2060

Ancient Monuments Laboratory
Report 17/99

METALLOGRAPHIC EXAMINATION OF MEDIEVAL IRON KNIVES FROM COPPERGATE, FISHERGATE AND BEDERN, YORK

D Starley

Ancient Monuments Laboratory Report 17/99

METALLOGRAPHIC EXAMINATION OF MEDIEVAL IRON KNIVES FROM COPPERGATE, FISHERGATE AND BEDERN, YORK

D Starley

Summary

Metallographic examination was carried out on samples from seven knives dated between the twelfth and sixteenth centuries. All the knives were of composite construction, combining steel with ferritic and/or phosphoric iron, using a wide range of construction techniques. The blades had been skilfully heat-treated to provide a hardened edge. Scanning electron microscope (SEM) based microanalysis of the iron and its inclusions revealed significant differences in composition, both between knives and between components of the knives. The compositional data were interpreted as evidence for specialist production of a range of ferrous alloys at this date. They also indicate the city's participation in a widespread trade network which supplied either the raw materials or completed blades.

Author's address :-

Dr D Starley
ENGLISH HERITAGE
23 Savile Row
London
W1X 1AB

ANCIENT MONUMENTS LABORATORY REPORTS SERIES

Metallographic Examination of Medieval Iron Knives from Coppergate, Fishergate and Bedern, York

David Starley

Introduction

Recent excavations in York have provided an exceptional opportunity to study the changing metallurgical traditions within the city since its Roman foundation. Waterlogged anaerobic conditions ensured that many of the iron artefacts were remarkably well preserved and offered the possibility of studying them by metallography, to give an insight into the materials available and the techniques used by smiths to produce these artefacts.

Whilst metallography can be used to look at the manufacturing history of any metallic artefacts, examination of the York assemblages has deliberately targeted ferrous knives and other edged tools. Such artefacts are often of composite construction, combining the hardenability and edge retention properties of steel with cheaper, more resilient grades of metal, particularly iron or iron–phosphorus alloys, for the bulk of the artefact. Thus they provide an excellent demonstration of the skill of the smith as well as showing changes in the methods of construction for composite iron artefacts, and the range of ferrous allows available to the metalworkers.

Visual and X-radiographic examination

Seven blades from the three urban sites of Coppergate, Fishergate and Bedern were examined visually and by X-radiography before sampling. Classification of the knife backs had been undertaken by Ottaway according to his typology (Ottaway 1992, 559). The purpose of X-radiography was partly to help determine the condition of the object prior to sampling, but also to non-destructively detect structural features, such as the presence of weld lines and pattern welding. This information was used to decide where to remove samples from the blades. Figure 1 shows the position of welds. On the original X-radiograph these show as dark (X-ray transparent) lines, because of the presence of low density material; either entrapped slag and scale or corrosion which has penetrated at these points of weakness. Most of the York blades examined showed longitudinal weld lines running along the length of the blade, suggesting a likelihood of butt welded edged blades. The one exception to this was sf 5271 from Coppergate, which showed no clear weld lines. Bedern 13 sf 772 was notable for a band of diagonally striated metal running through the centre of the blade, indicating a pattern welded blade.

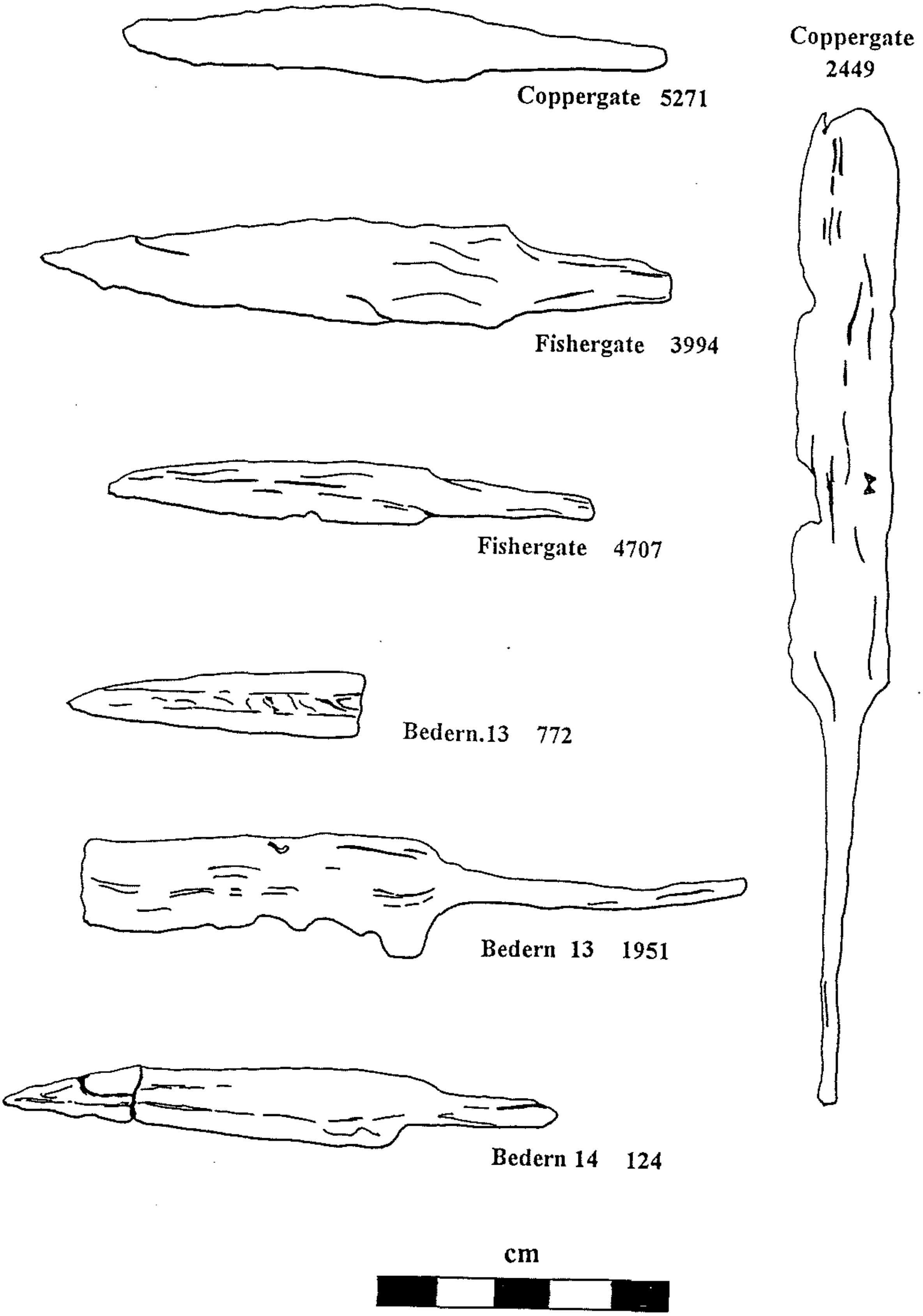

Figure 1 York medieval knives. Interpretation of X-radiographs showing weld lines

Metallographic Examination

Iron alloys used in the medieval period can be divided into three broad categories: ferritic iron, phosphoric iron and steel. All three types contain slag inclusions. The properties and basic microstructure of these alloys are described below.

Ferritic iron (Plate 1) Pure iron without significant impurities. Relatively soft and easily worked, but liable to bend and if used as a cutting edge would be rapidly blunted. Recognised in an etched microstructure as plain white crystals.

Phosphoric iron (Plate 2) Even trace levels of phosphorus (typically of the order of 0.1 to 0.3%) entering the iron during smelting may significantly harden the metal without disadvantageously affecting its toughness. In the etched microstructure phosphoric iron can be recognised qualitatively, due to "ghosting". This effect, caused by relief polishing (in which softer, low phosphorus areas are preferentially worn away), gives the ferrite grains a "watery" appearance with bright areas which may be difficult to bring into sharp focus with the microscope. The effect of phosphorus on the properties of the iron can be directly measured, by carrying out microhardness testing on the surface of the polished specimen. Chemical or physico-chemical analysis of the metal will allow quantitative measurement of the phosphorus content.

Steel is iron containing small amounts of carbon, typically 0.2 to 1%. It has advantages in being both tougher and harder that iron. Additionally, and very importantly, it can be hardened to a greater extent by appropriate heat treatment. Heating followed by quenching in water gives considerable hardness, but may make the artefact brittle. This can be avoided either by subsequently tempering the artefact, *ie* reheating, but to a lower temperature than it was quenched from, which helps relieve stresses within the structure. Alternatively, a less severe "slack" quench can be used, typically cooling, not in water but in a less thermally conductive medium, such as oil. The microstructures of steel reflect both the amount of carbon present, the severity of quenching and the effects of reheating. With 0.8% carbon, the eutectic composition, steel which has not been heat treated consists entirely of a dark-etching phase known as pearlite. Occasional steels which exceed this carbon content contain both pearlite and iron carbide. More common are lower-carbon steels which contain both pearlite and the carbon-free phase, ferrite. The ratio of these phases directly relates to the composition, thus a 0.4% carbon steel contains 50% pearlite and 50% ferrite, whilst at 0.2% carbon the proportions will be 25% and 75% respectively. When rapid cooling takes place, a range of other crystalline structures tends to form instead of pearlite, of which the two most common phases are bainite, and (for very rapid cooling) martensite (Plate 3). Unfortunately the presence of these phases prevent any accurate estimation of the amount of carbon in the alloy.

As well as identifying the alloys used and the heat treatments applied to them, metallography enables the method of construction to be determined. The main requirement of a blade is that it should have a hard cutting edge so that it can be sharpened and will hold the edge. Secondly, the blade should be sufficiently tough to prevent it breaking in use. Hardness should not be at the expense of brittleness, and a wholly martensitic blade is not ideal as it tends to be brittle. A skilful smith can combine steel and iron in a number of ways, such that the edge of the blade is composed of steel and can be hardened, but that the main body of the knife (the back) is of a low carbon alloy that is not prone to brittleness. Such a composite blade has the additional advantage that steel, which until post-industrial revolution times was an expensive commodity, could be used more sparingly. Sometimes, an additional requirement of knives was that they should be particularly visually pleasing.

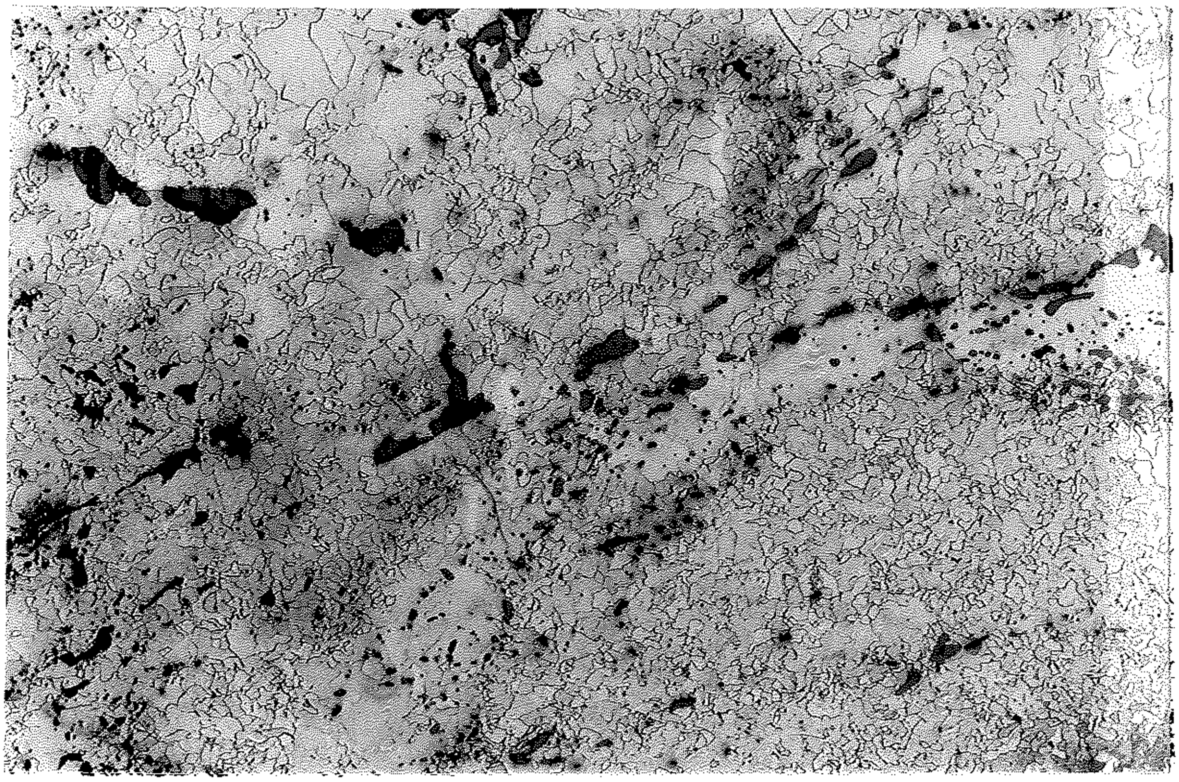

Plate 1 Ferritic Iron. Ferrite is visible as plain white polygonal crystals. The dark rounded particles are entrapped slag. Fishergate 4709, nital etched x100.

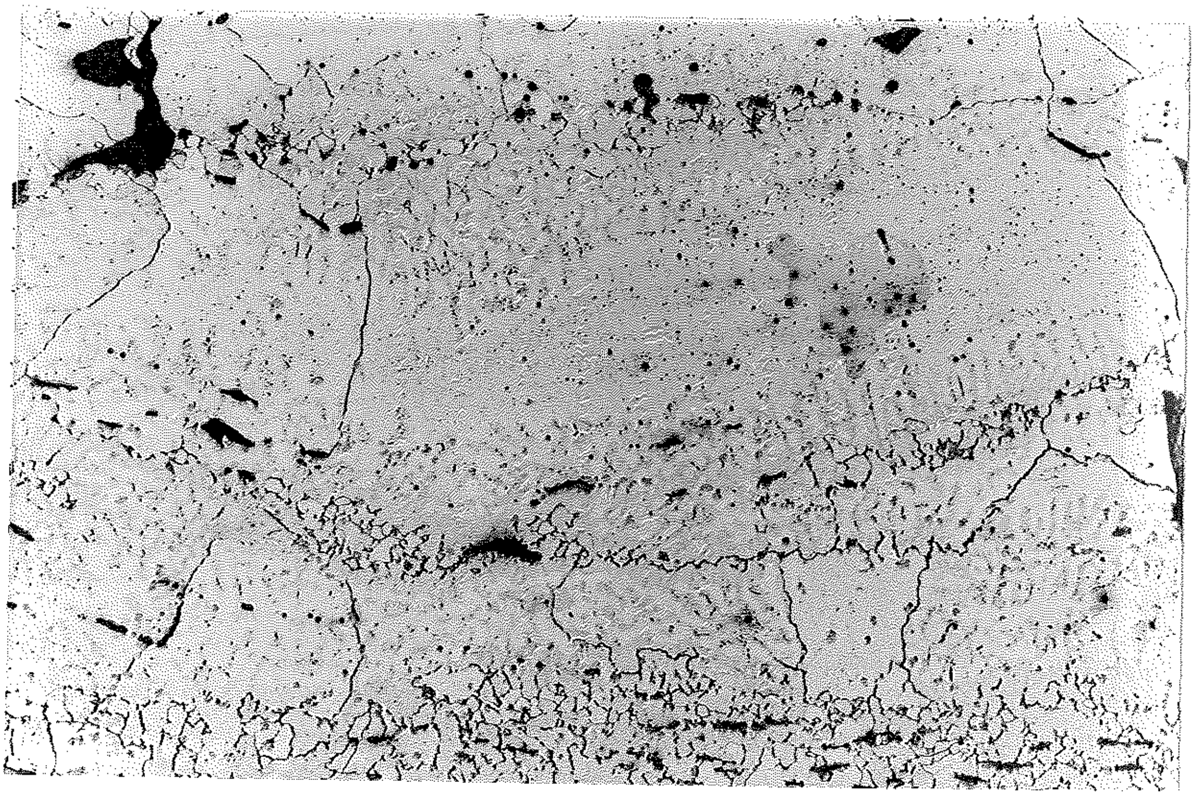

Plate 2 Phosphoric iron. The grain size is larger and "ghosting" is visible as brighter and darker areas within crystals. Coppergate 5271 nital etched x100

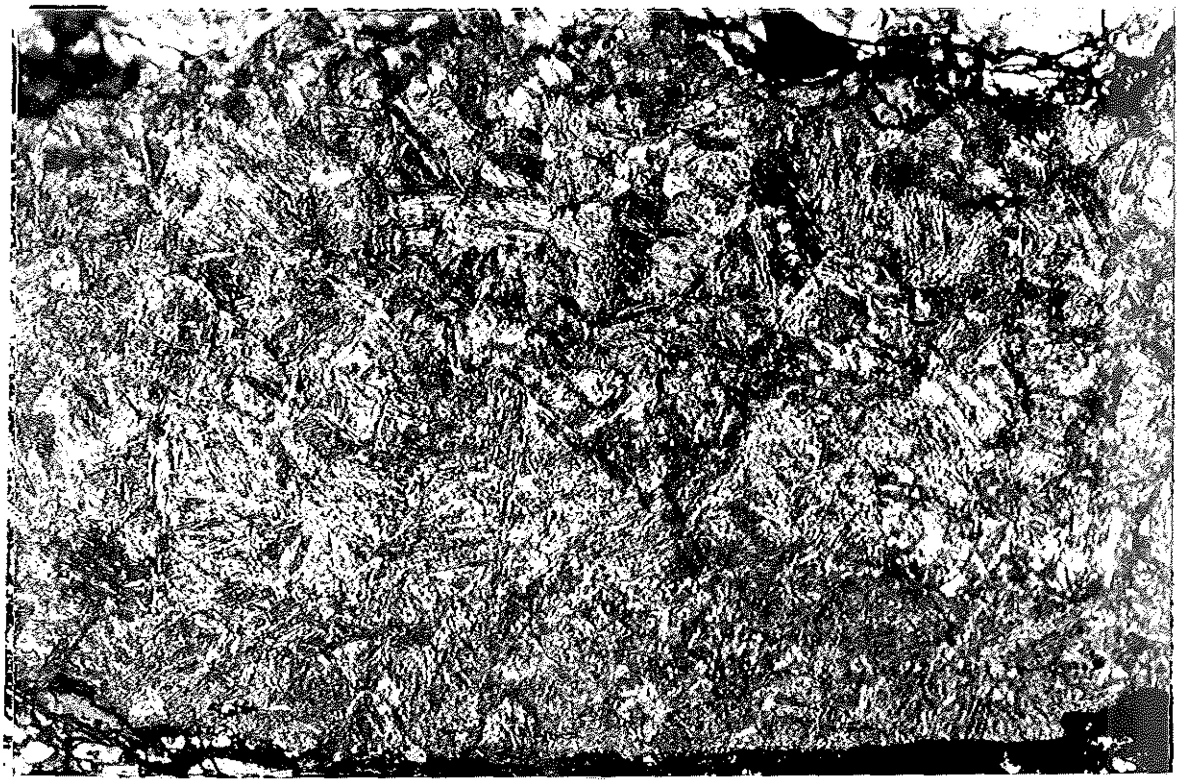

Plate 3 Tempered martensite. A needle like phase created by rapidly quenching steel, visually darkened by tempering. Coppergate 2449, nital etched x200.

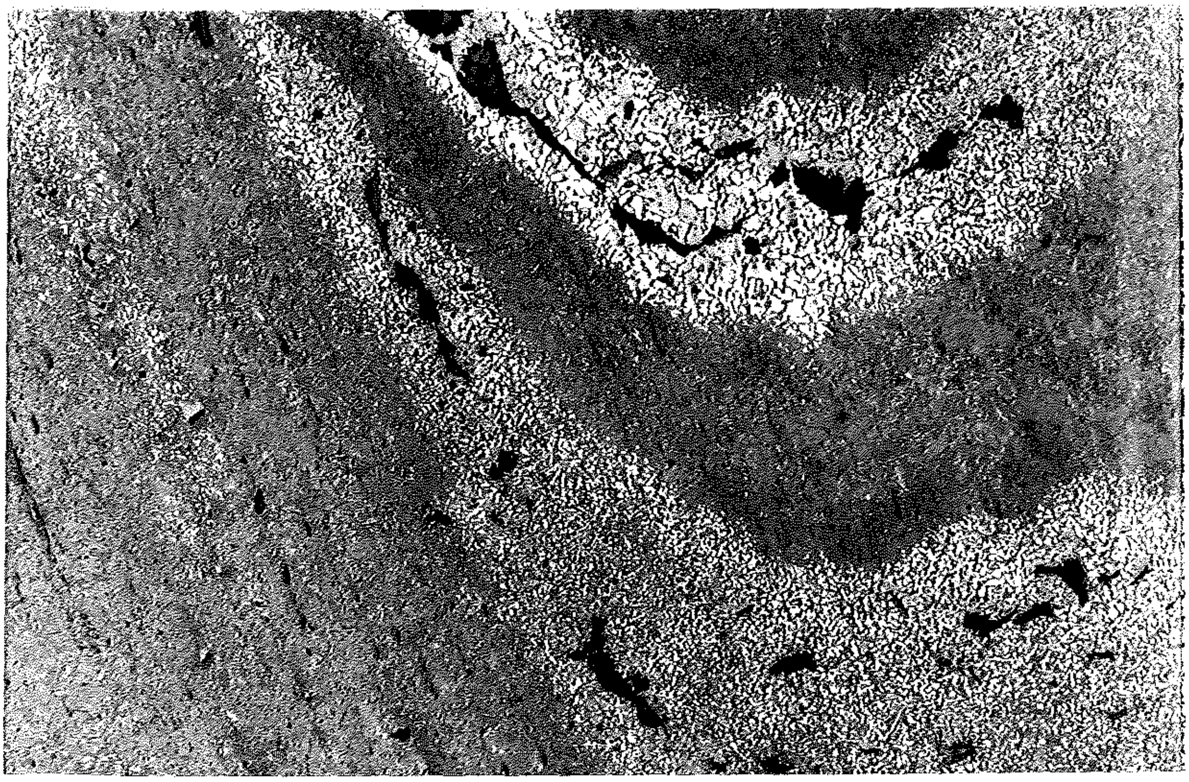

Plate 4 Pattern welded structure, comprising tempered martensite (dark) and phosphoric iron (light). Bedern 772, nital etched x100

The use of dissimilar metals, when polished and lightly etched can give a distinctive appearance to the surface of the blade. The best known technique is known as "pattern welding" in which the blade is built up of contrasting alloys, twisted together then welded into the blade (Plate 4).

The typology for metallographic structures of knives used in this study was originated by Tylecote and Gilmour (1986) and developed by McDonnell and Ottaway (1992). Of relevance to this report are the following types (Figure 2):

1a	steel core flanked by ferritic and phosphoric iron, ie core or sandwich welded
1c	steel core inserted as a tongue into the iron back.
2a	steel cutting edge scarf-welded to ferritic or phosphoric back.
2b	steel cutting edge butt-welded to the iron back
4	steel forms a sheath around an iron core.

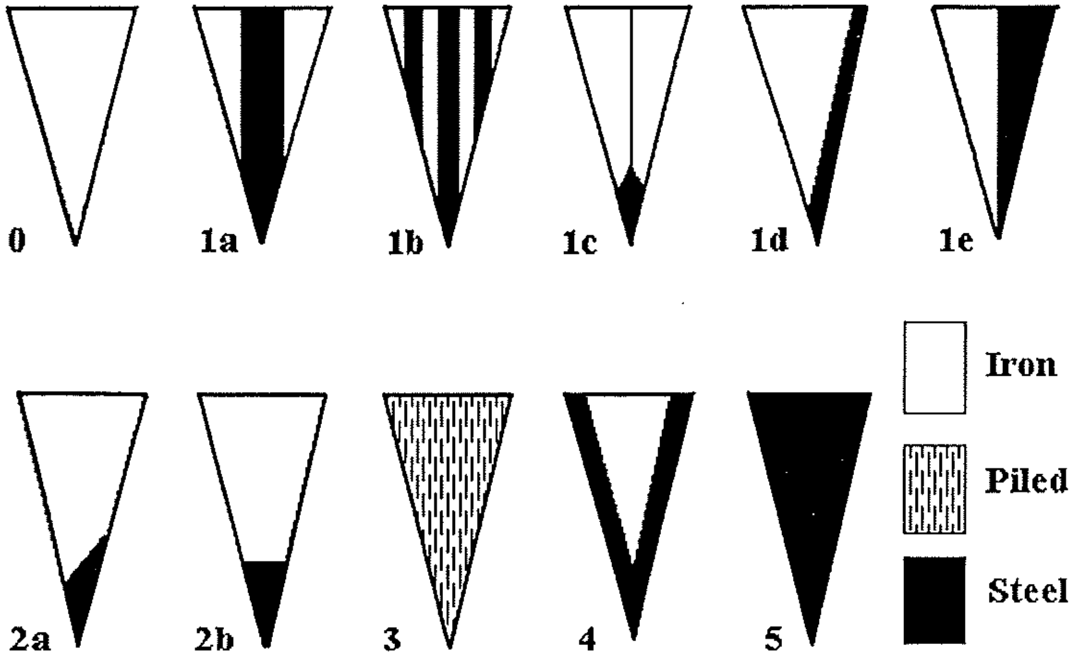

Figure 2 Schematic cross-sections of knife types. (after McDonnell and Ottaway 1992).

Sampling, metallographic preparation and microhardness testing

As far as possible each blade was sampled twice, with a narrow wedge cut from both edge and back of the knife and sufficient overlap to match the two sections (Figure 3). This was carried out in five of the knives but unfortunately for two more severely corroded examples (3994) and (1951) the metal was only sufficiently well preserved to obtain samples from the back of the knife. The most heavily corroded sample (3994) was cut with an aluminium oxide blade on a low speed water - cooled saw. The remaining artefacts were sampled with a combination of jewellers piercing saw and junior hack saw. The cut sections were then mounted in thermosetting phenolic resin and prepared using standard metallographic techniques; grinding on successively finer abrasive papers then polishing with diamond impregnated cloths. The specimens were examined on a metallurgical microscope in both the "as polished" *i.e.*, unetched condition and after etching in 2% nital (nitric acid in alcohol).

The results of the metallographic examination are represented visually in Figure 4. A Shimadzu microhardness tester was used to determine the hardness of different phases within the metallographic structure, which helped both to identify the alloy present and provide a direct measure of the effectiveness of the blades for cutting.

Microanalysis

Microanalysis was undertaken to provide compositional data which could show whether the iron and steel in composite blades came from similar sources. Some differences in composition should be expected from the conditions required to produce steel; a reducing atmosphere which encourages carbon to pass into and remain within the iron will also tend to reduce iron oxide within the inclusions to metallic iron, making the inclusions more glassy. In addition to this significant differences may also be apparent for minor and trace elements which may relate to the composition of ore from different geological sources or geographical areas.

Analysis of the metal matrices and inclusions within the iron was undertaken on a LEO 440i scanning electron microscope (SEM) fitted with Oxford ISIS energy-dispersive X-ray analyser (EDXA) with thin window. This was able to detect all elements above boron in the periodic table. The advantages of SEM based EDX analysis lie in the ability of the technique to undertake analysis at high magnifications on selected small areas, such as specific phases or mixtures of phases. The method is therefore highly suitable for heterogeneous archaeological materials. The sample was viewed in back-scattered mode before quantitative analysis was undertaken. This mode enhances atomic number contrast, rather than topography, allowing phases within the inclusions to be differentiated. Phases containing elements with higher atomic numbers, such as the iron in wüstite, appear lighter than low atomic number phases, such as glasses, with fayalite appearing as an intermediate mid-grey. Composition was determined over each inclusion as a whole rather than individual phases within them.

It should be noted that the technique can only to detect elements, not compounds. Figures quoted in Appendix II, which refer to the weight percentage of oxide, are derived from assumptions about the stoichiometry (*i.e.* the combining tendency) of each element. Minimum detectable levels vary from element to element: for oxides of sodium (Na),

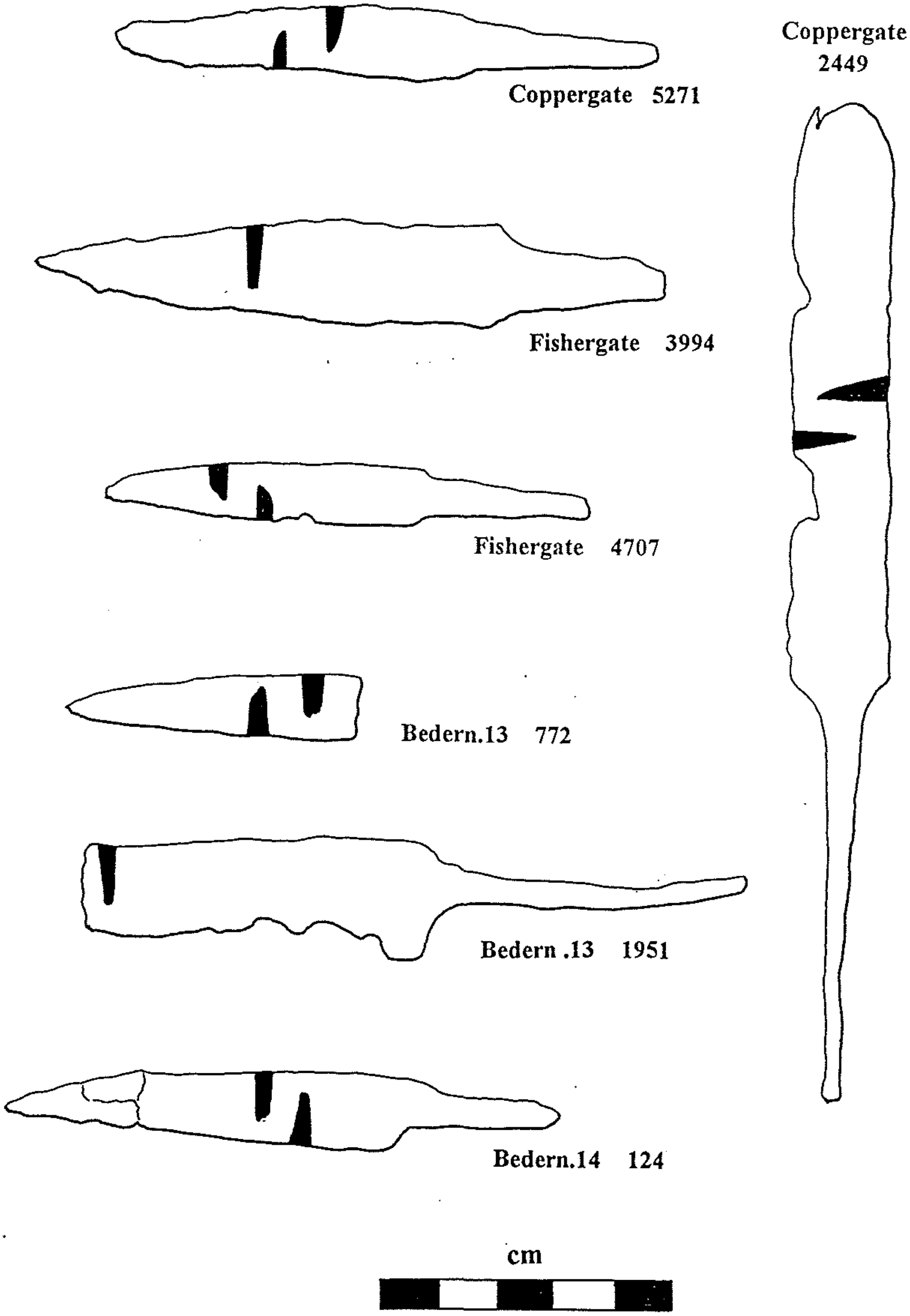

Figure 3 York medieval knives showing location of metallographic samples

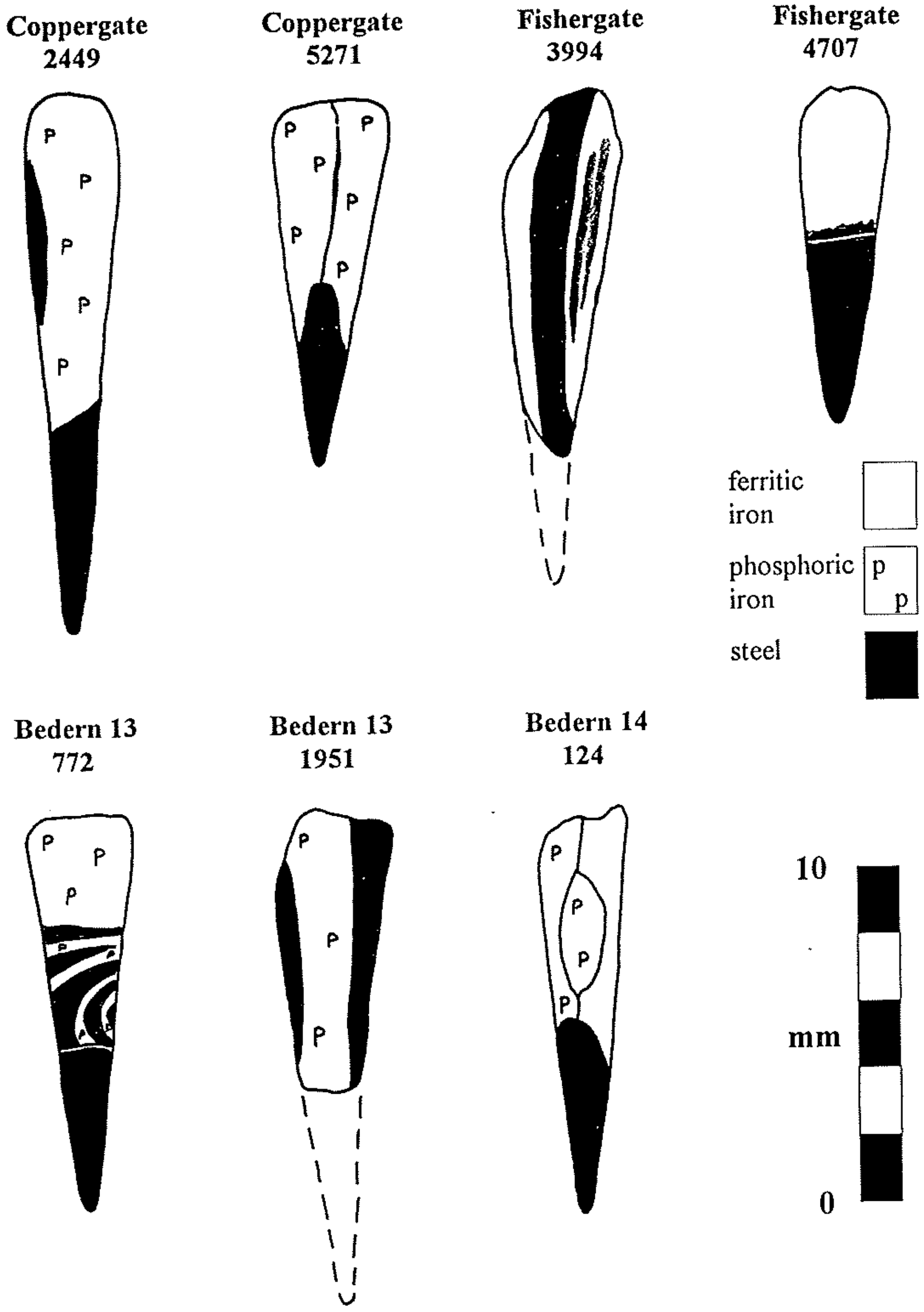

Figure 4 York medieval knives. Schematic cross sections showing constituent alloys

magnesium (Mg), aluminium (Al), silicon (Si), phosphorus (P), potassium (K), calcium (Ca) and titanium (Ti) these are approximately 0.1%, and for sulphur (S) and manganese (Mn) about 0.15%. Sensitivity is slightly greater for the pure metals within the iron matrix, however few impurity elements are present even at these levels. For the York knives, the most frequent impurity detected was phosphorus, with occasional traces of copper and nickel. Analyses of matrices are given in Appendix I and of individual inclusions in Appendix II.

Results of examination

Knife 2449 (AML Sample No. 960028) Coppergate
Context 10118, Fifteenth to sixteenth century, back type C1.

X-radiography revealed frequent striations along the length of the blade, but no distinct line which could positively be identified as a weld line. A probable maker's mark was also visible, appearing as two equilateral triangles with points touching: ⧓

Metallographic examination of the unetched sample showed the presence of slag inclusions. Throughout most of the blade these were of irregular, elongated shape, containing two phases and occupied 3% of the volume of the artefact. Towards the cutting edge of the blade very few («1%) very small inclusions were present.

Etching revealed that the blade was constructed of two components: The back of the blade was almost entirely coarse-grained (ASTM 2) ferrite with ghosting indicating the presence of phosphorus. A small area on one side of the back showed a slightly higher carbon content. By contrast the edge of the blade was of tempered martensite (Plate 3), with a high hardness. An oblique weld line separated the two zones.

Microhardness tests on the metal phases (100g load, 10sec load time) gave the following values:

phosphoric iron	163.6 H_v	tempered martensite	497.8 H_v
knife back	177.7 H_v	knife edge	473.0 H_v
	196.8 H_v		503.0 H_v
	189.3 H_v		424.5 H_v
	225.1 H_v		477.8 H_v
mean	190.5 H_v		475.2 H_v

The differences in hardness between iron and steel are evident. However, to put these values in perspective, it should be noted that the 190H_v value for phosphoric iron is of the order of 40-80 units higher than a pure, ferritic iron. Also the hardness of the steel is probably 100-200 units lower than an untempered steel.

Microanalysis further differentiated the two components. The iron in the back was shown to have a mean phosphorus content of 0.23%, but no other impurities, whilst the steel contained no phosphorus but 1.28% copper. The latter probably arose from contamination during working, but alternatively it might have resulted from an ore source containing traces of copper. Inclusions also showed distinct differences between the two alloys. As noted above, some of these differences are due to the conditions required for steel production. However, other significant differences are also present. Those in the steel contain much manganese whilst those in the phosphoric iron contains sulphur. The analytical results strongly suggest different sources for the two metals. Higher levels of sulphur in the phosphoric iron may suggest the use of mineral coal in the early working of this metal.

Interpretation
A high quality Type 2a blade in which a steel edge had been butt-welded to a phosphoric iron back. The blade had subsequently been quenched and tempered to give a mean edge hardness of 475 H_v. Differences in composition suggest geographically and possibly technologically different origins for the two alloys.

Knife 5271 (AML Sample No. 960029) Coppergate
Context 13902, Twelfth to thirteenth century, back type indeterminate.

No weld lines were visible in the X-radiograph.

In the unetched condition a marked contrast in the inclusion content and composition was visible between the edge and the back of the knife. The edge contained less than 1% of single phase elongated inclusions whilst the back had 5% of single and dual phase inclusions. These were often angular and were elongated or in the form of stringers.

When etched the back of the blade was shown to be mostly phosphoric iron (Plate 2) with a large grain size (ASTM 1), although small areas contained a mixture of finer grained ferrite (ASTM 5) with agglomerated cementite. The edge contained two phases; ferrite and spheroidised/agglomerated cementite (Fe_3C). The coexistence of these phases without the products of either slow cooling (pearlite) or rapid quenching (bainite and martensite) is significant. The alloy is a steel but one that has been held at high temperatures for longer periods than is metallurgically beneficial. Two possible explanations may be suggested. Firstly, an incompetent smith may have misjudged the heat treatment of the blade. More probably (considering the deliberate selection of materials and the skill that has been used in forging the blade), the knife could have been accidentally reheated at a later date, perhaps by being dropped in a fierce fire or in the conflagration of a building. The result, as shown by the microhardness figures, is a blade in which the edge is even softer than the back.

phosphoric iron	213.1 H_v	ferrite/spheroidised	185.7 H_v
knife back	180.0 H_v	pearlite	165.2 H_v
	181.1 H_v	knife edge	198.0 H_v
	199.3 H_v		206.0 H_v
	210.2 H_v		182.2 H_v
mean	196.7 H_v		187.4 H_v

Microanalysis confirmed the differences between the two components was restricted to their phosphorus content; the back contained 0.3%, the edge none. The inclusions in both parts are relatively similar for the oxides of calcium, aluminium and titanium, but the edge is notably high in the oxides of magnesium, manganese and, predictably, phosphorus.

Interpretation

A type 1c blade in which a steel "tongue" had been skilfully inserted into a phosphoric iron back. At some time, probably later in the knife's history, the blade had been severely heated, without subsequent quenching, such that its effectiveness was severely reduced. The composition of the two components suggests that the phosphoric iron and steel derived from different sources.

Knife 3994 (AML Sample No. 960030) Fishergate
Context 5131, Period 6c, early to mid fourteenth century, back type C3.

No unambiguous weld lines were visible in the X-radiograph. Because the edge of the blade was severely corroded only a single sample was taken from the back of the blade.

Before etching, microscopic examination of the inclusions within the section showed their presence to vary considerably from 1 to 3%. They were of elongated or stringer morphology and generally mottled appearance, although some were seen to contain two phases.

Etching showed the blade to be of sandwich construction. At high magnification the microstructure of the dark-etching band through the centre was shown to vary from tempered martensite towards the edge of the blade to nodular pearlite and bainite nearer to the back of the blade. The difference in structure is due to the thickening of the blade towards its back, which would therefore have cooled less quickly when the blade was quenched. The sides of the blade were heterogeneous in carbon content, being predominantly ferrite (ASTM 5) but with some bands of pearlite. The banded nature of this metal may indicate that the iron had been piled to give it more uniform properties.

ferritic iron	134.0 H_v	tempered martensite	585.3 H_v
knife back	138.4 H_v	knife edge	454.5 H_v
	119.5 H_v		634.2 H_v
	140.0 H_v		649.3 H_v
	133.3 H_v		612.5 H_v
mean	133.0 H_v		587.2 H_v

Microhardness shows a much greater contrast in hardness between blade and back compared with Coppergate 5271.

Analysis, surprisingly, found some phosphorus at one point in the steel but not as much as in the iron where 0.17% was detected. The latter suggests that this alloy borders on being classed as phosphoric iron. However, given the low hardness values and lack of ghosted structure, its initial classification as ferritic iron was retained. Inclusion composition showed the usual concentration of glass forming oxides in inclusions in the steel phase, although the concentration of phosphorus and, significantly, sulphur is greater in the iron. As mentioned above, the sulphur may be due to the use of coal in the early working of the bloom, or bars of metal. Interestingly the phosphorus content of the inclusions is very high at up to 17%. This suggests that a high phosphorus ore was used, but smelted at relatively low temperatures such that the phosphorus, which partitions between the metal and slag during smelting, passed largely into the slag.

Interpretation

A type 1a sandwich welded blade in which two heterogeneous, but largely ferritic, iron plates flank one of steel. The whole has been effectively heat treated by quenching and tempering to provide a hard edge on a tough back. The sandwich blade, whilst less sparing of steel than the butt or scarf welded knife, has the advantage that long-term resharpening will never reach a point whereby the steel edge is worn away. Few oxides show significant compositional differences between the iron and steel, though for the former, the high content of phosphorus pentoxide suggests a different ore source whilst its sulphur content may result from the use of mineral fuel during bloom or bar smithing.

Knife 4707 (AML Sample No. 960031) Fishergate
Context 5254, Period 6ab, early thirteenth to fourteenth century, back type C3.

X-radiography revealed distinctive narrow bands running parallel to the edge of the knife, indicative of a butt welded edge.

Microscopic examination of the unetched sample identified several lines of slag stringers, along weld lines. One of these was later found to correspond with the join between steel edge and iron back, the others would have originated during earlier working of the iron. The back of the knife contained variable concentrations of inclusions, up to about 5% by volume and generally small and grey. The edge contained fewer (1%) but larger inclusions of sub-round to elongated form.

The etched structure confirmed the position of a butt weld. The edge of the blade consisted of tempered martensite at the extreme edge, through bainite and nodular pearlite to pearlite near the weld. The back was entirely ferritic (Plate 1) with a grain size of ASTM 6, except for a region near the weld into which carbon had diffused. The weld was further distinguished by a light-etching band.

ferritic iron	112.5 H_v	tempered martensite	513.7 H_v
knife back	114.2 H_v	knife edge	634.2 H_v
	108.2 H_v		591.9 H_v
	127.7 H_v		508.3 H_v
	119.5 H_v		566.0 H_v
mean	116.4 H_v		562.8 H_v

Analysis of the metal matrices found no impurity elements present at detectable levels. Many of the inclusions in the back of the knife were almost pure iron oxide, being entrapped scale. Others were unusually high in the oxides of aluminium, potassium and calcium. Otherwise the inclusions in both components were free of phosphorus, manganese and sulphur.

Interpretation

A high quality type 2b blade with a steel edge butt-welded to an iron back. The whole has subsequently been quenched and tempered or slack quenched (*i.e.* quenched in a material of lower thermal conductivity that water, such as oil). The composition of the iron and steel are similar, but not particularly distinctive and a similar or the same source of ore cannot be ruled out.

Knife 772 (AML Sample No. 960032) Bedern 13
Context 1640, Period 1, early to mid thirteenth century, back type C.

The X-radiograph showed three zones in the knife: An edge, a back and between the two a band of metal with diagonally oriented striations characteristic of the twisted portions of pattern-welded blades.

In the unetched sample the position of weld lines were shown by lines of inclusions. Overall the blade contained about 2% inclusions, but in some areas these occupied much less volume. Near the edge the inclusions were dark grey, often fractured and of elongated to stringer morphology. In the pattern-welded region and back, inclusions were more variable in form, being angular and irregular but rarely as elongated.

After etching the sample the three regions of the blade were identified as a tempered martensite edge, a phosphoric iron back and a central pattern welded region in which bands of tempered martensite alternated with bands of phosphoric iron (Plate 4). Some diffusion of carbon into the phosphoric iron bands had occurred. A light-etching band marked the location of the weld between the edge and pattern welded region.

Phosphoric iron knife back	159.5 H_v	tempered martensite knife edge	559.8 H_v
	156.7 H_v		553.7 H_v
	186.9 H_v		503.0 H_v
	171.3 H_v		530.3 H_v
	166.2 H_v		477.8 H_v
mean	168.1 H_v		524.9 H_v

Microanalysis of the metal showed the steel in the edge and in the pattern-welded region to be similarly free of impurities. All the low carbon material contained phosphorus. In the pattern-welded region this was double (0.34%) that of the back (0.17%). This may be the result of deliberate selection; phosphorus tends to block the diffusion of carbon and hence would provide maximum visual contrast between two metals. Inclusion composition was very variable and added no useful information.

Interpretation
Technologically this blade is a Type 2b, with a steel blade and iron back. However, it is notable in also having a central pattern welded region, which would have required considerable skill, given the small size of the knife. Quenching and tempering had given a good though not especially hard edge. The smith made use of at least two alloys: steel and phosphoric iron. It also seems likely that a further, particularly phosphorus-rich iron was used in the pattern-welded region. This is a high quality blade, being both serviceable and aesthetically pleasing.

Knife 1951 (AML Sample No. 960033) Bedern 13
Context 5146, Period 7 late fourteenth to early fifteenth century,
Back type indeterminate.

Only the back of this heavily corroded knife had survived sufficiently to allow it to be sampled. However, even in the corroded region possible weld lines were apparent. A trace of non-ferrous metal may be associated with a maker's mark.

The unetched sample was seen to contain large amount of inclusions (5%) in a band running down through the centre. These were large, of irregular shape, generally elongated and contained multiple phases. By contrast the surviving outside regions contained only 1% of inclusions and they tended to be smaller, dark grey, of single phase and elongated or stringer morphology.

Etching revealed the outer surface of the blade to be tempered martensite with some bainite and the centre to be a banded structure including ferrite with phosphorus ghosting and a feathery structure, probably upper bainite, which suggests that this central region contains areas with some carbon, though probably not more that 0.1 or 0.2%, the lower of which would be consistent with hardness values around 250 H_v.

low carbon bainite	193.0 H_v	tempered martensite/	519.1 H_v
knife core	186.9 H_v	bainite	591.9 H_v
	184.5 H_v	knife sides	530.3 H_v
	254.4 H_v		657.0 H_v
	250.6 H_v		524.7 H_v
mean	213.9 H_v		564.6 H_v

Compositionally, low levels of phosphorus were found to be present in the low carbon region and in the steel on one side of the blade (right-hand side in Figure 4). This side also contained traces of copper, perhaps linked to the non-ferrous speck seen on the X-radiograph. The other steel component showed no traces of impurities. Surprisingly the steel on the opposite side (left on Figure 4) contained high-phosphorus inclusions. This was distinguished from the phosphoric iron by high levels of oxides of magnesium, titanium and manganese, and from the other steel by high sulphur and high manganese.

Interpretation

The interpretation of the blade is made less certain by the advanced state of the corrosion, which had oxidised the edge of the blade. However, it appears most probable that the blade corresponds to type 4 in which the steel forms a sheath around a phosphoric iron core. Quenching and tempering had been used to ensure an effective cutting edge. However as different sources of iron are suggested for the two sides of the blade, these may have been prepared and welded onto the core separately rather than wrapping a single sheet around.

Knife 124 (AML Sample No. 960034) Bedern 14
Context 1007, Period 9, sixteenth to seventeenth centuries, back type C.

The X-radiograph strongly suggested three bands within this knife, but with no evidence of twisting associated with pattern welding.

Metallographic examination of the unetched sample showed the contrast between the few inclusions in the edge of the knife (<1% sub-round to elongated, single phase) with greater numbers in the back (3% elongated, single and dual phase). The nital etch revealed the edge to be of tempered martensite, with a V-shaped weld line and some carbon diffusion across it into the low carbon back. The back itself was of very unusual composite construction with two sides enclosing a central core. Very faint ghosting was noted in places with very variable grain size (ASTM 7 to 1) and together with the slightly elevated hardness values for the low carbon region, it is clear that some phosphorus is present.

ferritic/phosphoric iron	163.3 H_v	martensite	612.4 H_v
knife back	159.5 H_v	knife edge	641.7 H_v
	168.2 H_v		681.8 H_v
	156.7 H_v		673.0 H_v
	180.0 H_v		641.7 H_v
mean	165.5 H_v		650.0 H_v

Of the three sections in the back, one side (left in Figure 4) and the core contained some phosphorus, but none was detected in the other side or in the steel edge. The phosphorus content in the inclusions mirrored that of the matrices, but few other trends were evident, except that the central low carbon region contained significant levels of sulphur and magnesium.

Interpretation
Basically, a Type 1c with steel cutting edge inserted into a low carbon back. The complexity of the back may have resulted from an attempt to create a decorative effect. However, the metals are so similar that this could not have been particularly effective and the recycling of small fragments may be a more probable explanation for the observed structure. The blade has been heat treated and the cutting edge showed the highest hardness of all the blades examined.

Table 1 Summary of metallographic results

SF No.	Site	AML No.	Microstructure		Hardness H_v	blade structure type	blade back type	date
2449	Coppergate	960028	back:	Phos	191	2a	C1	C15-16th
			edge:	TM	475			
5271	Coppergate	960029	back:	Phos	197	1c	indet.	C12-13th
			edge:	F+C	187			
3994	Fishergate	960030	centre:	TM+B+NP	133	1a	C3	e-mC14th
			sides:	F+P	587			
4707	Fishergate	960031	back:	F	116	2b	C3	eC13-14th
			edge:	TM+B+NP	563			
772	Bedern	960032	back:	Phos	168	2b	D	e-m C13th
			edge:	TM	525	pattern		
			centre:	Phos+TM		welded		
1951	Bedern	960033	core:	Phos+F+UB	214	4	indet.	lC14-eC15th
			outer:	TM+B	565			
124	Bedern	960034	back:	Phos/F	165.5	1c	C	e-mC13th
			edge:	TM	650			

B, bainite; F, ferrite; P, pearlite; Phos, ferrite with phosphorus ghosting;
TM, tempered martensite; UB, upper bainite.

Discussion

Scientific examination of the seven medieval knives from the three York sites using metallography, SEM based microanalysis, X-radiography and microhardness testing allowed a much higher level of understanding of the artefacts than non-destructive examination alone could have achieved. In particular it enabled determination of the iron alloys available to metalworkers, an assessment of the forging and heat treatment techniques of the smiths and a measure of the effectiveness of the knives in use. The unusually good preservation of the knives was an important factor in successfully sampling and examining the blades.

Looking firstly at the range of alloys, all blades incorporated steel in such a way that it formed part of the cutting edge. Steel has the important property of hardenability; appropriate heat treatment results in high hardness which allows a sharp edge to be retained. Like most knives and other edged tools and weapons, the York knives also incorporated other iron alloys. Low carbon iron has the practical advantage of not becoming brittle due to heat treatment but retaining its toughness. It would also have had the economic benefit of being cheaper. Three blades contained pure "ferritic" iron, three phosphoric iron and one a mixture of the two.

The use of microanalysis in the project allowed the alloys to be studied in greater depth. Few elements were present in the iron matrix in sufficient quantity to be quantified by the energy dispersive detector of the scanning electron microscope, although the phosphorus levels of the phosphoric iron, and occasional copper and nickel contents were above the limits of detectibility. Slag inclusions, which are a characteristic component of early iron, provided further compositional data on which to compare the individual components within the blades.

Data from microanalysis provided useful evidence relevant to a major topic of discussion in ferrous archaeometallurgy: the manufacture and supply of steel. On the one hand there is documentary evidence for importation of steel as a separate commodity, even as a frequent occurrence in fifteenth century London (Childs 1981). Little attempt has been made to match accounts, such as the "authoritative opinion" from 1577 which stated that "as for our steele it is not so good for edge tools as that of Colaine" (*i.e.* Cologne) (Hopkins (1970, 125), with the composition of renaissance, medieval or earlier blades.

Not only is the geographical origin of steel open to question but also its technological origin. Many archaeometallurgists believe that traditional bloomery processes were adapted to produce a more steely bloom when required, or that a heterogeneous bloom could be separated into high and low carbon parts. A third option is for iron to be carburised by heating it in a highly reducing, carbon-rich atmosphere so that carbon was absorbed into the metal. This carburising principle can be divided into two basic processes. The first is cementation, in which iron bars were converted to steel, then worked into artefacts. Later it formed the basis of a major industry, but the earliest historical evidence of it in Europe comes from Germany in the late sixteenth century (Barraclough 1976). The second process, which we now know as case carburisation or case hardening, is recorded earlier than this. Theophilus' *On Divers Arts*, written in about 1100 describes the hardening of files by heating in a carburising medium of ox horn and salt (Smith and Hawthorne 1963, 93). This reference has been used by numerous scholars to suggest that this was usual method of producing steel. However, in this technique carbon penetration is very slow and therefore more appropriate to objects like files in which a very hard, but only very thin surface layer is required. Such a layer would soon be lost when a knife was re-sharpened.

As mentioned above, it is recognised that the composition of inclusions in steel will differ from those in low carbon iron. This is a function of the highly reducing conditions required for the absorption and retention of carbon; these will also reduce iron oxide in the inclusions to metallic iron, with a corresponding increase in concentration of the other elements present. However the York data showed that for six of the knives the composition of the inclusions, and often the iron matrices, was sufficiently different to be certain that the alloys came from different sources. For the seventh blade (4707) the compositions of iron and steel were not sufficiently distinctive that either differences, or similarities could be used to say whether their sources were related. The marked compositional differences contrast with Wiemer's (Ottaway and Weimer 1993, 1277-1308) microprobe analyses of the Anglian knives which show most, though not all, knives to have similar trace element contents in the different metallic phases. It might be thought possible to use these distinct differences to source (provenance) the artefacts but attempts to do this have achieved very limited success due to a number of difficulties inherent in iron production. These have been summarised (Starley 1992, 55) as:

1. The wide variety of raw materials, particularly ores, which are available.
2. The ubiquity of ore sources and their lack of characterising features.
3. A lack of complementary data from production sites.
4. The heterogeneous composition of artefacts.
5. The alteration of composition by subsequent processing.

6. The possible re-working of scrap.
7. The deliberate or accidental addition of non-essential components.

Given these possible obstacles, it is not possible to suggest the origin of the alloys, or of the knives if the latter were imported to the city. What can be suggested, and it is an important step forward, is that the iron and steel have different origins and these differences are likely to be geographical. However, technological differences, probably including the use of coal in smithing (shown by the presence of sulphur in inclusions) are also likely to be a factor. The results from the knife analyses do appear to provide evidence of widespread trade in specialist ferrous alloys during the later medieval period.

The second purpose of the investigation was to study the techniques used by the smiths for forging and heat treating the blades. Other metallographic studies have shown that during some periods construction technique appears to be a cultural attribute (see below): Anglian and Saxon knives tend to be butt welded, whilst Anglo Scandinavian knives tend to be of "sandwich" construction. Relatively little metallographic work has been undertaken on medieval blades and the York material presented a rare opportunity to extend our understanding of smithing techniques forward in time.

Seven objects from thee sites provide a minimal data set from which to draw conclusions, however some trends were apparent. The first impression is of the variety of techniques used to combine the iron and steel components of the blade: Two horizontal butt welds (type 2b), two inserted steel tongues (type 1c), and one example each of a scarf weld (type 2a), wrapped steel (type 4) and sandwich construction (type 1a). Taken as a group this represents a considerable change since the preceding Anglo- Scandinavian assemblages in which the type 1 technique was dominant (McDonnell and Ottaway, 1992, 481). However, when dates of individual blades are taken into account a slower transition may be apparent. The knives examined range from the twelfth to the sixteenth century. Although the sample is too small to be statistically significant, it may be of relevance that both type 1c blades (steel tongue inserted into iron back), were amongst the earliest blades, perhaps showing some continuity from the Anglo Scandinavian period. Against this trend, butt and scarf welded knives continued through to the fifteenth/sixteenth centuries. Both the variety and the balance of butt-welded to sandwich construction blades is broadly similar to results from Winchester, one of the few contemporary British sites for which comparable metallographic data of knives is available (Tylecote 1990).

The final aim of the metallographic study was to assess the quality and effectiveness of the blades. Ideally a blade should have maximum hardness at its edge, but with greater toughness in the main body. All the blades examined had been constructed in such a way as to achieve this, although by different means. Heat treatment of the blades was, with one exception, excellent, achieving the ideal microstructure of tempered martensite. Direct measurement of the effectiveness of these blades was provided by microhardness testing. Results from this typically showed high hardnesses of 500 to 600 H_v. Both metallography and microhardness results testify to the skill and understanding of the smith in first quenching the blade to harden the steel edge, then tempering it by reheating to toughen it. An exception was knife 5271 which appears to have been reheated to a much too high temperature so that the hardness was adversely affected. This could have resulted from an error of judgement by the smith, although the damage may well have been done long after manufacture.

Particular mention should be made of the pattern welded blade 772. Despite the small size of the knife it had been built up with considerable skill from three components: A steel edge, a moderately phosphoric back and, between these two, a twisted combination of steel and highly phosphoric iron. When ground, polished and etched the sides of the blade would have showed a pleasing decorative effect, making this a highly desirable object. The pattern-welded knife's date, in the early to mid thirteenth century makes it a relatively late example of this technique, although another thirteenth century example has been recorded from Eynsham Abbey (Fell and Starley, forthcoming) and one thirteenth century and one fourteenth century example from Winchester (Tylecote 1990). A possible makers mark was noted on one knife, 2449.

Conclusions

The knives examined metallographically had all been constructed with considerable skill using high quality materials. A good understanding of heat treatment was shown in all but one case, the latter probably having been ill-treated at a later date, rather than by the smith. Thus all were originally high quality, effective tools. A late example of a pattern-welded blade, dating to the thirteenth century, was a particularly fine artefact. The seven blades appeared to show less consistency in the methods of combining iron and steel than had been seen in earlier studies of blades from Anglo-Scandinavian and Anglian York. The variation in metal composition, between and within individual blades, appears to indicate much wider range of stock material than existed in the city earlier. This may be linked to the increasingly specialised production of specific iron alloys and for greater access to widespread trade networks, including those for iron and possibly completed knives, than had previously been the case.

References

Barraclough, K.C. (1976) The Development of the Cementation Process for the Manufacture of Steel. *Journal of Post-Medieval Archaeology*, **10**, 66-88.

Childs, W.R. (1981) England's Iron Trade in the Fifteenth Century. *Economic History Review* **33**, 25-27.

Fell, V and Starley, D. *Metallographic Examination of Seven Iron Blades from Eynsham Abbey, Oxfordshire*. Ancient Monuments Report **70/98**.

Hopkins, H.J. (1970) *A Span of Bridges*. Newton Abbot, David and Charles.

McDonnell and Ottaway (1992) The Smithing Process. in Ottaway, P. *Anglo Scandinavian Ironwork from Coppergate.* The Archaeology of York, the Small Finds **17/6**. London, Council for British Archaeology, 480-486.

Ottaway, P. (1992) *Anglo Scandinavian Ironwork from Coppergate.* The Archaeology of York, the small finds **17/6**. London, Council for British Archaeology.

Ottaway, P. and Wiemer, K. (1993) Metallurgy of the Knives. in Rodgers, N. S. H. *Anglian and other Finds from Fishergate*. The Archaeology of York, the Small Finds **17/9.** London, Council for British Archaeology, 1277-1308

Hawthorne, J.G. and Smith, C.S. (trans.) (1963) Theophilus *On Divers* Arts. New York, Dover.

Starley, D.E. (1992) Medieval Iron and Steel Production: An Assessment of the Changing Technology of European Ferrous Alloy Production through the Analysis of Medieval and Renaissance Armour. Unpublished Ph.D. thesis, University of Bradford.

Tylecote, R.F. (1990) Scientific Examination and Analysis of Iron Objects. In Biddle, M. *Objects and Economy in Medieval Winchester*. Winchester Studies **7ii**. Oxford, Oxford University Press, 140-159.

Tylecote, R.F. and Gilmour B.J.J. (1986) *The Metallography of Early Ferrous Edge Tools and Edged Weapons*. BAR (British series) **155**, Oxford.

Appendix I **Composition or metal matrices of medieval knives from York**

Site details	Sample information			Composition (wt% element)						SEM
	AML ref.	Matrix	section	P	S	Fe	Co	Ni	Cu	ref.
Coppergate	960028	phosphoric	back	0.27	nd	99.73	nd	nd	nd	ykm01
small find 2449			back	0.16	nd	99.84	nd	nd	nd	ykm02
context 10118			edge	0.26	nd	99.74	nd	nd	nd	ykm03
			mean	0.23	nd	99.77	nd	nd	nd	
		steel	edge	nd	nd	98.55	nd	nd	1.45	ykm04
			edge	nd	nd	98.89	nd	nd	1.11	ykm05
			mean	nd	nd	98.72	nd	nd	1.28	
Coppergate	960029	steel	edge	nd	nd	100.00	nd	nd	nd	ykm06
small find 5271			edge	nd	nd	100.00	nd	nd	nd	ykm07
context 13902			mean	nd	nd	100.00	nd	nd	nd	
		phosphoric	back	0.37	nd	99.63	nd	nd	nd	ykm08
			back	0.22	nd	99.78	nd	nd	nd	ykm09
			mean	0.30	nd	99.70	nd	nd	nd	
Fishergate	960030	steel	core	nd	nd	100.00	nd	nd	nd	ykm10
small find 3994			core	0.08	nd	99.93	nd	nd	nd	ykm11
context 5131			mean	0.04	nd	nd	nd	nd	nd	
		ferrite		0.17	nd	99.83	nd	nd	nd	ykm12
Fishergate	960031	ferrite	back	nd	nd	100.00	nd	nd	nd	ykm14
small find 4707			edge	nd	nd	100.00	nd	nd	nd	ykm15
context 5254			mean	nd	nd	100.00	nd	nd	nd	
		steel	back	nd	nd	100.00	nd	nd	nd	ykm16
			edge	nd	nd	100.00	nd	nd	nd	ykm17
			mean	nd	nd	100.00	nd	nd	nd	
Bedern	960032	steel	edge	nd	nd	100.00	nd	nd	nd	ykm18
small find 772			edge	nd	nd	100.00	nd	nd	nd	ykm19
context 1640			mean	nd	nd	100.00	nd	nd	nd	
		white weld line	edge	nd	nd	99.50	nd	0.38	nd	ykm20
		pattern weld (phos)	back	0.34	nd	99.66	nd	nd	nd	ykm21
		pattern weld (steel)	back	nd	nd	100.00	nd	nd	nd	ykm22
		phosphoric	back	0.15	nd	99.75	nd	nd		ykm23
			back	0.18	nd	99.72	nd	nd		ykm24
			mean	0.17	nd	99.83	nd	nd		
Bedern	960033	phosphoric		0.09	nd	99.78	nd	nd	nd	ykm25
small find 1951				0.12	nd	99.88	nd	nd	nd	ykm26
context 5146		mean		0.11	nd	99.89	nd	nd	nd	
		steel (rhs)		0.10	nd	99.76	nd	nd	0.14	ykm27
		steel (lhs)		nd	nd	99.86	nd	nd	nd	ykm28
		mean		0.05	nd	99.88	nd	nd	0.07	
Bedern	960034	ferrite (lhs)		0.21	nd	99.79	nd	nd	nd	ykm29
small find 124		ferrite (rhs)		nd	nd	99.88	nd	nd	nd	ykm30
context 1007		ferrite (centre)		0.12	nd	99.73	nd	nd	nd	ykm31
		mean		0.11	nd	99.89	nd	nd	nd	
		steel		nd	nd	100.00	nd	nd	nd	ykm32

Appendix II Composition of inclusions in medieval knives from York

Site details	Sample information			Inclusion	Composition (wt% oxide)												SEM
	AML ref.	section	matrix	size (µm)	Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	S	K_2O	CaO	TiO_2	Cr_2O_3	MnO	FeO	ref.
Coppergate	960028	edge	steel	30*3	nd	1.6	5.8	20.6	0.7	0.3	3.0	2.9	0.4	nd	0.5	63.8	YK001
small find 2449	960028	edge	steel	30*5	nd	1.5	7.2	47.0	0.7	nd	5.9	8.3	nd	nd	9.8	19.4	YK002
context 10118	960028	edge	steel	20*4	nd	1.4	8.2	52.2	nd	0.4	6.5	8.3	0.5	nd	10.8	11.6	YK003
	960028	edge	steel	10*3	nd	1.6	8.6	38.5	0.5	nd	4.6	3.2	0.4	nd	3.2	39.1	YK004
	960028	edge	steel	15*15	nd	2.5	8.4	43.3	0.5	nd	4.5	4.4	0.4	nd	12.4	23.4	YK005
	960028	edge	phosphoric	100*10	nd	nd	7.8	9.2	7.7	1.5	0.4	1.1	nd	nd	nd	72.2	YK006
	960028	edge	phosphoric	80*15	nd	nd	2.2	8.9	5.7	0.9	0.2	0.7	nd	nd	nd	81.3	YK007
	960028	edge	phosphoric	70*30	nd	0.2	2.3	10.0	4.8	1.2	0.2	0.9	nd	nd	nd	80.3	YK008
	960028	back	phosphoric	100*30	nd	nd	2.1	6.5	3.2	1.3	0.2	0.4	nd	nd	nd	86.3	YK009
	960028	back	phosphoric	200*40	nd	0.2	2.7	8.0	4.4	1.3	nd	0.8	nd	nd	0.1	82.4	YK010
	960028	back	phosphoric	40*30	nd	nd	2.1	11.4	1.6	1.3	nd	0.3	nd	nd	nd	83.3	YK011
	960028	back	phosphoric	50*30	nd	nd	6.2	8.3	4.1	2.5	0.2	1.3	nd	nd	nd	77.4	YK012
	960028	back	phosphoric	60*60	nd	0.1	3.4	7.8	3.8	1.2	nd	1.1	nd	nd	nd	82.5	YK013
Coppergate	960029	edge	steel	20*3	0.6	0.7	11.3	53.2	nd	0.1	6.2	5.3	0.7	nd	0.4	21.3	YK014
small find 5271	960029	edge	steel	20*10	0.4	0.9	13.2	45.0	nd	nd	4.8	4.2	0.5	nd	0.7	30.0	YK015
context 13902	960029	edge	steel	15*10	0.5	1.1	15.2	53.4	nd	nd	5.9	4.6	0.5	nd	0.5	18.0	YK016
	960029	edge	steel	35*6	0.5	1.2	15.3	50.4	0.3	nd	5.4	4.7	0.5	nd	0.5	20.9	YK017
	960029	back	steel	30*10	0.3	0.9	14.2	47.6	0.3	nd	4.9	4.3	0.6	nd	0.4	26.3	YK018
	960029	edge	phosphoric/ferritic	90*50	nd	2.0	14.2	35.1	3.5	0.3	2.6	5.0	0.6	nd	2.8	33.9	YK019
	960029	back	phosphoric/ferritic	60*10	nd	1.5	12.6	31.6	3.3	0.4	2.9	4.8	0.8	nd	2.9	38.9	YK020
	960029	back	phosphoric/ferritic	150*100	nd	2.0	14.0	34.6	3.2	0.1	2.6	5.0	0.5	nd	2.5	35.3	YK021
	960029	back	phosphoric/ferritic	60*15	nd	1.8	14.3	35.7	2.4	nd	3.0	6.0	0.8	nd	3.6	32.1	YK022
	960029	back	phosphoric/ferritic	30*20	0.2	2.7	15.4	40.6	nd	nd	3.2	6.1	0.7	nd	3.0	27.9	YK023

Appendix II Composition of inclusions in medieval knives from York

Site details	Sample information			Inclusion	Composition (wt% oxide)												SEM
	AML ref.	section	matrix	size (µm)	Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	S	K_2O	CaO	TiO_2	Cr_2O_3	MnO	FeO	ref.
Fishergate	960030	edge	ferrite	20*20	nd	0.4	3.7	9.7	14.4	nd	0.4	1.6	nd	nd	0.6	69.1	YK024
small find 3994	960030	edge	ferrite	15*6	nd	0.5	0.4	10.4	17.0	0.8	0.3	0.7	nd	nd	0.4	69.2	YK025
context 5131	960030	edge	ferrite	100*10	nd	0.6	4.5	11.8	9.0	0.5	0.5	2.1	nd	nd	0.6	70.3	YK026
	960030	edge	ferrite	25*10	nd	0.2	0.7	10.4	8.7	0.5	0.1	0.9	nd	nd	0.1	78.2	YK027
	960030	edge	ferrite	25*12	nd	1.3	2.7	14.2	8.5	0.5	0.4	5.8	nd	nd	1.2	65.2	YK028
	960030	edge	ferrite	100*10	nd	1.5	4.9	15.3	1.7	0.3	nd	1.0	nd	nd	1.1	74.0	YK029
	960030	centre	steel	30*20	nd	1.4	8.5	51.9	nd	nd	3.9	4.0	0.4	nd	2.2	27.5	YK031
	960030	centre	steel	20*5	0.2	1.9	8.2	48.2	nd	nd	5.0	6.1	0.7	nd	2.1	27.4	YK032
	960030	centre	steel	20*6	nd	1.5	8.0	48.5	nd	nd	4.2	4.2	0.6	nd	1.3	31.3	YK033
	960030	centre	steel	20*15	0.1	1.6	8.6	55.5	nd	nd	4.2	4.8	0.6	nd	2.0	22.3	YK034
	960030	centre	steel	15*12	nd	0.9	5.3	31.1	2.5	0.2	2.8	3.3	0.3	nd	1.5	51.8	YK035
	960030	centre	steel	20*10	0.1	2.3	10.0	52.0	nd	0.1	4.5	8.0	0.7	nd	2.0	20.2	YK036
Fishergate	960031	edge	steel	10*8	0.8	1.2	6.0	64.2	nd	nd	3.9	7.5	0.3	nd	nd	15.9	YK037
small find 4707	960031	edge	steel	30*12	0.1	0.9	4.3	53.8	nd	nd	2.8	6.1	0.4	nd	0.1	31.3	YK038
context 5254	960031	edge	steel	25*10	0.8	1.1	6.5	59.8	nd	nd	4.4	7.2	0.5	nd	nd	19.4	YK039
	960031	edge	steel	20*20	0.8	1.0	5.5	58.5	nd	nd	4.0	7.6	0.3	nd	nd	22.1	YK040
	960031	edge	steel	30*20	0.7	1.0	5.9	62.2	nd	nd	2.7	6.6	0.4	nd	nd	20.3	YK041
	960031	edge	steel	40*20	1.2	1.2	6.3	73.0	nd	nd	4.4	8.9	0.3	nd	nd	4.3	YK042
	960031	edge	ferrite	15*12	nd	0.4	0.4	nd	nd	nd	nd	nd	nd	nd	nd	99.2	YK043
	960031	edge	ferrite	20*20	nd	0.4	0.4	0.9	nd	nd	nd	nd	nd	nd	nd	98.1	YK044
	960031	back	ferrite	40*20	nd	0.4	1.8	8.3	nd	nd	0.9	2.5	nd	nd	nd	86.0	YK045
	960031	back	ferrite	60*30	nd	0.8	0.4	0.5	nd	nd	nd	nd	nd	nd	nd	98.3	YK046
	960031	back	ferrite	80*10	0.5	0.4	14.4	28.7	nd	nd	10.2	9.2	0.4	nd	nd	36.0	YK047
	960031	back	ferrite	60*20	0.3	0.3	11.2	19.5	0.4	nd	9.1	6.8	0.2	nd	0.3	51.7	YK048

Appendix II Composition of inclusions in medieval knives from York

Site details	Sample information			Inclusion	Composition (wt% oxide)												SEM
	AML ref.	section	matrix	size (μm)	Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	S	K_2O	CaO	TiO_2	Cr_2O_3	MnO	FeO	ref.
Bedern	960032	edge	steel	30*10	0.3	1.0	5.1	37.0	0.7	nd	3.0	2.9	0.6	nd	1.4	47.8	YK049
small find 772	960032	edge	steel	30*20	0.2	2.4	7.5	53.8	0.2	nd	6.1	4.5	0.7	nd	2.0	22.2	YK050
context 1640	960032	edge	steel (weld line)	150*40	nd	0.1	0.2	nd	nd	nd	nd	0.3	nd	nd	0.1	99.2	YK051
	960032	pattern	weld-steel	12*12	0.2	2.3	7.4	61.8	nd	nd	3.5	6.4	0.5	nd	1.3	16.3	YK052
	960032	pattern	weld-steel	10*5	nd	1.9	6.1	36.3	0.4	nd	3.2	4.7	0.4	nd	1.0	45.8	YK053
	960032	edge	steel	60*30	nd	2.7	6.9	47.8	nd	nd	4.5	3.9	0.4	nd	1.9	31.7	YK054
	960032	edge	steel	90*10	nd	1.5	5.2	39.3	nd	nd	4.1	2.7	0.4	nd	1.9	44.6	YK055
	960032	back	pattern weld	100*18	nd	nd	0.5	5.3	0.6	nd	0.3	nd	nd	nd	nd	93.3	YK056
	960032	back	pattern weld	60*10	nd	nd	nd	nd	0.5	nd	nd	nd	nd	nd	nd	99.5	YK057
	960032	back	pattern weld	10*5	nd	3.1	9.6	40.6	0.7	nd	2.9	6.4	0.5	nd	0.8	35.3	YK058
	960032	back	phosphoric	20*20	nd	0.7	3.8	13.8	7.6	1.1	1.1	2.7	nd	nd	0.4	68.7	YK059
	960032	back	phosphoric	100*80	nd	1.2	8.1	18.9	3.6	0.4	2.8	4.9	0.3	nd	0.9	58.7	YK060
	960032	back	phosphoric	30*20	nd	0.9	2.2	16.6	6.3	nd	0.8	3.0	nd	nd	0.4	69.6	YK061
	960032	back	phosphoric	30*20	nd	3.3	14.3	31.1	2.5	nd	3.9	8.2	0.4	nd	1.6	34.4	YK062
	960032	back	phosphoric	40*8	nd	nd	0.2	11.7	2.0	nd	nd	0.1	nd	nd	nd	85.9	YK063
	960032	back	phosphoric	10*10	nd	4.4	16.9	38.3	5.2	nd	5.2	10.3	0.8	nd	3.0	16.0	YK064
Bedern	960033		steel (rhs)	20*7	0.3	1.3	6.0	51.3	nd	nd	7.5	11.7	0.6	nd	8.7	12.7	YK065
small find 1951	960033		steel (rhs)	10*10	nd	1.1	7.2	50.5	nd	nd	4.9	11.7	0.6	nd	6.2	17.7	YK066
context 5146	960033		steel (rhs)	100*10	0.2	3.4	10.8	53.1	nd	nd	10.6	9.2	1.0	nd	7.2	4.6	YK067
	960033		steel (rhs)	10*3	nd	0.5	5.8	34.9	0.9	nd	1.8	1.0	0.6	nd	2.2	52.3	YK068
	960033		steel (lhs)	20*5	nd	1.4	3.8	30.1	7.0	1.2	2.4	7.3	0.5	nd	13.6	32.8	YK069
	960033		steel (lhs)	10*3	nd	1.7	4.7	31.4	1.6	0.3	3.1	7.0	0.5	nd	10.7	39.3	YK070
	960033		phosphoric	7*4	nd	0.6	2.9	10.9	4.3	0.3	0.3	1.2	0.3	nd	3.4	75.9	YK071
	960033		phosphoric	40*20	nd	0.3	1.8	16.8	8.2	1.7	1.1	3.3	0.2	nd	0.4	66.1	YK072
	960033		phosphoric	50*20	nd	0.3	2.8	16.1	10.9	1.4	1.1	3.8	0.3	nd	0.4	62.7	YK073
	960033		phosphoric	10*4	nd	0.1	nd	nd	1.2	nd	nd	nd	nd	nd	nd	98.7	YK074
	960033		phosphoric	100*10	nd	0.2	3.5	18.6	7.4	0.5	0.7	4.1	0.1	nd	0.5	64.2	YK075
	960033		phosphoric	70*15	nd	0.3	1.7	16.1	3.9	0.7	0.2	1.0	nd	nd	0.2	75.8	YK076
	960033		phosphoric	150*100	nd	0.1	5.8	12.6	11.1	0.9	0.7	6.9	0.3	nd	0.3	61.2	YK077

Appendix II Composition of inclusions in medieval knives from York

Site details	Sample information			Inclusion	Composition (wt% oxide)												SEM
	AML ref.	section	matrix	size (μm)	Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	S	K_2O	CaO	TiO_2	Cr_2O_3	MnO	FeO	ref.
Bedern	960034	edge	steel	8*4	0.1	0.9	2.3	38.4	0.8	0.3	1.6	8.0	nd	nd	0.2	47.3	YK078
small find 124	960034	edge	steel	30*4	0.1	0.8	2.3	29.2	0.6	0.3	1.9	9.0	nd	nd	0.4	55.5	YK079
context 1007	960034	edge	steel	30*5	0.3	1.5	4.3	44.7	1.3	0.4	2.9	10.0	0.2	nd	0.3	34.3	YK080
	960034	edge	steel	10*6	0.4	2.5	7.8	39.5	nd	nd	4.2	13.2	0.8	nd	1.1	30.6	YK081
	960034	back	steel	9*5	nd	0.2	0.9	22.0	2.3	0.3	0.8	4.3	nd	nd	0.2	69.2	YK082
	960034	back	steel	7*4	nd	0.5	1.1	28.7	1.9	0.2	0.8	3.5	nd	nd	0.3	63.0	YK083
	960034	back	ferrite (lhs)	50*30	nd	0.3	9.3	18.7	5.1	1.0	1.8	0.8	0.4	nd	3.4	59.1	YK084
	960034	back	ferrite (lhs)	40*9	nd	0.4	13.9	22.1	4.6	0.4	1.9	0.4	0.5	nd	3.2	52.7	YK085
	960034	back	ferrite (lhs)	80*8	nd	0.3	2.9	21.4	3.4	0.3	0.3	nd	nd	nd	2.1	69.4	YK086
	960034	back	ferrite (lhs)	30*10	nd	0.2	1.2	14.5	10.8	0.4	1.3	1.3	nd	nd	1.5	68.9	YK087
	960034	back	ferrite (lhs)	30*8	nd	nd	13.2	11.7	8.0	0.3	1.5	1.4	0.6	nd	2.5	60.7	YK088
	960034	back	ferrite (rhs)	40*5	nd	nd	0.6	0.6	nd	nd	nd	nd	nd	nd	0.3	98.6	YK089
	960034	back	ferrite (rhs)	30*4	nd	nd	0.3	1.2	0.2	nd	nd	0.3	nd	nd	nd	98.1	YK090
	960034	back	ferrite (rhs)	25*4	nd	2.0	13.4	32.2	3.7	0.2	2.6	8.8	0.9	nd	2.1	34.1	YK091
	960034	back	ferrite (rhs)	100*7	nd	0.4	3.6	6.9	2.6	nd	0.5	1.6	0.3	nd	0.6	83.4	YK092
	960034	back	ferrite (rhs)	60*10	nd	1.4	2.1	16.6	0.4	0.2	1.3	12.8	0.2	nd	1.7	63.3	YK093
	960034	back	ferrite (centre)	40*15	nd	3.0	9.7	26.2	9.2	0.9	2.3	5.9	0.5	nd	2.9	39.5	YK094
	960034	back	ferrite (centre)	40*15	nd	2.8	9.3	24.9	7.2	0.8	2.0	5.7	0.5	nd	2.7	44.1	YK095
	960034	back	ferrite (centre)	80*30	nd	2.1	4.6	20.6	6.3	1.0	0.9	3.5	0.2	nd	2.0	58.9	YK096
	960034	back	ferrite (centre)	20*7	nd	2.1	7.0	22.1	9.6	1.3	1.4	3.8	0.4	nd	2.4	49.8	YK097
	960034	back	ferrite (centre)	15*7	nd	2.5	7.9	22.8	8.3	1.1	1.4	4.2	0.3	nd	2.4	49.1	YK098
	960034	back	weld line	20*12	nd	nd	nd	1.0	0.4	nd	nd	0.2	nd	nd	nd	98.3	YK099
	960034	back	weld line	100*5	nd	nd	nd	1.2	0.4	nd	nd	1.4	nd	nd	nd	96.9	YK100
	960034	back	weld line	200*20	nd	0.1	1.4	5.8	22.7	1.0	1.9	1.7	nd	nd	1.3	64.3	YK101
	960034	back	weld line	80*20	nd	nd	0.3	0.8	nd	nd	nd	nd	nd	nd	nd	98.9	YK102