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Centre for Archaeology Guidelines

Archaeometallurgy

ENGLISH HERITAGE

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 to identify and interpret metal working structures in the field and, during the post-excavation phases of a project, metal working waste products, such as slags, crucibles and moulds. The technologies used in the past can be reconstructed from the information obtained. Scientific techniques are often used by archaeometallurgists, as they can provide additional information.

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 at each stage of archaeological projects, and from their outset.

Figure 1 Experimental iron working at Plas Tan y Bwlch: removing an un-consolidated bloom from a furnace. *(Photograph by David Starley)*

These Guidelines aim to improve 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 2-4). This is followed by a section entitled 'Standards and good practice for archaeometallurgy', outlining its relationship with other aspects of archaeological projects (p 4). Then come the fully illustrated sections describing archaeometallurgical processes and finds: for iron (p 9), copper and its alloys (p 15), lead (p 18), silver and gold (p 19), tin (p20) and zinc (p 21). A shorter section on non-metallurgical high temperature processes illustrates finds that are often confused with metalworking debris (p 21). A glossary of common metallurgical terms is provided (p 23). Finally come sections introducing some of the scientific techniques commonly used in archaeometallurgy (p 23) and a list of specialists who may be able to advise on archaeometallurgical aspects of archaeological projects (p 26).

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 only be observed in areas where tin ores are found, iron working evidence is unusual before the beginning of the Iron Age, and precious metal working 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.

Bronze Age

Copper alloy and gold artefacts of this period show that these metals were worked. Some evidence exists for copper mining, 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, North Yorkshire and Cumbria, and other sources are known in mid and north Wales (Timberlake 1991). 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.

Little is known about how ores were transformed into metals in Bronze Age Britain. Neither smelting furnaces nor slags from the smelting of copper ores have been recovered from Bronze Age contexts in England (Craddock 1990; 1994), although some slag has recently been found on the Great Orme in North Wales (Jones 1999).

In the Bronze Age copper alloy artefacts were produced by casting and smithing. Clay mould or crucible fragments 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 (Buckley and Hedges 1987). However finds of this type are rare in Early Bronze Age contexts.

Some evidence for iron working has been found in contexts that are culturally assigned to the Late Bronze Age.

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. Only a few sites have so far 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, Gywnedd (Crew 1986; 1998).

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.

Most English 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. These gradually developed to incorporate some 'Roman' techniques.

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, for example at Bardown and Beauport Park (Cleere 1974). Other major iron smelting centres existed in the Forest of Dean, Northamptonshire and Lincolnshire but iron smelting evidence has also recently been found in other areas, such as at the Blackdown Hills, Devon (Griffith and Weddell 1996), and can be found almost anywhere. Iron smithing slags are routinely discovered on almost all Roman sites, and occasionally blacksmiths' workshops are found, for example at Ashton, Northants (Hadman and Upex 1975).

A number of large, circular, stamped copper ingots have been found, particularly in Wales (Kelly 1976), although no evidence of 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 are also known, but are far 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.

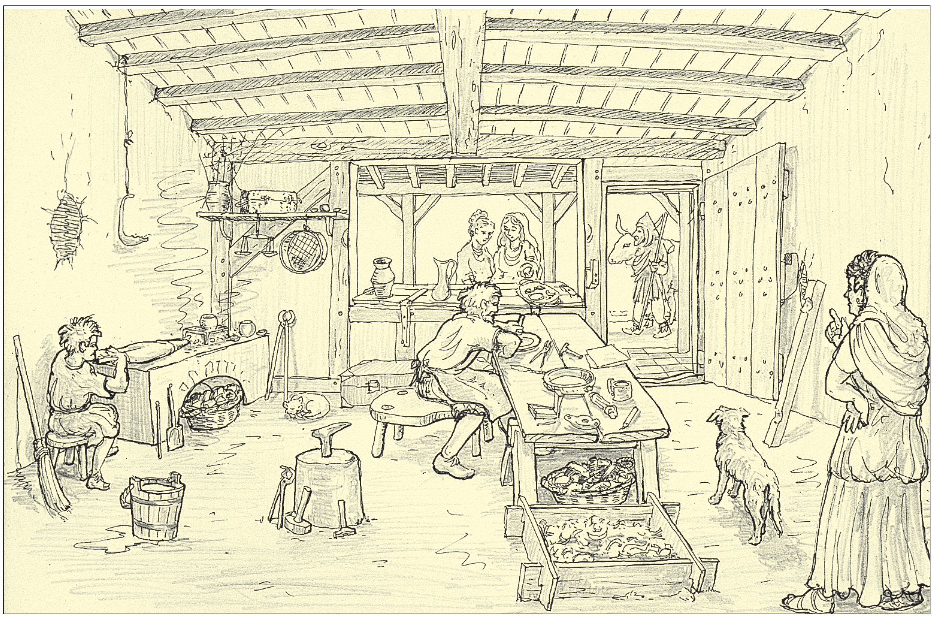

Figure 2 Reconstruction of a Roman workshop, based on excavated features and finds from Verulamium.
(Illustration by Michael Bayley)

The best known evidence for Roman lead production consists of large inscribed lead ingots, but some large litharge cakes, showing that silver was extracted from lead, have also been found in the Mendips and Welsh borders, for example at Pentrehyling (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. The casting of pewter is fairly well known from stone moulds that have been recovered from both urban and rural sites (eg Blagg and Read 1977).

Roman-period gold mining is known from Dolaucothi, Dyfed (Burnham 1997). Parting vessels, for separating silver from gold, have been found on a few urban sites (Bayley 1991a).

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 (Bayley 1992c).

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 (McDonnell and Ottaway 1992). Metalworking tools are found, both in burials, for example at Tattershall Thorpe (Hinton 2000), and on settlements, for example at 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.

The whole 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 1992b) 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, and scrap and waste metal. Ingot- and object-moulds are made from stone, clay and antler. Crucibles, scrap metal and clay moulds for small objects are common.

Medieval

From the medieval period onwards there was an increasing tendency for metal industries to be concentrated in towns, and often in particular areas of towns, although iron smithing also took place in many rural settlements. Another exception was bell-casting which was often, although not always, carried out where the bell was to be used (Greene 1989). Smelting was still carried out near the ore sources.

Water power was being used to operate bellows and trip hammers by the 12th century (Astill 1993) and its availability led to the development of the blast furnace for iron smelting from the end of the 15th century. Urban excavations frequently recover evidence for secondary working of the whole 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 the early medieval period. This change in scale is particularly noticeable in crucibles whose size increases (Figure 23 and Bayley 1992a), 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).

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 (Matthews 1999). Recycling became more efficient in later periods so quantities of finds are correspondingly reduced.

In the iron industry, blast furnaces, both charcoal-fuelled and (later) coke-fuelled, are well known archaeologically (Crossley 1990), but the finery-chafery forge and its later developments are less often identified. The few upstanding cementation furnaces (Cranstone 1997) and crucible steelworks are quite well known. Bloomery furnaces dating to this period have also been found, especially in more remote areas (Photos-Jones et al 1998).

As before, non-ferrous smelting is mainly concentrated in areas near suitable ore sources. Slag scatters and patches of bare polluted ground can indicate a bole hill lead-smelting site. Earthworks or ruins in ore-rich areas can indicate later smelting constructions, whether for lead, copper or tin.

Archaeological interventions on ‘industrial archaeology’ sites usually concentrate on surveys of above-ground buildings and features, but sampling of buried deposits can often clarify the uses to which the site was put.

Stages	Archaeological Action	Specialist 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 Project Design. Plan excavation and sampling strategy for metalworking features
Fieldwork	Survey site/landscape	Identify features located and estimate scale of activity
	Excavation	Advise on identification of metalworking features. Establish metalworking reference collection. 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 and estimate scale of work. Quantify debris by context, phase, area, etc
Dissemination	Incorporate archaeometallurgical reports into excavation report	Write archaeometallurgical report(s) for inclusion in excavation report and/or specialist publication

Standards and good practice for archaeometallurgy

This section sets out the relationship between archaeometallurgy and other aspects of archaeological projects. It also contains specific information, mostly drawn from medieval and earlier examples, addressed to all those who are likely to encounter archaeometallurgical evidence. The principles are the same when dealing with later sites, but the scale of the industry is sometimes far larger.

Most archaeological projects are initiated through the planning process when curators (county archaeologists, etc) identify the need for work to be done. The principles they follow are laid out in PPG16 in England (Department of the Environment 1990), NPPG5 and PAN42 in Scotland (Scottish Office 1994a and 1994b), Circular 60/96 in Wales (Welsh Office 1996) and PPS6 in Northern Ireland (Department of the Environment (NI) 1999). Having decided that a site needs evaluation, the curator produces a brief for the work and the contractors (archaeological units) then respond with a written scheme of investigation. Alternatively, work is sometimes commissioned by a statutory body such as English Heritage, in which case the documentation is known as a project design. In either case, a contractor is selected to undertake the archaeological project.

The successful completion of archaeological projects depends on careful planning and implementation, whether they are small watching briefs or more extensive excavations. Large archaeological projects normally pass through five phases (English Heritage 1991; Historic Scotland 1996):

- Project planning and the formulation of research design
- Fieldwork
- Assessment of potential for analysis
- Analysis and report preparation
- Dissemination

Each phase of a project should have clear objectives, and these should be regularly reviewed. This framework can be applied beneficially to all archaeological projects, although formal reviews might not be appropriate for minor interventions. 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 advise on an appropriate level of provision.

Project planning and the formulation of research designs

Curators should be aware of the archaeometallurgical potential of sites in their areas and should ensure that any briefs they draft require adequate investigation of these aspects of the archaeological record.

Given the frequency with which slags and other archaeometallurgical finds are discovered, contractors should approach appropriate specialists at the project planning stage. They can contribute to the research design and help to prepare an appropriate excavation and sampling strategy. If the site is thought to have been primarily metallurgical in function, then archaeometallurgy should be a major aim of the project design. Even when the metallurgical potential of a site is not thought to be large, some contact with a specialist is desirable, as small amounts of debris are not necessarily less important – and an initial contact will pay dividends when unexpected discoveries are made.

Prior to fieldwork, desk-based studies can indicate the likelihood of archaeometallurgical activities. The desk-based study should include any metalworking evidence from earlier archaeological interventions, but past metalworking activity can also be suggested by local geology, documentary evidence, place-names and even vegetation surveys (Brooks 1989; Buchanan 1992). There is rarely substantial evidence, however, for metalworking in urban areas before excavation.

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 1997; 2000). Metric surveys can determine the extent of metalworking debris that survives as earthworks, and so indicate the scale of metalworking activity. The interpretation of upstanding metalworking remains from either aerial photography or from metric survey requires input from a specialist (Cranstone 1994; Gerrard 1996; Starley 1999).

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 24 for further details).

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. Early consultation with a metalworking specialist and a site visit will enable the evidence to be better understood. The metalworking specialist can provide training, suggest appropriate sampling strategies, put together a site reference collection, and advise on cleaning and packaging procedures.

Figure 4 Iron Age bloomery furnace at Crawcwellt West, Merioneth. *(Photograph by Peter Crew)*

The three metalworking processes most likely to be encountered by archaeologists during fieldwalking, evaluation and full scale excavation are iron smithing, iron smelting and secondary non-ferrous metalworking, such as casting of copper, lead or precious metals. Additionally, in certain geological areas the smelting of non-ferrous metals might be encountered.

The range of possible metalworking evidence can be divided into structures and finds. Structures and 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 metal working sites should include the examination of

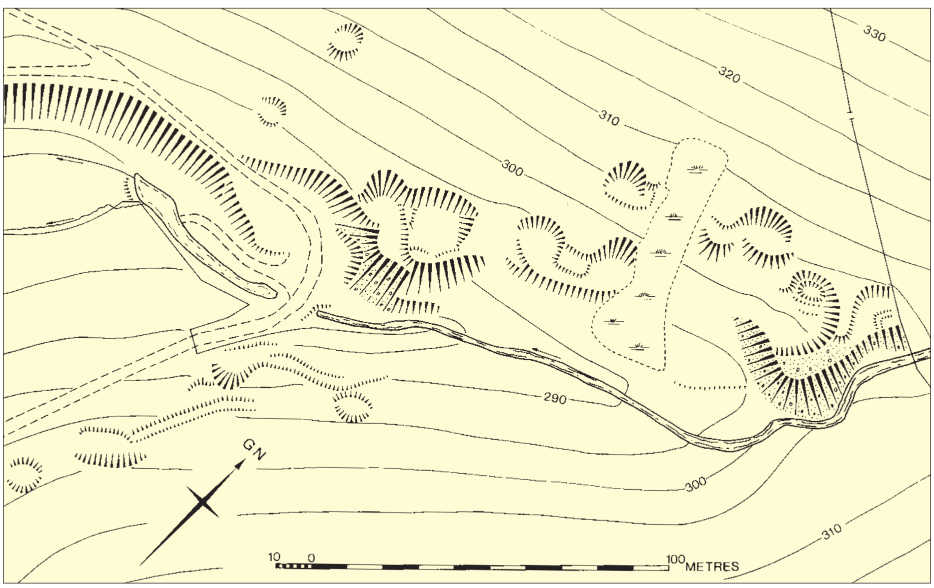

Figure 3 Earthwork survey of the Iron Age slag dumps at Sherracombe, Devon. *(© Crown copyright. NMR)*

associated features, such as domestic dwellings, in order to place the technology in its social and economic context.

Structures and context

The most useful contexts are those within buildings or areas where metalworking was practised (primary deposits). More frequently, however, metalworking debris is recovered from middens, pits and ditches, or from where it was used for surfacing paths (secondary deposits). 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 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 below). Some knowledge of the relevant metalworking processes is greatly advantageous when excavating furnaces and ground-level hearths. The dimensions and layout (plans and sections) of these 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.

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. The proportion of features left unexcavated should be recorded to provide a means to estimate the total quantity of slag.

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'. Where large quantities of debris are recovered, it can be difficult to make a distinction between structures and finds; for example, a large dump of slag can be considered as a structure or as a large quantity of 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. Some of the more important evidence, in the form of hammerscale from iron smithing, is too small to be noticed during trowelling but can be detected using a magnet. Soil samples should be taken from contexts containing hammerscale, particularly primary contexts.

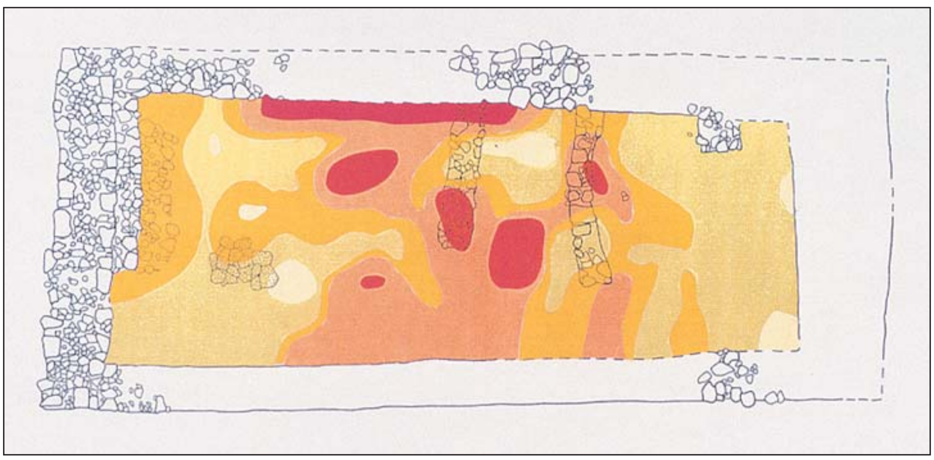

Figure 5 Plot of magnetic susceptibility readings, with darker tones indicating higher values (corresponding to higher concentrations of hammerscale), within the medieval smithy at Burton Dasssett, Warwickshire. The building is 12m long.

A workshop floor surface comprising a single context should be sampled throughout (at 0.2–0.5m 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 (Figure 5 and 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.

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

Lead waste and some minerals 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. In most cases they 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. 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.

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. A range of other evidence can be used to determine date, however, including material culture, radiocarbon dating, dendrochronology and archaeomagnetic dating. Mining and smelting sites, however, often yield very little datable material culture. This might, in part, be due to a focus on the obviously 'technological' aspects of such sites (hearths, furnaces, slags heaps, etc); excavation of ancillary areas will increase the likelihood of recovering datable artefacts. Most metalworking activities made use of charcoal fuel that can be radiocarbon dated. Samples should be 100g of clean, short-lived charcoal, preferably relatively large fragments (Mook and Waterbolk 1985). Waterlogged metalworking sites (especially mines and water-powered furnaces) can yield timbers that can be dated using dendrochronology (English Heritage nd; 1996). The final use of fired clay structures, such as hearths and furnaces, can be dated archaeomagnetically (see p 24).

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. The Roman and Medieval Finds Groups have issued guidelines (Cool *et al* 1993) defining a minimum standard for the recording of all registered finds and groups of bulk finds. The site archive should include plans, sections and context records relating to metalworking features, finds and debris and the records relating to the contexts in which they were found. The presumption within English Heritage and Historic Scotland is that projects will normally proceed to assessment and usually to the analysis phase, so there is no need to produce detailed catalogues at this stage.

Assessment of potential for analysis

An assessment report consists of a summary of the data and a statement of the academic potential for the site and recommendations for further work, storage and curation. This phase is an opportunity to update the research design in the light of the discoveries made, and to decide which parts of the data warrant further investigation (analysis phase). It is important that all the evidence for metalworking is considered as a whole (features and slags, as well as metallic and ceramic materials). Where possible all material remains should be seen by a single specialist. Alternatively, several specialists might be involved, but provision should be made to integrate their work.

The metalworking specialist will classify the debris into different types depending on relatively simple characteristics (colour, density, size, shape, surface morphology, etc). 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 may 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. On sites where little evidence of metallurgical activity is present, the assessment is often the final opportunity to examine the material. In these cases the total assemblage can be examined and interpreted in sufficient detail for inclusion within the final excavation report. More complex and important assemblages are often assessed in far less detail, with the assumption that an analysis phase will follow.

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, 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. 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 (eg medieval iron smithing), 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.

Analysis and report preparation

The analysis phase consists of the examination of those 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 below). 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 bottoms, 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 Figures 6 and 7).

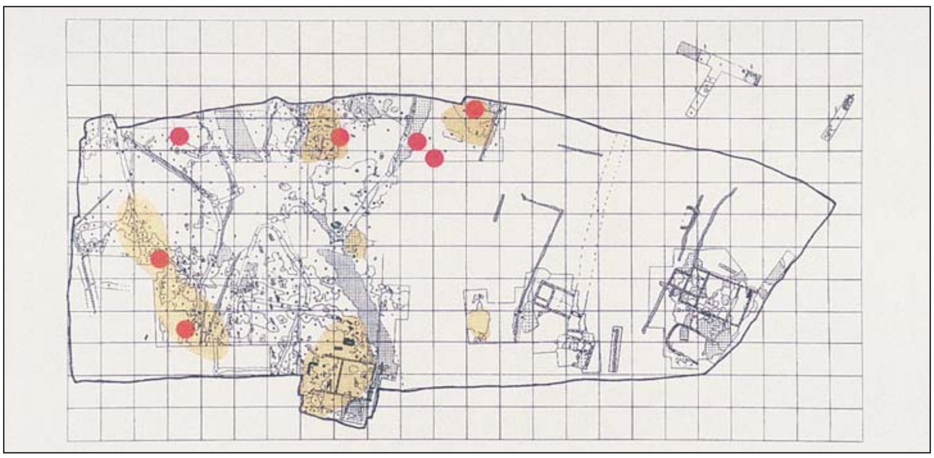

Figure 6 Plan of the excavated features at the Roman site of Shepton Mallet, Somerset, where iron smelting (yellow) and smithing (red) were taking place. Note the partial spatial separation of the two activities.

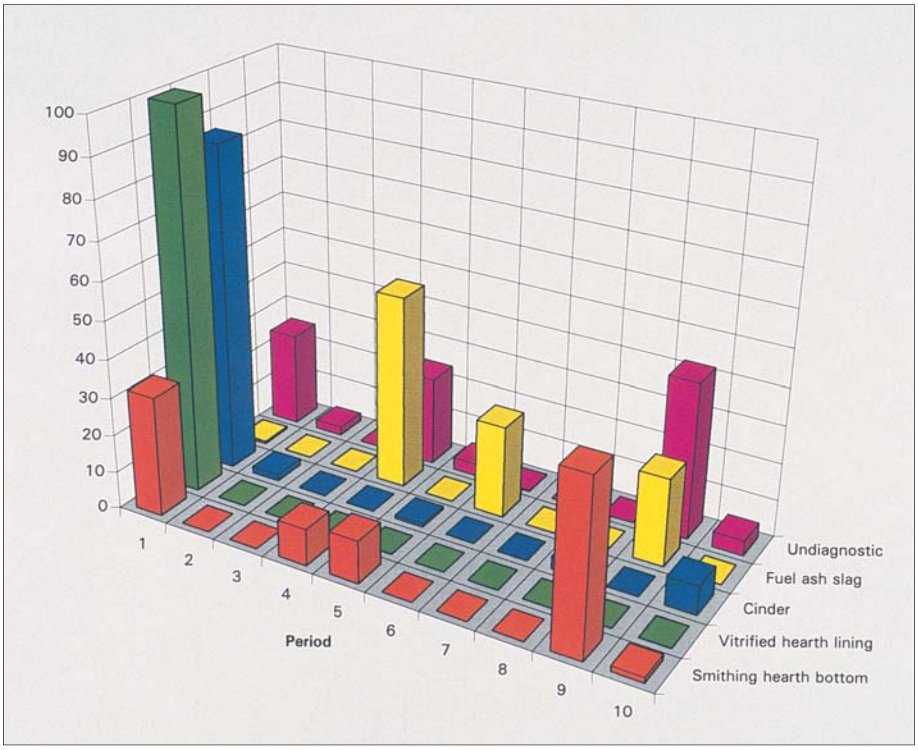

Figure 7 The histogram shows the proportions of different types of slag for each phase of occupation at medieval Wigmore Castle, Hereford and Worcester.

Quantification

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 may 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 slag (in cubic metres) should be multiplied by the density of the slag (3–4.5 for most slags) to give the total weight in tonnes.

The quantity of metalworking evidence recovered can be used to provide data on resource exploitation, such as charcoal production and woodland management. The evaluation of 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 Cleere 1976; Crew 1991). 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. 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. 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 Mighall *et al* 1990).

Scientific techniques

In order to determine the full range of technologies employed, a metalworking specialist might need to use physical and chemical analytical methods to determine a range of properties, such as chemical or mineralogical composition, melting point, density, etc (see p 23). 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 method of analysis chosen depends mainly on the questions asked. 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. Scientific analysis of slags, crucibles and other debris can identify the metals being worked or the specific process being carried out (temperature, reducing conditions, etc). Finished metal objects, miscast objects, waste and other debris can be chemically analysed to determine their composition. With metal objects, the composition of the bulk metal or of an inlay or plating can be an aid to accurate description. A group of related artefacts could be analysed to show patterns of alloy use. Distinctive trace element 'fingerprints' can suggest a provenance for the artefact or for the metal of which it is made.

The benefits of chemical analysis of metal artefacts can be illustrated through recent work on Roman copper alloys. Analysis has been used to revise typological classifications of artefacts such as brooches (Bayley 1998), and has shed light on the ways in which copper alloys reflect wider processes in society such as Romanisation (Dungworth 1997).

The microscopic examination of polished sections of metals (metallography) and metalworking debris can reveal information about how objects were formed. Metallography has been applied to copper alloy, and especially to iron, artefacts to show the wide variety of techniques used by early metalworkers (eg McDonnell and Ottaway 1992; Tylecote and Gilmour 1986; Wilthew 1987).

Dissemination

The results of analytical work should be integrated into the excavation report. The format and approximate length of reports should be agreed before work is started. Archaeometallurgical data and interpretations can be integrated into the main excavation report, be published separately (with a summary in the excavation report) or both. The exact format depends on the nature of the archaeology, the ways in which it was investigated and the importance of the archaeometallurgical results. In some projects, dissemination may 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. A full copy of all data produced must be supplied for inclusion in the site research archive (Museums and Galleries Commission 1992; Owen 1995).

Archaeometallurgical processes and finds – iron and its alloys

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. The terminology used within archaeometallurgy to describe these processes and materials has varied, so the terms used in these guidelines are defined below.

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 iron and have different properties. Early iron is typically heterogeneous and a mixture of alloys can be present in one object.

Alloys of iron and carbon are given different names, depending on the amount of carbon they contain, because this has a great effect on the structure and properties of the alloys and thus on their potential applications. Low carbon iron is an alloy containing up to 0.3% carbon. Steel contains from 0.3 to just over 1% carbon. Steel is an ideal material for cutting edges on tools and weapons because when it is cooled rapidly, or quenched, it becomes very hard, and if it is then heated, or tempered, it becomes tough as well. Cast iron contains 2–5% carbon, which lowers the melting temperature of the alloy to below 1200°C. This alloy could be melted, and therefore cast to shape, but it was brittle. Carbon alloys 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.

Phosphoric iron contains up to 1% phosphorus, which makes it harder. The phosphorus enters the metal from the ore during smelting. Its presence also influences the uptake and distribution of carbon and this might be the reason that phosphoric iron and ores were selected or avoided for specific applications.

Smelting

The bloomery and blast furnace processes are the two main methods of smelting iron.

Iron in summary

Plain iron contains less than 0.1% of other elements and is often known as ferritic iron. It has a melting temperature of 1545°C. Alloys include steel (~ 0.3 to just over 1% carbon), phosphoric iron (up to 1% phosphorous), low carbon iron (up to 0.3% carbon), and cast iron (~ 2 to 5% carbon).

Process	Description	Archaeological debris
Bloomery smelting (7th 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 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 is often found, as the iron bloom was usually 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 liquid cast iron, which was cast into objects or ingots. Limestone was added with the ore and reacted with the impurities present to produce a calcium-rich (rather than an iron-rich) slag and this increased the iron yield of the furnace. Cast iron could be refined to produce a bloom of plain iron (or lower carbon alloys) in finery or puddling forges. The bloom was then consolidated in a chafery forge.	Ore, fuel and bloomery furnace slag, the last of which was sometimes smelted in blast furnaces. Large quantities of blast furnace slag were produced. The furnace rarely survives to any height. Remains of associated buildings, possibly with casting pits or mould fragments. Evidence of waterpower should be expected.
Smithing	Most iron alloys were shaped, by smithing or forging, while solid. The metal was heated and then shaped or welded.	Smithing hearth bottoms, hammerscale and vitrified hearth lining. Ground level hearths might survive. Evidence of waterpower might be found.
Steel production	Steel was produced: during smelting in bloomery furnaces, by carburisation of plain iron, by cementation steel making and by reducing the carbon content of cast iron. Huntsman's method of making homogeneous steel was developed in the 18th century.	Evidence of early steel production is in the form of objects, bars, billets or blooms containing steel. The cementation process and Huntsman's method produced diagnostic evidence: fired clay from cementation chests, and heavily vitrified crucibles and frothy slag from Huntsman's method.

In this country the bloomery process was used for iron smelting 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 do not far exceed 1250°C, which is well below the melting point of the plain iron (and low carbon and phosphorus alloys) generally produced. 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, types of alloy that could be forged by a smith.

In contrast, blast furnaces, introduced to Britain c1500AD, 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. Raw, or untreated, ores rarely occur in any quantity on archaeological sites. If ores with higher iron contents were smelted, the yield of iron could be improved and less waste produced. Therefore, where possible, iron-rich ores were selected, perhaps washed, and then roasted in a roasting hearth before being smelted. These processes reduced the quantity of impurities, collectively known as gangue, which entered the furnace and thus reduced the amount of waste produced during smelting. Other geological formations contain less iron and are not suitable for bloomery smelting; they can be confused with iron slags (p 22). Roasting changes the colour of the ore, making roasted ore easier to spot on archaeological sites. The ore was also crushed to increase its surface area and hence the rate of reaction, although if ore is crushed too finely the particles can 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.

Figure 8 Roasted and crushed iron ore, prepared for smelting experiments. *(Photograph by Peter Crew)*.
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. Roasted ores (see photograph) 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 25). 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.

The bloomery process

Charcoal was exclusively used as the fuel for bloomery smelting. Coal could not be used as it contains sulphur, which would be absorbed by the iron, causing it to fall apart during 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.

Furnaces rarely survive to any height, so their likely structure and mode of operation have been reconstructed by supplementing the archaeological evidence with ethnographic data and experimental work (eg Cleere 1971, Crew 1991). Furnaces were constructed from clay, although some stone and tile were occasionally used. The clay was often modified with large amounts of temper, such as small stones, pieces of slag and possibly organic material. Sand was sometimes added to the clay for repairing the high-temperature zones of the furnace, to make it more temperature resistant. Clay bricks of a distinctive shape have been found on some Roman smelting sites. The basic furnace was usually a cylindrical clay shaft, probably 1–1.5m high, with an internal diameter of 0.3–1m. The walls of the furnace were normally at least 0.2m thick, to reduce heat loss from the furnace. To achieve sufficiently high temperatures for smelting, air was forced into the furnace near its base through one, or sometimes more, small holes around the circumference. These air inlets are often referred to as tuyères. There is a growing tendency, however, to describe the actual holes in the furnace wall as blowing holes, to differentiate them from any separate pipe or nozzle, historically called tuyères, used for channelling air into the blowing hole. In the majority of furnaces, an arch through the wall at the base enabled slag to be removed – either cold, or as hot tapped slag, often into an adjacent pit. While not in use the arch would be temporarily blocked.

Figure 9 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. See Figures 1 and 4. *(Photograph by Sarah Paynter)*

The charcoal in the furnace was lit and the furnace preheated. When hot, a charge of roasted ore and charcoal was added to the top, while bellows were used to pump air into the base of the furnace. The furnace functioned as a result of two types of reaction: the reduction of the iron ore to iron metal and the reaction of impurities in the ore to produce slag. The iron ore was reduced by carbon monoxide, produced by the reaction of oxygen with the charcoal. Reduction started high up in the furnace and progressed as the ore particles moved down. The impurities, or gangue, in the ore are predominantly made up of silica and alumina. These reacted with some of the iron oxide present to form a slag.

Figure 10 Vitrified clay lining with a blowing hole, from the Roman site at Ribchester, Lancashire. Note the slag attached below the blowing hole. 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. From the Roman and medieval periods there is some evidence for the use of replaceable circular or rectangular blocks of clay, with a blowing hole, that could be set in place in a prepared cavity in the furnace wall. These are often referred to as replaceable block tuyères.

In the hottest zone of the furnace, near the blowing holes, the temperature exceeded 1250°C. Here the liquefied slag separated from the solid iron metal particles that had formed and flowed to the bottom of the furnace. The iron particles 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 it was removed, probably through the top of the furnace. 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.

Figure 11 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 and are strongly magnetic.

Figure 12 A consolidated iron billet from the Roman site at Westhawk Farm, Kent, that has been cut in half (max dimension 40mm). Partially consolidated billets are more common finds than blooms. They vary in size, are often badly corroded and fragmentary, and are strongly magnetic.

Figure 15 Undiagnostic slags (from Housesteads, Northumberland) 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.

Different types of slag are produced during bloomery-smelting and smithing processes. These can be differentiated by their colour, density, morphology and size, but compositionally they are all very similar. They are often described as fayalitic because they have compositions similar to that of the mineral fayalite ($2FeO.SiO_2$), an iron silicate.

If a very iron-rich ore was used in the smelt, little waste slag was produced; it could remain at the bottom of the furnace without hindering the smelt, sometimes forming a furnace bottom. If the ore was less rich in iron, then more slag was produced. This would eventually obstruct the lower part of the furnace, so it had to be removed for smelting to continue. Removing the slag during the smelt, rather than allowing it to accumulate, enabled the smelt to continue for longer and a larger bloom of iron to be produced. The slag could be removed through a hole at the base, either by tapping when it was hot and fluid (tap slag) or by raking while it was hot and pasty (raked slag). In slag-pit furnaces, known in Britain from the Anglo-Saxon period, the slag ran into a pit underneath the furnace structure itself, to form a slag block. These are blocks of dense, dark coloured slag, somewhat larger than furnace bottoms. The furnace superstructure could then be relocated over a freshly dug pit. Each of these methods of removing slag gives it a characteristic morphology, and therefore slags are classified largely on this basis. Only the more common terms are used here, but more complex slag classification systems have been developed and used, particularly for unusual sites and assemblages.

Figure 13 Section through an Anglo-Saxon furnace bottom from Mucking, Essex. 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 typically 0.3m in diameter and 0.2m high, and will often contain pieces of reduced ore and fuel.

Figure 14 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 may 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.

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.

Large pieces of slag were often disposed of in antiquity and might also have been moved during more recent agricultural practices, often to field boundaries. Fuel ash slag (see p 21) is also sometimes found on smelting sites.

There is no known evidence of 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 and large, square post-built shelters are known on medieval sites.

During the Middle Ages the hand-blown bloomery was partly replaced by bloomeries with water-powered bellows (and/or hammers for primary smithing, described on p 15). Documentary sources suggest that there were developments in smelting technology and the bloomery furnaces themselves (Tylecote 1986, 188–9). These later sites are at present poorly understood and therefore any medieval site with evidence of water-powered iron smelting is of importance (Cranstone 1991).

The blast furnace

Documentary evidence suggests that blast furnaces were introduced to this country around 1500AD. Initially they used large quantities of charcoal fuel, necessitating careful woodland management to ensure adequate supply. Water was used to power the bellows for the furnaces, so they are located in river valleys, near the dam of a storage pond. The water-powered bellows gave a powerful air blast allowing higher temperatures to be reached. These temperatures were high enough to react the gangue impurities present with lime (calcium oxide), producing a lime alumina silicate slag. This made the blast furnaces more efficient at extracting iron because the lime replaced iron oxide in the slag, and therefore almost all of the iron compounds in the ore could be converted to iron metal. 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. It is not clear whether lime was introduced for this purpose in early blast furnaces or whether it entered the furnace as an impurity, perhaps in the ore. By the 17th century, however, it was being introduced intentionally in the form of limestone.

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 slag was also formed. The conditions in blast furnaces were more reducing than in bloomery furnaces, causing more carbon to enter the metal. The product of blast furnaces was cast iron, which has a lower melting temperature than plain iron and was therefore molten. It was tapped off at intervals and could be cast straight into objects such as guns, or into ingots. These castings were linked to a supplying channel of metal, resembling a sow feeding piglets, and so the castings were called pigs.

Blast furnaces were essentially tower-like constructions: the tower is known as the stack and the hearth is at its base. Early blast furnaces were stone-built, strengthened with external timber frames, and were usually square in plan, although other shapes are known. Typically they were 5–6.5m square and, although no early stacks survive, a documentary source estimates a height of 6m.

Later furnaces became taller, but were also built more solidly. It was normal practice to build two arches in the stack, in adjacent sides. One arch was for the air blast from the bellows and the other was for casting the iron and tapping the slag. Within the stack, the lining of the hearth (where the molten slag and iron collected) and the lower part of the stack were replaced at the end of each campaign. The hearth itself was made of a

Figure 16 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 much less iron. They do contain a small percentage of iron however, which gives them their colour. These slags can be found in large quantities and were often reused, for example as hardcore or scattered across fields to improve soil quality.

refractory material, such as sandstone. 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. There are some instances of two hearths in one stack, in order to increase the capacity for large cast objects (Crossley 1990). There are also descriptions of small hearth extensions, called forehearths, from which cast iron was ladled into small moulds, but as yet archaeological evidence of this has only been found for a coke-fuelled furnace (described below).

There were other structures associated with the furnace. The bellows were housed in the blowing house, built 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. 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 guns. Fragments of moulds and casting pits can be found at sites. There would also be a large building nearby for storing the fragile charcoal, and another for storing ore (Bowden 2000).

It was not until the early 18th century that blast furnaces were fuelled by coke, which is derived from coal, instead of charcoal. This technology was slow to be adopted, but by c1750 the technology was widespread and evolved rapidly. Coke ovens were developed, older furnaces were modified and the design of new furnaces changed. As coke is stronger than charcoal, the height of the furnace stacks could be increased without danger of the stack contents compressing and inhibiting the air blast. Wedge bellows were replaced by cast iron blowing cylinders, and then by steam engines; firebricks were developed for furnace linings. The sulphur content of the products and waste products (slags) of these processes can be used to identify instances when coke was used as the fuel.

Refining cast iron

When forgeable iron alloys were required, conversion or fining processes were used to convert the cast iron produced by the blast furnaces into a product similar to that of the

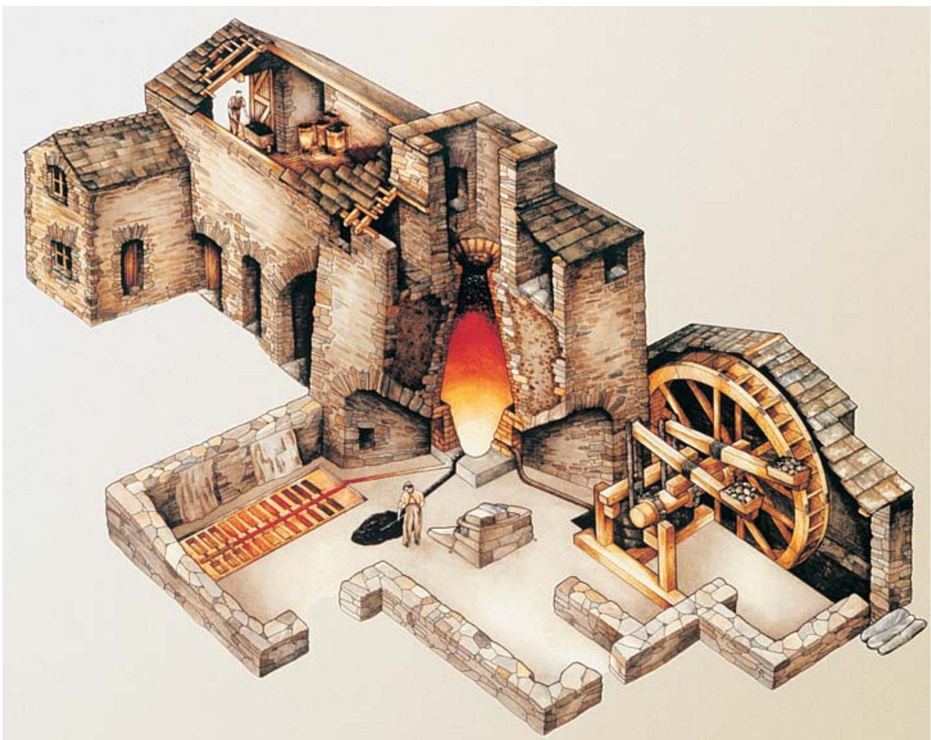

Figure 17 Reconstruction of Duddon blast furnace, Cumbria, which was built in 1736 and is now a Scheduled Ancient Monument. *(Illustration by kind permission of Alison Whitby and the Lake District National Park Authority)*

bloomery furnaces, by reducing its carbon content. This took place in finery forges, which were, in some cases, adapted bloomery furnaces.

In this conversion process, cast iron from the blast furnace was remelted in an open charcoal hearth under an air blast provided by water-powered bellows. The carbon in the iron was oxidised and removed and a bloom of low-carbon iron would form in the hearth. Slag was also formed, but this was liquid at these temperatures and so was largely separated from the bloom. The hot bloom was taken to a water-powered tilt-hammer for forging, which removed most of the trapped slag and shaped the metal into a bar. The repeated heating that was required in this process could take place in the finery hearth or in a separate hearth, sometimes known as the chafery, which was also blown by water-powered bellows.

Coal or coke could not be used in the early bloomery and blast furnaces or finery forges because of its high sulphur content, which had a detrimental effect on the forging properties of the metal. It could be used to fuel the chafery hearth, however, since the fuel in this process was simply required to reheat the iron. 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, a small quantity of flowed slag that resembles tap slag, large slag lumps and a type of porous slag, sometimes with traces of flow on the surface. Finery or chafery forge debris can be distinguished from that found on smelting sites by the absence of ore.

Once coke was being used to fuel blast furnaces, sulphur from the coke entered the furnace products. Many conversion forges had trouble producing forgeable iron from coke-smelted pig iron because of the impurities, and the finery process had to be adapted accordingly. A period of variability and innovation followed, as attempts were made to perfect a larger-scale, more efficient process. Eventually the reverberatory puddling furnace, for converting cast iron, was developed in the 1780s. Puddling furnaces produced slag very similar in composition to that from bloomery furnaces, but with a higher sulphur content, indicative of the fuel used.

Making steel

Steel was produced by various methods at different periods. The blooms from bloomery furnaces were heterogeneous in carbon composition and there is evidence from the Iron Age that steely portions of blooms were selected for certain types of tool (Fell 1993). Whether steel was also produced in dedicated bloomery furnaces, by manipulation of the smelting conditions and types and ratios of raw materials, is unknown. The varied properties of iron alloys were certainly recognised and exploited during the early medieval period (Gilmour and Salter 1998).

Another method of making steel was to surface carburise or case harden iron objects by heating them 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 hard. There is growing evidence that this method was known in the Iron Age (Fell and Salter 1998) and it was widely employed in the medieval period.

Documentary evidence suggests that the cementation method of making steel was introduced in the 17th century. Plain iron bars were packed in charcoal in a clay chest that was sealed and heated to increase the carbon content of the iron. The bars were then broken, reforged to improve their homogeneity, and reformed into steel bars (Cranstone 1997; Barraclough 1984). The interior brickwork of surviving cementation furnaces is vitrified and pieces of fired clay, used to seal the chests and later broken off, can also be diagnostic. In the 16th century some steel was made by partly decarburising cast iron, using a similar process to fining, but stopping before all of the carbon was removed (see Refining cast iron, above).

At the end of the 1740s, the development of very refractory clays made Huntsman's crucible method of steel making possible, although the process was not much used before the last decades of the 18th century (Craddock and Wayman 2000). This method involved breaking up cementation bars, placing them in crucibles, and heating them in a furnace to melt and mix the alloy, before casting more homogenous steel ingots. The crucibles used in this process became heavily vitrified and the slag that was produced had a frothy appearance.

Smithing

Bloomery smelting of iron results in a heterogeneous bloom, containing quantities of trapped slag, which must be refined to produce iron stock 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; Craddock and Wayman 2000). This primary smithing was often carried out at the smelting site, and therefore smelting and refining residues can be found together. The iron stock, or billet, produced would then undergo secondary smithing or forging, also while hot, to produce artefacts. Secondary smithing also includes the repair and recycling of iron objects.

The properties of iron and its different alloys have been described (p 9) and 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. 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.

Objects were formed from a combination of different iron alloys. For example, knives were made with a hard alloy for the cutting edge and a tough alloy for the back; pattern-welded weapons were made from different alloys 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, and this loss is greater during complex smithing operations such as pattern welding.

Figure 18 Late medieval illustration showing smiths at work. Note the waist-level hearth in the background and the anvil set in a wooden block.

Smithing takes place in a hearth or forge. A shelter would protect the hearth, and the smith, from the elements and also cause dim lighting round the hearth, allowing the smith to better judge the temperature of the iron from its colour. The smith would heat the metal to red heat in the hearth for shaping. Using hand tools and working on an anvil, the metal could be thinned down, thickened, straightened, bent, split, pierced and otherwise shaped. Iron could also be welded by heating the pieces to be joined to white heat and then hammering them together; this is known as fusion or fire welding. When iron is hot, however, an oxide scale rapidly forms on the surface, which can sometimes inhibit the formation of a good weld. The scale can be removed by using a flux, such as sand, which reacts with the iron oxide scale and forms slag. At welding temperatures the slag is fluid and is squeezed out from the join when the pieces of metal are hammered together. Fluxes appear to be unnecessary in many circumstances, however; for example, plain iron can be welded without using a flux. The extent to which fluxes were used in antiquity is unknown.

Medieval and later forges were waist high, and there is documentary and artistic evidence for this type of hearth dating back to the Roman period; archaeological evidence for such hearths rarely survives. Iron could also be smithed using ground-level hearths.

Early primary smithing hearths were sometimes circular – easily confused with the basal remains of a furnace. 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). An air blast was used to obtain high temperatures. A smithing hearth consists of a clay hearth wall, or some other device for separating the bellows from the hot fuel, with a blowing hole through which air was blown into the fuel bed. (Blowing holes are sometimes called *tuyères*: for clarification see p 10). 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 furnace linings (p 10), though hearth lining is generally thinner and is found in smaller fragments and smaller quantities. Sometimes the outline of the blowing hole is preserved. Fuel ash slag was sometimes also produced (p 21).

Smithing produced hammerscale. Flake hammerscale was produced in both primary and secondary smithing when a hot iron object, with an oxidised surface, was struck. Spheroidal hammerslag (also known as hammerscale) consists of small droplets of solidified slag produced during primary smithing as slag was expelled from the bloom, so spheroidal hammerslag can be found among smelting debris. It is also produced during secondary smithing by welding processes.

Hammerscale not only indicates that smithing took place on a site, but can also locate the activity precisely because it is often found in the immediate vicinity of the smithing hearth and anvil (see p 24). The anvil residues can become trampled into a smithing floor, which becomes cemented together with iron corrosion products into smithing pan.

Slag forms as the iron heats in the hearth from reactions between the fuel, the hearth wall and oxidised iron. Droplets of slag accumulate in the hot region near the blowing hole, coalescing to form a large spongy lump, known as a smithing hearth bottom, which is discarded by the smith before it begins to hinder the efficient operation of the hearth. These bulky smithing slags may be found heaped near to the smithy or may be transported farther away for dumping or reuse, for example in road construction.

Evidence of the structure that housed the smithing hearth sometimes remains. Stone anvils and hammer stones with slagged

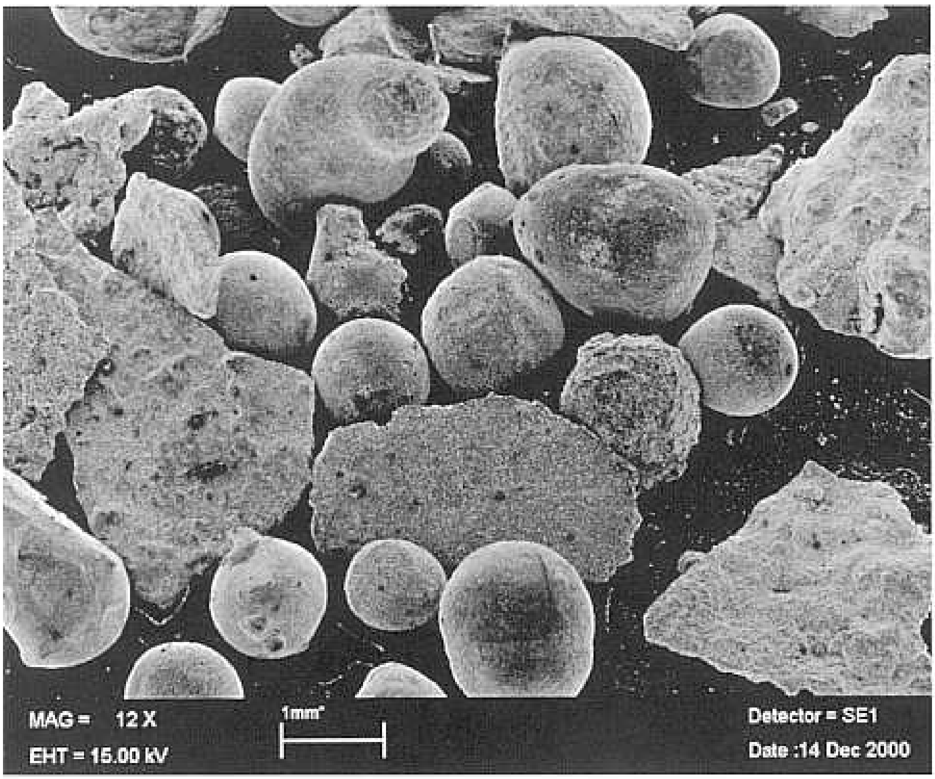

Figure 19 Scanning electron microscope (SEM) image of flake hammerscale and spheroidal hammerslag. Flake hammerscale consists of grey to black, fish-scale like fragments, typically 1–3mm across. Its small size means that it is rarely detected during excavation but it is sometimes recovered from environmental samples or from soil samples taken specifically to recover hammerscale. Flake hammerscale is highly magnetic and can be separated from soil using a magnet. Spheroidal hammerslag (often also referred to as hammerscale) consists of small round slag droplets, which can be hollow to varying degrees. It is usually magnetic.

Figure 20 Smithing pan from the Roman site at Westhawk Farm, Kent. It consists of a layer of debris, largely hammerscale, trodden down and corroded together (image 100mm high).

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. From at least the 12th century, waterpower was harnessed to drive the hammers to consolidate blooms (Astill 1993). Waterpower was also used to power the bellows and evidence of associated devices – such as grindstones – is also sometimes preserved.

Figure 21 Cross section of a smithing hearth bottom. 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 easily be misinterpreted as furnace bottoms. Smithing hearth bottoms from primary smithing, or refining will generally be larger than those from secondary smithing. Smithing hearth bottoms are sometimes slightly magnetic as they can contain fragments of iron broken from the bloom and some hammerscale.

Archaeometallurgical processes and finds – copper and its alloys

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 can be wrought. Copper is very ductile and soft, and so can be drawn into long wires or hammered into thin sheets. Although similar terms are usually employed for describing the alloys of copper, they are not always used to mean the same thing. Therefore a definition of terms is always helpful when alloys are being identified and described. The common alloys of copper discussed in these guidelines 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 increase the strength and also change the colour. Bronze and brass were used for wrought and cast objects, but the uses to which each alloy 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.

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	Description	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.

Smelting and alloying

Very little physical evidence for pre-Industrial Revolution copper smelting in Britain has been recovered, even though it is likely that identifiable debris, such as vitrified clay lining and slag, would have been produced. Fourteenth-century documentary records refer to the working of copper ores in Devon (Claughton 1992). Typical copper ores, which are found only in parts of the Highland Zone, are copper carbonate (malachite $Cu_2CO_3(OH)_2$) and copper sulphide (chalcocite Cu_2S and chalcopyrite $CuFeS_2$). While the smelting methods used in antiquity are not known, 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, or sometimes coalesces into a pool of metal. Evidence from other parts of Europe suggests that the commoner sulphide ores were smelted to produce a cake of matte (copper sulphide), which was then resmelted to give copper metal.

In the 16th century the Company of Mines Royal introduced German workers and techniques to the Lake District and to south Wales in particular. The smelting operations consisted of a complex sequence of steps, producing, first, matte and eventually copper metal. At the end of the 17th century, reverberatory furnaces were introduced and the elaborate Bristol and Welsh smelting processes were developed. Small, simple, water-powered copper smeltmills also appear to have been used in some areas (Day and Tylecote 1991).

The alloy bronze could be produced by smelting tin and copper ores together, but most bronze was probably produced by remelting together metals that had been smelted separately. Brass was not made until the Roman period; its production is described in the section on zinc (p 21).

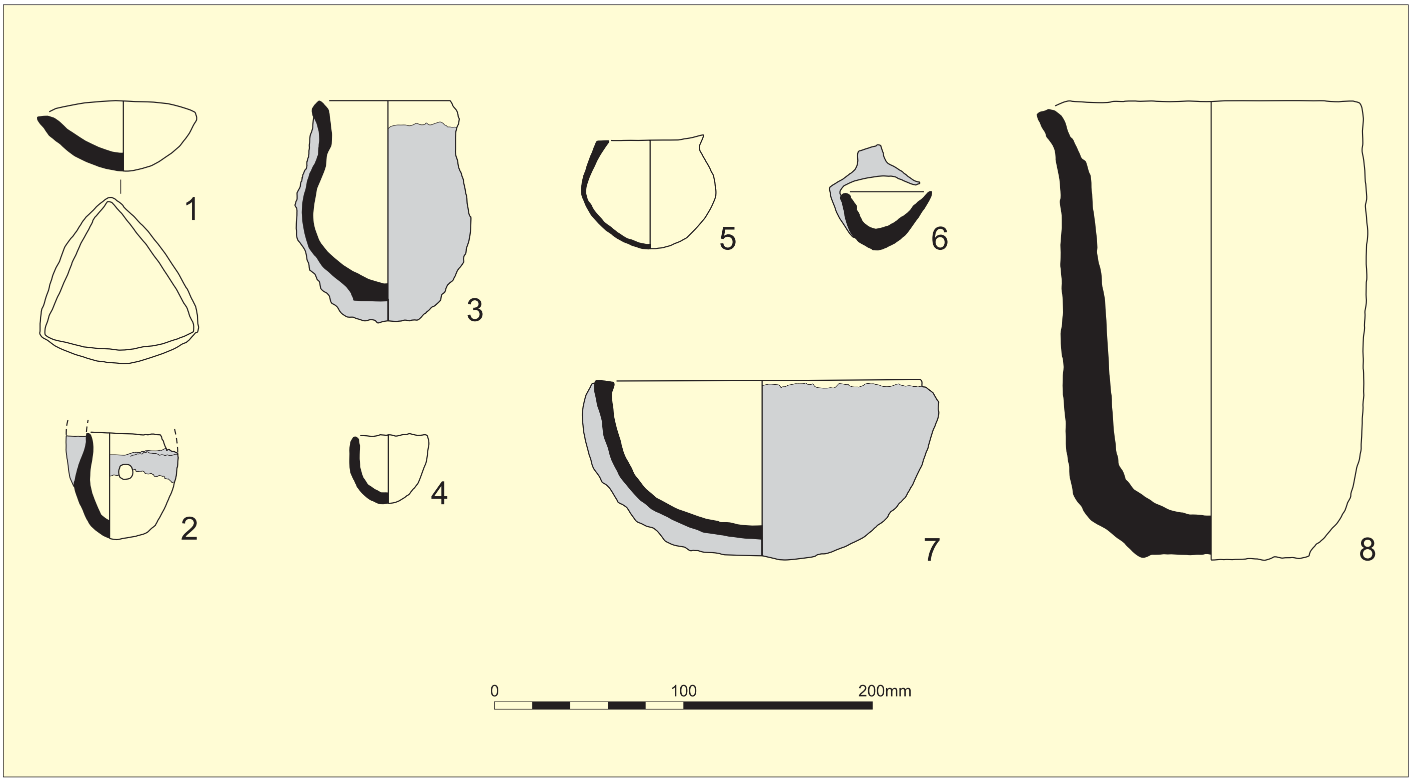

Figure 22 Drawings of common crucible forms of Iron Age to post-medieval date. **1**: Iron Age, **2** and **3**: Roman, **4** and **5**: Anglo-Saxon, **6**: early Christian, **7**: later medieval, **8**: post-medieval. The grey tone represents added clay, either lids (**2** and **6**) or extra outer layers (**3** and **7**).

Figure 23 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 25), however, is often the only way of determining the process in which the crucible was used.

Casting

Refined and alloyed molten metal could be cast directly into objects or into small ingots. Open, one-piece ingot moulds were made from stone or fired clay. Melting small amounts of copper does not necessarily require a custom-built hearth. Consequently crucibles, the vessels in which the metal was melted, moulds, used for casting the metal to shape, and the artefacts themselves are the most common archaeological evidence for copper casting. To produce a casting, the copper alloy would first be melted in a crucible, in a reducing atmosphere to prevent the metal from oxidising. The molten metal was then poured into a mould through a funnel-shaped opening, the in-gate or sprue cup. It 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 (Bayley 1988; 1990). From the Roman period onwards some crucibles are wheel-thrown, but handmade crucibles continued to be used into medieval times. The larger sizes occasionally date to the Roman period but most are later medieval or post-medieval (Bayley 1996). Some forms are relatively well dated but simple handmade thumb pots are virtually undatable. Most crucibles were open-topped, although a few types had lids or rims that were pinched together to produce an enclosed form. A few crucibles had knob-like handles on the side or lid. These lids and knobs are mainly Early Christian/Middle Saxon in date.

Moulds might be open or enclosed and were made from a variety of materials: sand, clay, metal 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 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. 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 and piece moulds. 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.

Figure 24 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.

Piece moulds were formed in two or more sections. An original object, or a pattern made in the desired shape, was pressed 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. Stone and metal piece moulds were far more durable and would have been used many times over (Bayley 1990; 1992a; 1992b). Patterns in wood or lead for making piece moulds are also known, but rare.

Figure 25 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.

Large objects such as cauldrons and bells were also cast in moulds. The process of making these moulds is well known from medieval documents such as Theophilus' *De diversis artibus* (Hawthorn and Smith 1979).

Figure 26 Part of the cope from a cauldron mould from Prudhoe Castle, Northumberland, Note the inner surface in reduced-fired (black) but the outer surface is oxidised-fired (red).

Figure 27 Sprue with two runners from Wicklewood, Norfolk, cut from a copper alloy casting.

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.

As well as the moulds themselves, corroded dribbles and spillages of metal may 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. Failed castings, where the molten metal failed to completely fill the mould, are also found.

Wrought metalworking

Wrought metalworking describes the processes of shaping solid metal, for example by hammering or cutting. Unlike ferrous alloys, copper alloys can be easily worked at room temperature. The properties of the metal, however, are affected when it is cold-worked. As the alloy is hammered, bent or twisted into shape, it 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 structure of metal to recrystallise, 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.

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. The most commonly found evidence of wrought metalworking consists of small pieces of scrap metal, such as turnings and sheet and wire offcuts. Metal filings and offcuts were collected for recycling, sometimes in boxes set into workshop floors (Figure 2 and Zienkiewicz 1993, figs 13–14). Whetstones and abrasives were used to create a good surface on metal objects, which were then polished. Alternatively the surface could be burnished with a hard material such as steel or agate (Bayley 1991b). Visual or metallographic examination of artefacts can provide evidence for wrought metalworking (see p 24).

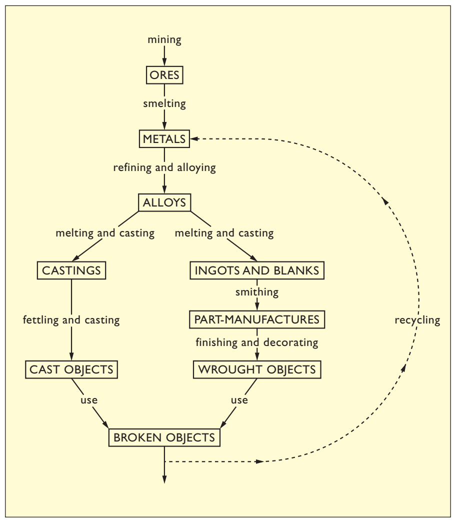

Figure 28 Flow chart showing how the product of one metalworking process is the raw material of the next.

In the medieval period waterpower was adopted for wire drawing, and for producing sheet metal, driving battery hammers and, in the post medieval period, for rolling mills.

Archaeometallurgical processes and finds – lead

Lead metal 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 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.

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 19).

Process	Description	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.

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 section on silver and gold (p 19)). There is relatively little archaeological evidence for early lead smelting, even in areas near the ore sources where it might be expected (the Mendips, Welsh borders and Pennines).

Lead ores were crushed to the optimum size for particular smelting processes. In the medieval period stamp mills were used for this purpose but later, edge-runner mills became common.

Early smelting structures were probably insubstantial, and any slag produced has been scattered or was resmelted by later, more efficient, smelting processes. The remains of Roman period smelting structures are shallow clay bowl-shaped depressions, 1–2m in diameter.

It is generally assumed that structures, known as bole hills or boles, were being used to smelt lead by the Saxon period, and these were the main medieval and Tudor method of lead smelting. Derbyshire boles were simple structures consisting of a hearth in a three-sided stall or stone-built enclosure in which pieces of rich ore and brushwood were stacked and set alight. In other areas different structures were used, though the process was the same. Areas with consistent winds were selected for boles because they did not use a forced draft. Experimental reconstruction has shown that it is not necessary to roast the ore before smelting, as this reaction occurs in the more oxygen-rich zones at the top of the fire. The gangue in the ore reacts with some of the lead oxide to form a liquid slag – all that is often found to indicate the presence of a bole site. As smelting took place, molten lead formed and was collected in a mould at the side of the hearth. This process was not efficient at extracting the metal, however, and much lead was lost into the slag. By the 1530s boles had grown from c1–2m to 5m across (Kiernan 1989). Bole sites are difficult to locate. Often the best indicators are strips of ground with poor, lead-tolerant vegetation downwind of the ridges where boles were situated.

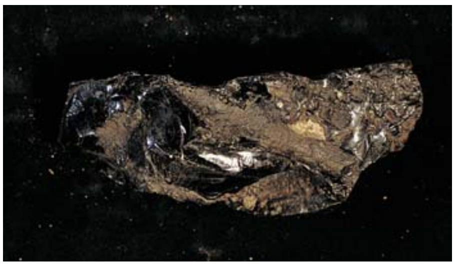

Figure 29 Lead smelting slags are known in small amounts from the Roman period onwards. They are usually glassy, very dense and black, green or grey in colour. Such slag often has a flowed surface, similar to iron-smelting tap slag (image is 100mm across).

Bole slags were being resmelted 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.

In 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. About the same time shaft furnaces, known as Burchard's furnaces, blown by water-powered bellows, were also introduced. The ore hearths remained dominant, however, changing only to incorporate water-powered bellows technology.

By the 17th century smelters were resmelting the slag from ore hearths in structures called slag hearths. These were usually water-powered and fuelled by coke. Water-powered ore hearths continued to be used until the late 19th century (Tylecote 1986).

In the later 17th century the cupola was introduced. These reverberatory coal-fired 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 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 flues became very long and complex, with condensing chambers to collect 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).

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 accidentally melted, 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. Roman pewter plates were cast in stacking stone piece-moulds (eg Blagg and Read 1977). 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 30 Lead melting dross that solidified in a hollow in the ground, from Kings Langley, Hertfordshire. It is a mixture of lead metal and oxides that were skimmed off the molten metal before it was cast.

Figure 31 A later medieval piece-mould made of fine-grained stone with holes for locating pegs at the corners from Hereford (length 57mm).

Archaeometallurgical processes and finds – other metals

Silver and gold in summary		
Native gold is the principal source of gold. Silver is mainly obtained from lead ores (p 18). 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	**Description**	**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 from gold	To part silver from gold, the silver was removed by reacting it with salt. Later, strong mineral acids were used.	Ceramic parting vessels.

Silver and gold

Unlike most other metals, the main source of gold is native gold, rather than an ore. Silver was mainly obtained from argentiferous, or silver-rich, lead. Precious metals have similar melting points 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 1988; 1991b).

Refining

Gold and silver were often refined before use, or reuse, as they were often significantly 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. The only effective way of determining the purity of silver was by fire assay, using the cupellation process.

Cupellation involved melting the metal to be refined with an excess of lead. Under a blast of air, the lead was oxidised, forming litharge (lead oxide). Any base metals present, such as copper and tin, were also oxidised and dissolved in the litharge. The litharge was then absorbed into the dish or hearth on which the process was taking place, leaving the prill of refined precious metal on the surface. Small-scale cupellation could be carried out on small shallow dishes, or discs, known as tests or cupels.

From Roman and Saxon times small ceramic dishes, often called heating trays, were used as cupels and makeshift varieties were sometimes made from potsherds. The reaction of the litharge with these ceramics produced a glassy surface. By 1600 AD cupels made from absorbent bone ash were being used in England. Small-scale cupellation was used to test the purity of a sample of precious metal: a process known as assaying. Analysis of some heating trays used for gold assaying has failed to detect lead, indicating that the cupellation process was not used. Instead, the gold was probably 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.

Figure 32 Bone ash cupels from the Tower of London. They are pale coloured and powdery. The absorbed lead in these objects makes them noticeably heavy for their size.

Figure 35 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.

Figure 33 Ceramic cupel from York. 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.

Figure 34 Segment of a litharge cake from Thetford, Norfolk. Examples up to 200mm in diameter and 30mm thick are known. They have a flat or convex base and normally have a central depression in their upper surface. They are very heavy for their size because of the lead in them and are fairly powdery and friable. Litharge cakes vary in colour from grey to greenish if much copper is present.

Large-scale refining of silver using cupellation took place in hearths lined with absorbent material, usually burnt and crushed bones (bone ash) or calcareous clay. The litharge and any base metals soaked into the lining but the precious metal was mainly left on the surface. The impregnated hearth linings that provide evidence for this process are known as litharge cakes.

When silver was extracted from argentiferous lead the same technology was used, also producing litharge cakes. These can be distinguished from litharge cakes produced by silver refining as there are normally no other metals present and the cake size is far larger, up to 600mm across and 60mm thick. This pure litharge is dull red in colour, but the cakes usually have a cream-coloured, weathered surface.

Parting

Cupellation could not be used to separate, or part, silver from gold, so a different technology was developed. The archaeological evidence for parting has only recently been recognised. Parting involved making the mixed metal into thin sheets, packing them into a pot interleaved with a 'cement' of crushed brick or tile mixed with salt, sealing up the pot and heating it, but to a temperature below the melting point of the metal. The salt reacted with the silver in the metal, forming silver chloride, which was volatile and was absorbed by the cement and the walls of the pot. When the pot cooled, the gold could be removed and remelted and the cement smelted to recover the silver (Bayley 1991a). With the introduction of distillation in the later medieval period, the method of parting changed to one using strong mineral acids.

Tin

Tin is a soft, white metal with a melting point of 232ºC. Documentary and archaeological evidence suggests that tin extracted from the ore cassiterite (SnO_2) in Devon and Cornwall was exported from the Bronze Age onwards and was of great economic importance. There are two main sources of cassiterite in the region: stream tin and lode tin. The ore obtained from veins in the rock, lode tin, was less readily accessible than stream tin, which was eroded from rock, largely separated from the gangue, and then deposited in streambeds. The stream tin was thus probably the first to be exploited and it only required washing before smelting. By medieval times the ore from lodes, which contained large amounts of gangue, was mined and so grinding and washing was necessary before smelting (Gerrard 1997; 2000). 'Black tin' is the term applied to both stream tin and to crushed and cleaned lode tin.

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. The latest date to around the 13th century, indicating that smelting technology probably changed little up to this time. The ingots are thought to have been formed by molten tin-metal cooling in small bowl-shaped furnaces. In medieval smelting, molten tin was tapped from the furnaces. Although both the metal and the iron-silicate slag were liquid, the two would separate out because of their different densities. In the post-medieval period, lime was substituted for iron oxide in the smelting process, blast furnaces were used to achieve higher temperatures and calcium silicate slags were produced (Tylecote 1986).

The crushing of lode ore took place in stamping mills. They used water-powered hammers, probably from the 13th century. Stamp mills can be positively identified by the presence of mortar stones with saucer-shaped hollows in 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 cassiterite from the gangue and the dressed ore was smelted in a furnace within the blowing house. Charcoal or carbonised peat was used as the fuel. Water-powered bellows provided an air blast to the furnace. The molten tin was tapped from the furnace hearth into a trough and was then ladled into smaller moulds or troughs. These troughs, often hewn from granite blocks, are good indicators of a blowing house. See Gerrard (2000) for further details.

Tin was alloyed with copper to produce bronze, and with lead to produce pewter and solders. High-tin pewter was used to make objects in similar forms to contemporary silver objects, because of its similar colour. It was more rarely used simply as tin metal, as the softness of the metal made it impractical for functional applications. It found favour for decorative applications, however, as the white colour of the metal contrasted nicely with copper coloured alloys. Other metals, such as iron, were plated with tin. Tin, like lead, could also be melted in domestic pots instead of crucibles because of its low melting point.

Zinc

Any attempt to reduce zinc ore in the same manner as other metals using charcoal fuel at around 1000°C, would result in the zinc metal becoming a vapour as soon as it was produced (it boils at 907°C), which would be lost as fumes. Consequently zinc was not generally available in Europe until the post-medieval period; documentary evidence records zinc extraction from the 18th century.

From the 1st century BC, however, copper was alloyed with zinc by the cementation process; the resulting metal is known as brass. In this process zinc carbonate or zinc oxide, which were known as calamine in antiquity, were ground, added to granulated copper and charcoal in a closed crucible, and heated to between 950°C and 1000°C (below the temperature at which copper melts). The presence of the charcoal ensured a reducing atmosphere (one containing little oxygen) in the crucible, so the zinc ore was reduced to zinc metal vapour, which was absorbed by the solid copper granules. The absorption of zinc lowers the melting temperature of copper, so eventually the metal melted, homogenising the mixture (Bayley 1998). Reverberatory furnaces for roasting calamine were introduced by the late 17th century. Zinc smelting, using sealed retorts in conical furnaces, was introduced in the 18th century in the Bristol area and more efficient processes were introduced in the 19th century. Archaeological evidence of these processes is rare.

Non-metallurgical high temperature processes

Many non-metallurgical processes generate materials that can be easily mistaken for metallurgical waste. High temperatures can be produced in ovens, hearths, kilns (for ceramics or lime), furnaces (for making or melting glass) and even when buildings burn down. These structures and many objects, such as pottery vessels, are commonly made from clay or stone, which contain silicates. If they are heated to sufficiently high temperatures these materials can melt and become glassy; they can then be confused with vitrified waste products from metallurgical processes. Temperatures high enough to produce vitrification were rarely achieved in antiquity, although occasionally pottery, brick and tile kilns became too hot and the ceramics inside were over-fired. Pottery wasters are glassy and blistered, and the shape slumped and distorted. Some bricks were deliberately vitrified to change their appearance.

Silicate materials, such as clay and stone, will form a glass at lower temperatures if fluxing compounds are present. Common fluxes are the alkalis – soda and potash – found in plant ashes. The ash from a fuel will thus react with the silicates in clay or stone vessels or hearths to produce glassy (vitrified) materials. These glassy wastes are usually described as fuel ash slag. Similarly, the ashes from burnt thatch or structural timbers may flux daub walls, during a house fire, to form vitrified clay. An equivalent process produces vitrified forts when their timber-laced ramparts are burnt. Fuel ash slag and vitrified clay can be produced in any high-temperature fire in which alkalis and silicates come in to contact and so, on their own, they are not indicative of a metallurgical process (Bayley 1985, Biek and Bayley 1979).

Alkali fluxes and silica can also be reacted together intentionally, to produce alkali silicate glasses. The raw materials were first fritted, ie heated together in a furnace so that they partly reacted. The frit produced was broken up and placed in crucibles, together with recycled scrap glass cullet, and then heated in the furnace more strongly to produce a homogeneous melt.

Glassy materials are also formed from the reaction of lead oxide with silica-containing materials, since lead oxide is also an effective flux. Lead silicate glasses are formed during metallurgical processes involving lead but,

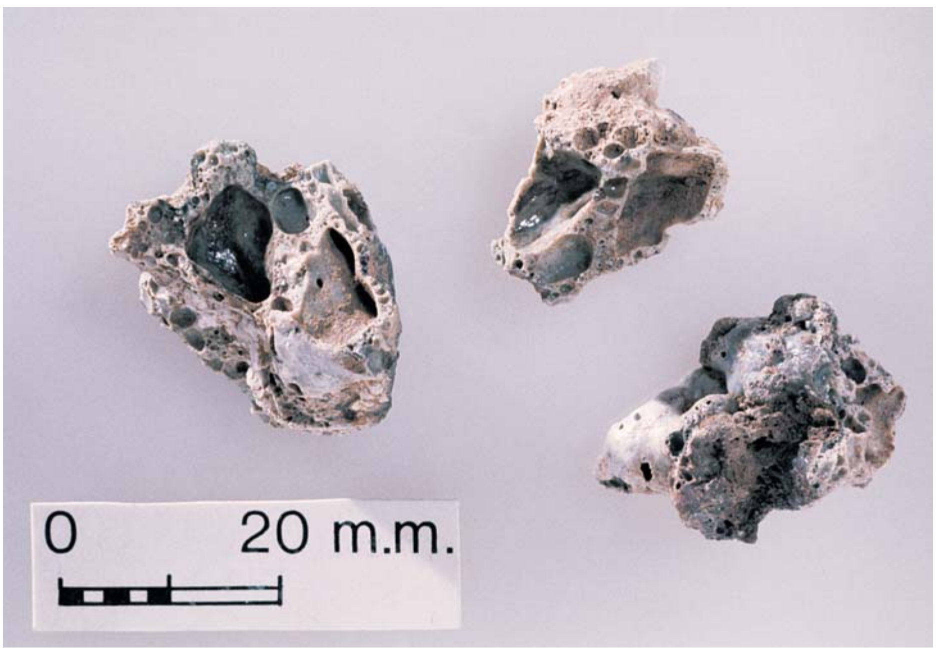

Figure 36 Fuel ash slags from Rivenhall, Essex. They are lightweight, vesicular and fragile, and are usually off-white to green or mid-grey in colour, generally much paler than iron-working slags.

Figure 37 Ceramic crucible sherds with a thin layer of glass on the inner surface from Glastonbury, Somerset. Crucibles containing glass, dribbles of glass and lumps of glass cullet are all evidence for glass re-melting, which was commoner than glass making until the late medieval period.

Figure 39 Daub and ceramic tiles from a Roman building in London destroyed by fire, which are stuck together by an accidentally-formed lead-rich glass.

as with alkali silicates, can also form accidentally. For example, if a building is destroyed by fire then the lead in the roof flashings, plumbing, or window cames within the building will melt and oxidise. This lead oxide will react with silicate materials such as bricks or tiles to fuse them into a mass of vitrified debris.

As with alkali silicates, lead silicates were also intentionally produced as glasses and enamels, and as ceramic glazes. Iron colours the glass or glaze pale amber, brown or olive green, while copper produces bright green or opaque red. Crucibles in which coloured glasses were made have thick layers of glass on the inner surface, unlike metal-melting crucibles where the glassy waste is mainly on the outside.

Some geological materials can be confused with iron-working slags in particular. Some forms of ironstone can be mistaken for tap slag or smithing slag. Pyrite (iron sulphide) nodules, pieces of puddingstone, bog iron ore and Niedermendig lava can all be confused with smithing slags. Deeply corroded iron objects and iron concretions are also apt to be wrongly identified.

Briquetage is the term given to ceramic containers in which seawater was evaporated to obtain salt. This resulted in a bleached appearance to the ceramic, which is usually fairly soft and oxidised-fired but does not have any vitrified surfaces.

Ceramic vessels were also used in the medieval period in the production of various chemicals. These processes were normally carried out at cooking temperatures and so did not produce vitrification, though powdery or crusty deposits are sometimes left on the vessels.

Figure 40 Section through a puddingstone boulder; the rounded exterior can be mistaken for iron slag.

Figure 42 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. 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.

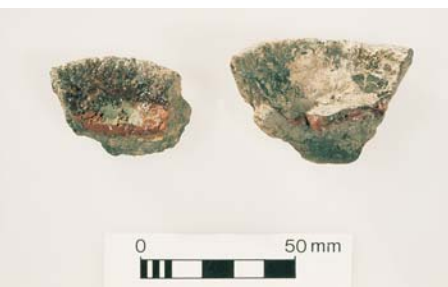

Figure 38 Crucibles containing deliberately made opaque red glass, from Chichester, Sussex.

Figure 41 Pyrites nodule. The weathered outside (right) may look like iron slag but the interior (left) has a silver colour and radial structure.

Definitions of commonly used terms

Alloy
The properties of pure metals may 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.

Crucible
A 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
Iron and its alloys are described as ferrous metals. The principal ones used before the Industrial Revolution were cast iron, steel, phosphoric iron and plain iron.

Furnace
A 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
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
A 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, adits 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, sand or bone. Moulds were not usually exposed to high enough temperatures to vitrify them.

Non-ferrous
Non-ferrous metals do not contain iron. The principal ones used before the Industrial Revolution 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. Iron, because of its high melting point, was often smithed to squeeze out slag still trapped inside.

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

Slag
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 as a slag during smelting. 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
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
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 may be accidentally or deliberately added.

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.

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. 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.

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 1995; Gaffney and Gater 1993; Gaffney *et al* 1991; Vernon *et al* 1999).

The two geophysical techniques most commonly applied on metalworking sites are magnetometry and magnetic susceptibility.

Magnetometry with a fluxgate gradiometer or a total field instrument (eg caesium 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 surveys 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 surveys 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.

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* (Aitken 1990). 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. Samples for archaeomagnetic dating should be taken by, or under the supervision of, a relevant specialist.

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 (x1–20 magnification) optical examination 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, and also to ensure that any data obtained is from representative areas.

High power optical microscopes (x50–1000 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.

Metallic samples can be etched to reveal the crystal structure of the metal. 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. Metallography can also identify the methods used to apply surface treatments, such as gilding, silvering and tinning. The shape of the inclusions 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 may have important cultural implications. For example, in many Saxon knife blades a steel cutting edge was butt welded to an iron back, while Anglo-Scandinavian smiths favoured 'sandwiching' the steel between two low carbon sides.

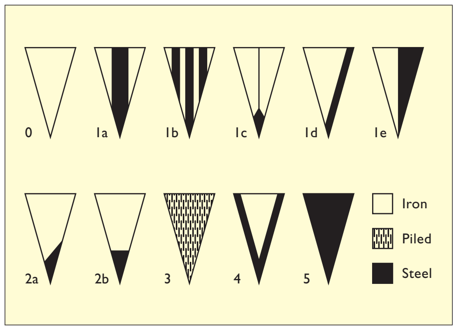

Figure 43 Schematic sections through knife blades showing different methods of construction (after Tylecote and Gilmour 1986, fig 1).

The shape of the metal crystals in non-ferrous alloys will show how the object was produced, for example cast alloys generally have characteristic dendritic structures. 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 field can be obtained. Images can be obtained in two modes. Secondary electron mode is used to look at the topography or shape of a sample (see Figure 19). Back-scattered electron mode shows the compositional differences across a sample, since areas with different compositions are seen as varying shades of grey (Figure 44). Sample preparation techniques vary depending on the mode in which the SEM is to be used. It can be used in conjunction with analytical techniques (EDS and WDS), which are described below.

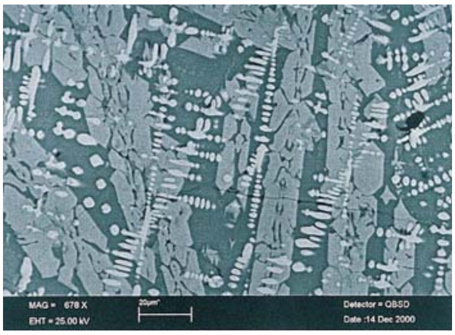

Figure 44 A back-scattered electron image of iron working slag showing several different phases.

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. The determination of the chemical composition 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 the most widely used method 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 contains peaks for each of the elements present in the object or sample. Peaks for organic materials cannot usually be detected with EDXRF. The spectra are detected in one of two ways: energy-dispersive detectors (EDXRF) allow the simultaneous detection of the whole X-ray spectrum, while wavelength-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. 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. Alternatively, EDXRF can be used quantitatively, but this is only possible where samples (typically a few millimetres across) are removed, mounted in resin and polished.

Similar spectra are also generated using an analytical SEM 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. This is particularly useful for the analysis of such heterogeneous materials as slags and iron.

A number of analytical techniques exist in which characteristic spectra are generated as light rather than X-rays. The techniques commonly used in archaeology are atomic absorption spectrometry (AAS) and inductively coupled plasma atomic emission spectrometry (ICP-AES). For these techniques a small powdered sample, such as a drilling, is taken. The sample itself is destroyed during analysis as it is dissolved in acid. These techniques can give very good accuracy, with detection limits below 1ppm for some elements, but they are most appropriate for bulk analysis of homogeneous materials rather than for analysis of particular features.

Mass spectrometry

The most sensitive analyses of archaeological metalwork are those made by mass spectrometry (eg ICP-MS), where atoms, ions or molecules are sorted and counted by mass. The principal application in archaeology is the analysis of lead isotopes in lead, copper alloys and silver. The relative abundance of these isotopes characterises the ore source, but the isotopes in different British ore sources are similar.

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. Glass is not crystalline, but XRD analysis could detect crystalline glass colourants or opacifiers if these are present. This technique is also useful for analysing corrosion products, precipitated salts, pigments and soil samples.

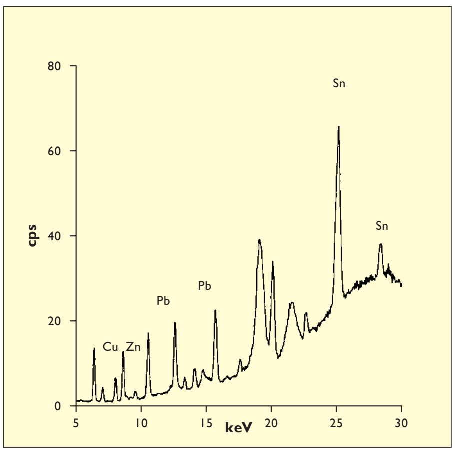

Figure 45 An XRF spectrum obtained from a crucible used for melting copper alloys, from Mucking, Essex.

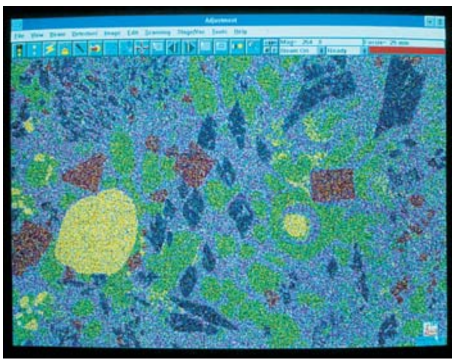

Figure 46 False-colour back-scattered electron image of a litharge cake showing several different phases. The green areas represent a lead-copper oxide phase; the blue unreacted bone ash hearth lining, the red a tin-calcium-lead oxide phase; and the yellow droplets of silver metal (image width c1mm).

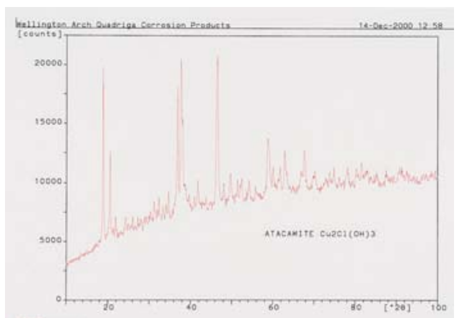

Figure 47 XRD spectrum of the metal patina from the Quadriga, Wellington Arch, London.

Where to get help

Advice is available to curators and contractors, archaeologists, conservators and museum professionals. The number of active archaeometallurgists is small, but most of them would rather be consulted than find out too late about missed opportunities.

The English Heritage Centre for Archaeology and the Archaeology Committee of the Historical Metallurgy Society run occasional training days for archaeologists on how to recognise and deal with slags and other industrial debris. If you would like information on future Slag Days, please write to David Dungworth at the address below.

Some archaeologists and finds researchers have developed skills in the excavation of metalworking sites and in the identification and assessment of archaeometallurgical finds. They are often the best source of advice in the early stages of a project. They normally do not, however, have access to the scientific facilities that can be used to check identifications and undertake detailed investigations.

The institutions listed below all have one or more scientists on their staffs who are capable of providing metallurgical advice and services, including scientific analyses of objects and samples. Some specialise in identifying metalworking debris, while others focus on the application of a particular scientific technique. Where appropriate, they will refer you to another specialist. The individuals' special interests are listed below, but most are able to provide advice on a wider range of topics as well.

(Please note that inclusion in this list is no commitment to provide help.)

Centre for Archaeology (incorporating the former Ancient Monuments Laboratory)

English Heritage, Centre for Archaeology, Fort Cumberland, Fort Cumberland Road, Eastney, Portsmouth PO4 9LD

Justine Bayley
023 9285 6794
justine.bayley@english-heritage.org.uk
Iron Age to medieval metal and glassworking; artefact analysis

David Dungworth
023 9285 6783
david.dungworth@english-heritage.org.uk
Metalworking and artefact analysis

Sarah Paynter
023 9285 6782
sarah.paynter@english-heritage.org.uk
Metal and glass working; artefact analysis

Advice is available to all, free of charge. If prior arrangements have been made, assessments and analysis of finds from EH-funded projects will be undertaken free of charge. It is sometimes possible to provide a similar service for developer-funded excavations, although a charge is normally made for this work. Material that contributes to current research projects is dealt with free of charge, even when not from EH-funded projects.

Bradford University

Ancient Metallurgy Research Group, Department of Archaeological Sciences, Bradford BD7 1DP

Gerry McDonnell
01274 233531
j.g.mcdonnell@bradford.ac.uk
Ironworking, artefact analysis

Joint research projects, small and large, are encouraged. Service work can also be undertaken at cost.

British Museum

Department of Scientific Research, London WC1B 3DG

Paul Craddock
0207 323 8797
pcraddock@british-museum.ac.uk

Several individuals work on archaeometallurgical projects but their activities are normally restricted to sites being excavated by the Museum or research on finds in the Museum's collections.

Cardiff University

School of History and Archaeology, Cardiff University, PO Box 909, Cardiff CF10 3XU

Kilian Anheuser
029 2087 5157
AnheuserK@cf.ac.uk
Analysis of ferrous and non-ferrous metalwork and fine art

Analytical services (including metallography) available at cost.

Durham University

Department of Archaeology, South Road, Durham DH1 3LE

Chris Caple
0191 374 3627
christopher.caple@durham.ac.uk

Phil Clogg
0191 374 3215
p.w.clogg@durham.ac.uk
Analysis of archaeological materials, including geochemical survey

Joint research projects, small and large, are encouraged. Service work can also be undertaken at cost.

Institute of Archaeology
University College London, 31–4 Gordon Square, London WC1H 0PY

Thilo Rehren
020 7679 4757
th.rehren@ucl.ac.uk
Analysis of metal and glass working processes

Postgraduate teaching in scientific analysis of archaeological materials is undertaken. Local projects and post-excavation research are encouraged. A wide range of appropriate analytical techniques is available in-house and within UCL.

National Museums of Scotland
Chambers Street, Edinburgh EH1 1JF

Paul Wilthew
0131 247 4143
ptw@nms.ac.uk
Analysis of ferrous and non-ferrous metals and metal working debris

Kathy Eremin
ke@nms.ac.uk
0131 247 4201
Analysis of non-ferrous metals, metal working debris and glass

These specialists deal primarily, but not exclusively, with Scottish material.

National Museums and Galleries of Wales
Department of Archaeology and Numismatics, Cathys Park, Cardiff CF10 3NP

Mary Davies
029 2057 3228
mary.davies@nmgw.ac.uk
Artefact analysis

This department deals primarily, but not exclusively, with material from Wales.

Nottingham University
Department of Archaeology, University of Nottingham, University Park, Nottingham NG7 2RD

Julian Henderson
0115 951 4840
julian.henderson@nottingham.ac.uk
Analysis of glass

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Joint research projects, small and large, are encouraged; advice and support are given to student and society projects. Analytical services available at cost.

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The Royal Armouries deals mainly with arms, armour and material from military sites. No charges normally made for this sort of work.

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Advice and analysis can be given on artefacts and industrial waste from archaeological and historical/ex-industrial sites. Analytical services are available at cost.

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Welcome discussion of dissertation projects for MSc students, involving analysis of materials from high temperature technologies.

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Cover image Experimental iron smelting, using hand bellows *(Photograph by Peter Crew)*

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