iron smelting). Therefore, although a variety of ore sources were employed, most of these were fairly iron rich. At least some bloomery iron smelting took place on a fairly modest scale and could use ore sources that were small enough to have escaped the attention of later industrialists and geologists.

Charcoal was exclusively used as the fuel for bloomery smelting. Coal could not be used as most contains sulphur, which would be absorbed by the iron, making it brittle and unsuitable for forging. There are no known charcoal production sites prior to the medieval period, but at early sites charcoal might have been made in small pits adjacent to furnaces, as observed in other parts of Europe. Wood was unsuitable as it could not provide a reducing atmosphere which would transform iron ore into metallic iron.

Furnaces rarely survive to their full height (Fig 9), so their likely structure and mode of operation have been reconstructed by supplementing the archaeological evidence with a detailed examination of waste slag (Paynter 2007a), ethnographic data and experimental work (eg Crew 1991; 2013; Girbal 2013; McDonnell 2013a; Smith 2013). Furnaces were constructed from clay, although some stone and tile were occasionally used. The clay was often modified with large amounts of temper, especially sand but also small stones, pieces of slag and possibly organic material.

The form and size of bloomery furnaces varies considerably and their partial survival probably masks even more variation. In a few rare cases, furnaces were constructed against a bank and have survived to a height of 1m (Fig 9). In most cases very little superstructure survives and it is usually difficult to know the original height of the furnace with certainty (Fig 4).

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Figure 9

Section through a late Iron Age furnace at Stockbury, Kent. The furnace is built of clay which has a characteristic orange-red, oxidised-fired outer surface with a grey-black inner surface, which displays some vitrification. Scale bars are 1m and 2m in length. [photo © Kent Archaeological Projects and supplied by Tim Allen]

Figure 10

Experimental bloomery furnace reconstruction (external diameter 0.7m). The tapping arch, through which the liquid slag enters the tapping pit, can be seen at the front of the furnace. Cf Figs 1 and 4.

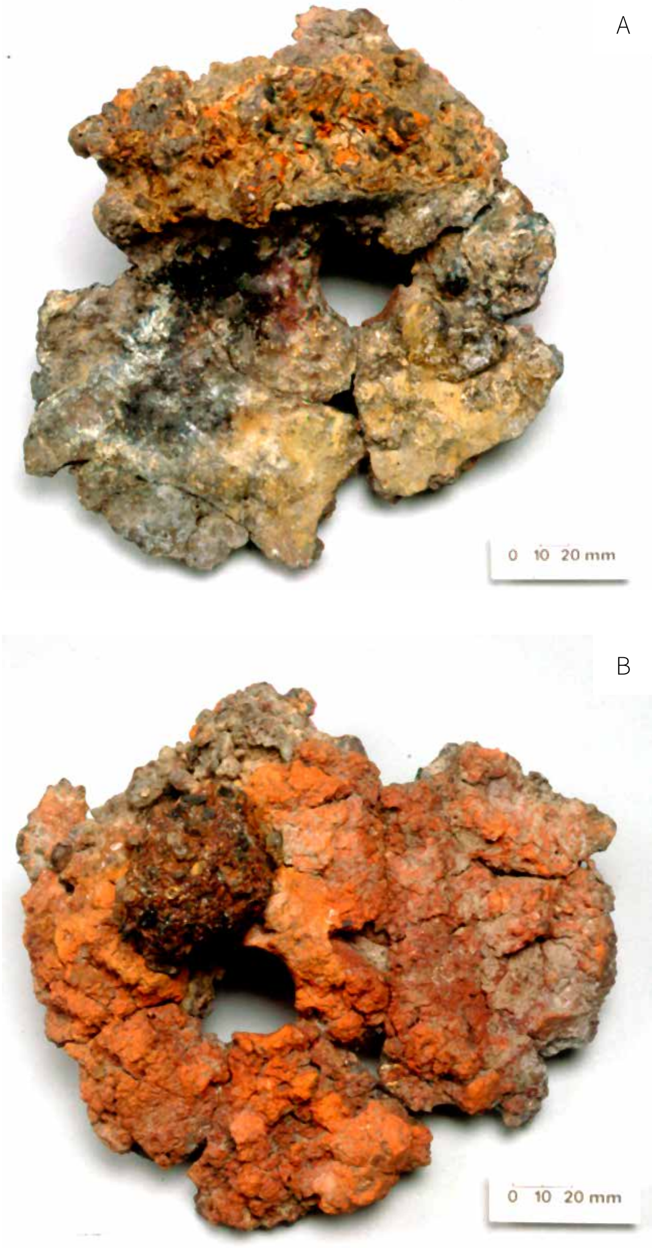

Figure 11

Vitrified clay lining with a blowing hole, from the Roman site at Ribchester, Lancashire. Vitrified furnace lining is produced by a high temperature reaction between the clay lining of the furnace and the alkaline fuel ashes or slag. The outer parts are usually orange (oxidised-fired) ceramic, while the inner zone is grey or black (reduced-fired) and often vesicular with a glassy surface. Furnace linings might have been repaired repeatedly or replaced, and can show a sequence of vitrified layers. Although furnace walls were relatively thick, usually only the inner surface survives, or is noticed, as the heat of the furnace will not have fired the outer part. The hottest area of the furnace was near the blowing hole (see photograph), and consequently vitrified clay lining containing the preserved outline of the hole is often recovered.

Two types of reaction occurred in the furnace: the iron ore was reduced to metallic (but solid) iron and the impurities in the ore reacted to produce a fluid slag. The high temperatures needed for these reactions (and a fluid slag) were provided by the combustion of fuel. The use of charcoal also provided the reducing atmosphere which ensured that iron ore was reduced into metallic iron. The furnace was heated and charges of roasted ore and charcoal added to the top. In most cases extra air was needed to provide a high enough temperature. Furnaces are known with small holes near the base through which air could be introduced (Fig 11). It is likely that bellows were used to blow air into the furnace, however, these do not survive in the archaeological record (probably because they were made of wood and leather). As the ore descended through the burning charcoal fuel, some of it would be reduced into a lump of metal. The bloomery furnace usually operated bellow the melting temperature of iron and so the iron formed a spongy mass or bloom, usually just below the hole through which air was introduced

The formation of slag inside the furnace from the reaction of gangue minerals had to be carefully managed: if too much slag accumulated then it would block the flow of air through the furnace. The ways in which the smelters managed the formation of slag can be reconstructed from furnace architecture. Where a furnace has been heavily truncated it might still be possible to reconstruct both the form of the furnace and the ways in which the slag was managed from the nature of the slag (Dungworth 2011; Paynter 2007a). Slag management can be divided into two main categories. In the first case, most of the slag was periodically removed from the furnace by opening the furnace near the base and letting molten slag flow out (tapping, see Fig 16), while in the second case the slag was allowed to accumulate in the furnace (often in a pit at the base of the furnace, see Fig 14). Nevertheless, these distinctions are not always clear cut and considerable variation existed within each category.

In the hottest zone of the furnace, near the blowing holes, the temperature was probably slightly in excess of 1250°C. Here the liquefied slag separated from the solid iron metal and flowed to the bottom of the furnace. The metallic iron coalesced and eventually formed a spongy lump known as a bloom. The bloom usually attached to the furnace wall just below the blowing hole and grew until it started to interfere with the air blast, at which stage smelting was stopped. The bloom was then removed, either through the top of the furnace (Fig 1) or through the tapping arch. Since the iron did not melt during the process, the bloom contained a lot of trapped slag and was usually compositionally heterogeneous. Therefore, although the main product of bloomery furnaces was plain iron, the blooms commonly included regions of other alloys as well, such as steel and phosphoric iron.

The main aim of bloomery smelting was the production of a lump or bloom of iron (Figs 12 and 13). The smelting took place below the melting temperature of the iron and so the iron formed in the solid state as a spongey mass, or bloom. Blooms very rarely survive in the state in which they were extracted from the furnace. The blooms would often have been smithed into billets or bars for transport and trade and examples of these are fairly well known (Fig 13; Crew 2013). During the smithing of a bloom small fragments (often referred to as gromps) could easily become detached, and these are occasionally found in smelting slag assemblages.

The preservation of prehistoric bloomery smelting furnaces has generally been rather poor – very few survive as little more than burnt patches with traces of clay wall (Fig 4), usually ~0.3m in diameter. The original height of these furnaces is uncertain and some might simply be the truncated remains of shaft furnaces (Cleere 1972; Dungworth 2011; Girbal 2013; Tylecote 1986, 140). Prehistoric bloomery smelting slag takes a variety of forms but generally includes little or no tap slag. In most cases the slag was allowed to accumulate within the base of the furnace (or a pit at the base of the furnace) as a large slag cake or furnace

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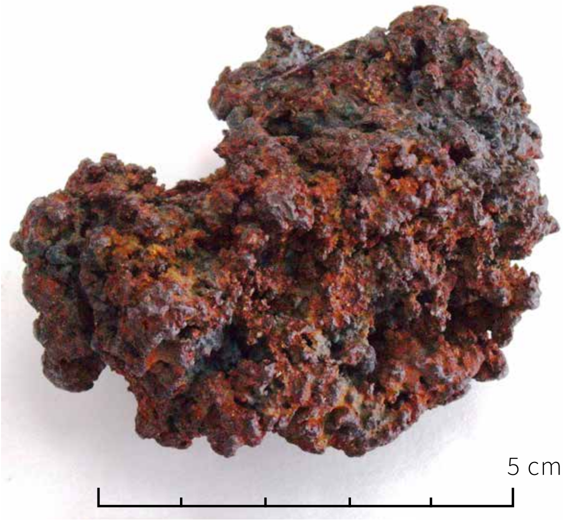

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Figures 12 and 13

12. Iron blooms are rare finds on archaeological sites: here an ethnographic example is shown. Blooms are made up of many small particles of iron coalesced into a spongy lump. They are often badly corroded and fragmentary but are strongly magnetic.
13. Partially consolidated blooms, billets and bars of iron. They vary in shape and size, are often badly corroded and fragmentary, but have a high density and are strongly magnetic. **Top**: Three bun-shaped blooms from Dean, 2–2.5kg, probably Roman. **Centre left**: Square-section Roman bars, with the typical diagonal facets from hot-cutting of longer bars, from Houghton Down, Hampshire and Hangerbury Hill, Dean. **Centre right**: Cuboid billet of second century date from Banc y Coed, near Ffestiniog 1.9kg. **Bottom**: An early 12th-century bar (possibly a "piece") from Winchester, Hampshire, 1.3kg. Scales in cm.
[Photo © Peter Crew]

bottom: >0.3m diameter and 10kg or more in weight (Fig 14, Paynter 2007a). Slag cakes (and fragments of slag cakes) often have impressions of charcoal and other organic material. Organic material could have been used to pack the pit at the base of the furnace. In some cases such slag can contain such an abundance of charcoal impressions that it has a rather loose and porous structure (Dungworth 2011; Tylecote 1986, 137). Some sites have also yielded quantities of slag prills or small flows of slag (Fig 15) where the direction of flow is vertical (or at least fairly steep) – such flows appear to have occurred within the furnace (Dungworth 2011). The quantities of slag found on prehistoric bloomery smelting sites is often rather small, suggesting production to satisfy a low level of demand. The size of iron billets and currency bars suggests that a smelt would typically yield around 2kg of smithed metal (Crew 2013).

Bloomery iron smelting is widespread in the Roman period and some regions saw quite intensive metal production (Hodgkinson 2008; Jackson 2012; Schrüfer-Kolb 2004). At least some of the furnaces survive to a height of 1m and these are most commonly cylindrical with an internal diameter close to 0.3m – examples are also known with walls that taper inwards (Fig 9). Roman iron smelting sites are generally characterised by the presence of tap slag (Fig 16), however, there are sites where at least a proportion of the slag appears to have remained as slag cakes or furnace bottoms in the furnace (Fulford and Allen 1992). Some Roman bloomery smelting sites yield small quantities of slag and appear to represent the continuation of some prehistoric modes of production. Some sites, however, have very large slag heaps associated with them, suggesting a high level of production to meet non-local needs (Hodgkinson 2008). A few Roman period sites have indicated that larger furnaces (up to 1m in diameter) were used for bloomery iron smelting (eg Crew 1998a). The few Roman iron billets that survive display a range of weights within the range 2–15kg (Crew 2013).

There is evidence for iron production in the early medieval period, however, this is often disparate and fragmentary. In southern and eastern England the recovery of large smelting slag blocks (McDonnell 1993) indicates the use of slag-pit furnaces of a kind that is well known from northern and central Europe (Pleiner 2000, 149–162). These generally date to the early Anglo-Saxon period and it is tempting to see this as a technology imported by immigrants. Broadly similar smelting which made use of non-tapping furnaces and yielded furnace bottoms or slag cakes is known from Millbrook, Sussex (Tebbutt 1982), Burlescomb, Devon (Reed *et al* 2006), Clearwater, Gloucestershire (Pine *et al* 2009) and Ramsbury, Wiltshire (Haslam 1980). The use of furnaces with provision for tapping slag is also known from the late Saxon period at Ramsbury (Haslam 1980, see Bowyer and Keys 2013 for a re-examination of the dating), Stamford (Burchard 1982) and West Runton, Norfolk (Tylecote 1967).

Slag tapping from shaft furnaces became the most frequent method of bloomery iron smelting through the rest of the medieval period. Although a good deal of slag was tapped from the furnace (eg Crew and Charlton 2007), there are sites where a proportion of slag was also allowed to accumulate at the base of the furnace, eg the rather porous slag cakes or furnace bottoms from the 14th–15th-century bloomery at Minepit Wood, Sussex (Money 1971, 105). A similar pattern can also be seen in the slag from the 13th-century bloomery at Stanley Grange, Derbyshire (Challis 2002). The size and shape of medieval furnaces, and the provision of air blast, is rather poorly known as relatively few have been excavated and these have often been severely truncated. In many respects the furnaces and associated slags of this period resemble those of the Roman period.

Documentary sources suggest that there were significant developments in smelting technology in the medieval period (Tylecote 1986, 188-9). From the 13th century onwards, terms such as mill are increasingly used to refer to ironworking sites. This suggests that water power was being harnessed for bloomery iron smelting. From later practice it is known that water power was ultimately used to drive both bellows and hammers, however, the earliest applications of

14

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Figures 14–18

14. Section through a prehistoric furnace bottom. Furnace bottoms are dense, dark-coloured slags that solidified in the furnace and can retain the shape of the furnace base, sometimes with part of the baked clay structure attached. Furnace bottoms are of varied size (some are as small as 0.3m in diameter while others exceed 0.5m), and will often contain pieces of reduced ore and fuel. The smaller varieties are sometimes referred to as slag cakes, with furnace bottom reserved for the larger examples (scale = 0.15m).
15. Slag prills resemble very small pieces of tap slag (cf Figure 16) but usually display more evidence for vertical (rather than close to horizontal) flow.
16. Tap slag has a characteristic shape, resembling a flow of lava, with rivulets of slag on the upper surface and a rough under surface which can have adhering sand or clay. Tap slag is dense with few relatively large bubbles, as it flows out while hot and fluid. It is dark in colour, usually grey to black, sometimes with a liverish or maroon upper surface. The size of tap slags can vary from individual runs of a few hundred grams to accumulations weighing 10kg or more. Hot, fluid slag can also form long, thin runs.
17. Frothy tap slag from a late bloomery at Goscote, West Midlands. The section at the front reveals the high porosity of this slag. Although this type of slag has increasingly been noted from sites which appear to have made use of water power, it has also been noted from bloomeries where water power was not used. The frothy texture suggests high air pressure inside the furnace while the slag was liquid but a relatively quick solidification when the slag was tapped, which would prevent the escape of the gas which had been dissolved in the slag).
18. Undiagnostic slags (from Ribchester) are small or fractured pieces of slag that have the dark colour of iron-rich slags, but do not have any diagnostic surface morphology. Therefore, although indicative of iron-working, they cannot be used to distinguish between smithing and smelting. They are sometimes the largest proportion of slags in an assemblage.

water power are not well understood. During the 14th and 15th centuries the size of blooms rapidly increased from 10–20kg to around 100kg and this could be due in part to the application of water power. While a few water-powered bloomery sites have been archaeologically investigated (Crossley and Ashurst 1968; Dungworth 2010; Tylecote 1960; Young and Poyner 2012) many questions remain. Tylecote (1960) and Dungworth (2010) noted especially porous or frothy tap slag (Fig 17) at putative water-powered sites, however, similar material has also been discovered on slightly earlier sites with no evidence of water power (Young and Poyner 2012).

Some later medieval bloomery sites have yielded small amounts of slightly greenish slag which contain relatively low levels of iron (Dungworth 2010; Money 1971). This slag shows some similarities to the blast furnace slag (see below) and suggests that late bloomeries were on occasion run at higher than usual temperatures and with a more reducing atmosphere.

While bloomery smelting slag takes on many different forms (Figs 14–18) there is relatively little variation in its chemical and mineralogical make up. Most bloomery smelting slag contains a significant proportion of the iron silicate mineral fayalite ($2FeO.SiO_2$) and such slags are often referred to as fayalitic. The slags formed during the smithing of iron (Fig 32) are also iron-rich, fayalitic slags and as such can resemble smelting slags. Much of the slag on a site might not be diagnostic of any particular iron-working process, being fragmentary, corroded or possessing intermediate characteristics, and is simply referred to as undiagnostic slag (Fig 18).

There is little evidence for either the tools or bellows used in the smelting process, except in some later literary sources. 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. Shelter would have been essential for the storage of ore and charcoal and for protecting the furnaces. Examples of round stake-wall smelting huts have been found on prehistoric sites (Crew 1998b) and large, square post-built shelters are known on Roman (Hammer 2003; Paynter 2007b) medieval sites (eg Money 1971).

3.2.2 The blast furnace

Documentary evidence suggests that blast furnaces were introduced to this country towards the end of the 15th century (Awty and Whittick 2002; Crossley 1990). The blast furnace process was fundamentally different to the bloomery process and over the next two centuries it gradually replaced the earlier process.
The blast furnace was substantially larger than the bloomery furnace: the early examples were stone-built, tower-like structures, 5–6.5m square and probably over 6m high (Crossley 1990, 158). The height of the furnace allowed the production of a more reducing atmosphere which could produce an iron-carbon alloy, ie cast iron, which would melt (Fig 19). Blast furnaces were provided with large bellows which were powered by water wheels. This gave a powerful air blast allowing higher temperatures to be reached. The reducing atmosphere and the high temperature meant that more of the iron was extracted from the ore and the resulting slag was rich in silica (Fig 21). Blast furnaces could even smelt bloomery-furnace slags, since these contained fairly large amounts of iron that could be extracted by the new, more efficient process. By the 17th century, limestone was also added to the blast furnace charge, however, it is unclear whether this was normal practice for the earliest furnaces.

A blast furnace comprised a hearth where the metal and slag could collect with a shaft above this. It was normal practice to provide two arches, in adjacent sides (Fig 19). One arch was for the air blast from the bellows and the other was for casting the iron and tapping the slag. The hearth itself was made of a refractory material, such as sandstone, although later furnaces used fire clay. This material eroded gradually with use, but this had the advantage of increasing the capacity of the hearth, and thus the size of the castings that could be made.

The blast furnace would work continuously for months at a time, in production runs known as campaigns, and was repaired between campaigns. The charge put into the mouth at the top of the furnace at regular intervals would typically consist of iron ore, fuel and limestone. The iron ore was reduced as it travelled down the furnace and cast iron and slag formed at the base of the furnace (both molten, with the lower density slag floating on top). The cast iron was tapped off at intervals and could be cast straight into objects, such as guns, or into pig iron. These castings were linked to a supplying channel of metal, resembling a sow feeding piglets, and so the castings were called pigs. Most of the pig iron was sent to forges for conversion to wrought iron (see pp 29–31).

Furnaces were frequently built against a slope or bank which provided a charging platform often with a bridge house leading to the mouth of the furnace where raw materials could be poured into the top of the furnace (Fig 19). There were other structures associated with the furnace. The bellows were housed in the blowing house, built

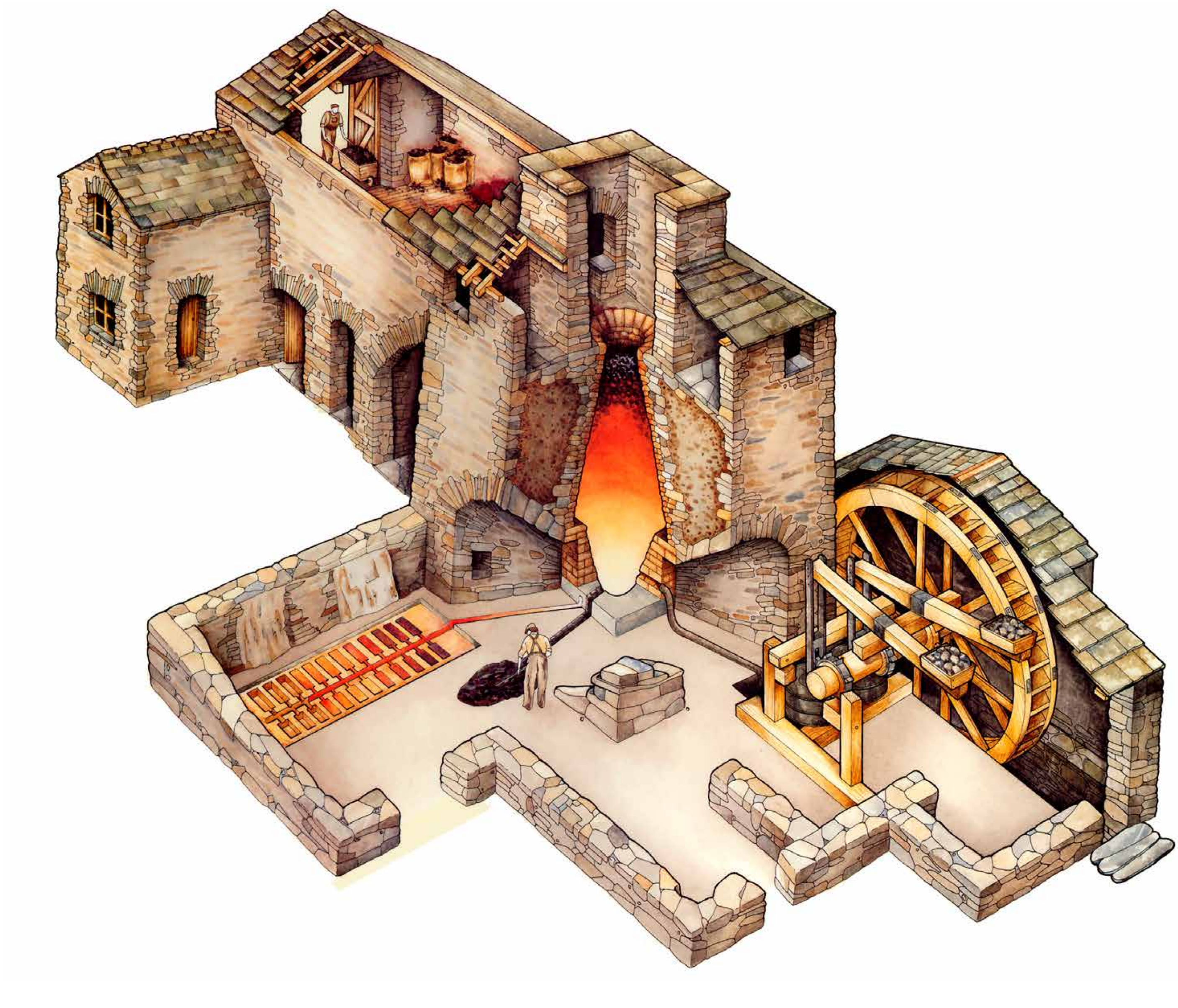

Figure 19

Reconstruction of Duddon blast furnace, Cumbria which was built in 1736 and is now a Scheduled Monument.

[illustration by kind permission of Alison Whitby and the Lake District National Park Authority] alongside a water wheel for power. Earlier bellows were wedge-shaped and made of leather and wood with iron nozzles, known as tuyères, which fitted through custom-made holes in the stone furnace lining. Later bellows were cylindrical and made of iron; these could be powered by a water wheel or by a steam engine. From the 1830s, the blast was sometimes preheated in a stove, ultimately firebrick Cowper stoves, which could be as large as the furnace. The casting house covered the area where castings were made, either using moulding sand for casting pig iron and small objects, or in a pit containing moulds for large objects such as cannons and steam engine cylinders. There would also be large buildings nearby for storing charcoal and ore (Bowden 2000).

The need for water power meant that early blast furnaces were located in suitable river valleys (often relatively small tributaries). In addition, the need for such power over several months meant that rivers were dammed to form ponds with leats to control and manage the water supply. Smelting campaigns would often end during the summer months when the supply of water ran low. During this time the iron smelters could carry out repairs, reline the furnace and stockpile necessary materials such as ore and fuel. Until the 18th century blast furnaces used charcoal fuel and the size of the furnace and the duration of the campaign required the supply of very large quantities of charcoal. The earliest blast furnaces in England are all located in areas with abundant woodland. The supply of sufficient charcoal was achieved through careful woodland management; commonly by coppicing woodlands cyclically.

The reliance of the early blast furnace on charcoal put pressure on the supply and cost of wood, timber and charcoal. Through the 17th century efforts were made to use coal in place of charcoal in a number of metal industries. Around the turn of the 18th century, iron was successfully smelted using coke (Day and Tylecote 1991; King 2001–2). Coke is coal which has been heated to remove some of its impurities. This technology was developed in Coalbrookdale, Shropshire but its adoption by the rest of the iron industry was slow. Initial attempts to convert this pig iron into bar iron had limited success. This may have been because the pig iron produced in the early coal-fuelled blast furnaces, mostly grey cast iron, was not of the same quality as that produced in the charcoal-fuelled furnaces, mostly white cast iron (King 2010). The coke-fuelled blast furnace pig iron may also have contained small amounts of sulphur (from the coke) which would tend to make the bar iron brittle. Nevertheless pig iron was increasingly used to produce cast (rather than forged) artefacts (where traces of sulphur did not overly affect the properties of the metal). Precision casting in iron played a significant role in the development of engineering and munitions (and the grey cast iron of the coal-fuelled furnace is better in this respect than the white cast iron of the charcoal-fuelled furnace). The casting of large iron cylinders contributed to the success of the emerging steam engine technology which was subsequently used to help drain water from deep mines and improve air blast for smelting (see pp 28).

The process of coking coal seems to have initially borrowed the methods used by charcoal burners. The coal was simply heaped up on a stone surface and a coating of coal dust and earth used to prevent complete combustion. Specialised coking ovens were also developed; these were usually a beehive shape and were initially front loaded (Cranstone 1989) but later top loaded (Battye *et al* 1991).

By the middle of the 18th century coke-fuelled blast-furnace technology began to be increasingly adopted by the rest of the British industry (Hyde 1977). The switch from charcoal to coke resulted in the relocation of the industry. The earlier industry was concentrated primarily in areas with abundant woodland such as the Weald and the Forest of Dean, while the later industry moved to the coal fields of the Midlands, Yorkshire, South Wales and the Scottish Midlands.

The earliest coke-fuelled blast furnaces appear to be comparable in size and form to the contemporary charcoal-fuelled furnaces – indeed the earliest examples were re-used charcoal-fuelled furnaces. The nature of coke fuel made some changes desirable and over time furnace design developed. Coke is a stronger material and so can support a taller charge of fuel and so furnaces tended to be built larger. By the end of the 18th century furnaces were being built over 10m high and the extra height might have played a part in the dramatic increase in the production of cast iron in the 18th century. In the early 19th century furnace shape changed from a square plan to a circular one (Fig 20). In addition the furnaces were now increasingly made using bricks rather than stone, although the brick structures were often held together with the aid of iron bands or sheets. From about the 1790s, they often had multiple tuyères, with the blast (provided using a steam engine) conducted to them through cast iron pipes. The topography of the coalfields

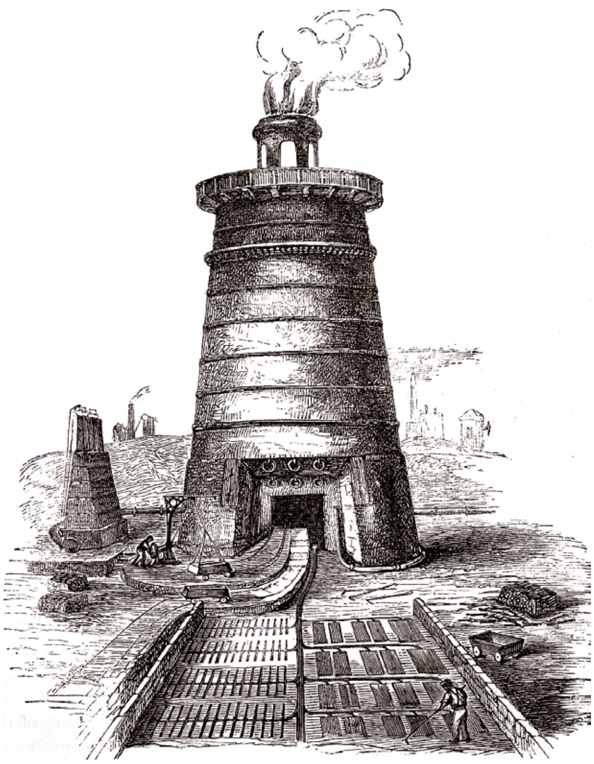

Figure 20

A 19th-century blast furnace of circular plan. The furnace is entirely built of brick and is strengthened with iron bands. Note the pig beds in the foreground where the cast iron was tapped from the furnace. The small structure to the left of the furnace is an oven where the air was heated before being introduced into the furnace. This image omits details of the blowing mechanism as well as the charging incline (Muspratt 1860, Fig 279).

provided far fewer opportunities for iron smelters to build their furnaces against slopes or banks which could be used as charging platforms. From the early 19th century inclines and hoists were increasingly used to carry raw materials to the top of the furnaces.

The success of the coke-fuelled blast-furnace industry relied on the identification of suitable coals which could be converted into low-sulphur coke – but it also benefited from the use of steam power and advances in the provision of the air blast. Newcomen atmospheric engines were used from the 1740s, however, these were mainly used to recycle the water used to drive conventional waterwheels and bellows. By the last quarter of the 18th century steam engines were used to drive blowing cylinders which provided increased and more steady air flow. The air pressures which could obtained inside the furnace increased considerably which reduced the amount of fuel needed (King 2011). The higher blast rates also lead to an improvement in the quality of the cast iron. Higher temperatures would produce a more fluid slag which could accept a greater proportion of limestone; and lime-rich slags will tend to absorb sulphur (Morton and Wingrove 1970; White 1980).

The early 19th century saw the introduction of hot blast in the iron smelting industry (Belford 2012). By heating the air that was drawn into the furnace the iron smelters could further reduce the amount of fuel needed. In addition, the heated air allowed the use of coal rather than coke and enabled the exploitation of the famous blackband ores of the Scottish Midlands which were mixtures of coal and iron ore. Initially stoves were heated with coal (Fig 20), but from the 1860s onwards the waste heat from the blast furnace was increasingly directed into Cowper stoves that heated the incoming air. The use of hot blast required water-cooled tuyères to prevent these overheating and melting. At least some hot-blast slags display characteristics quite different to earlier blast-furnace slags – they are often grey and less vitreous (Fig 23), however, there has been little systematic study of dated samples to determine the detailed relationship between smelting technology and slag appearance.

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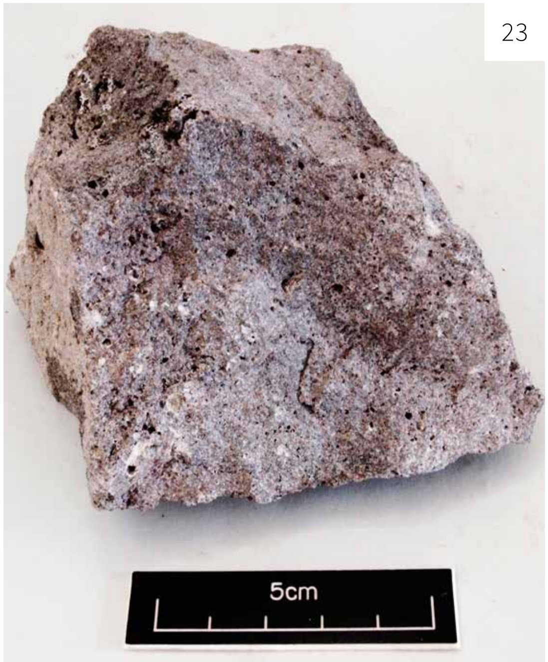

Figures 21-23

21. Blast-furnace slags are usually glassy in appearance and range in colour from blue and green to grey or brown. They usually have abundant fracture surfaces with little or none of the original surface remaining. They are less dense than bloomery-furnace fayalite slags, as they contain mush less iron. These slags can be found in large quantities and were often reused, for example as hardcore or scattered across fields to improve soil quality.
22. Early blast furnaces could be successfully run with a policy of dumping waste slag in the immediate vicinity, but this became problematic as furnaces produced more and more slag. Some slag was cast into simple bricks and used as kerbstones and the like. Increasingly, slag was cast into wagons or bogies so that the it could be transported and dumped in slag heaps some distance from the furnaces.
23. Late blast furnace slag from Bilston (sample held in the National Slag Collection). The texture and grey colour of many late blast-furnace slags resemble some concrete products (such as breeze blocks or cinder blocks).

The layout of late blast furnace sites was quite different from the earlier examples. It became increasingly common to construct two or more furnaces in a line and these would be accompanied by inclines, stoves and engine houses. Blast-furnace complexes would also be provided with a network of railways to move raw materials, finished metal and waste products which could cover an area of 20ha or more.

3.2.3 Refining pig iron

The product of the blast furnace was pig iron which is a brittle material, completely unsuited for use by the blacksmith. When forgeable iron was required (and there was usually much more demand for forgeable iron than cast iron), processes were used to convert the pig iron by reducing its carbon content. Several different process were developed over time and these are described below in chronological order.

Most early blast furnaces were associated with finery forges which could supply malleable wrought iron for the blacksmith. The finery used water power for both bellows and hammers: a blast furnace and a finery forge would often form a pair on the same water course. Pig iron was melted in an open charcoal hearth under an air blast provided by water-powered bellows (Den Ouden 1981; 1982; Dillmann *et al* 2012; Morton and Wingrove 1970). The carbon in the iron (as well as some other impurities, such as silicon) was oxidised and removed and a bloom of low-carbon iron would form in the hearth. The hot bloom was taken to a water-powered hammer for forging, which removed most of the trapped slag and consolidated the bloom of iron. The bloom was drawn out into a bar using the hammer, being reheated periodically in another hearth known as the chafery, which was also blown by water-powered bellows. Coal or coke could not be used in the finery because of its sulphur content but it could be used in the chafery hearth where the iron was reheated (but not melted).

Although the operation of finery and chafery hearths is known from historical sources (eg Berg and Berg 2001) few examples are attested archaeologically (see Crossley 1975a). Understanding such sites is often made difficult by the fact that they were often converted from water-powered bloomeries, and some were subsequently converted for other uses later on (all had ceased to be used in the 19th century). Archaeological evidence for finery and chafery forges can include the wooden foundations for the forge hammers and the wooden support for the anvil, plus evidence to indicate the presence of water power to drive the bellows for each hearth and the hammer. The hearths themselves were above floor-level and therefore rarely survive.

Fining generated various types of debris, including hammerscale, tap slag, large slag lumps and a type of porous slag, sometimes with traces of flow on the surface. Fining slags share many characteristics with bloomery tap slags (Morton and Wingrove 1970; Photos-Jones *et al* 2008). The tap slag from the finery hearth usually contains rather low levels of sulphur (due to the use of charcoal fuel) while the large lumps of slag (hambones or mossers – see Fig 24) from the coal-fuelled chafery hearth often have high levels of sulphur (Morton and Wingrove 1970).

The advent of coke-fuelled blast furnaces put pressure on the finery and chafery hearths. The increased productivity of the new furnaces required ever larger volumes of cast iron to be converted. While the early blast furnace was often accompanied by a single finery, by the 18th century the proportion of finery forges to blast furnaces had risen (King 2011). The geographical association between blast furnaces and fineries also waned depending on the nature of the iron produced and the markets for it, as well as the availability of water power. While fineries proliferated in the West Midlands to supply wrought iron to the forges of the Black Country (Hayman 2005), they were in decline in the Weald which increasingly specialised in munitions and other castings (Cleere and Crossley 1995).

The high demand for malleable iron encouraged many in the later 18th century to search for ways to increase production and lower costs, especially

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Figures 24 and 25

24. Large lump of slag (hambone) from finery and chafery forge at Colton, Cumbria (sample held in the National Slag Collection).
25. Tap slag from Downside Mill.

through the use of coal rather than charcoal fuel. Most of these involved the use of reverberatory furnaces of various kinds for different processes. The reverberatory furnace had two chambers: a hearth where coal was burnt and, separated from it by a low wall, an area where the raw material could be melted. At the far end of the chamber was a chimney which would draw flames and heat from the hearth into the main chamber. The furnace had a low roof which would reflect heat onto the raw material being melted. The low wall between the coal fire and the main chamber ensured that the coal ash would not contaminate the raw material. The reverberatory furnace had been adopted for copper and lead smelting in the 17th century (see p 42). Reverberatories included 'air furnaces' for foundry work (from 1690s); 'balling furnaces' for recycling scrap iron (from 1740s); some 'potting and stamping process'; and 'puddling'.

A variety of processes were patented and practised and these are often referred to as 'potting and stamping' (Hayman 2004; King 2011). The processes varied somewhat but all seem to have included a stage in which fragments of iron were heated in crucibles (often with a variety of fluxes and other materials). The crucibles were heated in reverberatory furnaces and so were able to use coal rather than charcoal. The fragments of iron from this process were then heated together and forged with a water-powered hammer into blooms and then bars. Potting and stamping processes and any diagnostic residues are very poorly known from archaeological sources (Morton and Gould 1967).

By the end of the 18th century a new process for producing malleable iron was developed by Henry Cort at Fontley in Hampshire (Mott and Singer 1983). The new process was called puddling and used a reverberatory furnace for melting cast iron and reducing the carbon content (as well as impurities such as silicon). The process was subject to a series of patents which also covered the working of the blooms into bars using a water-powered rolling mill (Mott and Singer 1983). The use of both a reverberatory furnace and rolling mills was not new but these techniques were successfully combined to produce a quality of malleable iron which met with the approval of the Admiralty. Initially it proved difficult to successfully reproduce the technology in the main iron-producing districts but when combined with the refinery or 'running out hearth' (which reduced the silicon content and converted grey cast iron into white cast iron) the technique was fruitful. Cort's early furnaces were provided with a sand base and this tended to react with some of the iron to form fayalitic slag – similar slags were also formed in reheating and refinery hearths (Phelps *et al* 2012). Puddling sites, such as Cort's site at Fontley (Killick and Gordon 1987), and the Millington's site at Swalwell (Proctor 2011), will often yield quantities of tapped slag. This slag closely resembles bloomery tap slag (cf Fig 16) but can be distinguished through scientific analyses. Early puddling was sometimes referred to as 'dry puddling' to distinguish it from the later 'wet puddling' processes (see below).

While many aspects of the puddling process remained largely unchanged for the next 150 years, there were significant developments in the nature of the puddling furnace. The sand base of the furnace was replaced with fayalitic slag and hammerscale which provided oxygen to help the removal of carbon and other impurities (Day and Tylecote 1991; Flemings and Ragone 2009; Photos-Jones *et al* 2008). Indeed the reaction between the carbon in the cast iron and the oxygen in the slag and scale produced blue flames that were called 'puddler's candles'. This version of puddling was referred to as 'wet puddling' or 'pig boiling'. Wet puddling was an efficient process that allowed increased production (Flemings and Ragone 2009) and it was also possible to take pig iron in an unrefined state. Later puddling hearths were provided with cast iron bases. In the 19th century the puddling process was adapted to allow the formation of steel rather than plain iron. The quality could be rather variable and for many applications the puddled steel was re-melted before use, and so was in competition with crucible steel (see below). Both of these processes were largely superseded by the Bessemer and Open Hearth processes (see below).

From 1860 it became increasingly popular to tap cast iron into convertors or hearths which would convert pig iron into mild steel (Tylecote 1992). The first example was the Bessemer convertor which comprised an iron vessel with a firebrick lining. The pig iron was melted in the convertor and then air pumped into the molten metal. The oxygen in the air caused the silicon and carbon in the cast iron to oxidise (and the heat thus generated raised the temperature and kept the metal molten). The later Bessemer convertors were installed so that molten pig iron could be tapped directly from a blast furnace into the convertor. Once the conversion was complete the mild steel (essentially iron containing small amounts of carbon, $<0.3\%$) was poured from the convertor into ingots. The process was initially successful because Bessemer had used a low-phosphorus pig iron. The first firms which took out licences for his patent had difficulties reproducing his success with pig iron that contained appreciable amounts of phosphorus. This was solved by the use of haematite pig iron and the addition of speigeleisen, a high manganese alloy of iron, where the manganese carried impurities into the slag. Later, Gilchrist and Thomas developed the use of an alkaline (or basic) refractory lining which would contribute to the formation of a slag which had greater power to absorb phosphorus. Even later versions of this process made use of pure oxygen (rather than air) as the nitrogen present in the air could make the iron/steel slightly brittle. The contemporary (and slightly later) technical literature contains some information on the nature of waste products but this is mostly limited to occasional chemical analysis (eg Percy 1861–4; Bell 1884) with no descriptions of hand specimens.

An alternative conversion process (the Open Hearth process) was developed by Siemens in the 1860s. Scrap metal, molten pig iron and iron ore were charged into a furnace: the oxygen in the iron ore would help to oxidise the carbon in the pig iron and so remove it. The reaction between pig iron and iron ore was slower than in the Bessemer process and so more controllable – it was possible to stop the process at a particular stage to produce steel or mild steel as required. Iron ore was often omitted where the desired product was a high-carbon steel. The Open Hearth process was fuel efficient as it made use of the regenerators developed by Siemens. The furnace was provided with several underground chambers (regenerators) which were filled with bricks arranged in a chequer-board fashion, ie with regular spaces for air to flow. These chambers were connected via tunnels and pipes to the air inlets, the Open Hearth furnace and the chimney. By means of valves, the air supply could be regulated so that hot waste gases would heat the bricks in one chamber which could then be used to heat the air coming in to the furnace. This preheating of the incoming air greatly reduced the amount of fuel required to achieve a given temperature. Heat regenerators were applied to many other types of furnace (such as reverberatory furnaces, crucible steel furnaces, etc). Material residues of the Open Hearth process are not well known from contemporary accounts or from archaeological contexts. In part, the lack of available evidence is due to the strategies used by iron and steel producers to dispose (and sometimes re-use) waste materials such as slag. For much of the 20th century iron slags were transported (usually by rail) some distance from the production site and dumped in large heaps. The excavation of such slag heaps is challenging given their scale and the difficulty of dating deposition.

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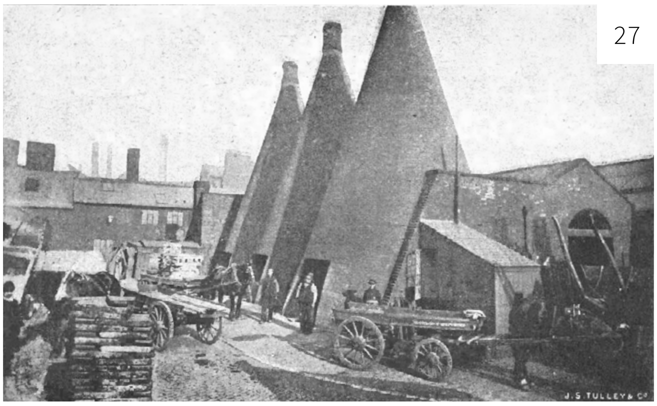


Figures 26 and 27

26. The foundations of the earliest steel cementation furnaces in England. The furnaces at Coalbrookdale, Shropshire were built in the 17th century.
27. Early 20th-century steel cementation furnaces in Sheffield, South Yorkshire.

3.3 Making steel

Steel was often a more valued material than plain iron as it was harder and so could take (and retain) a sharper edge. Steel has been produced by various methods at different periods of time. The earliest steels were probably produced in bloomery furnaces: the blooms were heterogeneous and as early as the Iron Age steely portions of blooms were selected for certain types of tool (Fell 1993; McDonnell 2013b). Steel can be deliberately produced in a bloomery furnace, by manipulation of the smelting conditions and types and ratios of raw materials but it is not clear how often this was done. The varied properties of iron alloys were certainly recognised and exploited during the early medieval period (Gilmour and Salter 1998; McDonnell 1989). The metallographic examination of early ferrous tools and weapons shows that many were manufactured by welding together steel and other iron alloys (Tylecote and Gilmour 1987).

Another method of making steel was to surface carburise or case harden iron objects. The plain iron would be forged to the desired shape and then heated in a bed of charcoal. Carbon from the charcoal entered the outer surface of the iron, creating a shell of steel. If the object was then quenched the shell became harder. There is evidence that this method was known in the Iron Age (Fell and Salter 1998) and it was widely employed in the medieval period (Williams 2003).

The cementation method of making steel, in which bars of iron were converted into steel, was introduced in the 17th century. The earliest steel cementation furnaces were in Coalbrookdale, Shropshire (Belford and Ross 2007) and were circular and *c*5m in diameter (Fig 26). While the superstructure had not survived later furnaces (eg Derwentcote, Durham, Cranstone 1997) were beehive- or bottle-shaped (Fig 27). Later furnaces tended to be larger – up to 8m in diameter (Barraclough 1984).

It is possible that the earliest furnaces packed iron into charcoal-filled crucibles but the standard later practice included the use of stone chests. Plain iron bars were packed in charcoal in a chest made from sandstone that was sealed and heated – the firing and cooling cycle would typically last for two weeks. The plain iron used in the cementation furnace had to be of a good quality. Phosphoric iron would not absorb carbon and so would not form a steel. The earliest steel cementation furnaces in Britain probably used iron from the Forest of Dean (one of the few areas with low-phosphorus ores) while the later industry was largely based on the use of imported Swedish iron (Barraclough 1984; Mackenzie and Whiteman 2006). The bars removed from the cementation furnace were called 'blister steel'. The metallographic examination of samples of blister steel shows that this was not a uniform material and the proportion of carbon could vary significantly across the thickness of a bar (Mackenzie and Whiteman 2006). Blister steel bars were often broken up and then reforged to improve their homogeneity; the resulting steel was known as 'shear steel'. The interior brickwork of surviving cementation furnaces is usually vitrified. The examination of fragments of the Coalbrookdale furnace suggests that parts were subject to temperatures in the range 1300–1500°C. The chests at Derwentcote were sealed with sand and clay (Cranstone 1997) and the Sheffield practice was to use the sludge from the bottom of cutlery grinders' troughs (Barraclough 1984). The sealing material would be partially vitrified by the heat of the cementation furnace and this waste material was known in Sheffield as 'crozzle' (Fig 28).

Figure 28

Waste from steel cementation (crozzle) used to top walls in Sheffield. Crozzle comprised a mixture of steel swarf and sand that was used to seal steel cementation chests. The high temperature of the steel cementation furnace led to the partial fusion of this mixture. [Photo © Roger Doonan]

In the 1740s Benjamin Huntsman developed the use of sufficiently refractory materials (for both furnace and crucible) which allowed blister steel to be melted (Barraclough 1984). This method involved breaking up cementation bars, placing them in crucibles, and heating them in a furnace to melt the alloy, before casting homogenous steel ingots ('crucible steel'). The process was not widely used before the last decades of the 18th century (Craddock and Wayman 2000). While crucible steel had obvious advantages for the production of high-quality tools, it was also used for the manufacture of decorative items such as buttons (Craddock and Lang 2004). The 'secret' of the crucible steel process was undoubtedly the refractory materials used to construct the furnaces and crucibles. A high-carbon steel (eg 1.7% carbon) would begin to melt at about 1320°C but would not be fully molten until 1400°C. The crucible steel furnace was constructed from sandstone with a cellar beneath and a chimney above to provide the necessary draught for the coke fire. The interior of the furnaces would over time become highly vitrified. The crucibles were made from carefully selected and processed raw materials. Early accounts often stress the use of clay from Stourbridge – this fireclay had long been prized in the glass industry for the manufacture of their crucibles (which needed to withstand temperatures in excess of 1300°C and the corrosive effects of molten glass). Later recipes usually specify a blend of clays from several locations. It has been suggested that the earliest crucibles also contained a significant proportion of graphite (Barraclough 1984). Naturally graphitic clays had been exploited for some years for the production of crucibles used for precious metalworking (Martinón-Torres 2012).

The raw materials for the crucibles were carefully processed by grinding and sieving to remove any impurities (such as iron pyrites). Over time the used crucibles became heavily vitrified; a proportion of the old crucibles could be crushed and re-used to produce more crucibles. During melting the remains of any slag previously trapped in the metal would rise to the surface and combine with any flux used (Barraclough 1984).

3.4 Smithing

Iron (and many of its alloys) becomes relatively soft when heated so that it can be smithed or forged using a hammer into a variety of shapes. In addition, the metal can be joined together by forge welding. The techniques used in smithing, and associated waste products, varied depending on the nature of the iron (or alloy) and the size and shape of the object being formed.

Bloomery iron is a heterogeneous material: the proportion of alloying elements (such as carbon and phosphorus) can vary considerably even with a single bloom. In addition, it is a composite material and (like wrought iron) can contain quantities of trapped slag. The bloom would need to be refined to produce iron stock (such as billets or bars) suitable for forging into objects. The initial stages of refining the bloom involved hammering it while hot to consolidate the metal and expel the trapped slag; losses at this stage can be considerable (Crew 1991; Sauder and Williams 2002). This primary smithing was often carried out at the smelting site, and therefore smelting and refining residues can be found together (Paynter 2007b). Bloom refining residues can include hammerscale (Fig 30), small prills of fayalitic slag expelled from the bloom and smithing hearth cakes (Fig 32).

The iron stock, or billet, would then undergo secondary smithing or forging, also while hot, to produce artefacts. Forging is carried out above 700°C and the metal becomes softer the hotter it is, however, excessive heat (above 1300°C for plain iron) can damage and even burn the metal. In general plain iron can be forged at higher temperatures than steels or other iron alloys. Plain iron with slag inclusions needs to be forged at a sufficiently high temperature that these will be at least partially molten (around 1100°C). The range of techniques employed by blacksmiths to shape iron (see Andrews 1991) appear to have changed little over the last few millennia. Using hand tools and working on an anvil, the metal could be thinned down, thickened, straightened, bent, split, pierced and otherwise shaped. Many of the tools described in modern textbooks can be compared directly with examples from archaeological contexts (eg Hinton 2000; Manning 1991). Secondary smithing also includes the repair and recycling of iron objects.

Figure 29

Late medieval illustration showing smiths at work. Note the waist-level hearth in the background and the anvil set in a wooden block.

Iron and its different alloys have different properties: plain iron is relatively soft and often contains slag inclusions, steel is harder than plain iron and can be made even harder by quenching (see below), and phosphoric iron is harder than plain iron although it can be somewhat brittle when cold (and is unaffected by quenching). The smiths' skill encompassed the control and appropriate application of these properties in forming objects. Smiths recognised that not all iron behaved in the same way, and stock metal with different properties would have been available. For example, Iron Age currency bars are thought to be a form of stock iron and the elaborate socketed ends or welded tips on these bars are a significant feature, demonstrating visibly the forging properties of the iron (Crew 1995). Finds – such as blooms, billets and bars and all forms and types of stock iron – are important to further research into the trade and use of different iron alloy types (Fig 13).

Objects were formed from a combination of different iron alloys. For example, knives and other edged tools were often made with a hard alloy for the cutting edge (eg steel) and a softer but tougher alloy (plain iron) for the back. The different parts of metal were heated and then forge welded. Forge welding requires a higher temperature than ordinary forging – for steels this was around 1200°C and slightly higher (1300°C) for plain iron. Modern blacksmiths often use a flux, such as sand, to clean the surfaces that are to be welded, however, plain iron can usually be welded without using a flux (due to the presence of the trapped slag inclusions). The extent to which fluxes were used in antiquity is unknown. The different alloys were often visible in the finished and polished object. This technique was also used for the productive of some prestigious pattern-welded weapons. Rods or bars of plain iron and steel were welded together and repeatedly folded and twisted during forging to obtain an attractive patterned surface (Gilmour and Salter 1998). Some iron is lost during smithing (hammerscale, see Fig 30), and this loss is greater during welding and complex smithing operations such as pattern welding.

The smithing of iron produced distinctive forms of slag and waste. The periodical heating of iron (and its alloys) inevitably led to some oxidation of the metal at the surface. As the red-hot metal was forged, some of this oxidised surface film would be detached (the 'sparks' seen when a smith forges iron). Fragments of this film, often referred to as flake hammerscale, are regularly found in archaeological deposits associated with iron smithing (Fig 30; Dungworth and Wilkes 2009; Mills and McDonnell 1992; Palmer 2015; Young 2011). Detecting hammerscale is relatively easy as it is magnetic. Plotting the distribution of hammerscale has great potential to uncover detailed aspects of the layout and use of space in blacksmiths' workshops (Fig 5). Flake hammerscale is often accompanied by small amounts of spheroidal material which is also magnetic (Fig 30). These spheres can form in a variety of ways but especially the joining of iron (and its alloys) by forge welding (the other two methods responsible for the production of spherical hammerscale are iron

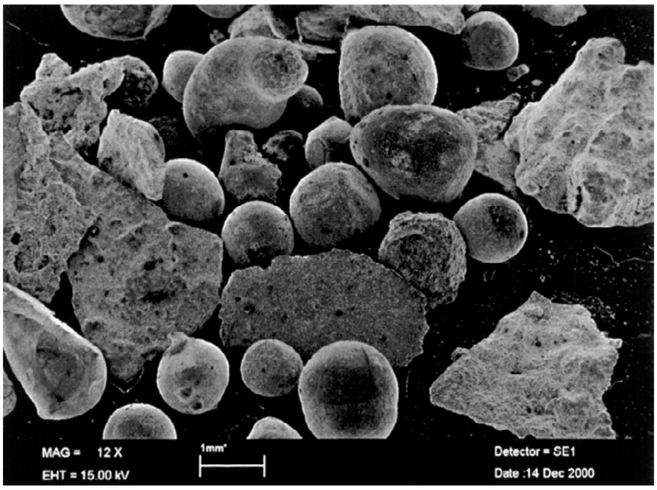


Figure 30

Scanning electron microscope(SEM) image of flake hammerscale and spheroidal hammerscale. Flake hammerscale consists of grey to black, fish-scale like fragments, typically 1–3mm across. Its small size means that it is rarely detected during excavation but it is sometimes recovered from environmental samples or from soil samples taken specifically to recover hammerscale. Hammerscale is highly magnetic and can be separated from soil using a magnet. Spheroidal hammerscale consists of small round slag droplets, which can be hollow to varying degrees.

smelting and the accidental burning of iron). The extreme heat and pressure produced during forge welding caused the oxidised films at the surface of the metal to momentarily melt and this was then ejected from the weld and formed a series of droplets (Dungworth and Wilkes 2009). Crew (1988) has reported the presence of slag spheres from smelting furnaces – in almost all respects these smelting slag spheres resemble spherical hammerscale produced during welding. Dungworth and Wilkes (2009) demonstrated that similar spheres can also be produced by burning iron alloys. Where large quantities of hammerscale build up it can become cemented together with iron corrosion products into smithing pan (Fig 31). The archaeological investigation of hammerscale has mostly concentrated on the material produced by hand forging, however, comparable material would also be produced during mechanised iron forging or rolling (Young 2011).

Blacksmithing will also generate a variety of lumps of slag, the most distinctive of which is the smithing hearth cake. Some hammerscale will fall from a heated piece of iron into the fire and react with fuel ash, the hearth wall and any flux used. Droplets of slag accumulate in the hot region near the blowing hole and coalesce to form a lump, known as a smithing hearth cake (Fig 32). Smithing hearth cakes vary considerably in size and form but some have a concave upper surface (often displaying the greatest degree of vitrification) and a convex lower surface (often with abundant impressions of charcoal fuel).

31

32

Figures 31 and 32

31. Smithing pan from the blacksmith's workshop on Hythe Road, Colchester. It consists of a layer of debris, largely hammerscale, trodden down and corroded together (image 20mm wide). The hammerscale visible in the surface includes several spherical examples.
32. A partially sectioned smithing hearth cake. These are normally plano-convex to concavo-convex in section and circular or oval in plan. Their size and weight can vary considerably, from 100g to more than 2kg, although the majority weigh 200–500g. The upper surface sometimes has a depression produced by the air blast, or is sometimes irregular, where the last formed slags have not been fully incorporated. The lower surface usually has impressions from charcoal or the hearth lining. The size of the cake depends on the amount of iron forged, how much slag it contained, whether fluxes were used and how often the hearth was cleaned out. The larger smithing hearth cakes can be misinterpreted as furnace bottoms. Smithing hearth cakes from primary smithing, or refining, will generally be larger than those from secondary smithing. Smithing hearth cakes are sometimes slightly magnetic as they can contain fragments of iron broken from the bloom and some hammerscale.

If left in place, a smithing hearth cake will begin to impede the flow of air from the bellows and so it would be pulled out and discarded. While smithing produced some cakes of slag (Fig 32) it would also produce smaller amorphous lumps of slag (Fig 18). Smithing slags produced in a coal-fired hearth will tend to be less dense than those produced in a charcoal hearth. Smithing slags can be found heaped near to the smithy or they could be transported farther away for dumping or reuse, for example in road construction. Recent smithing by Dogon smiths in Mali (Soulignac and Serneels 2013) provides some indications of the rate at which smithing slag might be produced by traditional forging in a charcoal hearth. Smithing 3kg of stock iron over a period of approximately 4 hours yielded around 2kg of finished iron object, 215–675g of slag and an estimated 700–900g of hammerscale.

Blacksmiths needed to heat their metal in a hearth which was capable to achieving the temperatures required for the work they were undertaking. Medieval and later forges were often built of stone or brick with the hearth at waist height. The excavation of such workshops usually finds no direct evidence for the hearth or anvil (eg Mills and McDonnell 1992). Many earlier hearths were probably situated at floor level although some raised hearths are suggested by iconographic sources (Halkon 2013). Archaeological excavation in Southwark found numerous blacksmiths' workshops in use from the late 1st century AD until the middle of the fourth century (Hammer 2003). The hearths were set at ground level, showing that smithing took place on the floor rather than using raised hearths and anvils. The size and form of the hearth varied greatly but most were simple hollows in the ground (0.3–1m in diameter, Hammer 2003, Fig 110). Hearths occasionally have a clay lining and even elements of a simple superstructure to retain the fuel and heat and perhaps to protect the bellows. The hearth was filled with a bed of fuel, predominantly charcoal, but from the Roman period onwards there is growing evidence for the use of coal (Dearne and Branigan 1995). Medieval and later blacksmiths made increasing use of coal (and even coke) and this would tend to produce more glassy smithing slags. An air blast was used to obtain high temperatures, although no evidence for the nature of the bellows survives archaeologically. Vitrified clay hearth wall or hearth lining is most likely to be produced in the hottest part of the hearth, around the blowing hole. Vitrified clay hearth linings are similar to smelting furnace linings (Fig 11), though hearth lining is generally thinner and is found in smaller fragments and smaller quantities. Sometimes the outline of the blowing hole is preserved. The absence of hearth features and clay hearth lining fragments on some later sites is consistent with the use of raised hearths.

Blacksmithing would usually take place within a building or shelter to protect the hearth, and the smith, from the elements and also provide dim lighting round the hearth (Crew 1986), allowing the smith to better judge the temperature of the iron from its colour. Some smithing workshops were in rather simple wooden structure such as the Roman examples at Southwark (Hammer 2003) while others were stone buildings (Mills and McDonnell 1992). Stone anvils and hammer stones, with slagged surfaces, have also been found. There might also be indications of the location of a wooden anvil or a wood block into which a small metal anvil was inserted. Metal tools such as anvils, tongs and hammers do survive, but hardly ever in a workshop context. There is no evidence for the type of bellows used at early sites, although their location can sometimes be inferred.

The forging of iron has also benefited from varying degrees of mechanisation from the medieval period onwards. Waterpower was harnessed to drive hammers: the flow of water drove a water wheel and this was used (via a wheel with cams or teeth) to raise and then drop a hammer (the same principle was also used to power bellows). Such plating forges were used to produce an increasing variety of iron goods, such as frying pans, saws and cutlery, with some specialist centres emerging, eg Sheffield.

From the 17th century water power was used to roll metal into sheets and cut (slit) these into rods (Johnson and Bearpark 1978; King 1999).

Iron could only be worked in this way when it was red hot and so rolling and slitting mills also had furnaces where the metal could be heated. Rolling used two cylinders each of which rotated under power from a water wheel. The distance between the two rollers could be adjusted to produce sheets and strips of the desired thickness (Fig 33). Slitting mills also used rollers but the rolls had blades fitted which cut the metal. Rolling and slitting were important for producing metal rods of the correct thickness for the nail trade and the greatest concentration was around the Black Country, reflecting the importance of the nail-making industry to that region (King 1999). The rolling mill also formed an essential element of Cort's development of the puddling process (see p 30).

Another important application of the roiling mill was for the production of tinplate which began in earnest in about 1725 at Pontypool. Tinplate comprised a sheet of iron (or from 1880s, steel) with a thin layer of tin on the surface. The fully developed process required two rolling mills, heating and annealing furnaces, and pots for a pickling medium (acid), washing and tinning (Minchinton 1957).

Further mechanisation of iron working took place with the adoption of steam power. In the 18th century some of the earliest application of steam power in the iron industry was to compliment rather than replace water power. Water was collected in mill ponds and then

Figure 33

Rolling iron bars at the Black Country Museum.
[photo © Paul Belford]

used to power water wheels but this supply could run dry, especially in the summer months. In many cases, therefore, steam power was used to pump water from the tail race back up to the mill pond and allow it to be re-used (Hayman 2005). As steam technology (and the associated engineering of gears and related mechanisms) developed it became possible to use steam power in more diverse ways. Matthew Boulton and James Watt used steam power for a rolling mill in 1781 which meant that slitting and rolling mills no longer had to be sited next to suitable rivers. In 1842 Naysmith patented a steam-powered hammer suitable for forging large pieces of iron. The hammer was raised vertically above the forging and then dropped. The steam hammer was better able to cope with the largest items that needed forging. With the use of steam power to control the descent of the hammer, it was eventually possible to control great power with considerable precision.

3.5 Casting

Iron with a sufficiently high carbon content (2–5%) can be melted relatively easily (ie a melting temperature of 1200°C) and so cast into shape. Such cast iron could have been accidentally formed in bloomery furnaces (if the smelting conditions were especially reducing), however, it would be brittle and so would probably have been rejected by blacksmiths. The introduction of the blast furnace at the end of the 15th century provided large quantities of cast iron, most of which was converted in fineries to malleable iron (see p 29). Nevertheless, some of the cast iron was formed directly into artefacts by pouring the molten metal into moulds. Cannons were usually made this way (Crossley 1975b) as were a range of other relatively large objects, such as firebacks and grave slabs. Over time the range of articles which were made using cast iron expanded (pots, pans, cooking ranges, mangles, drain pipes, bridges, machine and engine parts, etc). Indeed the development of precision casting for the engineering trade was often an essential requirement for other innovations in the iron industry. The use of cast iron cylinders for steam engines (for pumping water or air) used in the iron industry was only possible because of skills and expertise in iron casting. Early moulds were made from loam (a mixture of clay, silt and sand) and then fired but later moulds were often made using 'green' sand (sand with a little clay). The 'green sand' moulds contained small amounts of moisture and were not fired, but relied on their porosity to prevent the formation of too much steam.

The early casting of iron was undertaken at the blast furnace. This was practical where large artefacts such as cannons were to be cast. Where a furnace was used to cast smaller objects it was sometimes provided with a small hearth extension, or forehearth, from which cast iron was ladled into small moulds. Casting direct from a furnace could be a rather doubtful business due to the uncertain quality of the metal. The 18th century saw the appearance of foundries which bought (rather than made) their pig iron and re-melted it in 're-melting furnaces'. Two kinds of re-melting furnace are known. The first was a reverberatory furnace known as an air furnace and introduced in 1690s (King 2001–2). The second was known as the foundry cupola and is a variety of small blast furnace (Tylecote 1991). At least some of the smaller cupolas appear to have been made from joining sections which could be stacked on top of each other, and enabled the cupola to be moved on occasion. Re-melting cast iron and the addition of fluxes or alloying elements (such as manganese) tended to improve the quality of the cast iron and of the castings made. Cupola melting of cast iron and casting in 'green sand' moulds has continued to the present day but has rarely been identified in the archaeological record.

4 Archaeometallurgical Processes and Finds:

Copper and its alloys

4.1 Background

Pure copper has a melting point of 1084°C, lower than that of plain iron, and is a very versatile metal. Copper and copper alloys can be melted and cast to shape or they can be wrought (hammered). Copper is very ductile and soft, and so can be drawn into long wires or hammered into thin sheets. The common alloys of copper are bronze (copper with tin), brass (copper with zinc) and gunmetal (copper with tin and zinc). If lead is also added, then the alloy is described as leaded, for example 'leaded bronze' and so on. Alloying increases the hardness of the metal, reduces the melting temperature, and can also change the colour (Fang and McDonnell 2011). Bronze and brass were used for wrought and cast objects, but the uses to which each alloy

Copper in summary

Copper is a soft and ductile metal, with a melting temperature of 1084°C. Alloys of copper include brass (with zinc), bronze (with tin) and gunmetal (with tin and brass). Sometimes lead was also added and the alloys are then described as leaded.

Process	Summary	Archaeological debris
Smelting	Ores were smelted in one or more stages. Molten metal was produced. Later, complex smelting operations and then reverberatory furnaces were introduced.	There is little evidence for early copper smelting, although it is likely that debris such as slag and vitrified clay would have been produced. In later periods there can be evidence for waterpower.
Casting	Metal could be melted in a crucible and cast directly into objects or into ingots using moulds. Moulds were made from sand, clay, metal or stone and could be open or closed, one piece (investment mould) or two (piece mould).	Crucibles, moulds, metal spills, failed castings and surplus metal trimmed from castings (sprues, flashings and runners).
Wrought metal working	The solid metal was shaped, for example by cutting or hammering, which, if done at room temperature, caused the metal to harden and become brittle. Heating (annealing) the work-hardened metal at intervals restored its toughness and softness.	Scrap metal, such as turnings or offcuts, metal sheet, rods, bars and wires. Small ingots or blanks, tools and anvils are rarer finds. Waterpower can be used for mechanised processes at later periods.

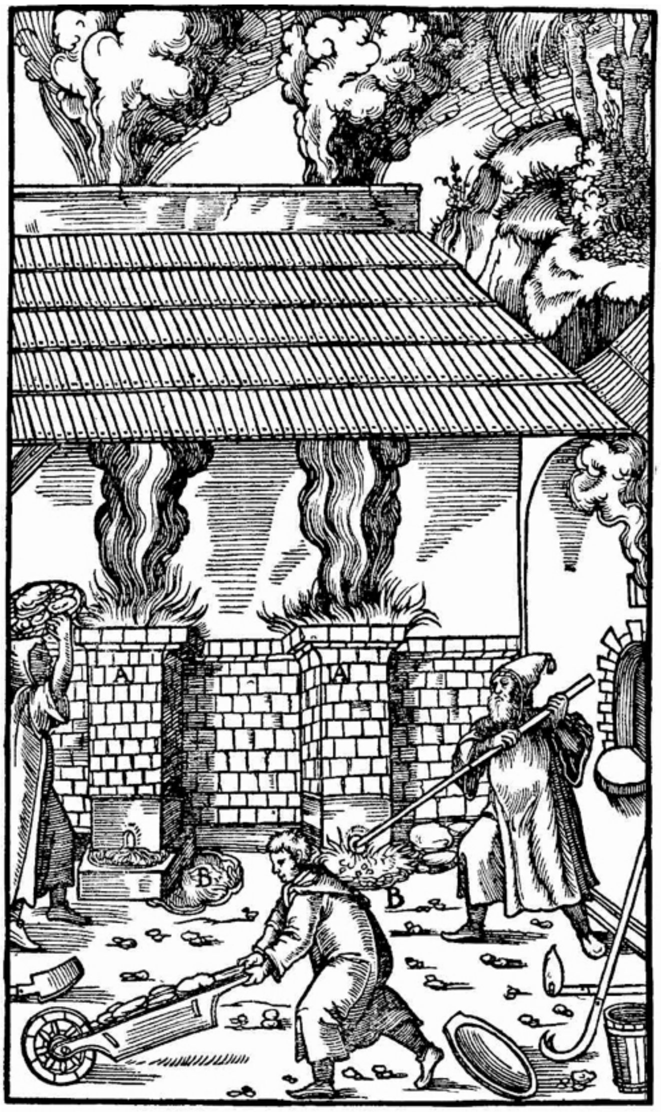
was put tends to vary with time. Additions of lead to copper alloys could improve the quality of castings, but was detrimental for alloys that were to be worked or gilded.

4.2 Smelting and alloying

Copper-based artefacts were widely used in Britain from the end of the third millennium BC and Britain has numerous of copper ores, including copper carbonates (eg malachite $Cu_2CO_3(OH)_2$) and copper sulphides (eg chalcocite Cu_2S, chalcopyrite $CuFeS_2$ and 'grey ores' $Cu_{12}(AsSb)_4S_{13}$). Nevertheless relatively little physical evidence for copper production in Britain has been recovered that pre-dates the Industrial Revolution. Until recently it was widely assumed that the intensive exploitation of copper ores in the recent past would have destroyed all traces of early mining. Nevertheless field survey, underground exploration and archaeological excavation have identified at least twenty sites in Britain and Ireland where copper ores were mined in prehistory (Crew and Crew 1990; Dutton and Fasham 1994; O'Brien 2004; Timberlake 2003a; 2003b; Timberlake and Marshall 2013; Timberlake and Prag 2005). Mining techniques included firesetting (the use of heat to weaken or shatter rock) and antler (or bone) picks, as well as a variety of hand-held and hafted stone tools. Suitable stones were often carefully selected and brought considerable distances. Stones were sometimes modified to make them easier to haft (Pickin 1990).

Although a growing number of mining sites can now be shown to have been exploited in prehistory (Timberlake 2003a), there has been a general absence of smelting evidence such as furnaces or slags (Craddock 1990; 1994). Replication experiments have shown that copper carbonate and copper oxide can be smelted directly, using charcoal fuel and an air blast to obtain sufficiently high temperatures. The molten metal sometimes forms prills (droplets) scattered through the smelting slag, which forms from the reaction of gangue in the ore with metal oxides. The prills could have been recovered by crushing the slag. The evidence for copper smelting from Pentrwyn on the Great Orme headland in Gwynedd (Williams 2013) has recently been dated to the late Bronze Age. Tangible remains of Roman and medieval copper smelting is virtually unknown and it is likely that copper was imported from Europe in the later Middle Ages.

In the 16th century the Company of Mines Royal was provided with monopolistic control of copper production and introduced German workers who applied their techniques in the Lake District and



A—Furnaces. B—Forehearths.

Figure 34

Copper smelting furnaces of the 16th century as illustrated in Agricola's *De Re Metallica*.

south Wales (Day 1991). The roasting and smelting operations consisted of a complex sequence which produced, first, matte (copper sulphide) and eventually copper metal, over a period of four months. The furnaces are not described in detail but were probably similar to those described by Agricola, ie simple shaft furnaces (Fig 34). The fuel and copper ore would be charged at the top of the furnace and slag and matte or metal tapped from the bottom. The contemporary accounts show that the bellows were driven by water power and peat fuel and coal were used as far as possible, although the later stages of copper refining required charcoal (Day 1991). Nevertheless, the material evidence for the mining and smelting described in 16th-century documents has received relatively little attention.

Copper production appears to have gone into decline for much of the 17th century due to heavy competition from continental producers, but was revived in the final decades of that century by two developments. The first was the passing of legislation which removed the crown's prerogative (and the power of the royal companies) and encouraged private investors. The second was the introduction of the reverberatory furnace for smelting copper. This introduction is known from documentary (King 2001–2) rather than archaeological sources and so is incompletely understood. The reverberatory furnace was a low rectangular furnace which was much longer than it was wide. The fire was placed at one end and separated from the ore by a low wall (Fig 35). The heat from the fire was drawn across the ore by the draft formed by a chimney at the far end of the furnace and the low ceiling would reflect heat down onto the ore. The physical separation of the fuel from the ore meant that smelters could use coal instead of charcoal (and thereby save money). The atmosphere in the furnace could easily be changed from heavily reducing through to heavily oxidising through opening and closing doors and vents. This encouraged the development of smelting procedures which used alternating steps with oxidising and then reducing conditions, although archaeological evidence for this is virtually unknown.

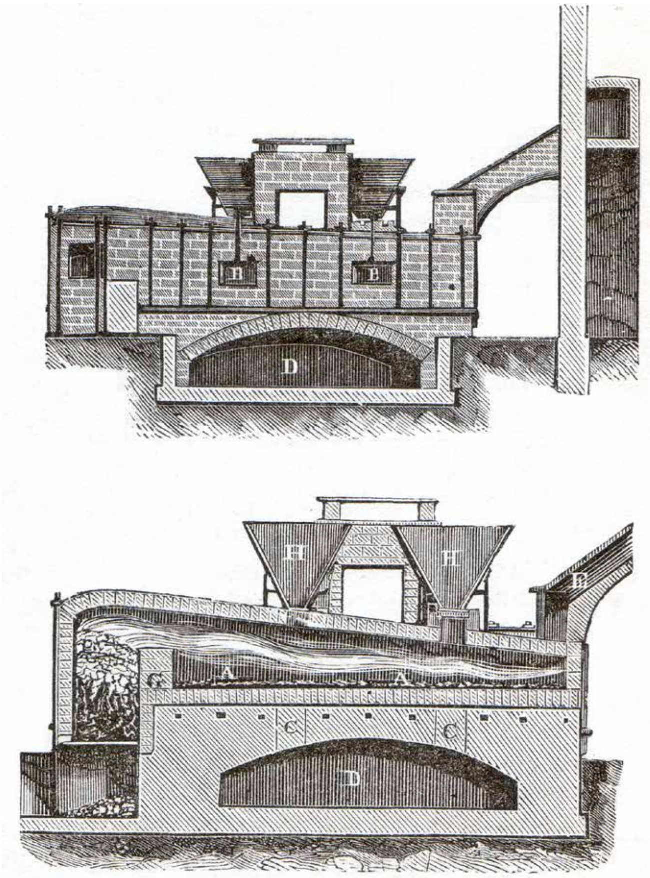


Figure 35

A reverberatory furnace for smelting copper with exterior view (above) and a cross-section (below). The coal fire to the left is separated from the ore by a low wall (G). The heat from the coal fire is drawn across the ore by the draught induced by the chimney (E).

The ore would be charged and strongly heated in oxidising conditions to calcine the ore and drive off as much sulphur as possible. The calcined ore would then be melted to form a slag and a matte (mixture of copper and iron sulphides). The matte would then be calcined again and the calcined matte melted in several steps until a pure copper was formed. Each melting stage would produce some slag and the slag from the later stages would be sufficiently rich in copper that it would be added to fresh ore to help oxidise that ore and recover some of the copper from the slag. By the 19th century copper smelters carefully blended ores from different mines. In this way they could combine sulphide and naturally oxidised ores which would tend to react together and remove sulphur (the 'Welsh process').

A variety of copper-based alloys have been produced. Most bronze (a copper-tin alloy) was probably made by melting previously smelted copper and tin. Similarly, leaded alloys would have been produced by adding metallic lead to the molten alloy. Brass (a copper-zinc alloy) was not made until the Roman period; its production is described in the section on zinc (p 58). Many mixed alloys could have been produced by recycling mixed scrap copper alloys with relatively little thought to the exact composition of the finished metal.

4.3 Casting

Copper has a melting temperature which is sufficiently low that it can be melted and so objects can be shaped by casting into suitable moulds. Melting small amounts of copper (or copper alloys) does not necessarily require a custom-built hearth, although a reducing atmosphere is needed to prevent the metal from oxidising – this was usually achieved by using charcoal fuel. In order to achieve sufficiently high temperatures to melt the copper it would be necessary to use bellows to increase the flow of air. Where crucibles were placed in simple charcoal-filled hearths, it was usual for the bases to be rounded or pointed to help keep them upright. Wheel-thrown crucibles often have flat bases which are better suited to placing in a hearth with a flat base (often with the fuel in a separate compartment, such as a reverberatory furnace or a muffle furnace). Crucibles could be used to produce alloys (eg bronze) from different metals (tin and copper): the copper would be melted first and then the tin added. Alloys generally have lower melting temperatures making them easier to cast: bronzes have lower melting temperatures than pure copper. Crucibles could also be used to melt scrap metal. The crucibles had to be made from a refractory clay, ie one which could withstand the high temperatures needed to melt copper alloys. The high degree of firing makes crucibles fairly durable although most are recovered as fragments rather than whole vessels. The patterns of vitrification can be used to reconstruct how crucibles were placed in a hearth. If a crucible was covered with charcoal and blown from above then the vitrification would be most pronounced at the rim.

The melting of copper alloys can easily lead to the formation of small amounts of slag. If the copper alloy is subject to even slightly oxidising conditions then some of the metal will oxidise and can then react with fuel ash, fragments of broken crucibles and other materials to form lumps of amorphous slag. As these slags weather the presence of small amounts of copper produces a distinctive green colour.

In some cases the molten metal was cast into open moulds to produce suitable pieces of metal to begin forging (see below) but in other cases more complex moulds were used to produce a largely finished object. Large and/or complex moulds were usually provided with a funnel-shaped opening – the in-gate or sprue cup (Fig 41). The molten metal was poured into the in-gate and ran down through channels (runners) into the actual shape to be cast (the matrix).

Crucibles come in various shapes and sizes, from thimble-sized to larger than pint beer-mug sized (Fig 36; Bayley and Rehren 2007). Prehistoric crucibles were made by hand and come in a variety of sizes and shapes. Some of the earliest (Bronze Age) examples (Needham 1980) are fairly large shallow bowls (typically 200mm across) and circular in plan. These crucibles were provided with three legs and although 100mm tall overall, the legs formed almost half of this height. The crucibles had thick walls (around 20mm thick) and capacities of around 150ml (thus capable of holding perhaps 1kg of copper alloy). Iron Age crucibles tend to be triangular (Wainwright 1979); and were probably formed as shallow bowls and then had three corners made by slightly pinching the clay while still wet. These are commonly 60–90mm across and 35–50mm deep with walls 5–15mm thick and capacities of around 50ml (ie capable of melting around 300g of molten copper alloy).

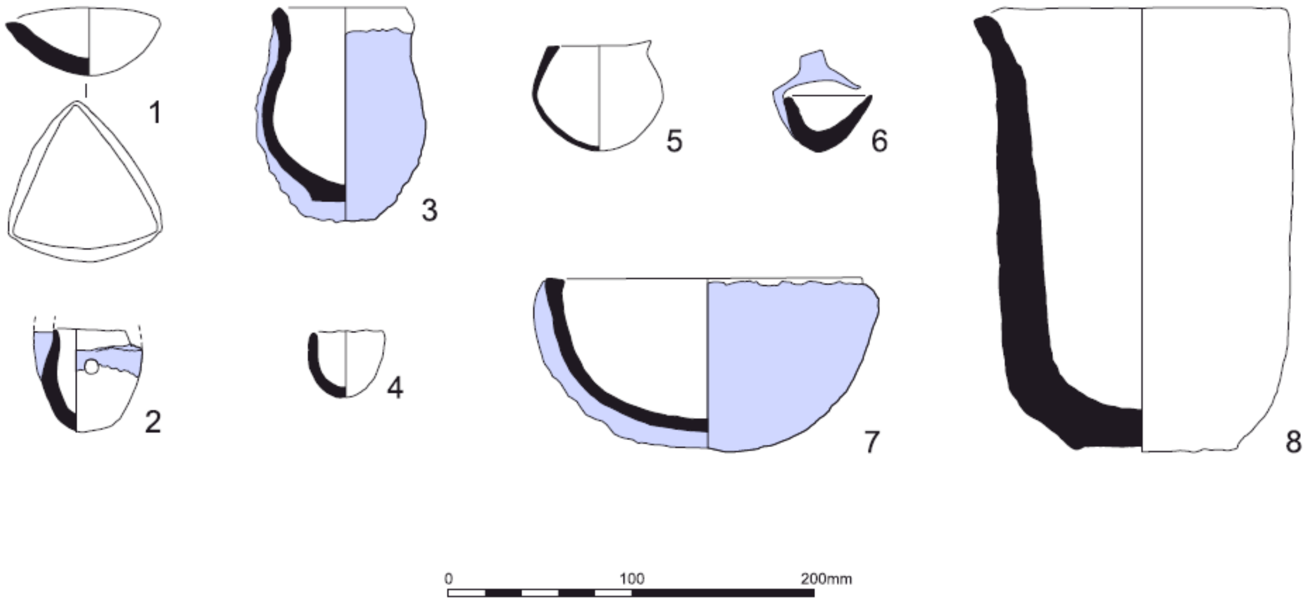


Figure 36

Drawings of common crucible forms of Iron Age to post-medieval date. 1: Iron Age, 2 and 3: Roman, 4 and 5: Anglo-Saxon, 6: early Christian, 7: late medieval, 8: post-medieval.

From the Roman period onwards some crucibles are wheel-thrown, but handmade crucibles continued to be used into medieval times. Roman wheel-thrown crucibles typically have external diameters of 50–150mm and are 50–100mm high with wall thickness of 3–6mm (giving capacities of 100–500ml, equivalent to 0.5–3kg of molten copper alloy). Many (although not all) Roman wheel-thrown crucibles also have an extra layer or coating of clay on the outside (Fig 37; Bayley 1991c). This coating could have provided a degree of insulation which would have helped keep the metal molten for longer and prevent failure of the crucible proper through thermal shock. It is rare for handmade crucibles to have these extra outer layers. It is possible that while potters made wheel-thrown crucibles (largely following existing beaker and cup forms) these had walls which were too thin for a metallurgical application. The metalworkers could have added the extra outer layer of clay themselves to provide a suitably thick wall. In addition, the extra outer layer of clay produced a more rounded base profile which would be more stable in a charcoal-filled hearth.

Few early or middle Saxon crucibles have been recovered; the examples from Bloodmoor (Blakelock 2005; Cowgill 2009) are simple bowls or beaker shapes in a variety of sizes. The vessels were made by hand from a quartz-rich fabric. The smallest are only 20mm across and 20mm high, while the largest are 100mm across and perhaps up to 100mm deep. The crucible walls are 5–15mm thick and the largest vessels could have held 100ml of molten metal (a little under 1kg). A silica-rich outer surface appears to have been produced by rolling in sand while it was still damp. A few crucibles are also known from contemporary sites in the west and north, such as Dinas Powys (Alcock 1963) and Dunadd (Lane and Campbell 2000). These are all simple and rather small handmade forms with bowls being among the most common.

Many more sites have provided evidence for melting copper alloys in the late Saxon period. The examples from Winchester are made by hand using not very refractory clays (Bayley and Barclay (1990) while those from York (Bayley 1992) and Lincoln (Bayley 2008) are usually wheel-thrown in Stamford ware. Other sites often yield both handmade and Stamford ware crucibles, eg London (Bayley *et al* 1991). Stamford ware was used for the production of a range of domestic forms but the clays used were well suited for the melting of copper alloys due to their refractory characteristics (Bayley *et al* 1991). The Stamford ware crucibles have maximum diameters of 60–90mm, rim diameters of 30–70mm and heights of 50–70mm (the bases were pushed out). The walls are typically 2–5mm thick giving capacities of 25–200ml (200g–1.5kg of molten metal). A small proportion of the crucibles were provided with an extra outer layer which would have provided greater insulation and protection from thermal shock.

Evidence for later medieval crucibles is less abundant although the assemblage from the Guildhall, London (Bowsher *et al* 2007) shows that by the end of the 13th century crucibles usually were often larger. The Guildhall crucibles have vertical sides with rounded bases. The diameters are usually 100mm and the walls 10–20mm thick; although none from this site survived to their full height, the capacity is estimated at 400–500ml (3–4kg of molten metal).

The 15th century saw the appearance of distinctive triangular crucibles (Cotter 1992; Martinón-Torres 2012; Martinón-Torres *et al* 2008). These were rather small crucibles made from highly refractory clays (originally from Hesse, but with later production elsewhere). The crucibles were wheel thrown with flat bases but the rim was pulled to produce a triangular form (similar round vessels are known in virtually the same fabric). The crucibles were produced in a range of sizes with heights from 20mm to 150mm (giving volumes of 5–500ml). The crucibles were made from highly refractory clays with very low alkali and iron content. In addition, some were tempered with quartz and some with graphite. These crucibles were probably used for a range of metallurgical activities including casting molten metal as well as testing ore quality and more alchemical procedures (Martinón-Torres 2012). The flat bases of these crucibles suggests that most heating took place in reverberatory or muffle furnaces.

Figure 37

Roman crucible from Dorchester, Dorset (120mm high). Crucibles are invariably grey or black as a result of being reduced-fired. Crucible clay was usually tempered with fine sand or, occasionally, organic matter. Crucibles can become vitrified because of the high temperatures at which they are used, either developing a thin external 'glaze' or becoming glassy and bubbly throughout their entire thickness. Some crucibles have an added outer layer of less refractory clay, to improve heat insulation and to increase the robustness of the vessel, and this usually becomes heavily vitrified. Small quantities of the metal being melted can become chemically bound in the crucible surface, or physically trapped as droplets of metal. Copper can be seen as green corroding droplets or as bright red patches where it has reacted with the glassy surface of the crucible. Chemical analysis (see p 65), however, is often the only way of determining the process in which the crucible was used.

By the 16th century fairly large and thick-walled crucibles often with flat bases became the norm for casting copper alloys (eg Bayley and White 2013). These crucibles could be up to 240mm high with capacities of 1.5l (equivalent to over 10kg of molten metal). These crucibles were made with a high proportion of grog (old pots) as temper and the absence of any rilling (as well as the coarseness of the grog) suggests they were probably made by mould forming.

Casting copper alloys requires a mould in order to produce a casting of the desired size and shape. Moulds might be open or closed and might be made from a variety of materials: sand, clay, metal

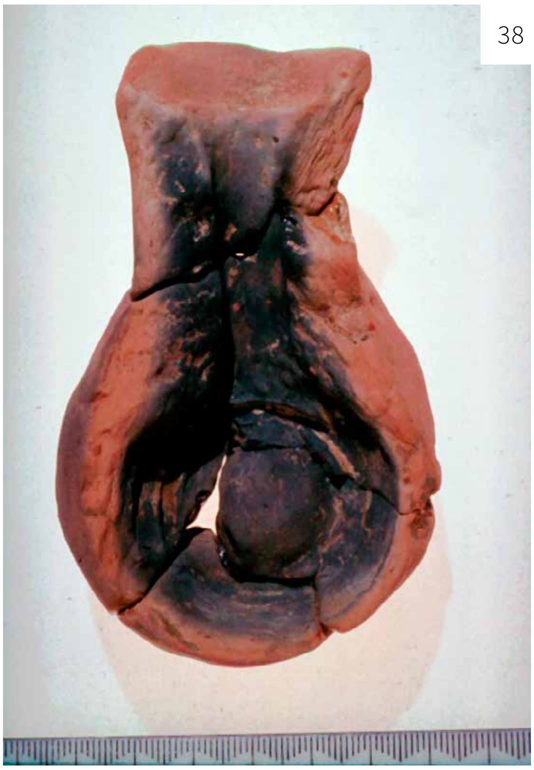
38


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Figure 38–41

38. Part of an investment mould from Beckford, Worcestershire. It has no mating surfaces since it was made in one piece. Note the in-gate at the top and the runner down to the circular object.
39. Complete clay piece mould for a trumpet brooch from Prestatyn, Clwyd. The in-gate is by the foot of the brooch. The locating marks round the edges of the two halves (valves) of the mould which would have aided correct assembly, can clearly be seen. Fragments of luting clay, which was used to seal the join, is also sometimes found.
40. Part of the cope (outer part) from a cauldron mould from Prudhoe castle, Northumberland, Note the inner surface in reduced-fired (black) but the outer surface is oxidised-fired (red).
41. Sprue with two runners from Wicklewood, Norfolk, cut from a copper alloy casting.

or stone. Moulds for small objects were usually made of either fired clay or, less commonly, fine-grained stone. Clay moulds are not common finds, partly because they are fragile and so do not survive well. The clay used to make moulds was usually carefully selected and processed and was usually tempered with fine sand or organic matter. Clay moulds are invariably grey or black (reduced-fired) on their inner surfaces, which were in contact with the cast metal, and orange-red (oxidised-fired) on the outer surfaces. Clay moulds were usually broken open to recover the casting, so identification of the objects cast is often difficult. When clay moulds survive well, the way they were made and used can be determined (Figs 38 and 39). Often the largest and most easily identifiable fragments of ceramic moulds are the funnel-shaped in-gates.

Two main types of clay moulds are found, investment (lost-wax) moulds (Fig 38) and piece moulds (Fig 39). Investment moulds were made by first modelling an object in wax and coating it thickly in clay. The clay/wax assembly was then fired and the wax melted or burnt out to leave a fired clay mould. Molten metal was poured into the mould and allowed to solidify, then the mould was broken to remove the casting.

Piece moulds were formed in two or more sections. An original object, or a pattern made in the desired shape, was impressed into a lump of clay and locating marks made round the edge. Another piece of clay was pressed over the pattern. The two valves of the mould were then separated, the pattern was recovered, and the mould reassembled and sealed (luted) with more clay. The mould was then fired and used. Although the valves of clay piece moulds could be taken apart, they were fragile and therefore are not likely to have been used more than once. Multiples clay piece moulds could also be assembled using a single pattern which allowed the casting of several identical objects at once (Armitage *et al* 1981; Bowsher *et al* 2007). Patterns in wood or lead for making piece-moulds are known, if rare.

Stone moulds were more durable than clay but required greater effort for their manufacture. Only some types of stone are able to withstand the high temperatures involved in casting copper alloys. Stone was used to make moulds in the Bronze age (especially in the north and west) but are rarer in later times. Bronze age stone moulds are often simple one-piece open moulds for the casting of simple flat axes, although more complex objects such as spearheads were cast using stone moulds (Tylecote 1986). Later stone moulds are usually restricted to ‘ingot’ moulds, that is simple rectangular cavities. Some Bronze age metal moulds are also known and these were used mainly for casting palstaves and socketed axes. Bronze moulds were used during the Roman period for the manufacture of brooches (Bayley *et al* 2001). Nevertheless, it is likely that most copper casting made use of clay moulds.

Large objects such as cauldrons and bells were also cast in moulds. The process of making these moulds (Fig 40) is well known from medieval documents such as Theophilus’ *De Diversis Artibus* (Hawthorn and Smith 1979). Sometimes a tallow model was used, the mould was formed around it, and then the tallow was melted out. Another method was to shape the inner part of the mould (the core) first, then to make the outer part of the mould (the cope) around it. The cope was then removed, in pieces if necessary, and the core trimmed down. When the mould was reassembled there was a void left between the cope and the core to receive the molten metal. These moulds were broken to remove the casting (Blaylock 2001; Dalwood and Edwards 2004; Dungworth and Maclean 2011).

As well as the moulds themselves, corroded spillages of metal can be found. Castings were cleaned up (fettled), with surplus metal such as flashings (the metal that ran between the valves of a piece-mould), runners and sprues trimmed off, and these are also sometimes found (Fig 41). Failed castings, where the molten metal failed to completely fill the mould, are also found.

4.4 Wrought metalworking

Wrought metalworking describes the processes of shaping the solid metal, for example by hammering or cutting. Unlike ferrous alloys, copper alloys can be easily worked at room temperature. The most commonly used tool would be the hammer, although comparison with modern practice shows a variety of other tools could be used, such as strakes. Wrought work most commonly produced sheets, strips and wires. Larger items could be made from sheet by riveting components together. Early rivets were simply small fragments of copper alloy. These could be initially cast into shape but were also formed by rolling up a short length of strip or sheet. The rivet was inserted into the sheets to be joined and hammered from both sides to form 'heads'. Most cauldrons made before the later medieval period were made in this way.

When copper alloys are hammered at room temperature the metal becomes work-hardened. This increased hardness is often desirable, but it also leads to increased brittleness. If a large amount of working is required to produce a particular object, the metal must be heated between successive bouts of working otherwise it will eventually break. This heating stage is known as annealing, and it causes the crystalline structure of metal to regenerate, restoring its original toughness and softness so that working can continue. Annealing takes place at temperatures that could be achieved in a domestic hearth: less than 800°C (Dungworth 2013).

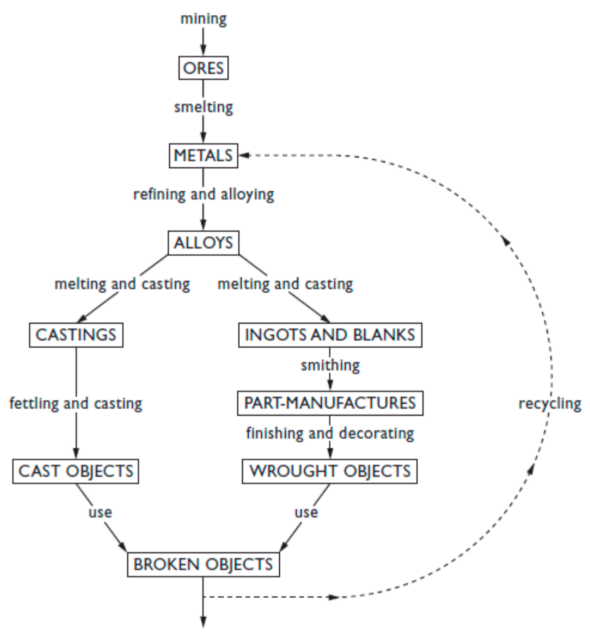

Figure 42

Flow chart showing how the product of one metalworking process is the raw material of the next.

Large ingots of metal are not usually found on wrought metal working sites. The metal workers used small ingots or blanks as their starting point, producing sheets, bars, rods and wires of metal, which were then worked further to produce finished objects using hammers, files, gravers, chisels, dies and punches. Anvils made of various materials, such as bone, wood and iron, are occasionally found. Evidence for wrought metalworking comprising small pieces of scrap metal, such as turnings and sheet and wire offcuts, is occasionally found. Metal filings and offcuts were collected for recycling, sometimes in boxes set into workshop floors (Fig 2 and Zienkiewicz 1993, Figs 13–14). Whetstones and abrasives were used to create a good surface on metal objects, which was then polished. Alternatively the surface could be burnished with a hard material such as steel or agate.

Water was used to power hammers for the production of sheet metal and hollow ware, such as basins, from at least the 16th century. This formed a significant industry in some areas, such as Bristol (Day 1973). Water power was also used to draw wire; and in the 16th century it was harnessed to power rolling mills.

The archaeological evidence for the wrought working of copper alloys is often most apparent in the objects themselves. Visual examination can indicate how an object was wrought to shape (eg early cauldrons). Where the outward form of an object does not provide obvious clues as to the forming process, this can be uncovered through an examination of its microstructure (see p 64). Aspects of the later, water-powered industry can be determined from a study of the surviving mill buildings (Day 1973).

5 Archaeometallurgical Processes and Finds: Lead

5.1 Background

Lead has a low melting point of 327°C and lead ores can be reduced to lead metal below 800°C. Lead is very soft and is easily formed into sheets. It has a tendency to creep, that is, to distort slowly over long periods of time. Because of its high density, lead was often used to make weights.

Alloys of lead and tin were used as soft solder and, from the Roman period onwards, they are also used for casting objects – which are described as pewter.

5.2 Smelting

The common lead ore is galena (lead sulphide, PbS) which often contains minor amounts of silver. The silver content was often the main economic reason for mining and smelting the lead (see p 53–55). There is relatively little archaeological evidence for early lead smelting and few of these sites have been studied in sufficient detail to fully understand the lead smelting technology. A great many sites are known but not dated (eg Murphy and Baldwin

Lead in summary

Lead is a very soft, dense metal with a low melting point of 327°C. Lead ores were often mined and smelted for the silver that they contained (p 54–55).

Process	Summary	Archaeological debris
Smelting	Lead ores can be smelted at less than 800°C, so simple structures could be used, which rarely survive. Early furnaces (bole hills) made use of natural draughts. Later, bellows-blown furnaces (ore hearths) were developed, which were subsequently adapted for waterpower. Reverberatory furnaces (cupolas) developed in the 17th century and were coal fired. Smelting produced molten lead metal and liquid slags. The lead-rich slags from early processes were often re-smelted later.	Shallow clay depressions have been found from the Roman period. Later structures were sometimes stone built. Sparse vegetation can indicate lead contamination. Some slag and evidence of waterpower can be found. The flues of reverberatory furnaces often survive.
Lead working	Owing to the low melting temperature of lead, domestic pots could be used instead of crucibles when melting lead. Limestone, wood or antler moulds could be used instead of clay ones for casting lead.	Ingots are quite common. Lead sheet, offcuts and lead-melting dross are sometimes found. Moulds, failed castings and sprues indicate that lead was cast.

Figure 43

Lead smelting slags are known in small amounts from the Roman period onwards. They are often glassy, very dense and black, green or grey in colour, although the surface can be creamy coloured due to the formation of lead carbonate on the surface. While some lead slags have a flowed surface, similar to iron-smelting tap slag, some lack any diagnostic morphology.

2001; Smith 2006; Smith and Murphy 2010). Later lead smelting is described in a number of documentary sources but marrying this historical evidence to the available archaeological evidence is a continuing challenge.

The common lead ore, galena (PbS), is much easier to smelt than most other metals. If galena is heated in air then it tends to oxidise to the sulphate ($PbSO_4$) and ultimately the oxide (PbO). Both of these compounds will readily react with galena to form metallic lead and sulphur oxides (the latter will be dispersed as a gas). Any gangue minerals (especially silica) will react with some of the lead oxide to form lead-rich slags (Fig 43).

The recovery of over a hundred inscribed Roman lead ingots suggests lead production occurred on a large scale. Excavations have identified Roman lead smelting at a number of sites, including Llangynelin, Dyfed (Page 2005), Flint (Petch and Taylor 1924) and Scarcliffe Park, Derbyshire (Lane 1973), however, insufficient information is currently available to determine details of the smelting technologies employed. In most cases all that remains of the smelting furnace is a bowl-shaped depression with signs of burning. No clear evidence for superstructure has been recovered. In contrast with the largely undated bole smelting sites (see below) the Roman smelting does not appear to have made use of prevailing winds to aid the smelting process.

Field survey (plus a small amount of excavation) has recognised a large number of early lead smelting sites in upland regions with associated lead ores (Murphy and Baldwin 2001; Smith 2006; Smith and Murphy 2010). These sites are known as boles or bales and some have been traced through place name evidence suggesting that some were in use in the medieval or early modern period. Bole sites are often sited on exposed hilltops – it is likely that such sites were chosen to exploit prevailing winds. Some sites have also been identified during field survey through the presence of lead-tolerant flora or in extreme cases the complete absence of plants. Few boles have been systematically excavated (eg Anguilano *et al* 2010; Timberlake 2002).

Although parallels for boles are often sought in the historical literature (Blanchard 1981; Kiernan 1989), the documentary evidence (largely Tudor in date) indicates large, if simple, hearths that do not match the slight archaeological remains (eg Anguilano *et al* 2010). The few boles that have been excavated usually comprise an area approximately 1m in diameter with some evidence for burning with a scattering of lead slag (Anguilano *et al* 2010). The late 16th-century description of a Derbyshire bole (Kiernan 1989, 40–43, Figure 4) indicates a rectangular furnace 6m long and 3m wide with stone walls on three sides (the fourth side being exposed to the prevailing wind. The documentary sources suggest that bole smelting used wood rather than charcoal and that each smelt would consume 30 tons of wood and 40 tons of ore but yield 18 tons of lead. It is likely that the bole smelting would be a seasonal activity undertaken only a few times a year.

Documentary sources indicate that bole slags were being re-smelted using charcoal fuel in a foot-operated, bellows-blown hearth known as a blackwork oven in Devon by the late 13th century (Claughton 1992) and in other areas somewhat later. Historical sources show that during the 16th century, lead smelters changed from boles to structures known as ore hearths. Air was blown into the hearth with bellows and this forced draft made the process more efficient at extracting lead. In Derbyshire these hearths were fuelled with kiln-dried wood, and the kilns can be found near the ore hearth remains, but in the northern Pennines peat was used. Ores rejected by bole smelters, as well as bole slags, could be smelted in ore hearths. The ore hearth began to make use of water-powered bellows technology and so most were sited in river valleys adjoining the mining districts. Water-powered ore hearths continued to be used until the late 19th century (Tylecote 1986). By the 17th century smelters were re-smelting the slag from ore hearths in structures called slag hearths (Paynter *et al* 2010) which were usually water-powered and often fuelled by coal or coke.

In the later 17th century the cupola was introduced (King 2001–2). These coal-fired reverberatory furnaces consisted of a chamber containing the ore and another containing the coal fire. The heat from the fire was drawn into the smelting chamber. The chimney provided an induced draught which removed the need for bellows and the provision of doors allowed the smelters to manipulate the atmosphere (oxidising-reducing) inside the furnace. The advantages of this process were yet greater smelting efficiency and fuel economy. From the mid-18th century this technology was rapidly adopted and towards the end of the century the associated flues became very long and complex, with condensing chambers to collect metal-rich residues. As the stone from these constructions has often been robbed, frequently all that remains are the trenches leading from furnace to chimney. Such furnaces were used into the 20th century (Crossley 1990).

Archaeological evidence for many of the latter processes and furnaces (such as blackwork ovens, ore hearths, slag hearths and cupolas) is limited. While samples of waste materials have been collected during fieldwork it is sometimes unclear whether these represent raw materials (ie slag from an earlier process, such as bole smelting) or are waste products.

5.3 Lead working

Newly smelted lead was cast into ingots, often known as pigs, which are quite common, particularly from the Roman period. The main evidence for lead working, however, is lead melting dross. This is the oxidised layer of metal, which forms on the surface of the melt and is skimmed off before the metal is poured. Other evidence of melting is harder to detect because any domestic pot could be used, instead of a crucible, owing to the metal's low melting point. The low melting point also means that the metal can easily be melted accidentally, so the presence of melted lead is not necessarily an indication of lead working. Much lead was used as sheets and sheet offcuts are common finds. Lead from buildings was frequently recycled, being easily melted down and re-cast.

For casting lead or pewter objects, fine limestone, wood or antler moulds could be used instead of clay because the moulds did not have to stand high temperatures (Fig 44). Roman pewter plates were cast in stacking stone piece-moulds (eg Lee 2009). Antler burrs were carved to act as moulds for late Saxon brooches (eg Newman 1993). As with copper alloy casting, sprues and failed castings are sometimes found.

Figure 44

A later medieval piece-mould made of fine-grained stone with holes for locating pegs at the corners from Hereford (length 57mm).

6 Archaeometallurgical Processes and Finds: Other metals

6.1 Silver and gold

Unlike most other metals, the main source of gold is native gold, rather than an ore. Gold mining occurred in Wales during the Roman period (Burnham and Burnham 2004). Silver was mainly obtained from argentiferous, or silver-rich, lead and the mining of lead was often undertaken for the silver that it contained (see p 49). Precious metals have similar melting temperatures to those of copper alloys and were melted in clay crucibles. The metals could be cast to shape or, more commonly, worked as solid metals. Both silver and gold are very soft. They were alloyed with each other and with other metals, commonly copper, and the alloys have the advantage of being harder than the pure metals (Bayley 1991a).

Silver and gold in summary

Native gold is the principal source of gold. Silver is mainly obtained from lead ores (p 49). Silver and gold are soft metals with similar melting temperatures to those of copper alloys. They were commonly alloyed with each other, and with copper and other metals.

Process	Summary	Archaeological debris
Refining silver and gold	To separate silver from base metals the cupellation process was used. This involved melting the silver alloy with added lead and oxidising the melt. Cupellation could also be used to test the purity of silver (assaying). Shallow dishes (cupels) were used for small-scale cupellation and assaying, but large-scale cupellation took place in hearths. Gold refining and assaying usually did not use lead.	Early cupels are ceramic (heating trays). Later ones were made from bone ash. Litharge cakes are formed during large-scale cupellation.
Parting silver and gold	To part silver from gold, the silver was removed by reacting it with salt. Later, strong mineral acids were used.	Ceramic parting vessels.

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Figures 45–48

45. Primary litharge the waste material produced during the extraction of the small amounts of silver that occur naturally in most lead. The litharge has a red colour but the surface usually weathers to a cream colour (lead carbonate). Primary litharge often occurs in large lumps and lacks the greenish colour often seen in secondary litharge.
46. Secondary litharge the waste material produced during the recovery of silver from debased silver alloys. Secondary litharge is red but often weathers to a greenish colour due to the presence of small amounts of copper. Secondary litharge generally occurs in smaller lumps than primary litharge.
47. Ceramic cupel or heating tray from Bainbridge Roman fort and settlement. The vitrified upper surface is rich in lead and highly coloured. There is a central depression where the assayed metal solidified. Sometimes droplets of silver or gold that failed to coalesce became trapped in the area surrounding the depression (Gardner 2009).
48. Bone ash cupels from the Tower of London: the top and right examples are unused while the left and bottom examples have been used. Unused cupels are pale coloured and powdery. The absorbed lead in used cupels makes them noticeably heavy for their size. Note also the circular impression in the centre of the used cupels where the silver formed.

6.1.1 Refining

Gold and silver were often refined before use, or reuse, especially if the metal had previously been debased. The purity of gold could be determined by using a touchstone, which was a black stone used to obtain a smear of metal, the colour of which was an indication of its purity. Gold could be refined somewhat in a crucible by using oxidising conditions – copper and other base metals would be oxidised and form a dross or slag while the gold (and any silver) would remain unchanged. Silver was removed from gold-silver alloys by a parting process (see below).

Silver was extracted from lead (and recovered from debased silver) by a process known as cupellation. Slightly different cupellation processes were used depending on the scale of the refining and the nature of the starting material. Nevertheless, the processes were all fairly similar. The raw material (lead or debased silver) was placed in a hearth with fuel and a strong air blast used to oxidise the base metals which were then absorbed into the hearth lining. The silver (as well as any gold) remained at the centre of the hearth. Lead-rich hearth lining (litharge) is the most commonly recovered evidence for this process.

The use of the cupellation process for the extraction of silver from freshly smelted lead (primary cupellation) is known from a few Roman sites (eg Bayley and Eckstein 1998; Dunster and Dungworth 2013). The litharge from these sites tends to occur as fairly large pieces up to 60mm thick and probably from heaths around 0.6m in diameter (Fig 45). The other elements present in litharge cakes suggest that the hearth lining comprised clay, possibly mixed with wood ash.

The cupellation process used to recover silver from debased silver alloys is well known from a number of urban sites from the Roman period onwards (Girbal 2011). In order to ensure that the hearth lining effectively absorbed the oxidised base metals it was common to add lead to the debased silver. The lining of the hearth could be made from clay (and wood ash) or from bone ash.

Before the cupellation process was used to recover silver from debased silver alloys it was common to carry out a test first to determine the proportion of silver present. This test comprised simply of a very small-scale cupellation: the weight of silver was compared to the weight of the test piece to determine silver content. From Roman and Saxon times small ceramic dishes, often called heating trays, were used as cupels and makeshift varieties were sometimes made from potsherds (Fig 47). The reaction of the litharge with these ceramics produced a glassy surface. By 1600 AD cupels made from absorbent bone ash were being used (Fig 48).

Analysis of some heating trays used for gold assaying has failed to detect lead. This suggests that the gold was simply melted in strongly oxidising conditions to burn out the base metal impurities, perhaps with a flux of some sort. Ceramics used for gold assaying are usually made of harder, more refractory, fabrics than those used for silver.

Later processes were developed to improve the extraction of silver from lead. In the Pattinson process (1833) the lead was allowed to cool slowly; the first metal to solidify was rich in lead which left the remaining molten lead enriched in silver. The silver was then recovered from this enriched lead using cupellation. The Parkes process (1852) used the addition of zinc to extract silver from lead: zinc and lead are immiscible but silver readily dissolves in the zinc. The zinc-silver compounds could be easily separated from the lead and then heated to drive off the zinc.

6.1.2 Parting

Cupellation could not be used to separate, or part, silver from gold, so a different technology was developed. Two different parting processes are known from historical and archaeological sources: salt parting (Bayley 1991a) and sulphur parting (Rehren 1996), although the former appears to have been more common.

For salt parting, the gold-silver alloy was hammered into thin sheets, packed into a pot interleaved with a ‘cement’ of crushed brick or tile mixed with common salt (NaCl). The pot was then sealed up and heated, but to a temperature below the melting point of the metal. The salt would react with the silver, forming silver chloride, which would then be absorbed by the cement and the walls of the pot (Fig 49). When the pot cooled, the gold could be removed and re-melted and the cement smelted to recover the silver (Bayley 1991a).

Sulphur parting could employ sulphur or metallic sulphides (such as antimony sulphide) which would react with the silver (to form silver sulphide) and leave the gold unchanged. With the introduction of distillation in the later medieval period, the method of parting changed to one using strong mineral acids.

Figure 49

Parting vessels were not always purpose-made and a wide variety of vessels were used; all were lidded or would have been sealed with clay. They are the only metal-working vessels that are normally oxidised fired. They are readily identifiable as they usually have a pale pink-purple colour on the inside rather than the orange-brown normally associated with oxidised-fired ceramics. Sometimes areas of lemon-yellow colour, specular haematite crystals (as here on a fragment from Lincoln), or even flecks of gold are visible. Some parting vessels show no surface vitrification, while others have a thick, exterior glaze that can be turquoise or deep green.

6.2 Tin

Tin is a soft, white metal with a melting point of 232°C. Its primary use was in alloying copper to form bronze, however, it was also alloyed with lead to form pewter and from the 18th century it was applied to iron sheets (tinplate). Tin ores are found in only a few locations globally and the important cassiterite (SnO_2) deposits in Devon and Cornwall were exploited from the Bronze Age onwards.

6.2.1 Mining

Cassiterite can be found as veins (lodes) that extend to considerable depths but much of this ore was not exploited until the 18th century when steam power made deep mining possible. Streams have also eroded the exposed veins of lode tin and deposited this in sediments in the valleys that radiate from the area of lode tin. These deposits could be excavated and the stream tin sorted by washing (it is much denser than the sediment). Stream tin was probably exploited before lode tin, however, archaeological evidence for either activity is rare before the 18th century.

Tin ores would usually have to be crushed and sorted to reduce the proportion of gangue minerals (Gerrard 2000). From the 14th century the crushing (or stamping) of ore increasingly used water-powered hammers. Stamp mills can be positively identified by the presence of mortar stones with saucer-shaped hollows on which the ore was crushed. The partly crushed material from the stamp mill was ground to a fine powder in a crazing mill. Around the mid-16th century most crazing mills were abandoned because of the introduction of the more efficient wet stamping process. Water was used to separate the dense cassiterite from the lighter gangue. Some of the clearest remains of mining are the heaps of waste gangue minerals that surround mine site.

6.2.2 Smelting

There is little archaeological evidence for early tin-smelting processes. A number of tin ingots have been found with a roughly plano-convex shape, however, most of these have not been recovered from an archaeological context and so cannot be dated. High grade cassiterite can be reduced to metallic tin at fairly low temperatures in a bowl furnace (Timberlake 1994). Lower grades of cassiterite can be smelted at low temperatures, however, the presence of abundant gangue minerals would prevent the smelted tin from collecting at the base of the furnace. If higher temperatures were employed (eg >1000°C) then the gangue minerals would combine to form a slag. This slag would tend to contain some tin depending on the smelting temperature and the atmosphere (oxidising-reducing) inside the furnace. The rather amorphous shapes of the few examples of early tin smelting slag that have been reported indicate that it would have been fairly viscous (Lawson-Jones 2013; Malham *et al* 2002). Most reported tin slag occurs as relatively small fragments and these could have been broken up to recover some of the trapped tin.

In the 14th century water wheels began to be used to power the bellows in what quickly became known as 'blowing houses' (Greeves 1994). The furnaces were largely built of stone blocks (often granite) although they were probably lined with clay and the preferred fuel was charcoal. The molten tin was tapped from the furnace hearth into a trough and was then ladled into smaller moulds or troughs (Gerrard 2000). From the beginning of the 18th century the coal-fuelled reverberatory furnace was used for smelting tin ores (Smith 1996). Smelting debris from a number of sites (Farthing 2005; Malham *et al* 2002) including manually-powered bellows smelting, blowing houses and reverberatory furnaces has been examined. It is striking that the chemical composition of slags from sites with manual bellows and water-powered bellows show few differences; the reverberatory furnace slags, however, have quite distinct compositions (higher iron and calcium content and usually less tin).

6.2.3 Alloying

Tin has been used with copper since the Bronze Age to produce the alloy bronze. The vast majority of bronzes contain 8–12wt% tin which yields a substantially harder metal than pure copper but which retains enough toughness to be serviceable for the manufacture of tools and weapons (Allen *et al* 1970). Bronzes with greater amounts of tin have found occasional specialist uses: 20–25% tin produces a silvery white metal which was used in Roman times for the manufacture of mirrors, and the brittleness of the alloy made it suitable for the manufacture of church bells (a lower tin content would give a tougher metal which would not ring when struck).

From the Roman period onwards tin was alloyed with lead to produce soft solder and pewter. Alloys of tin and lead have very low melting temperatures (<200°C) and so can be used to join other metals together. Soft solder can be used by bronze smiths as well as by plumbers and window makers who need to join lead components together. Pewter was used for the production of tableware during the Roman period (Lee 2009) and became popular again in the late medieval and post-medieval periods (Egan 2005). Its low melting temperature means that pewter does not need to be melted in refractory crucibles. Medieval and later texts often refer to the use of iron pans or pots for melting pewter; earlier pewter melting may have used domestic pottery. The archaeological record provides little direct evidence for the casting of pewter. Stone moulds for casting plates are known from the Roman period (Lee 2009) and it is likely that clay was used for at least some types of object. Documentary sources suggest that copper alloy moulds were used from at least the 15th century.

Tin has occasionally been used to coat the surface of another object (copper alloys and iron) to give a silvery white appearance. From the early 18th century increasing quantities tin were used in the manufacture of tinplate (p 38).

6.3 Zinc

Zinc has low melting (420°C) and boiling temperatures (907°C) and so any attempt to reduce zinc ore using charcoal fuel at around 1000°C, would result in the zinc metal being produced as a vapour and so lost as fumes. Consequently zinc was not generally available in Europe until the post-medieval period. Zinc was manufactured in India and small quantities were imported from the 16th century. Zinc manufacture was introduced into Britain in the 18th century. Nevertheless, zinc is found in much earlier copper alloys, such as brass (copper-zinc alloy).

From the 1st century BC brass was produced by a cementation process. Ground zinc ore was mixed with copper and charcoal in a crucible which was then sealed and heated to between 950°C and 1000°C (below the temperature at which copper or brass melts). The charcoal provided a reducing atmosphere in the crucible, so the zinc ore was reduced to metallic zinc metal, which was absorbed by the solid copper (Bayley 1998). Crucibles for brass cementation have been recognised from Roman (Bayley 1998) and post-

Figure 50

Base fragment of a 16th-century brass cementation crucible from Taynton, Gloucestershire. The intense blue-purple colouration is due to the reaction between the crucible and zinc.

medieval contexts (Dungworth and Wilkes 2010). Prolonged use of crucibles for brass cementation can cause the clay to turn blue or purple (Fig 50).

During the 18th century the direct manufacture of metallic zinc was introduced to Britain. Zinc ore and a reducing material (charcoal or coal) was packed into a ceramic retort. The retorts were placed inside a conical furnace (similar to a steel cementation furnace). The holes at the base of the retorts were connected by pipe to buckets outside the furnace. The heat of the furnace reduced the zinc ore to metallic zinc which then descended the pipes and collected in the water-filled buckets. The retorts were made from similar clays to the brass cementation crucibles and usually have the same intense blue-purple colour (Dungworth and White 2007).

6.4 Other metals

The metals described above are those that are most frequently encountered in the archaeological record. The chemical analysis of these metals will often reveal the presence of small amounts of other metals. In most cases these other metals would not have been deliberate additions; instead the ores used would contain impurities which could be carried through to the finished metal. The extent to which finished metal will contain such impurities (sometimes referred to as trace elements) will depend on the nature of the ore and the smelting and refining processes employed. Common impurities in gold include platinum group metals while copper alloys can often contain arsenic, nickel and antimony. While impurities can be removed by refining, this will often mean a lower yield metal (eg losses in refining slag). In some cases the presence of impurities may have beneficial properties. The arsenic in the earliest copper artefacts (Allen *et al* 1970) simply reflects the nature of the ores used. Nevertheless, early copper smiths often seem to have been aware of the physical characteristics of copper with or without arsenic and used these alloys appropriately (McKerrell and Tylecote 1972). In the medieval period the copper alloy used to manufacture cauldrons (Dungworth and Nicholas 2004) was particularly rich in impurities (it was a bi-product of extracting silver from argentiferous copper ores). In this case the impurities had no detrimental effect on the finished metal goods (the interior of the cauldron would be coated in tin) and the impurities ‘bulked out’ the metal.

7 Non-Metallurgical Residues and Materials

A variety of materials are sometimes confused with the debris from metallurgical processes. These include naturally-occurring materials (especially geological material), debris from non-metallurgical industries, conflagration debris, heat magnetised residues and plastics and tarmac.

7.1 Geological materials

Some types of iron ore (especially bog iron ore), pyrite (iron sulphide) nodules, pieces of puddingstone, and lava can all be mistaken for slag.

Iron-rich concretions are often recovered during archaeological excavations. These comprise lumps of soil or sediment joined together by iron compounds (Fig 53). They form as a result of the re-deposition of iron compounds in a similar manner to the natural phenomenon of iron panning. The process is sometimes enhanced by the presence of iron objects or scrap metal.

7.2 Debris from non-metallurgical industries

Few early non-metallurgical industries reached temperatures high enough to vitrify materials and so produce debris that can be recovered archaeologically. Occasionally pottery, brick and tile kilns became too hot and the ceramics inside were over-fired. Pottery wasters have slumped and distorted shapes and can be glassy and blistered (Historic England 2015b).

Any industry which used wood or another organic fuel to provide heat would produce quantities of ash. If the temperatures were sufficiently high then this ash would vitrify and produce a durable residue – vitrified fuel ash (Fig 54). Some vitrified fuel ash can form as a result of the fires used in some metallurgical processes, however on its own it is not diagnostic (Biek and Bayley 1979).

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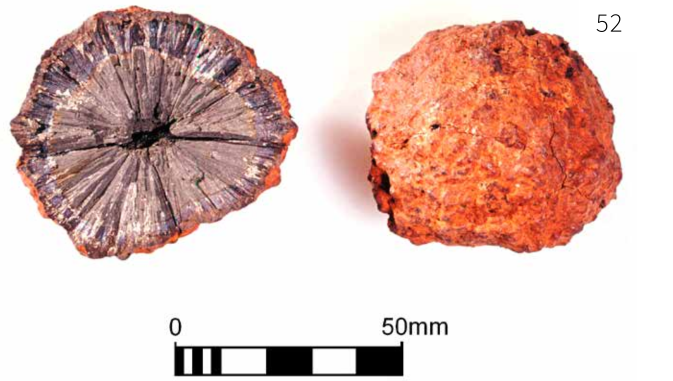

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Figures 51–55

51. Section through a puddingstone boulder; the rounded exterior can be mistaken for iron slag.
52. Pyrites nodule. The weathered outside (right) can look like iron slag but the interior (left) has a silver colour and radial structure.
53. An iron concretion consisting of pebbles and sand grains bound together by iron compounds. They are amorphous orange-brown lumps that respond poorly to a magnet but do not have the typical vitrified surfaces of metal working debris.
54. Vitrified fuel ash from Furzton, Buckinghamshire. They are lightweight, vesicular and fragile, and are usually off-white to green or mid-grey in colour, generally much paler than iron-working slags.
55. Vitrified coal ash (clinker) from the 17th-century coal-fuelled glass furnace at Silkstone, South Yorkshire.

The working of glass requires very high temperatures and glass production sites yield a variety of diagnostic residues (English Heritage 2011a). This will often include recognisable glass waste as well as crucibles which crucially have most vitreous material inside the crucible while the vitrification of crucibles for melting metals is usually restricted to the exterior. Glasshouses of the 17th century and later often yield large quantities of vitrified coal ash (clinker, Fig 55) which can be difficult to distinguish from clinker formed in different contexts (eg blacksmithing or heating steam engines).

The manufacture of salt usually made use of ceramic containers (briquetage) in which brine was heated. Briquetage is usually fairly soft and oxidised-fired (orange-red) but does not have any vitrified surfaces.

7.3 Conflagration residues

Where a structure has burnt down (deliberately or by mischance) durable residues can form and these can be mistaken for slags. The ashes from burnt thatch or structural timbers can react with daub walls to form vitrified fuel ash and/or vitrified clay. This material is not readily distinguishable from the vitrified fuel ash described above.

Buildings that contain a greater variety of building materials can produce more complex conflagration debris (Fig 56). Lead fittings within a building (window lead, plumbing or roof lead) will easily melt, oxidise and react with brick, tile or stone to form glassy residues. A severe fire can even melt window glass which will react with other materials such as brick and tile.

7.4 Heat-magnetised residues

Soils samples taken for the recovery of plant macrofossils (English Heritage 2011b) often contain magnetic residues which are mistaken for hammerscale (Keys 2012). A variety of naturally-occurring materials and sediments containing at least some iron can acquire a weak magnetism as a result of exposure to heat.

7.5 Plastics and tarmac

Modern plastics and tarmac that have been subject to high temperatures will easily melt and can take on colours and forms which resemble a range of metalworking slags (Fig 57). These materials can usually be distinguished from slags by their low density, softness and low melting temperature.

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Figures 56–57

56. Daub and ceramic tiles from a Roman building in London destroyed by fire, which are stuck together by an accidentally-formed lead-rich glass.
57. Partially melted lumps of plastic. These superficially resemble blast furnace and other vitreous slags

8 Scientific Techniques Applied to Metalworking

This section provides an introduction to a few of the scientific techniques that have been applied to the study of early metalworking, including geophysics, microscopy and various methods of chemical analysis. The data obtained can be used to explore a wide range of issues, such as resource exploitation, economy, trade and exchange and cultural affinities.

The scientific study of early materials can provide a wealth of information about the raw materials and manufacturing techniques used. Only the most commonly used methods are described.

8.1 X-radiography

X-radiography is an imaging technique that is particularly useful for examining and recording archaeological metalwork and some types of debris. The main archaeological applications are the identification of objects and examination of their morphology, methods of construction and condition (English Heritage 2006a). X-radiography has been used to identify inlays, stamps, weld lines and pattern-welding in iron artefacts, examine crucibles and moulds (where metallic particles might be trapped in the ceramic fabric), distinguish slag from corroded iron artefacts, and detect hammerscale and other debris in soil samples.

8.2 Geophysics

Geophysical techniques have considerable potential in the study of early metalworking sites and are useful tools for assessing the scale, date, preservation and significance of sites (English Heritage 2008; Vernon *et al* 1999). The two geophysical techniques most commonly applied on metal working sites are magnetometry and magnetic susceptibility.

Magnetometery with a fluxgate gradiometer or a total field instrument (eg alkali vapour) is usually carried out as a prospection technique, as these instruments can take readings continuously, making it possible to survey large areas quickly. Gradiometers record localised variations in the gradient of the earth's magnetic field. These variations can be caused by fired structures and magnetic materials (metallic iron and some slags) as well as by underlying geology. High-resolution gradiometer surveys, in which the data is gathered at smaller intervals than the norm (for example 0.25m), are used for distinguishing features such as furnaces, typically 0.5m in diameter.

Magnetic susceptibility is a measure of the degree to which a body becomes magnetised. Human activity can enhance the susceptibility of surrounding soils. Magnetic susceptibility is rarely used for survey of large areas, but detailed work can be very informative. This technique has the advantage of only measuring to a depth of about 100mm below the coil (depending on the size of the coil), therefore reducing the amount of interference from nearby features with strong responses. It can provide an estimate of, for example, the amount of hammerscale in a sample because this can be related to the signal magnitude. Measurements are made either on the soil *in situ* or on samples recovered from a site (including cored samples).

In situ smelting furnaces result in distinctive dipolar features in magnetometer surveys, which can be further emphasised if the data is not clipped and is plotted on a coloured scale. Magnetic susceptibility survey can also indicate, by a high response, the location of iron working. Bloomery iron slag typically produces a higher magnetic response than topsoil. Magnetic surveys of slag rich areas usually produce a very 'noisy background', with extreme peaks. Large dumps of slag can be so strongly magnetic that they distort the magnetic field for several metres around, masking responses from adjacent occupation features.

Survey of iron smithing sites can reveal strong magnetic responses in areas (workshops) where hammerscale is concentrated. A ground-level hearth should also provide a significant response, although waist-high hearths rarely survive *in situ*. The position of such a hearth (or of an anvil) can be indicated by a low response in an area surrounded by high values (Mills and McDonnell 1992). Survey of non-ferrous metalworking sites should detect hearths and areas of burning, and possibly large dumps of crucibles, moulds or other debris. Domestic hearths, however, can give similar signals.

8.3 Archaeomagnetic dating

Archaeomagnetic dating is a technique that can be used to date the fired clay of furnaces, hearths and slag that have cooled *in situ* (English Heritage 2006b). Materials such as clay, which contain a significant proportion of magnetic minerals, acquire a remanent magnetisation when they are fired. This magnetisation is in the same direction as that of the Earth's magnetic field at the time. The precise direction of the Earth's field varies over time; hence, if a fired clay feature is found that has not moved since it was last fired, it is possible to date the firing using the direction of magnetisation recorded in the feature. Dating ironworking features can be challenging due to the formation of magnetic materials, not least an iron bloom. Samples for archaeomagnetic dating should be taken by, or under the supervision of, a relevant specialist.

8.4 Microscopic examination

Optical and electron microscopes can provide invaluable information on the surface condition and internal microstructure of a wide range of materials, including metals and metalworking debris. The principal types of microscope used are low and high power optical microscopes, and scanning electron microscopes.

Low power (x1–x20 magnification) optical examination (eg Fig 31) can reveal traces of metal on crucibles, traces of silvering or other decoration on a metal artefact, or tools marks and other features diagnostic of the method of manufacture (eg casting seams). It should be used before other analytical or investigative techniques in order to evaluate what further analysis will be useful, whether there are any features in particular that require analysis, for example decorative inlay,

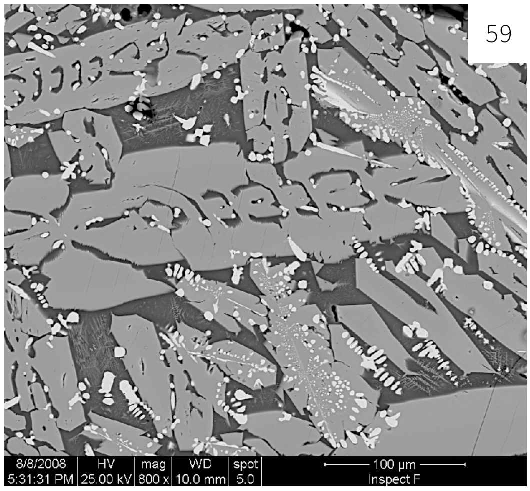


Figure 58

58. Optical microscope image of high-carbon steel from an experimental bloom smelt. The long white laths are iron carbide (cementite) and the areas inbetween are a mixture of cementite and ferrite (plain iron).

Figure 59

59. A back-scattered electron image of prehistoric iron working slag (Shooter's Hill, London) showing several different phases. The white areas are wüstite (and iron oxide) while the larger grey crystals are fayalite (and iron silicate).

and also to ensure that any data obtained is from representative areas.

High power optical microscopes (x50–x1000 magnification) can only be used on flat, polished specimens to determine the internal microstructure of materials. Scott (1991) provides a good introduction to the structure of metals, metallography and the phase diagrams that help explain the microstructures it reveals. Metallography requires the removal of a small sample, which is then mounted in a resin block and polished.

Polished metallic samples can be etched to reveal the crystal structure of the metal (Fig 58). From this an assessment can be made of the type of alloy, its mechanical properties and the ways in which it was treated during manufacture and use (eg Allen *et al* 1970; Blakelock and McDonnell 2007). Metallography can also identify the methods used to apply surface treatments, such as gilding, silvering and tinning. The shape of any non-metallic inclusions often shows the way the artefact has been wrought.

Different iron alloys (plain iron, steel and phosphoric iron) can be identified using a microscope. If a material has been heat treated or quenched, for example to increase the hardness of the metal, this will also be apparent. Steel and iron were sometimes welded together to form composite artefacts. Such structures are frequently found in edged tools and weapons. Techniques for combining different alloys might have important cultural implications. For example, in many Saxon knife blades a steel edge was butt welded to an iron back, while Anglo-Scandinavian smiths favoured 'sandwiching' the steel between two low carbon sides.

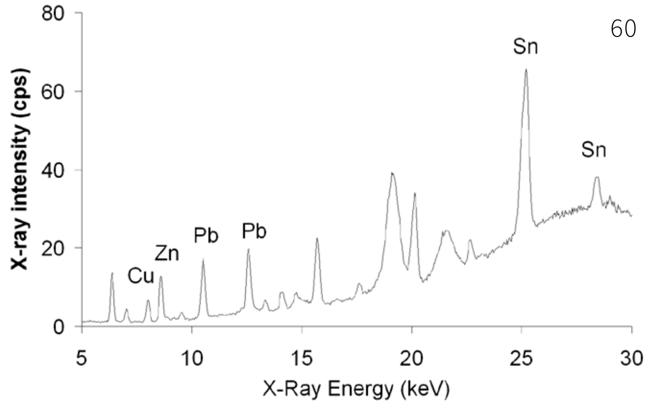
The shape of the metal crystals in non-ferrous alloys will show how the object was produced, for example cast alloys generally have the characteristic dendritic structure. An additional tool frequently used in metallography is hardness testing, which gives a direct measurement of the mechanical properties of small samples.

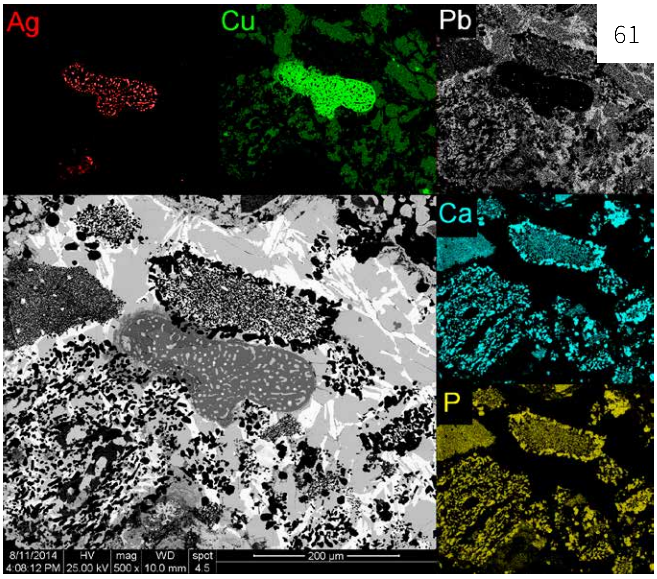
Scanning electron microscopes (SEM) use a beam of electrons, rather than light, to examine a sample. The advantages of electron microscopes are that a much greater magnification and depth of focus can be obtained. Images can be obtained using a variety of detectors, of which the secondary electron detector and back-scattered electron detector are most widely used. Secondary electron detectors provide an image of the topography or shape of a sample (see Fig 30). Back-scattered electron detectors show the compositional differences across a sample (usually a flat, polished sample), since areas with different compositions are seen as varying shades of grey (Fig 59). Sample preparation techniques vary depending on the mode in which the SEM is to be used. The SEM can be used in conjunction with analytical techniques (EDS and WDS), which are described below.

8.5 Chemical analysis

A variety of different analytical techniques are available depending on the questions that are being asked, the nature of the material, and constraints associated with sampling, costs and time. The most common analytical techniques determine either the chemical or mineralogical composition of a material (Pollard *et al* 2007). The chemical analysis of a material can be qualitative (simple presence or absence) or quantitative (proportions of different elements in percentages or parts per million). Many archaeological materials are heterogeneous and corroded; therefore, analysis of very small samples or of surface layers can be misleading.

X-ray fluorescence (XRF) is one of the most widely used methods of chemical analysis in archaeology. A beam of X-rays is directed onto an object, or sample, which then emits an X-ray spectrum. The spectrum (Fig 60) contains peaks for each of the elements present in the object or sample (this does not include light elements associated with organic materials). XRF spectra are detected in one of two ways: energy-dispersive detectors (EDXRF) allow the simultaneous detection of the whole x-ray spectrum, while wave-dispersive detectors (WDXRF) measure the intensity of each characteristic peak individually. EDXRF is relatively cheap and quick, and can determine the presence of most elements within a few seconds. WDXRF is more expensive and slower, but is more accurate and can detect smaller amounts of each element.





Figures 60 and 61

60. An EDXRF spectrum obtained from a crucible used for melting copper alloys, from Mucking, Essex.
61. SEM image (bottom left) and five X-ray maps for various elements in a litharge cake showing several different phases. The red (silver) and green (copper) maps show a silver-copper droplet near the centre, the white (lead) map show the distribution of lead throughout the sample. The light blue (calcium) and yellow (phosphorus) maps show the presence of calcium phosphates which derive from the bone ash hearth lining.

EDXRF can be used qualitatively on whole artefacts (so long as they can be fitted into the sample chamber – typically 100mm across) and causes no damage. Used in this way, EDXRF permits the identification of the range of elements present in a material, for example the technique can determine if a crucible was used for melting copper alloys or silver. EDXRF is effectively a surface technique: analysis of corroded objects will usually provide data on the surface corrosion rather than the uncorroded core. EDXRF can be used quantitatively, but only where samples are removed, mounted in resin and polished.

XRF instruments are also available as small units which can be taken into the field – variously referred to as portable XRF (pXRF) or Handheld XRF (HH-XRF). All of these field instruments are EDXRF and will provide good limits of detection for metals but reduced sensitivity for light elements (Mg–P). Portable or handheld XRF are well suited to the analysis of large numbers of objects or samples which cannot be brought to a laboratory for analysis (Shugar and Maas 2012). These instruments can be used to carry out geochemical surveys, especially of metalworking sites (eg Dungworth *et al* 2013).

Similar XRF spectra are also generated in a SEM. This can be fitted with an energy dispersive (EDS) analyser. Alternatively an SEM can incorporate wavelength dispersive spectrometry (WDS) and, if dedicated to analysis using WDS, is referred to as a microprobe, and the technique as electron probe microanalysis (EPMA).

Most analytical SEMs permit great flexibility. Multiple element analysis can be undertaken of a single spot (down to a few microns in diameter) or of larger predetermined areas. Line scans and maps can be used to show the distribution of individual elements in one or two dimensions (Fig 61). This is particularly useful for the analysis of such heterogeneous materials as slags and iron.

A number of analytical techniques generate characteristic spectra in the visible spectrum rather than as X-rays. The most widely used instrument is inductively coupled plasma mass spectrometry (ICP-MS). For this technique a small powdered sample (typically 40mg) is taken, for metallic samples this is usually done by drilling. The sample itself is destroyed during analysis as it is dissolved in acid. ICP-MS can give very good accuracy with limits of detection limits 1ppm (or less) for many elements. It is a bulk analysis method and so cannot distinguish between different components or phases of a composite material.

8.6 Isotope analysis

The proportions of different isotopes of the same element can provide insights into the origin of archaeological materials. The principal application in archaeology is the analysis of lead isotopes in lead, copper alloys and silver. The relative abundance of these isotopes characterise the ore source, but the lead isotopes in different British ore sources are similar (Rohl and Needham 1998). Most isotope analysis has been undertaken using Thermal Ionisation Mass Spectroscopy (TIMS), however ICP-MS has seen increasing use for isotope analysis.

8.7 X-ray diffraction

X-ray diffraction can determine the structure of a compound, as opposed to the chemical composition. A small powdered sample is required. XRD is useful because many materials contain the same elements but have different structures, for example iron ores. This technique can only identify crystalline materials. This technique is also useful for analysing corrosion products, precipitated salts, pigments and soil samples.

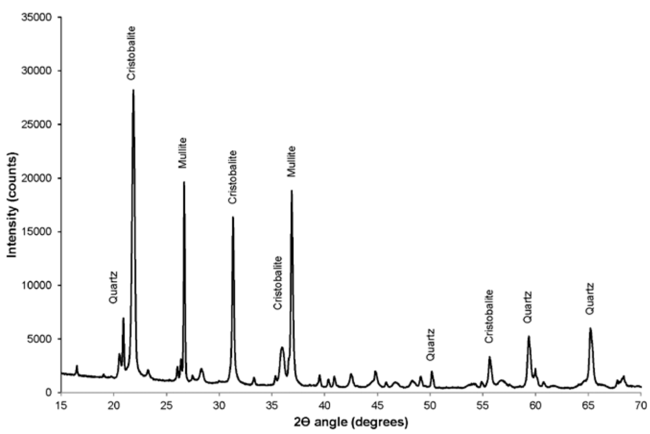


Figure 62

XRD spectrum of fragment of a steel cementation furnace (Coalbrookdale, Shropshire). The range of mineral phases present gives some clues as to the temperature attained.

9 Where to Get Advice

Historic England provides advice on all aspects of archaeometallurgy. In addition, specialist interest groups, in particular the Historical Metallurgy Society, provide a forum for the discussion of archaeometallurgical research. A variety of resources are available and many of these are now available online.

9.1 Historic England

Advice on archaeometallurgy can be sought from Historic England which employs Science Advisors (www.HistoricEngland.org.uk/advice/technical-advice/archaeological-science/science-advice/) who provide support and advice on all aspects of archaeological science. Advice can also be obtained from David Dungworth and Sarah Paynter who work in the Historic England archaeological science laboratories (www.HistoricEngland.org.uk/research/approaches/research-methods/Archaeology/ancient-technology/). Historic England occasionally provides training days for archaeologists on how to recognise and deal with slags and other industrial debris.

9.2 The Historical Metallurgy Society

The Historical Metallurgy Society (http://hist-met.org/) is dedicated to the exchange of information and research in all aspects of the history of metals and associated materials from prehistory to the present. The Society holds several conferences and meetings each year which showcase the latest research, and explore a wide range of metallurgical landscapes and locations. The Society publishes a peer-reviewed journal (*Historical Metallurgy*) as well as occasional papers, including *Metals and Metalworking: a Research Framework for Archaeometallurgy* (http://hist-met.org/publications/hms-occasional-publications.html) (Bayley *et al* 2008). The Historical Metallurgy Society also provides Archaeological datasheets (http://hist-met.org/resources/datasheets.html) and the illustrated catalogue of the National Slag Collection (http://hist-met.org/resources/national-slag-collection.html).

9.3 Regional Research Frameworks

A number of Regional Research Frameworks also provide a review of current knowledge relating to archaeometallurgy. Topics that would benefit from further research in a given region are highlighted. The Regional Research Frameworks can be accessed through the Association of Local Government Archaeological Officers website (www.algao.org.uk/england/research_frameworks).

9.4 Published archaeometallurgical research

Published reports (both in specialist journals and within archaeological site reports) form a vital resource for understanding the archaeological evidence for early metalworking and the bibliography contains many relevant examples. Many of these publications are now available online as publishers move to make all content available electronically.

9.5 Historic England Reports

Historic England has undertaken specialist examination of metalworking assemblages for over 40 years (eg Bayley 1991c; 2008; Bayley and Eckstein 1998; Blakelock 2005; Dungworth *et al* 2013; Dunster and Dungworth 2012; Girbal 2011; Mills and McDonnell 1992; Phelps *et al* 2011). The specialist reports are often made available ahead of the production of the relevant site reports and often contain supplementary detail that is not repeated in the final publication. The entire library has been digitised and made available online (http://research.historicengland.org.uk/).

9.6 ADS Grey literature

The rapid increase in the recording and reporting of archaeological remains that followed from 1990 (due to changes in the legal framework for funding archaeology in the UK) has not been followed by an equally rapid expansion of conventional publication. The requirement (as part of the planning process) to record and report on archaeological remains that would be lost as a result of construction work has led to the proliferation of 'grey literature'. This comprised detailed archaeological reports which were provided to Historic Environment Records although many of these were not published as such. In order to make this data more accessible, reports are now deposited with the Archaeological Data Service (http://archaeologydataservice.ac.uk/archives/view/greylit/index.cfm)

10 Glossary

Alloy the properties of pure metals can be dramatically changed by combining them or adding non-metallic elements to form alloys. For example, steel is an alloy of iron and carbon; bronze is an alloy of copper and tin.

Bloom the lump of iron that forms inside an early iron smelting furnace. The bloom formed below the metaling temperature of the metal and so has a spongy appearance.

Crucible is a vessel to hold a metal while it is melted. Metals are melted to *refine* them or before casting them in *moulds*. Crucibles were usually made from *refractory* ceramics and, because they were exposed to high temperatures, the clay was sometimes partially vitrified.

Ferrous the principal ferrous metals used before the 20th century were cast iron, steel, phosphoric iron and plain iron.

Furnace is a structure used to hold the *ore* as the metal is extracted from it by *smelting*. Furnaces were usually made from clay and, because they were exposed to high temperatures, the clay was sometimes partially vitrified. The archaeological remains of furnaces and *hearths* are often similar.

Hardness is a measurement of the strength of a material (its ability to resist plastic deformation). Hardness is measured by making an indentation in a polished sample of metal, usually with a diamond and a known weight.

Hearth is a structure used to obtain the temperatures necessary to work metal, the exact temperature depending on the metal being worked and on the process used. Hearths were used to melt non-ferrous alloys in *crucibles*, anneal copper *alloys* and heat iron before *smithing*. Hearths were usually made from clay and, because they were exposed to high temperatures, the clay was sometimes partially vitrified. The archaeological remains of hearths and *furnaces* are often similar.

Mine in order to obtain *ores* it is usually necessary to dig into the earth. In many cases this might consist of little more than a pit or quarry. The term mine is usually reserved for the more complex system of tunnels and shafts that are used to extract *ore*.

Mould one technique for shaping metals is to melt and pour them into a container. Once the metal solidifies it takes on the shape of the container. Moulds were usually made from clay, but could also be made from metal, stone, sand or bone. Moulds were not usually exposed to high enough temperatures to vitrify them.

Non-Ferrous the principal non-ferrous metals used before the 20th century were copper, tin, lead, zinc, silver, gold and mercury, and alloys of these metals.

Ore many rocks and minerals contain metallic elements but not all are ores. A rock containing metallic elements can only be regarded as an ore if the technological, social and economic conditions enable people to extract the metallic element(s) by *smelting*.

Refine the initial product of most *smelting* processes is an impure metal, which is then refined. The refining process depends on the nature of the metal and the available technology. Copper was often refined by melting and partially oxidising it to remove impurities. Bloomery iron, because of its high melting point, was often *smithed* to squeeze out any *slag* still trapped inside.

Refractory materials are those which can stand high temperatures without *vitrifying*.

Slags are vitreous waste products of many metalworking activities. Slags can be produced during *smelting, refining, smithing* and even during casting of metals. Most ***ores*** contain unwanted components (eg silica) and these are removed during smelting as a slag. The size, shape and composition of slags are related to the processes that produced them.

Smelt the process of extracting metal from *ores* is smelting. This is usually carried out at high temperatures in a *furnace*, using a fuel such as charcoal.

Smith most metals can be shaped while solid by hammering (smithing). In some cases (eg iron) the metal needs to be heated in a *hearth* to make it sufficiently soft to allow easy smithing. In some cases (eg copper *alloys*) a metal is made much harder by smithing. This work-hardening can be removed by heating (annealing) the metal.

Strength the strength of a material is a measure of the stress (load per unit area) it can support before failing.

Toughness is a measure of the energy required to break a material. It is difficult for a crack to grow in a tough material, whereas a crack in a brittle material, such as a glass or ceramic, will grow very rapidly.

Vitrification is the change into a glassy (vitreous) state, brought about by heating a material. The temperature at which this change takes place can be reduced by the presence of fluxes, which can be accidentally or deliberately added.

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