Medieval metalwork: an analytical study of copper-alloy objects

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ABSTRACT: Copper-alloy objects of the medieval and early post-medieval periods were analysed to establish whether there was any pattern to the alloy compositions used, as a function of object type, or date or place of manufacture. Objects from NW Europe, of 12th–17th century date and mostly at least partly utilitarian, showed compositional correlations, to the extent that characteristic compositions were identifiable for some regions for the late medieval and early post-medieval periods. A method is presented of displaying compositions graphically which proved useful in exploring the phenomenon of alloy evolution. The use of scrap metal of unknown pedigree seems not to have been usual; the few instances of such practice can usually be recognised. It has been shown that dating and provenancing (in broad terms) is possible for many object types using alloy compositional data.

Background

Historians of fine art have quite naturally been drawn to the works of painters of the medieval and immediately post-medieval periods when some of the finest examples of artistic achievement were created. This is true also of students of the applied arts such as metalwork, but there has tended to be a concentration on the study of the finest examples, to the detriment of the works of lesser craftsmen. Gold- and silver-smiths executed the commissions of kings and emperors, while workers in copper alloys satisfied the needs of lesser rulers and of the senior church hierarchy. Much of the surviving art-metalwork in copper alloys of the medieval period has a religious context and accordingly some is richly decorated.

In contrast with precious metalwork there is a complete spectrum of copper-alloy metalwork from the finest applied-art pieces, through a wide range of at least partly functional objects to those with little or no decoration. The intermediate part of the spectrum, including such items as candlesticks, ewers and mortars, has received a limited amount of attention; the utilitarian metalwork, including skillets and cauldrons, has received little serious study. The work reviewed here concentrated on the middle and lower parts of the spectrum of sophistication, those parts most in need of consideration.

The study of the works of gold- and silver-smiths (and even those of pewterers) is greatly facilitated by the requirement of their guilds that craftsmen mark their work. Thus, the place and time of manufacture of objects, and in some cases the identity of the maker, can be determined with some certainty. In contrast, very few copper-alloy objects are marked. Until recently art-historians wishing to study the development of style, as a function of time and place of manufacture, have had to rely on the less satisfactory approach of studying documents and paintings. Documents do not commonly describe items in sufficient detail for object-types to be clearly and unambiguously recognised, and paintings by known artists showing items of metal work carry no guarantee that the objects were made locally or recently, relative to the artist's time and place of painting.

The advent in about 1970 of alloy analysis techniques, which required no or infinitesimally small amounts of metal to be removed, and yet provided data on a wide range of the alloy constituents present, opened up the possibility that a programme of analysis could provide new information. Three requirements had to be satisfied before analysis could provide information on the date and place of manufacture of copper-alloy objects:

- Analysis of a reasonably large body of material had to show useful variation in the alloy compositions of the items in the full population of objects
- Compositional variation had to show local consistency with some recognisable feature or features of the sub-populations concerned
- The collection of sub-populations had to be calibrated or characterised by the inclusion of examples which are inscribed or in some other way identifiable as coming from a known period and/or place of manufacture

Hindsight has shown that all three conditions are satisfied by the medieval period for cast copper-alloy objects made in north-west Europe. These conditions may not be satisfied for either earlier or later periods nor for other geographical areas, nor for wrought copper-alloy objects.

When the present work was beginning, almost no information was available on the alloys used for most types of medieval objects, and only in respect of the finest were there a reasonable number of published analyses. Werner (1977) undertook the sampling and analysis of over one hundred items in German and other museums, including fine candlesticks, aquamaniles, censers, crucifixes and other items of religious importance. Most are from the 11th–15th centuries. He further laid the foundations of an understanding of the ways in which the alloys used reflected the technical and economic situation of the region and period and how this changed with time. He also attempted to devise means of using the analytical information to discriminate between early medieval objects and fakes or copies made much later. This preoccupation was not soundly-based statistically and his conclusions were unreliable. However, his pioneering work on establishing the nature of the materials used by medieval metalworkers should be recognised.

A mere handful of analyses were published or available in archives relating to less fine objects of a monastic, domestic or utilitarian nature cast in copper alloys in the medieval period. It was to improve knowledge of these that the work reviewed here was directed, although fine objects were included when the opportunity arose, since these were likely to be useful for comparison with Werner's (1977) data.

The analytical work

An analytical technique was developed (see Appendix) and access was granted to allow sampling of about 50 objects in two Cotswold antique dealers' shops and in museum collections in Coventry, Carlisle and Leicester. The feasibility of the project was quickly demonstrated in that useful analytical data were obtained from samples small enough to leave acceptably small traces of their removal.

The range of objects included candlesticks, ewers, cooking vessels, mortars and weights. The analytical results demonstrated that the first of the three requirements set out above was satisfied since the alloys used to cast them ranged widely from brass to leaded bronze through various complex intermediate compositions. It was clear that, if there was to be any chance of using analysis as a means of gaining a fuller insight into the technology of the period, and in particular the possibility of developing analysis as a diagnostic technique, then very many more objects had to be analysed. Fortunately the curators of the county and national museums and private collectors who were approached were always sympathetic in allowing further, larger-scale sampling, even when there was little prospect of an early dividend on the effort involved, and the author is extremely grateful for their support.

The approximate numbers of objects of each type analysed are given in Table 1. Note that some objects provided more than one sample. The populations in each group are biased towards later material but the memorial letters are all early (14th century), as are most tripod ewers, and particular efforts were made to seek out early weights such as steelyard weights (early 14th century).

The nine elements analysed belong to one of three categories. The first (alloy base) contains just copper, which is the main element present and common to all

Table 1: Approximate number of objects and samples analysed

Object type	Objects	Samples
Candlestick	325	625
Cooking vessel	215	-
Ewer/jug	140	-
Lectern	50	250
Memorial letter	170	-
Mortar	165	-
Weights & measures	170	-
Other	170	-

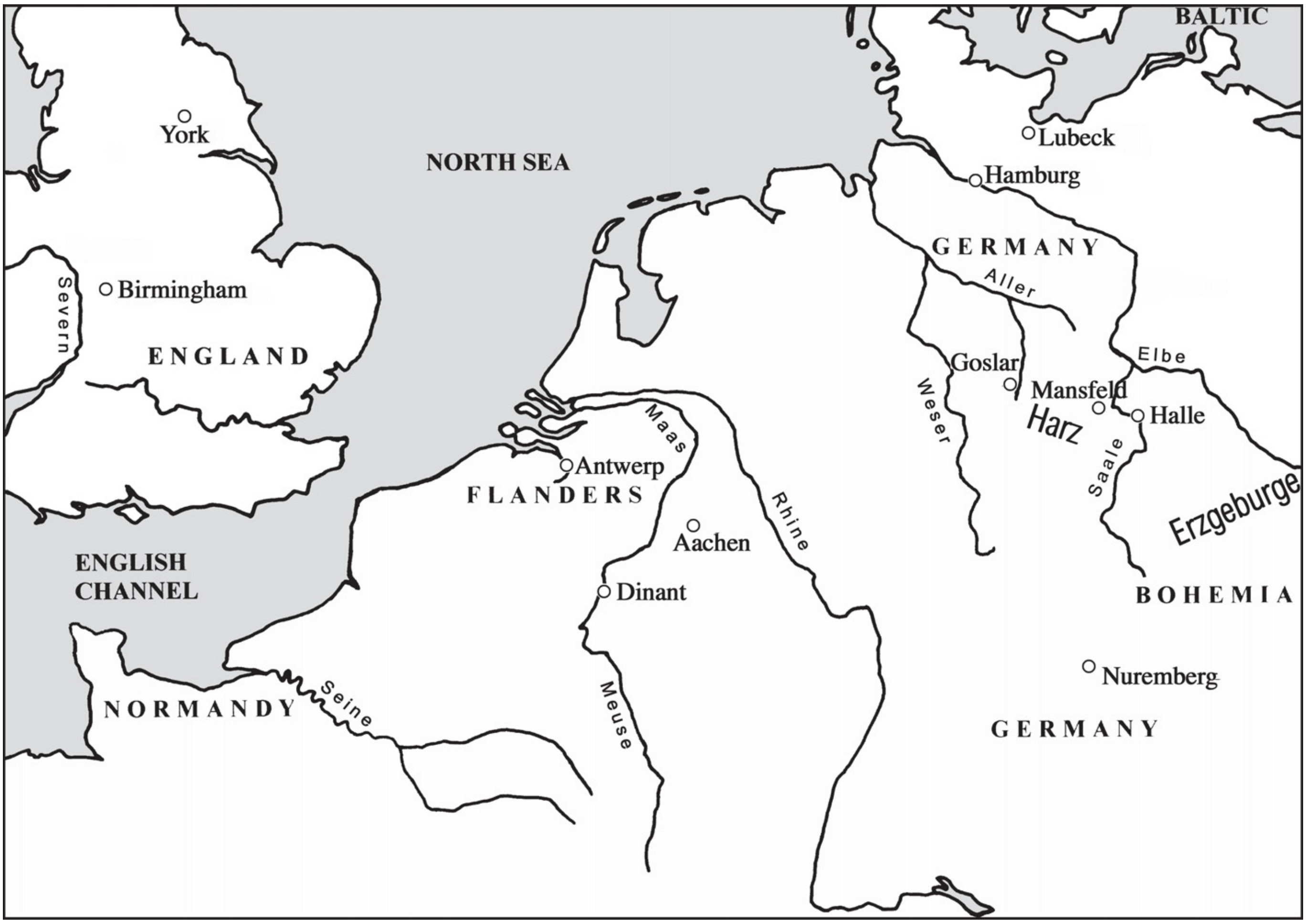

Figure 1: Map showing places and areas mention in the text.

the alloys. The second (alloying elements) contains zinc (Zn), tin (Sn) and lead (Pb); tin and lead as the metals and zinc via calamine would have been deliberately added under a measure of control by the craftsmen in order to achieve certain properties and characteristics in the final alloy. The third (impurity elements) contains nickel (Ni), iron (Fe), antimony (Sb), arsenic (As) and silver (Ag) which would have been present in the final alloy incidentally. These may have been present as impurities in the metals in the other two categories or have been the result of pick-up during melting and casting.

Attempts at dating and provenancing

As the number of objects included in the study increased, the impression was reinforced that the range of compositions used was not random. This was contrary to the advice received at the outset that little of use could be achieved by trawling museum collections for objects. The frequent absence of information on the origins of these objects was unfortunate, but not a serious disadvantage (see below). A further worry was that the uncontrolled use of scrap metal would blur any patterns, making any deductions on matters of time and place of manufacture impossible. The 'proof of the pudding' argument allowed this objection to be dismissed; the possibility of occasional use of scrap could never be eliminated but it cannot have been usual, at least in the late medieval period, or the degree of order observed would not have been apparent.

The third requirement stated above meant that certain types of object were deliberately sought out where these commonly had inscriptions and/or dates which were seen as valuable reference points in terms of time and place of manufacture. This was not difficult for the late part of the period during which it was customary to inscribe and date at least some of the finer examples of mortars, skillets and cauldrons. Many 17th, some 16th and a few from earlier centuries have survived. Inevitably it was more difficult to find objects of known date from the medieval period but for this (and other periods) weights proved invaluable. They were seldom dated but could be assigned to a small time-span by virtue of arms or other decoration.

It became clear that data on the levels of alloying elements were primarily valuable in the exploration of where an object was made, whereas data on the levels of impurity elements were primarily valuable in saying when an object was made. In reality the situation was rarely quite so clear-cut and all nine values were always taken into account.

Impurity elements

Werner (1977) explored and explained the variation in impurity elements in medieval copper alloys. Impurity levels were found to be very low in early (11th–13th century) alloys but seemed to rise steadily over the 14th–17th centuries. This can be explained in terms of the initial exploitation of 'pure' oxidised ores from the surface and sub-surface layers which led to low levels of impurities in the final alloys. After these ores had been exhausted, mining to lower levels inevitably involved unaltered 'impure' ores, usually sulphides of complex chemistry, and these contributed impurities to the final alloy. These arguments appeared to apply particularly to nickel, antimony and arsenic which rose in level, although not in exactly the same way, with the passage of time.

The present programme confirmed the picture and showed remarkable reliability, in particular using nickel values, in indicating dates for alloys of a range of types, and those probably produced in widely different metal-working areas. In this context 'date' should be taken to cover a period of up to a couple of centuries. It is not clear whether this implies a near-uniform nickel content in copper extracted at a large number of centres, or that the degree of uniformity indicates that most metal used over a wide area came from only a few sources. The latter seems more likely, particularly early in the medieval period.

Although nickel, antimony and arsenic levels tend to be higher in later alloys, the ways in which the levels changed with the passage of time are not identical and by examining all three, approximate dating to a period spanning a century is sometimes possible. Usually objects can be assigned either to the period before about AD 1400 or to the period covering the 15th–17th centuries.

The nickel levels of alloys from the medieval period are low (mostly well below 0.5%) and even alloys of the 16th and 17th centuries usually have nickel levels below 1.0%. Occasionally nickel levels above 1.0% are encountered, and this almost certainly indicates that alloys were made using copper from a source different in kind or location from the majority. Werner (1977) drew attention to the nature of the copper extracted at Mansfeld, a location between the Harz mountains and Halle on the Saale. The copper is of good quality but is known to contain nickel levels above 1.0%. It is not surprising therefore that objects believed or known to have been made in Nuremberg, upstream from Halle, (*eg* a cup weight from Peterborough Museum 3.70% Ni), or in Hamburg or Lübeck, downstream from Halle, (*eg* a vessel lid from the British Museum: 50, 5–7, 1, with 1.56% Ni) have higher than normal nickel levels. The metal of the Lacock Abbey cauldron, cast in 1500 in Mechelen by Pieter Waghavens (Brownsword 1991; Vandenberghe 1978), has high nickel and this may have come from Mansfeld via Hamburg and Antwerp.

Another small group of objects of British provenance also have high nickel in their alloys; the above explanation of traded metal being brought from Mansfeld may have applied to them but another explanation seems more likely. The objects, cauldrons and vessel fragments, including several excavated at the site of a foundry in Exeter (Blaylock 2000), all have West Country or South Wales find sites remote from Continental sources of metal. This may point to a local, probably small-scale, copper extraction industry in the region, perhaps that of the Bere Alston area.

Alloying elements

Although variations in alloying elements often relate to areas of production, there are some technical constraints which mean that the choice of alloy type and sometimes even the levels of alloying additions are proscribed. For instance, copper alloys containing lead or tin did not, it seems, lend themselves to gilding or enamelling, whereas satisfactory coating was possible on brass or copper itself, provided they had very low lead contents (<2%). It was well known at an early date that the best performance from bells was achieved when alloys of high tin but low lead content were used. The process of wire drawing was most successfully carried out on brass having a high zinc but low lead content; only the highest grade of raw materials and the most highly developed technology would have led to this in the medieval period.

With the exceptions noted above, few constraints would have applied to the choice of alloy for most cast products. Useful casting alloys result from the addition to copper of zinc, tin or lead, singly or in combination, within wide limits of amount. The founder was therefore free to choose both the nature of the alloying metals and the amounts added to minimise his materials costs, subject only to the overall requirements that the final object be fit for the intended purpose. These requirements would have been mainly technical (strength, corrosion resistance *etc*) or technological (ease of casting) but probably at least partly aesthetic (colour). The relative costs of copper, zinc (via calamine), tin and lead would therefore have had the strongest influence on the choice of alloying additions. These relative costs would have been different in the various parts of Europe according to their proximity to the metal sources. Thus, for instance, tin would have been a relatively affordable addition in England, which was an important source of tin at the time, but zinc (via calamine) would have been a relatively expensive import from the Low Countries. This was reflected in the high tin:zinc ratio of English alloys. Conversely, in the Low Countries, near to the calamine deposits on the middle reaches of the Meuse and around Aachen, and the developed technology for producing copper-zinc melting stock from calamine, a low tin:zinc ratio is common, as this alloy would have been more economical than one containing relatively expensive tin, imported from England or Bohemia.

Lead was always the cheapest of the four metals (Cu, Zn, Sn, Pb) across north-west Europe, so there would have been every incentive to have as much lead as possible in the alloys consistent with the requirements dictated by the end-use. Lead does not dissolve in copper alloys as zinc and tin do, so it is present as metallic lead globules and inter-granular films in the microstructure. These weaken the material and render objects made from high-lead alloys (>10% Pb) prone to fracture when mistreated, and also to internal oxidation when heated. Such alloys would have been regarded at the time as of inferior quality, suited to casting objects such as large weights and measures, mortars and, notwithstanding the above comment on the effect of heating, cauldrons and skillets. One advantageous property of high-lead copper alloys is the facility with which they can be cast into objects of thin section such as cauldrons.

Alloys used to cast candlesticks, ewers, hanging lavers and chafing dishes are found to be of lower lead content, rendering the objects better able to withstand a certain amount of rough treatment in use without fracture. Within this range of lower lead levels there are discernible differences over the north-west European region.

Thus the choice of alloy constituents added to copper reflected the local economies, particularly availability and cost, of the use of the three metals (Zn, Sn and Pb), and craftsmen in different regions adopted different solutions to the problem of finding the most economical composition for their casting alloys. These can now be recognised through alloy analysis and used *inter alia* for provenancing. This recognition is aided by a method of presentation of the compositional data which uses a triangular scatter plot (see Appendix); the appropriate alloy descriptions are given in Figure 2.

Late medieval and early post-medieval alloys

While it would have been more logical to have presented and discussed the findings relating to early material before doing so for later material, the order of treatment is reversed. This is because the later groups were easier to recognise, as the populations of object-types were larger, and more settled metal availability meant less variation, giving clearer patterns; it is also the historical order in which the project proceeded. The earlier material was then considered in the knowledge of the situation for the later material and benefited from this perspective. Its discussion follows.

Characteristic compositional profiles

Traditional stylistic analysis of certain object types, say candlesticks, involved the grouping together of examples having certain stylistic features in common. A group formed in this way was not unreasonably taken to share a broadly common origin as regards date and place of manufacture. It became plain at an early stage in the present investigations that a group formed on a stylistic basis contained examples with similarities also of their alloy compositions which could therefore also be linked to their origin. Additionally, one group with consistent stylistic differences from another exhibited consistent compositional differences indicating a different origin.

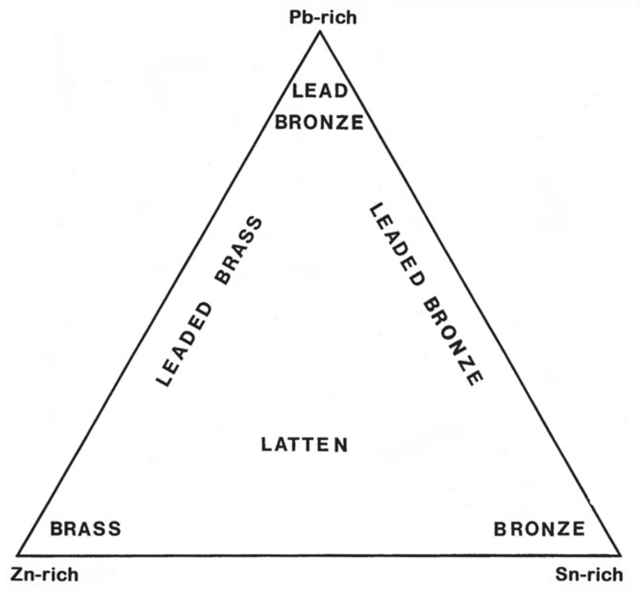

Figure 2: Alloy-descriptive terms on a pseudo-ternary diagram (see Appendix).

Figure 3: Bunsen-type small candlestick (National Museum of Wales 19.151); believed to be English.

It is thus possible to identify general alloy compositional features, a profile, which can be linked to the place of manufacture, usually a region within north-west Europe. Alloys can be referred to as English or Flemish, for example, where the corresponding stylistic analysis leads to a consensus as to origins. Inscriptions are obviously invaluable in fixing these profiles.

As an example of this link between style and alloy compositional profile, and both of these with origin, the instance of 'bunsen' candlesticks can be cited. This type of candlestick, whether of simple form (Fig 3) or in the branched, two-socket version, is generally agreed to be English and from the 15th century. A reasonable number of surviving examples have been analysed and shown to have broadly similar alloy compositions, all with zinc, tin and lead of 3–10% (with most 4–8%), satisfying the second requirement for useful groups noted above (Brownsword 1985). These compositions can be best appreciated by presenting the data on a triangular scatter-plot (Fig 4). The points, representing individual candlestick parts, appear in an area of the triangle which can be regarded as corresponding with the English 15th–century approach to choosing a suitable alloy for making domestic candlesticks. The points can be enclosed by a hexagon which can be accordingly labelled 'English 15th century'.

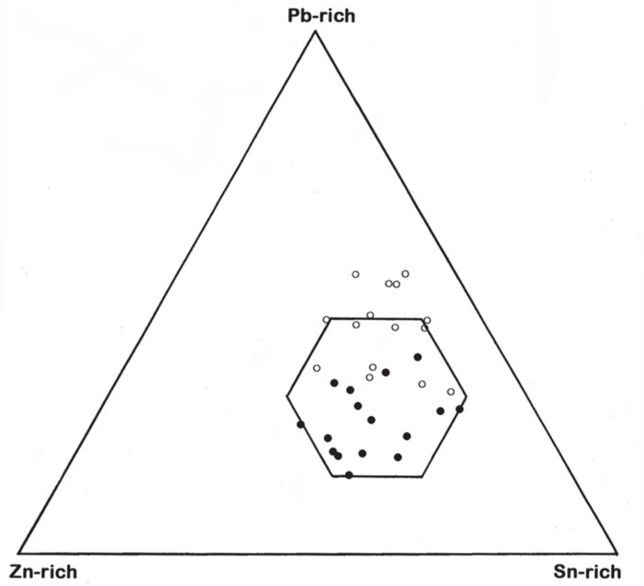

Figure 4: Data for candlesticks, believed to be 15th-century English. The English 15th-century hexagon is superimposed. Key: filled circles = simple bunsen candlesticks (probably early-15th century), open circles = candlesticks with a bunsen socket but with a raised cone in the centre of the base supporting a more elaborately-decorated stem (later 15th century).

The implication of this labelling is that further analyses of bunsen candlesticks would be expected to give points lying within the hexagon; this was very largely the case. The size of the hexagon was chosen on a trial and error basis such that most of a particular group gave plotted points within the hexagon. Points just outside the hexagon represent compositions on the extremes of a type. However, a few points well outside the hexagon corresponding with the style of object to which, *prima facie*, the example belongs should raise suspicion. The explanation for this may lie in the use by the founder of some re-melted scrap (clearly a rare event or the situation would have been far more chaotic than it is), or in the possibility that the object is a copy or a fake.

A type of candlestick with a thin stem, decorated with a number of raised rings or knops (Fig 5), is generally agreed to be of 15th-century Flemish origin, contemporary with the bunsen type, and so directly comparable with it. The analytical results from the multi-knop type were of zinc-rich alloys and give rise to points on the triangular diagram which form a group, again reinforcing the link between stylistic and alloy compositional similarity. However, the points occupy a part of the triangle well-separated from that occupied by the

Figure 5: Multi-knop small candlestick (Rouen Museum); believed to be Flemish.

bunsen candlesticks. This outcome was to be expected in view of the arguments already put forward on regional solutions to the matter of alloy choice dictated by local supply and cost factors. The multi-knop points can also be contained within a hexagon which can be regarded as descriptive of Flemish 15th century alloys used in the casting of candlesticks (Fig 6; Brownsword and Pitt 1983b). The hexagon was defined by data from the candlesticks and two inscribed Flemish items, dated 1442 and 1483. When analysed, further examples of multi-knop candlesticks fell within the 'Flemish 15th century' hexagon.

The above exercise established the parameters for

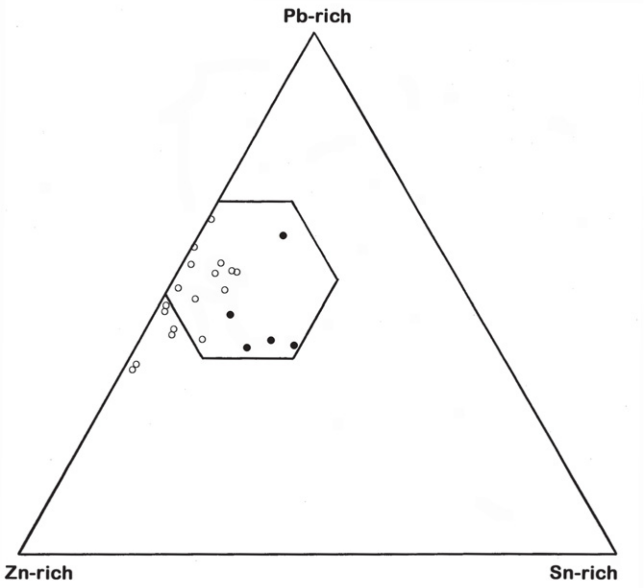

Figure 6: Key: open circles = multi-knop candlesticks, believed to be 15th-century Flemish, filled circles = inscribed Flemish items. The Flemish 15th-century hexagon is superimposed.

provenancing objects by examining the profile of the alloys used to cast them, specifically in this case distinguishing contemporary English from Flemish objects of the 15th century. It follows from this argument that objects similar to candlesticks, that is small castings required to be fairly robust and of a pleasing golden colour, which were probably made by the same craft group if not in the same workshops, would be expected to have been cast in very similar alloys to the candlestick alloys. The data from objects such as chafing dishes (Fig 7) or hanging lavers (Fig 8) would be expected to fall within the areas on the triangular diagram for candlesticks of the same period made in the same region. Thus a point for a chafing dish of the 15th century made in

Figure 7: Chafing dish (Victoria and Albert Museum M94-1953).

Figure 8: Hanging laver (Victoria and Albert Museum M2669-1931).

Flanders would be expected to lie within the 'Flemish 15th century' hexagon and a contemporary dish from England to lie within the 'English 15th century' hexagon. This particular example, discussed below, makes the general point that the approach considers the relationships between alloys rather than, other than consequentially, between objects.

Although alloying element data is primarily of value in considerations of the place of manufacture, the influence of the date of manufacture cannot be entirely separated. In the above example, the geographic description of the origins of the objects was always qualified by their date, and comparisons were made with roughly-contemporaneous objects. This is necessary because the economic situation, which it is argued determines the craftsman's alloying strategy, was not likely to have been static over a period of several centuries. As ore sources were exhausted and others opened up, as transport improved, as trade was impaired or improved by conflict or political stability, the supply situation and cost of the metals used would have changed. Successive craftsmen in a given area would, as a result, have modified their alloying strategy to reach new optimal compositions for the particular period in which they were operating. Craftsmen in another area would have been subject to different influences but would very likely have been similarly interested in moving to new optimal compositions for that area and time. It is not surprising therefore that when hexagons are drawn on the triangular diagram representing 'Flemish 16th century' or 'English 16th century' alloys that these are displaced relative to the corresponding 15th century hexagons. This illustrates the process of alloy evolution.

For the 15th/16th centuries the alloy compositional contrast is most marked between English and Flemish objects, but the products of other metal-founding areas are possibly discernible. The picture is less clear for Germany which, being a large and politically-fragmented region, had a number of widely-separated metalworking areas, each with its own set of circumstances relating to availability and costs of materials. It is not possible therefore to refer to German compositions in the way that has been proposed for Flemish and English alloys. Alloys used in areas bordering the North and Baltic Seas probably have much in common with those of Flanders in the late medieval period; those used in south and east Germany have some similarities to English alloys, since the area is remote from calamine-producing areas and near to the source of Bohemian tin. No attempt has been made to cover other geographical areas of metal-casting. They would probably be more difficult to distinguish from the main areas of cast metalwork production which have been covered.

In moving to the 17th century there seems to be evidence for what a biologist would refer to as convergent evolution. Differences in alloying strategy between different geographical areas diminish and largely disappear. By then there would appear to have developed a degree of consensus as to the type of alloy to be used for candlesticks and similar objects, an alloy close to the zinc-rich corner of the triangle which approximates to 'brass'. It is not clear whether this evolution was driven by improvements in technology or trade in making the zinc-rich, golden-coloured alloys more affordable, or by the demands of the customer for such desirable alloys even if at higher cost. Certainly by the mid-18th century, when zinc metal was extracted and available in Europe in relatively large quantities and low cost, the movement to brass became a stampede.

It is possible on the basis of the above arguments to draw a series of hexagons for each major metal-casting area for the 15th, 16th and 17th centuries (Fig 9). Some overlap occurs. That for one area and two adjacent centuries is to be expected, as nothing changed dramatically at the turn of the century. The area of overlap represents compositions used towards the end of the earlier century or at the beginning of the later century.

Application of profiles

Some multi-knop socket candlesticks were perforated at several positions on the base, with a pattern of small holes arranged in groups of five. This decoration also occurred on other candlestick types, chafing dishes, hanging lavers and lecterns. Some pricket candlesticks (Fig 7) had a crenellated border to the drip pan and this feature was also found on chafing dishes and hanging

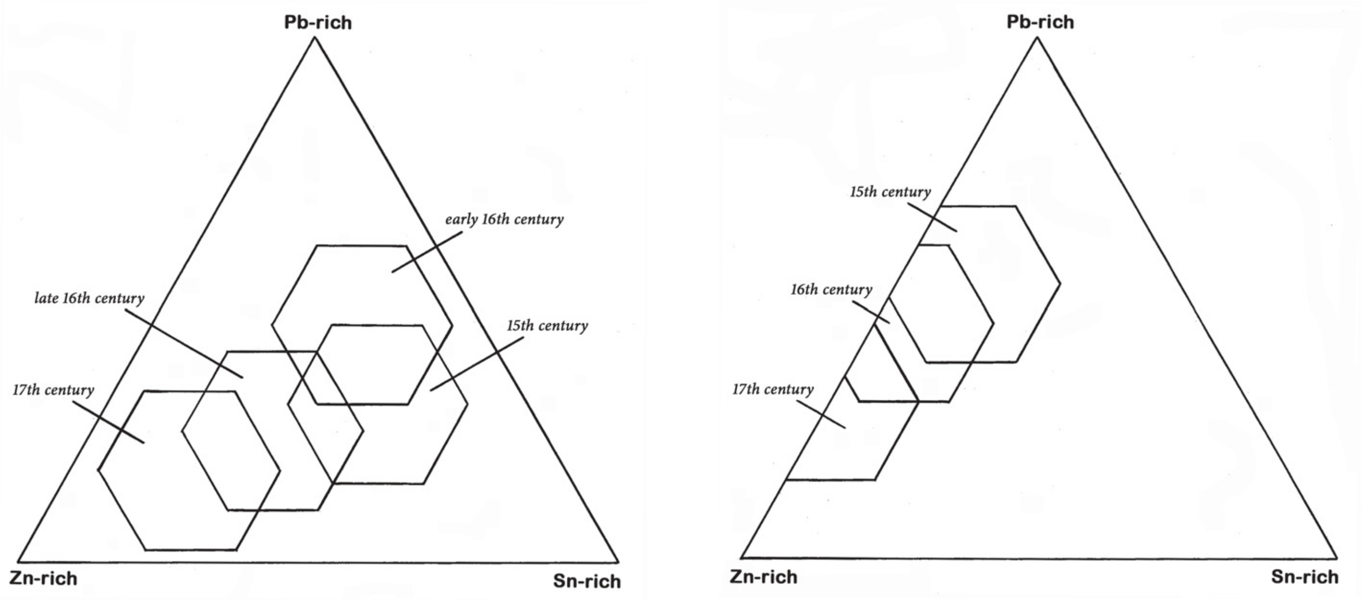

Figure 9: Diagrams summarising the compositional characteristics of English (left) and Flemish (right) domestic objects of the 15th, 16th and 17th centuries by means of their respective hexagons.

lavers. The points for these objects (Fig 10) lie within the 15th-century Flemish hexagon, with a few exceptions within the 16th-century Flemish hexagon and elsewhere. This result was expected, since these decorative features are considered to be typically Flemish of this period, and provides further support for the link between style, alloy composition and origin of such metalwork.

The hypothesis, that dating and provenancing one object type could be carried out using alloy compositional profiles derived from another, was based on the belief that several object types would have been made by the same craft group, if not by the same craftsmen. They would almost certainly have used the same alloys for the two types of casting and so, if similar alloy profiles were recognised on analysis, conclusions on date and provenance derived for one object type could reasonably be applied to the other. The hexagon maps were very largely, although not exclusively, developed using candlestick analytical data. Data from a survey of chafing dishes was therefore used to test the hypothesis.

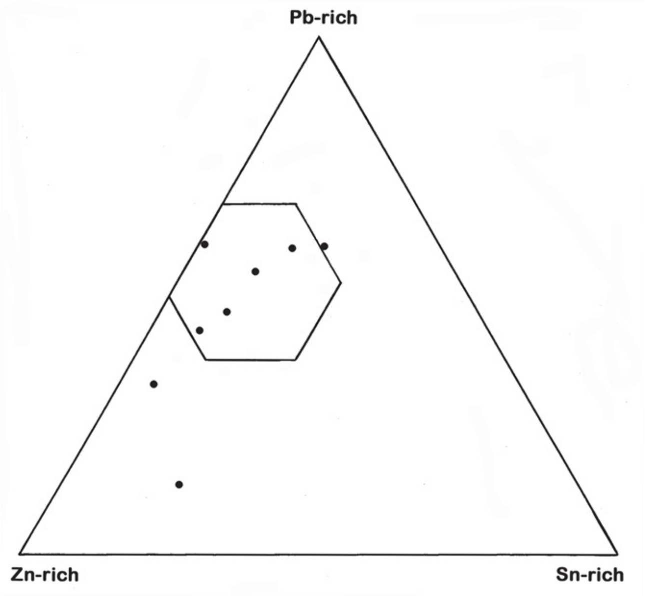

Figure 10: Plotted compositions for candlesticks, chafing dishes, hanging lavers and a lectern, having perforations and/or crenellations. The Flemish 15th-century hexagon is superimposed.

Lewis (1973) had studied chafing dishes and drawn up a classification based on stylistic features, linked to depictions of these objects in paintings, and other evidence (Table 2). Many of the objects he studied were sought out in collections and sampled for analysis so that the stylistic and alloy compositional classifications could be compared. Some additional examples of earlier types were included.

The alloy data for the chafing dishes are shown in Figure 11, together with the hexagons for the 15th and 16th

Table 2: Classification of chafing dishes according to style (after Lewis 1973) and alloy composition.

Lewis' type	Lewis' stylistic attribution		Compositional attribution	
A	Flemish	15th century	Flemish	15th century
B	English?	*c*1500	English	16th century
C	Continental	16th century	Flemish	16th century
D	English?	16th century	English	15th century
E	German	*c*1600	German?	16th century

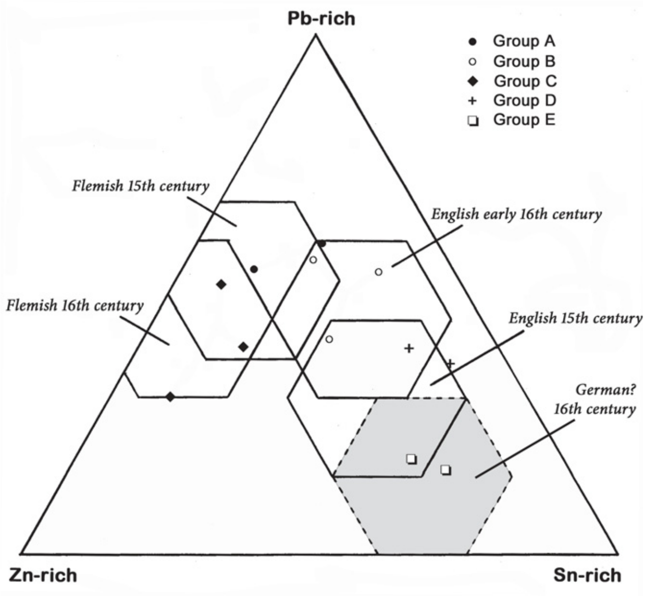

Figure 11: Plotted compositions for chafing dishes of 15th- and 16th-century date. The appropriate characteristic hexagons (see Table 2) are superimposed.

centuries for Flanders and England. If the location of the groups of points corresponding with each dish-type within the array of hexagons is taken to indicate their origin in time and geographically, then the extent of agreement between the conclusions of Lewis and the present work is remarkable. Given that Lewis may have mis-classified one item, the remainder have very similar classification by the two approaches (Table 2). Two early types could not be firmly provenanced in Lewis' treatment, although he believed that they might be English; the points for them lie respectively in the 15th and 16th century English hexagons so they are almost certainly English (Fig 12).

Figure 12: Chafing dish (private ownership), replacement handles.

A further test of the technique was a pair of large, free-standing altar candlesticks in Southwell Minster. They have been dated on stylistic grounds to the late 15th century and claimed by de Ruette (1996), who carried out an extensive study of the stylistically similar eagle lecterns, to be of Flemish origin. However, the analytical data gave points lying in the English 15th-century hexagon and well away from the Flemish 15th-century hexagon. On this basis, and taking account of their present location, their English origin seems almost certain (Brownsword 1998).

The object types discussed above all belong to the category described earlier as decorative/functional objects. The owner of such an object would have been seeking satisfaction of the function but with the additional dimension of an attractive appearance. A gold-like colour would have been a desirable feature and so zinc-containing alloys were used which gave this colour. On the other hand the colour of most purely utilitarian objects was not important, and so cheaper, essentially zinc-free, alloys were used for these object types. In England, these leaded bronzes, used for mortars (Fig 13), cooking vessels and large weights, were probably the normal alloys used by founders, whereas the zinc-containing quaternary alloys used for decorative items were probably the normal alloys used by braziers (Brownsword 1994). The situation may have been different in continental Europe.

Leaded bronzes occupy a different part of the triangular diagram from the zinc-containing alloys; lacking zinc, they range along the right-hand side of the triangle. This fundamental difference of alloy type makes the hexagon approach less useful in characterising them. Fortunately many 17th- and some 16th-century mortars and cooking

Figure 13: Mortar from the Mary Rose *(pre-1545) (Portsmouth Museum MR80A 1672).*

vessels are dated and/or inscribed and so their origins are certain. Alloys range from those with relatively high tin:lead ratios, which plot mid-way along the triangle's right edge or nearer the tin-rich corner, to lower tin:lead ratios which lie nearer the lead-rich corner. The former can be regarded as superior alloys which would have been more costly. This may have been the determining factor in alloy choice, so fine examples would have been cast in higher-tin alloys than mundane contemporary examples.

It is nevertheless true that dated 15th/16th-century objects show a slight bias towards the tin-rich corner, whereas those of a similar kind from the 17th century are biased towards the lead-rich corner. The situation therefore is not clear-cut on dates for English material. Too few known Continental leaded-bronze items have been analysed for any distinction to be made, based on tin/lead proportions, although several objects contain more zinc than the bulk of English objects and so the plotted points are set a little way in from the edge of the triangle.

Early medieval

Note that the term early medieval here refers to the 12th-14th centuries rather than meaning the later 1st millennium AD.

Characteristic alloy compositional profiles

The early medieval period is more difficult to understand than the later period discussed above, for two main reasons. Firstly, the number of objects surviving from the earlier period is less, partly because fewer were made and partly because a smaller proportion have survived the time-dependant risks of loss and re-melting of unwanted or damaged items. Additionally, the few surviving objects of the 12th–14th centuries are thinly distributed through museum collections over a wide area of north-west Europe. It was therefore difficult to obtain material for analysis in sufficient quantities to characterise a century and place of origin, as was possible for the later period.

Secondly, the number of important centres where copper-alloy objects, certainly the finer ones, were manufactured was fewer in the early medieval period. Outside these areas, scrap re-melting would have been commoner for the small amount of metal-casting carried out. Trading of the materials required was more difficult because of the relatively small number and scale of mining and metal extraction activities and the poor communications except by water. Thus the choice of alloy compositions would have been even more strongly dictated by truly local availability and price than in the later period.

Figure 14: Small cauldron (Museum of London 7856); believed to be medieval English.

In the early medieval period, the cost of any object of copper-alloy would have been beyond the means of the vast majority of householders. Only by the 14th century would a few be in a position to afford an item as basic as a copper-alloy cooking vessel (Fig 14); these were probably cast widely across north-west Europe using the cheapest alloys available – leaded-bronzes. At this time the supply of metal would have been rather haphazard, and likely to have been supplemented by the re-melting of scrap objects from an even earlier period where these were available. Thus the compositions of the alloys used for early utilitarian objects, and even in those used for decorative/functional objects such as ewers (Fig 15), might be expected to show a greater degree of variability than that found amongst later alloys, making the interpretation of analytical results more difficult.

Initial analytical results from early medieval material showed a considerable variation in composition. This was only partly explicable in terms of the degree of sophistication of the objects; superior alloys were usual for fine objects. Only with the fine art-metalwork of the most famous workshops did there seem to be a prospect of correlating the compositions of the alloys with the time and place of their use. The objects have been the subject of much stylistic and art-historical study which has helped in interpreting the compositional data.

Figure 15: Tripod ewer (Carlisle Museum RF458); believed to be medieval English.

The products of Limoges, an early fine-metalwork centre, can be recognised stylistically and also metallurgically. The metal used to make fine altar candlesticks and other religious objects was copper, essentially unalloyed. The copper was cast and/or worked to shape and then embellished with enamel or gilding; at least as much effort went into finishing as into making the object. The techniques were very similar to those of workers in precious metals. Pure copper is weaker but more malleable than its alloys; these properties made it easy to work but prone to accidental damage in use, so many Limoges candlesticks in museum collections are damaged. Copper is, however, ideally suited to enamelling. Whether the desire to enamel the products led to the selection of copper as the medium, or the ready availability of only unalloyed copper to the craftsmen led to the development of enamelling as the main embellishment technique cannot be known. However, the relative isolation of Limoges from the sources of zinc (via calamine) and tin in northern Europe might support the latter view.

In the 12th and 13th centuries the output from other centres of copper-alloy metalworking was also almost exclusively of fine items for religious use. The two main areas were the towns and cities in and to the north of the Harz mountains in Lower Saxony, and the Rhine-Meuse region, particularly the middle reaches of the Meuse. The former held important copper deposits and the latter deposits of calamine, which was the source of zinc in copper alloys. There were probably lesser contributions from a limited number of other towns and cities scattered across north-west Europe, including England, where the requisite craft base existed.

Figure 16: Altar candlestick base (British Museum 78, 11-1, 90).

The search for possible characteristic alloy compositions in objects of the 12th and 13th centuries was concentrated on data from altar candlesticks (Fig 16) and aquamaniles (Fig 17). These two object-types have been the subject of much art-historical research, in particular the monumental work of von Falke and Meyer (1935). The benefit of their work to the present research was that, for almost all of the objects, an opinion had been expressed as to the date and place of manufacture of the objects. The degree of certainty varied, but this information has proved invaluable in helping to understand early alloying strategy.

The alloy compositions of the early fine candlesticks, excluding the Limoges material, are represented on Figure 18, together with aquamanile data. They occupy the lower part of the triangle, reflecting a relatively low lead content; this accounted for a relatively high copper content (80±5% rather than the 75±5% for later alloys) which is a common feature of many of these early alloys. Most show balanced amounts of both tin and lead and so appear towards the centre of the baseline. Only at this position was there a sufficient concentration of points

Figure 17: Lion aquamanile (Fitzwilliam Museum M15-1917), restored tail.

to justify superimposing a hexagon (grey), albeit larger than for later material, enclosing points from objects with similar alloy compositional profiles. However, the material represented within the hexagon is by no means uniform in character. It covers aquamaniles and candlesticks, in tripod and in animal form; the suggested dates range over the 12th and 13th centuries and the places of origin from the Meuse to the Harz. The implication of this grouping is that, for a considerable period in the 12th and 13th centuries, there was a rough consensus as to the composition of alloys suitable for casting fine metalwork; this was true for both the main areas of production. This may have been helped by the presumed reciprocal trading in Goslar copper from the Harz and zinc-containing brass derived from calamine from the Meuse, via the Aller, Weser and Maas/Meuse rivers.

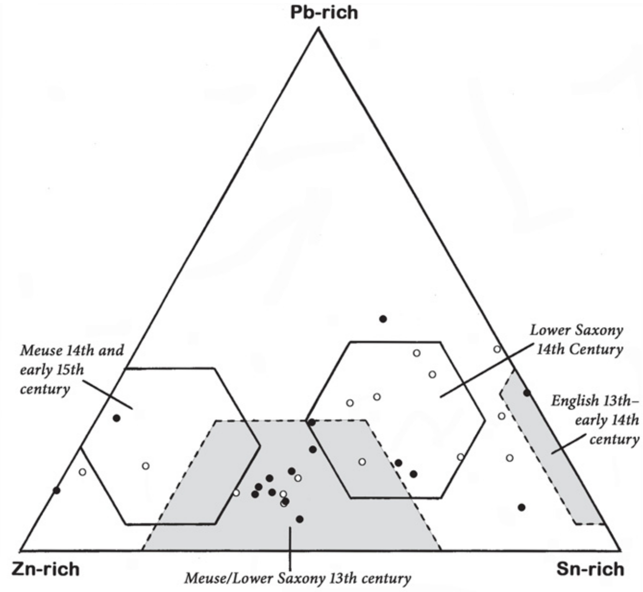

Figure 18: Plotted compositions for fine objects, mainly altar candlesticks and aquamaniles, 12th–14th centuries. Key: filled circles = candlesticks, open circles = aquamaniles.

Difficulties over metal supplies would have been greatest early in the 12th century and at locations remote from the metal production centres. The points on Figure 18 away from the main (grey) hexagon probably represent objects cast in circumstances when one or both of these factors applied; the craftsman would have had, within reason, to use the materials to hand, including scrap metal. As a result, the positions of these scattered points are of limited value in assessing the likely origins of the objects, other than pointing away from the two main centres of production. There may be exceptions, in which a view as to the origin of an object based on stylistic analysis may be reinforced by a knowledge of the alloy used in manufacture; for example, a small candlestick base in the British Museum (Fig 16), believed to be English, has a composition close to the tin-rich corner of Figure 18 (Stratford 1984). There is some evidence to suggest that in the late 13th century, and more obviously in the 14th and early 15th centuries, alloy compositional profiles for the two main centres developed away from the early hexagon; the two hexagons, likely to be for the Lower Saxony and Meuse areas, are shown in Figure 18.

Before 1300, there was probably very little secular cast copper-alloy metalwork, with the possible exception of some early candlesticks. During the 14th century, however, the production of small domestic cast items must have increased considerably, judging by the numbers of candlesticks and ewers that have survived. Ownership of even simple examples would still have been by only a very small proportion of the population, but the demand was sufficient for the development of facilities for casting repeat units of the same or similar design. This was not yet mass-production, but the beginnings of the concept. Objects were probably made on a speculative basis for sale, rather than on the basis of a commission which applied earlier for most, if not all, of the fine religious items.

Alloy compositional data for candlesticks and ewers believed to have been cast in the 14th century cover an area near the lead-rich corner of Figure 19. Many are of lead-rich leaded bronzes, and so are near to the right-hand edge of the triangle, but others contain some zinc and so cover a fairly large area at the top of the triangle. The points cannot be encompassed by a hexagon of the

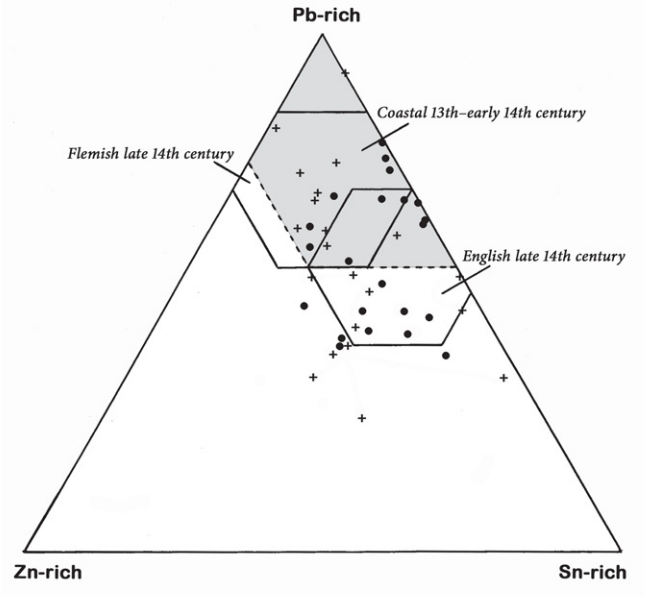

Figure 19: Plotted compositions for simple objects. Key: + = tripod ewers, undecorated except for a zoomorphic spout-end, filled circles = simple socket or pricket candlesticks with a disc-shaped base having three short legs.

standard size; it is perhaps to be expected that the less well-ordered situation of the 14th century would require a larger hexagon than normal (shown grey in Figure 19).

The larger (grey) hexagon in Figure 19 encompasses points derived from a variety of candlesticks, some having prickets, some sockets, while most have small, simple tripod legs; these are attached to bases which in some cases are disc-like (Fig 20) but in others are slightly conical. The stems are sometimes hexagonal in section and sometimes circular, with facetted or spherical knops. This variety indicates widely-separated origins; it is believed that they were the products of craftsmen working away from the few early centres, in an industry which had developed in a wide area of north-west Europe, from Normandy along the English Channel and North Sea coastal areas, including England, to North Germany. They used relatively cheap materials including, probably, some scrap metal. The small, but irregular, amounts of zinc in some alloys probably arose from the addition of some zinc-containing scrap metal to the melting pot.

English alloy compositions for the late 13th and early 14th centuries probably occupy the same area of the triangle but there are indications that, by the second half of the 14th century, compositions had a higher tin:lead ratio and so had drifted down the right-hand edge of the triangle towards the 15th century English hexagon (see Fig 4). A similar evolutionary process is seen in the Flemish compositions of the second half of the 14th century towards the left-hand edge of Figure 19, moving towards the 15th century Flemish hexagon in Figure 6.

If this model is close to being correct then it appears that simple tripod ewers, decorated only with a zoomorphic spout-end (Lewis, Brownsword and Pitt 1987), were made on both sides of the Channel but with the majority being of English manufacture in the 14th century. In the case of small candlesticks with tripod-disc bases made in the same period, the same may also be true with some being made in the area from Normandy to Flanders and some in England, particularly those without wings on the socket (Fig 21). The English bunsen candlesticks of the 15th century developed from these tripod-disc examples (Brownsword 1985).

Figure 20: Small tripod candlestick (Rouen Museum 575), note shape of stem and 'wings'.

Figure 21: Small tripod candlestick (Museum of London 8412), note shape of stem and absence of 'wings'.

Application of profiles (with particular reference to English practice)

Fortunately for those interested in English practice in the 14th century, initial difficulties in interpreting the wide range of compositions used to cast fine and decorative household objects have been at least partly resolved. This has included an understanding of English alloying policy using not only imported zinc-containing alloy but also a different type of brass which was possibly produced in England, though at a time before its recognised earliest production.

British museums have in their collections a considerable number of cast copper-alloy objects which are agreed to be of English (or British) 14th-century manufacture. Some are decorated and carry inscriptions or arms which confirm the date-range and country of origin; other items are undecorated but have stylistic similarities which make their origin clear. Those which were buried or lost, for instance down wells, have find sites in Britain; a few contained coin hoards. This range of objects will now be considered. They were cast in England (or Wales/ Scotland) rather than being imports from the Continent, though at least some of the metal used came from continental sources. In this group are a mortar, numerous ewers and jugs, a few candlesticks, a number of letters, which would have been let into marble tomb slabs (Brownsword 1987), and steelyard weights (Fig 22) with lead cores but copper-alloy outer casing (Brownsword and Pitt 1983a).

It appeared that there was no consistency of approach to alloying, and points derived from the alloy compositions were strewn across the triangular scatter plots. In part this was due to the variety of object types but even within groups of similar objects there was a considerable range of alloy compositions. Eventually a rather complex picture was revealed, as understanding developed in a number of related fields. The discussion below is subdivided into objects made of leaded bronze (with negligible zinc content) and of those made of alloys with significant levels of zinc.

Leaded bronze

The leaded-bronze alloys used were excellent materials from a foundryman's viewpoint and the products had adequate strength and durability in service, but they lacked the golden colour so much desired in copper-alloy objects. Alloys with a high lead:tin ratio are coppery in colour, while those with higher tin content have a yellower colour; both change considerably with the development of a patina to give colours covered by the term bronze.

Figure 22: English Type A steelyard weight (later 13th century) (Cambridge Archaeology and Anthropology Museum CAS.83819).

A group of English jugs and ewers of 14th-century date was the subject of a parallel stylistic and technical study (Finlay 1996, Brownsword and Pitt 1996). With the single exception of the Gower ewer, treated in some detail below, the objects are essentially zinc-free but vary considerably in their tin:lead ratio. Some, including the finest examples in terms of style and decoration, are of an inferior lead-rich alloy, whereas one is much richer in tin (Fig 19). This lack of correlation between fineness of execution and grade of alloy was initially difficult to interpret, since fine items might be expected to have been made in superior alloys. It was eventually realised, however, that the alloy quality correlated with the method of casting and hence, almost certainly, with the type of craftsmen involved in the production of the jugs and ewers.

The majority, made in leaded-bronze, all display evidence of having been cast in a piece mould. The fit of the two outer mould-halves was imperfect, and this allowed slight penetration of liquid metal into the gap to produce a raised fin running diametrically across the base and up each side. Efforts to remove this casting flash in finishing were rarely completely successful. They are clearly evident in figures 16 and 18 in Finlay's paper (1996) and can still be made out, though less clearly, on the finer examples of his figures 13–14. The craftsmen concerned appear to have been founders who worked in leaded-bronze, casting weights, cooking vessels, mortars and candlesticks using the clay pattern, piece-mould technique. The sharing of technique with ewers and lavers seems not to be coincidental.

By contrast, it seems almost certain that a different group of craftsmen was involved in casting a tripod ewer (British Museum: 1975, 10–11; *ibid*, fig 3) as there is no evidence of a raised line and the object shows every indication of having been cast using the lost wax process. This is true also of the Gower ewer (*ibid*, fig 9). Both carry lettering and decoration closely similar to that on extant, or recently re-melted English bells of the period and it seems likely that the craftsmen involved in casting the tripod ewers were bell-founders. Support for this view comes from the use, in one case, of an alloy high in tin; tin-bronze was the normal medium for a bell-founder, although the alloys used to cast bells contained even more tin – true bell-metal.

It is doubtful whether the separation of the crafts and their products was as clear-cut as the above statements suggest, particularly away from London. Activity in the capital was probably on a large enough scale for specialisation to develop and become formalised, but in provincial centres the casters of metal objects would almost certainly use a variety of techniques and alloys, some not even copper alloys. The relationships between the various craft groups, the alloys they used and their products is discussed more fully elsewhere (Brownsword 1994).

Latten

The colour of gold is approached in alloys of copper with zinc, in amounts between 15–20% or with slightly less zinc if tin is also present. The presence of lead in modest amounts has little effect on the colour of the alloy. Not only do such alloys have a golden colour when new or freshly cleaned, they change colour much less with patination. They were therefore used for the manufacture of the finest items, intended to impress those who saw them. These zinc-rich alloys were available at reasonable cost to craftsmen in the Low Countries where they were produced, but were a relatively expensive import to craftsmen working in London. The latter would have had reason to reserve the alloys for the finest items, or to dilute the expensive material with cheaper metals such as tin or copper, where this was acceptable to the customer.

Evidence for this emerged in objects believed to be English and of 14th-century date. A number which containing zinc at more than trivial concentrations also contained iron, at an unusually high level for an impurity element. Further, the iron:zinc ratio was roughly the same even though the zinc level varied from a few percent to over 15%. This suggested that a common source of zinc, relatively high in iron, was diluted to a greater or lesser extent in the melting pot by adding other metals such as copper, tin or lead not containing significant iron. Using this model it has been possible to compute the likely composition of the putative common brass melting stock: a zinc content of 19.5% and 1.7% iron (Brownsword 1997b). An example of a fine object, cast essentially without dilution, is the Gower ewer (18.3% Zn, 1.58% Fe), probably the product of a London bell-founder in the late 14th century (Finlay 1996).

Other objects, which might be described as prestige items, have low levels of dilution and so fairly high zinc contents, sufficient to impart the golden colour to the alloy. Amongst these are the Type A steelyard poises (Brownsword and Pitt 1983a), most memorial letters (Brownsword 1987), candlesticks from London (Museum of London: A2647) and Pevensey (Lewes Museum: 1953.42.70) and two lidded flagons (Brownsword 1997a). It was possible to follow the evidence for dilution even to levels of zinc as low as 3%

in objects which could not be classed as prestige items (Brownsword 1997b).

If the imported high-zinc melting stock were an expensive material in London and the surrounding areas, the cost and availability of this material to craftsmen working well away from London would have encouraged other approaches to alloying. Such workers may have dispensed altogether with the zinc contribution to the alloy and settled for working in a relatively high-tin bronze. This type of alloy was used for the 'Lincolnshire' letters (Brownsword 1987) and a decorated ewer (British Museum: 1975, 10–11), which may therefore have been made in a centre such as York. An alternative solution to the problem for some provincial founders may have been through the use of English-made brass, as mentioned above.

A few objects contained zinc at a level high enough to indicate that a golden-coloured object was aimed for, although the zinc level was modest when compared with other English 14th-century objects. More surprisingly the alloys contained very large amounts (for impurity elements) of antimony and/or arsenic, quite unlike the majority of latten objects. This suggested a drastically different approach to alloying. Again a model was constructed to compute the likely composition of this second putative brass melting stock which had 10.5% Zn, 0.7% Fe and 6.7% Sb (Brownsword 1997). This brass must have been made using copper high in antimony and/or arsenic, extracted from tetrahedrite-type ores. On the Continent this poor grade of copper would not have been considered fit for brass production, which indicates a source not only remote from the Continent but also from the main ports in south-east England. Such a brass-making centre may have operated in the lower Severn area, since the find-sites for the objects made from these unusual alloys are all in the greater Severn basin. Interestingly, two virtually identical small flagons (Fig 23) which came from the site of Weoley Castle, Birmingham, were cast in alloys representative of each of the two types of brass source (Brownsword, Pitt and Symonds 1983-4; Brownsword 1997a).

Figure 23: Small flagon (lidless) from Weoley Castle, Birmingham (Birmingham Museum WC325).

Most of the 14th-century decorative objects cast in copper alloys in the Low Countries have compositions falling within the large hexagon on Figure 19, signifying alloys with only modest zinc content but fairly high lead content. However, a small number of contemporary objects sampled have compositions richer in zinc but poorer in lead, which plot within a separate hexagon of normal size much nearer the zinc-rich corner of the triangle. The objects are fine examples of decorative/functional metalwork and include chandeliers, a lectern, a hanging laver and two small candlesticks. It is suggested that these items may have been produced in Dinant, as opposed to further north in Flanders, as the latter group have compositions within the larger hexagon. It may therefore be possible to be more precise in the application of the term 'dinanderie' than was previously possible (Brownsword 2003a). The alloy compositions contained in the small hexagon, which has been tentatively labelled the Dinant hexagon for the 14th (and early 15th) century, were not involved further in the evolutionary process starting with the 13th-century Meuse alloys, since activity in Dinant came to an abrupt end with the sack of the town in 1466.

Two fine items of art-metalwork, figures of Moses and a Prophet in the Ashmolean Museum, were believed to have come from the same general area of the Meuse valley, although made much earlier (*c*1200 AD). They were subjected to thermo-luminescence (TL) dating of retained core material which gave unexpectedly late dates and were, as a result, removed from display. Metal analysis provided such a convincing early medieval alloy compositional profile that an alternative explanation of the late TL date was sought. It was possible using a forensic approach to build up a case for the later adaptation of early medieval castings involving considerable re-heating which, or course, reset the TL clock and so explained the late TL-derived dates (Brownsword and Blackwell 1984; Brownsword and MacGregor 1986). As a result the figures have been reinstalled in the museum display case.

Conclusions

As a result of the programme of metal analysis undertaken at Coventry over the past twenty or so years, considerable progress has been made in establishing the nature of the alloys used by craftsmen casting copper alloy objects in the medieval and early post-medieval period.

It became clear at a fairly early stage that mortars were not, as commonly believed, made in 'bell-metal', if the strict term be preserved for an alloy with high tin and negligible lead content used to cast bells in the medieval and later periods. Mortars were instead cast in a leaded-bronze having only a few percent of tin but a larger (sometimes much larger) percentage of lead in the alloy. Similar alloys were also use for skillets, cauldrons and the larger weights and measures (Brownsword and Pitt 1981). The misnaming is understandable since the foundry stamps of known bell-founders include depictions of mortars, cauldrons and ewers (Walters 1912) and 17th-century examples of both bells and mortars have survived from the Whitechapel and Burford foundries amongst others. It became clear however from the analyses that bell metal was used exclusively to cast bells and the cheaper leaded bronze was used to cast the other items; this statement notwithstanding, similar foundry techniques would have been used for making mortars and cauldrons as for bell-founding.

Having established that leaded-bronze was used to make mortars and cauldrons, it was a little disturbing to find that 16th- and 17th-century inventories contained references to '… brasse pottes' and '… brasse' mortars; clearly, 'brasse' could not be equated with brass, the modern alloy of copper with zinc. In turn, were the craftsmen who cast objects in 'brasse' brasiers, and if so, how did they relate to other craftsmen such as belyeters, potters and founders? This led to a digression into the quagmire of the terms used in contemporary documents for the various craftsmen and their products. The additional dimension of the alloy types used by each initially complicated the issue but eventually provided the key to understanding the early picture and how to correlate it with modern metallurgical terminology. It emerged that each craftsman worked, by and large, with a particular alloy type and made those objects for which that alloy type was suited. The results of the digressive researches into the English metal crafts were presented as part established fact, part conjecture and a diagramatic summary included in an article which followed (Brownsword 1994) is reproduced here (Fig 24). The structure on the Continent would probably have had broad similarities but with differences of detail and, possibly, less clear distinctions between crafts.

It is clear that metal was not fed into the melting-pot in an uncontrolled manner and that the craftsmen understood the effects of the additions they made. The relative costs of the additions were also appreciated and alloys were made up so as to provide the material which satisfied the technical and aesthetic requirements at minimum cost. The fact that the local availability and costs varied with time and place within the medieval and immediately post-medieval period and over the whole area of north-west Europe led to different solutions being adopted in the different circumstances in which the various craftsmen operated. These factors are reflected in the alloy compositions of objects and their compositions can, in many cases, be recognised as characteristic of a relatively short period (about a century) and of a relatively small area of production (corresponding to a small country or a region of a larger country).

A method of presenting information on the main alloying element additions has been developed which allows an area of the scatter diagram to be regarded as characteristic of a particular time and place of production. Defined by one type of object, the area would be expected to contain the points from further examples of the same kind or even of a different kind if of a similar degree of sophistication and so likely to have been made by the same craftsmen.

Prima facie evidence for date and provenance may be provided by plotting the main alloying element data for the object on the scatter diagram and noting the characteristic area in which it lies. This may however be misleading in some instances; the object may come from a region or period inadequately covered in the survey. In addition, if the objects under study are not simple domestic items, the difficulty of alloy enhancement can arise. Prestige items, such as altar candlesticks, may have been commissioned in a superior, zinc-richer, alloy, rather than the normal characteristic alloy. Such alloys would give rise to plotted points away from the appropriate hexagon, usually displaced in the direction

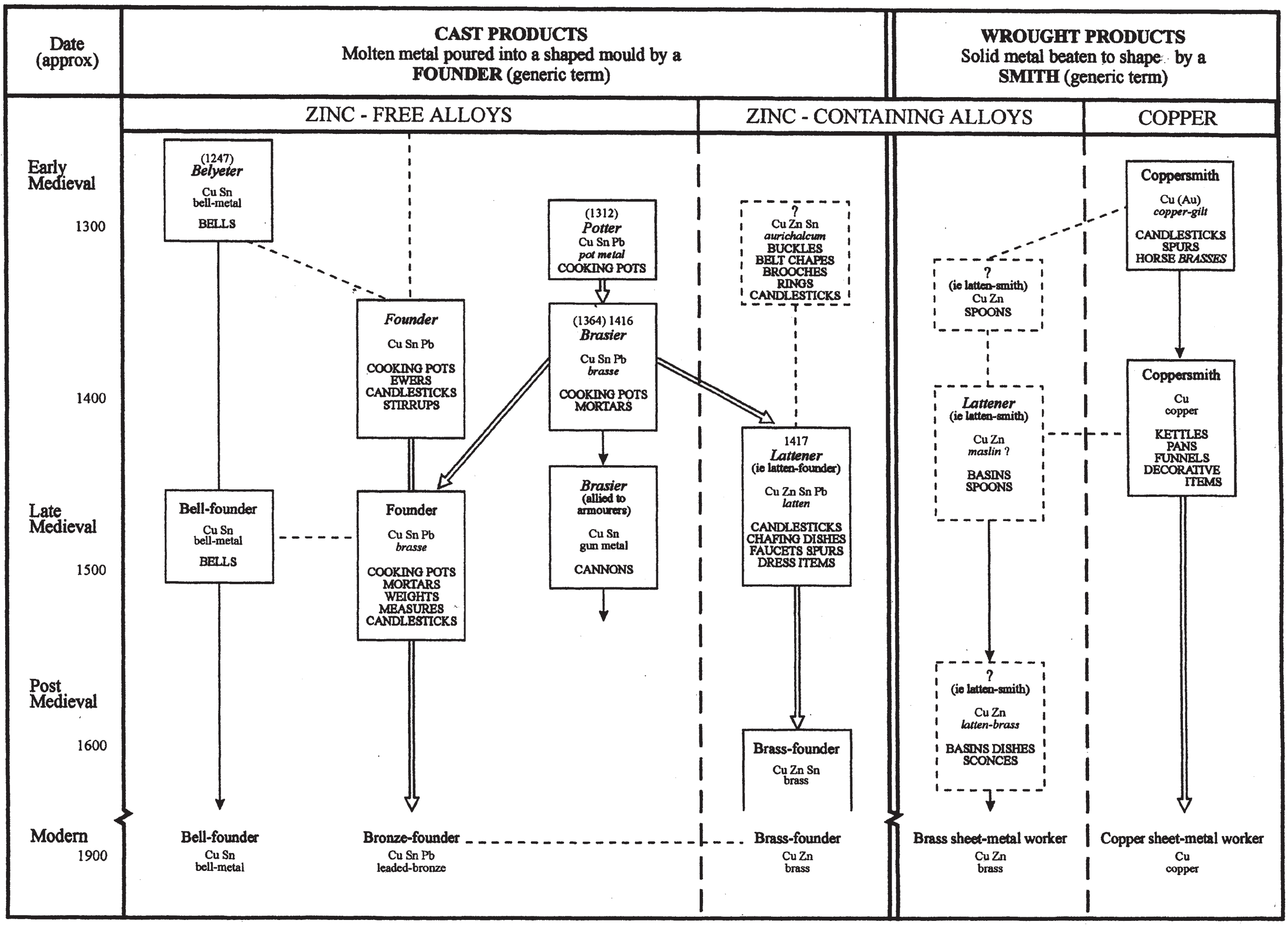

Figure 24: Diagram illustrating the link between metal-workers, the type of alloy they used and the range of objects made by them. Contemporary terms, with dates, for the workers and their alloys are in italics (Reproduced from Journal of the Antique Metalware Society *with permission).*

of the zinc-rich corner. It appears that, for instance, German 16th- and 17th-century candlesticks can give plotted points ranged widely over the triangular scatter diagram.

Early in the medieval period (12th–13th centuries), metal availability was probably more haphazard and scrap recycling was probably important. Thus few characteristic areas can be identified on the diagrams for this period. Such areas can, however, be identified for later centuries, up to the 17th century. These characteristic areas occupy different positions for different regions at the same time and for the same region at different times. Thus alloy evolution can be described in terms of the movement of characteristic areas with the passage of time.

This can be appreciated best with zinc-containing alloys; the zinc dimension pushes compositions away from the lead-tin baseline and allows useful differences to be manifest. For leaded-bronzes, the approach is less useful since the compositions are all arranged along or near this line.

The picture outlined above, based on many hundreds of individual analyses, of which only a few can be used in illustrations, provides a context in which the data can be applied. Some technological aspects have been explored, such as the possible 14th-century production of brass in England (Brownsword 1997) and the use of a by-product from silver extraction for making cooking vessels, mortars and large weights (Brownsword 2001). The other main area of application is to the matters of dating, provenancing and authentication.

Particular problems arise with English objects of the 14th and 15th centuries, which normally have fairly modest zinc content, but these sometimes have higher zinc content in prestige items which must have cost the owner a premium. The Gower ewer is an extreme example of this use of expensive material out of the normal context.

Figure 25: Separately-cast ewer spout (Ashmolean Museum 1884.14).

The attribution of an origin to a group of similar objects is less hazardous; the separately-cast ewer spouts with zoomorphic ends (Fig 25) have compositional plotted points in the area characteristic of English, 15th-century castings and so can be taken to be of this origin (Fig 26). Broad confirmation of date can be sought from a study of impurity element levels.

A plotted compositional point which lies just outside the expected area is probably an extreme of an acceptable variation; one well outside should arouse suspicion. However, unusual compositions can arise from the very rare cases of scrap being added in a less controlled manner, but even these can sometimes be interpreted and explained (*eg* a cauldron with 6.8% zinc in the British Museum (Fig 27; Brownsword 2003b)).

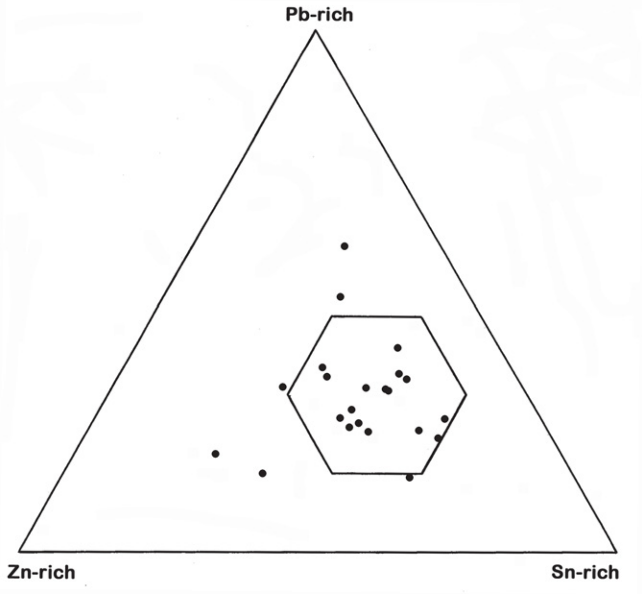

Figure 26: Compositions for separately-cast ewer spouts carrying an animal head at the spout end. The English 15th-century hexagon is superimposed.

Authentication is in the end a matter of judgement and the result is an opinion; the analytical information provides only part of the picture. The analytical data have to be absorbed and assessed, much as wine is judged by a wine-taster's educated palate. In both cases, many years of experience are necessary for the resulting opinions to be worth having.

Figure 27: Large cauldron (British Museum OA7677).

Acknowledgements

The research reported would not have been possible without the enthusiastic support and assistance of many members of museum staff, specialist antique dealers and others too numerous to be mentioned individually. I hope that this general acknowledgement will be taken as sufficient recognition of the debt I owe to them and the thanks that are due to them.

Of those involved at Coventry University (formerly Polytechnic), I would single out the late Ernest Pitt for devising the analytical regime which made the project possible and for the good-humoured way in which he worked with a non-analyst. The senior staff at Coventry University were throughout supportive of a rather unusual research project and I am grateful to them for that support.

Appendices

Analytical technique

The technique used was a wavelength-dispersive XRF method which analysed drilled samples (10–20mg) mounted on Mylar film. A qualitative/semi-quantitative analysis was carried out using a continuous spectrometer scan of the emitted spectrum over an angular range which covered the elements Fe, Ni, Cu, Zn, As, Ag, Sb and Sn (K radiation) plus Pb (L radiation). Quantitative analysis was carried out using fixed-angle counting at peak and background positions for each element in the sample and in appropriate standards. Details of this counting strategy and other information are given in Brownsword and Pitt (1983).

Triangular scatter plots (pseudo-ternaries) used to present compositional information on groups of copper alloys

Copper, since it is present in all the alloys in large quantities, is taken as read and the relative contribution of the alloying elements zinc, tin and lead to a particular alloy is calculated. This is then plotted as a point on the scatter-plot or pseudo-ternary. To encourage the spreading of points across the triangle, the values for the alloying elements are weighted: viz Zn x 1, Pb x 2 and Sn x 3. So :

$$fn(Zn) = \frac{Zn}{(Zn+2Pb+3Sn)}$$

$$fn(Pb) = \frac{2Pb}{(Zn+2Pb+3Sn)}$$

and

$$fn(Sn) = \frac{3Sn}{(Zn+2Pb+3Sn)}$$

Since $fn(Zn) + fn(Pb) + fn(Sn) = 1$, each function can be plotted as though a component of a ternary alloy. Strictly this assumes a constant value for the percentage of copper. However, alloys can reasonably be plotted together on a given triangle if the Cu variation is limited to a range of x±5% Cu. It is not useful to use the method for alloys with Cu contents greater than 90%.

Points near to the zinc-rich corner represent copper-zinc brasses while those near to the tin-rich corner represent copper-tin bronzes. Points near to the lead-rich corner represent copper-lead alloys (these do not have an accepted common name although lead bronze may be appropriate), as is indicated in Figure 2. The above examples at the triangle corners are binary alloys, *ie* copper with just one of the other metals. Ternary alloys, *ie* copper with two of the others, are represented along the triangle sides: copper-zinc-lead alloys, leaded brasses, lie along the left side, copper-tin-lead alloys, leaded bronzes, lie along the right side. Copper-zinc-tin alloys lie along the baseline; these do not have an accepted common name.

In the vast majority of cases the alloys are quaternary alloys, containing all four constituents copper, zinc, tin and lead in various proportions. These lie within the triangle, rather than at its corners or along its edges. Compositions may lie close to an edge and so approximate to ternary alloys such as leaded bronzes but the benefit of the use of these triangular plots is that arguments about the proper naming of alloys need not arise; the position of the point in the triangle can be a sufficient description of an alloy composition for the purposes of comparison with other compositions.

It is the case that alloys with similar levels of the four components (Cu, Zn, Pb, Sn) have points representing them which are close together on the triangular plot; conversely alloys with different levels of the component metals have points set apart on the plot. This makes any arguments of compositional similarity or difference easier to present and appreciate than by the use of the raw percentages of the components.

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