The Metallurgical Examination of Ferrous Grave Goods from Wasperton Anglo-Saxon Cemetery MN80-85

Royal Armouries Technological Report 2006/1
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Background

Excavations carried out at Wasperton, Warwickshire (NGR SP 265585) between 1980 and 1985 recovered evidence of a cemetery spanning the late Roman (C4th) to early Medieval (C7th) periods. The cemetery included the remains of 215 inhumations and 26 cremations. The excavation had been initiated by The Birmingham University Field Archaeology Unit under the direction of Martin Carver and completed by Gill Crawford of the Warwickshire Museum. A catalogue for the site was produced for the doctoral Thesis of Jonathan Scheschkewitz (Kiel University), completed in 2004. In 2005 an assessment of potential for analysis was undertaken on behalf of Field Archaeology Specialists (Starley 2005). Given the heavily mineralised, often fragmentary condition of the artefacts, the examination relied heavily on the X-radiographs undertaken at Bradford University. Although possible features associated with the construction of the blade, such as butt-welded steel edges, were provisionally identified, few were of an unequivocal nature and the use on metallographic examination was recommended. On the basis of this report six knives, one possible fire steel and eight spearheads were sampled for metallographic examination (optical microscopy), to determine the materials, technology and quality of construction of these artefacts. Although Saxon knives and spearheads are perhaps two of the most thoroughly studied classes of archaeologically recovered ferrous objects, there remains much site to site variation in the use of alloys, the choice of manufacturing methods, the level of skills of the craft workers and the functional quality of the artefact. Perhaps most significantly for Wasperton, was the question of whether these funerary goods are equivalent, in all these qualities, to domestic tools and weapons used by the population during their lifetimes.

Metallographic Examination

Metallography is a powerful technique providing a measure of the materials and construction methods used and an assessment of the smith’s skill, and the quality and effectiveness of the artefact. This is particularly true of edged tools and weapons for which a compromise of edge hardness and inner toughness is required.

Metallography is, except under exceptional circumstances, a destructive technique requiring the removal of samples. For any assemblage the merits and difficulties of such a technique must be balanced. For the Wasperton ferrous objects there was some concern that the level of information that could be extracted by this method was likely to be more restricted than would be expected for better-preserved, freshly excavated, artefacts. However, examination of the better-preserved artefacts did suggest that useful information could still be extracted. Such a programme of investigation at least allows "preservation by record" for an assemblage for which, even under the best environmental conditions, the surviving metallic portions will continue to deteriorate. Considering these circumstances, the removal of samples from the artefacts was seen as useful and ethically justifiable.

Iron alloys used in the early medieval period can be divided into three broad categories: ferritic iron, phosphoric iron and steel. As the metal was never melted all three types contain some slag inclusions from the smelting process as well as scale from subsequent smithing. The properties and basic microstructure of these alloys are as follows:

Ferritic iron. 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. Levels of phosphorus of the order of 0.1 to 0.3% entering the iron from the ore 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", which gives the ferrite grains a "watery" appearance with bright areas that 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.
Steel is iron containing small amounts of carbon, typically 0.2 to 0.8%. It is both tougher and harder that iron and, very importantly, it can be hardened to a greater extent by quenching in water which gives considerable hardness. To avoid associated brittleness the artefact may subsequently be tempered *i.e.* reheated 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, cooling in a less thermally conductive medium, such as oil. The microstructures of steel reflect the amount of carbon present, the severity of quenching and the effects of reheating. With 0.8% carbon, the eutectoid composition, steel that has not been heat-treated consists entirely of a dark-etching phase known as pearlite. Occasional steels that exceed this carbon content contain both pearlite and iron carbide. More common are lower-carbon steels that 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. 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 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. 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 object (or the back of a single edged knife) 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 and weapons was that they should be particularly visually pleasing and the technique of pattern welding deliberately combined dissimilar alloys so that after polishing and etching a decorative effect was achieved.

The limited variations in the means of combining of iron and steel within a blade are summarised in the Typology of Tylecote and Gilmour (1986) (Figure 1).

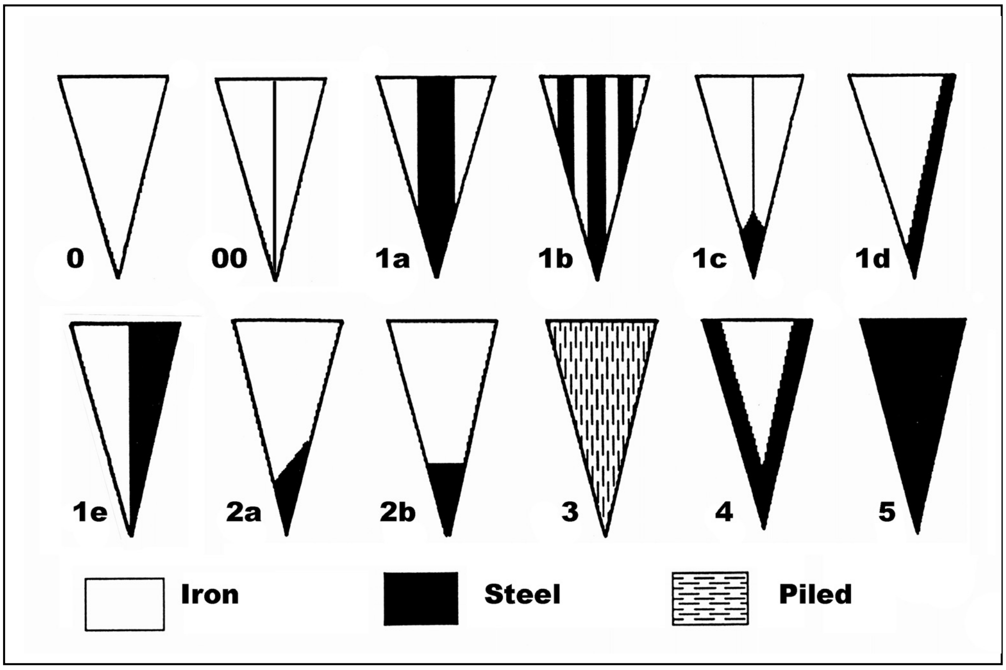


Figure 1. Blade Edge Typology of Tylecote and Gilmour (1986).

Choice of samples

Due to the poor condition of the artefacts and concern that the more highly mineralised examples would provide little information, the first selection criteria was an adequate state of preservation. Beyond this artefacts were selected to include a range of possible technologies of construction, including examples whose X-radiographs indicated composite construction and those which showed no evidence for this. As mentioned above it is edged tools and weapons that generally show both the highest quality construction and the widest range of iron alloys. Of the assemblage six knife blades were chosen and eight spearheads. Additionally, one example of a class of object, variously described as a purse hanger or fire steel was selected, It was intended that examination would confirm the function, as it was assumed a fire steel would need to contain a significant carbon content, although to the researcher's knowledge no examples have previously been examined.

Methodology: metallographic preparation and microhardness testing

Generally each knife and spearhead was sampled twice. Using a low speed cut-off wheel with aluminium oxide wafering blade, a narrow wedge cut from both edge and back of the knives and both sides of the spearheads and sufficient overlap to match the two sections (Figure 2).

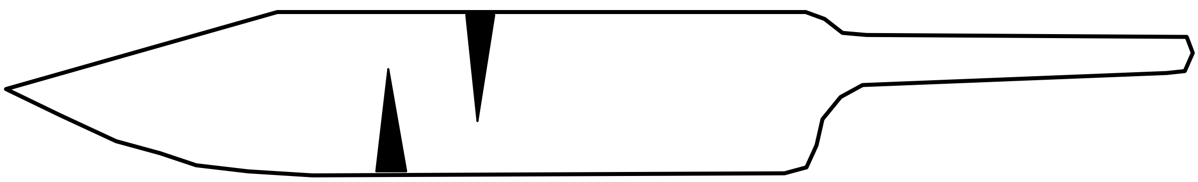


Figure 2. Schematic illustration of sample locations on a knife blade.

The cut sections were mounted in cold-setting epoxy 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).

A Shimadzu microhardness tester was used to determine the hardness values of different phases within the metallographic structure, which helped both to identify the alloy and microstructure present, but also to provide a direct measure of the effectiveness of the artefact, particularly where a sharpenable edge was required.

Results: Individual Knives

1217/8 (Grave 4, Find 234). RA ref AM2001: Knife from inhumation, Phase 2-3, 470-650AD.

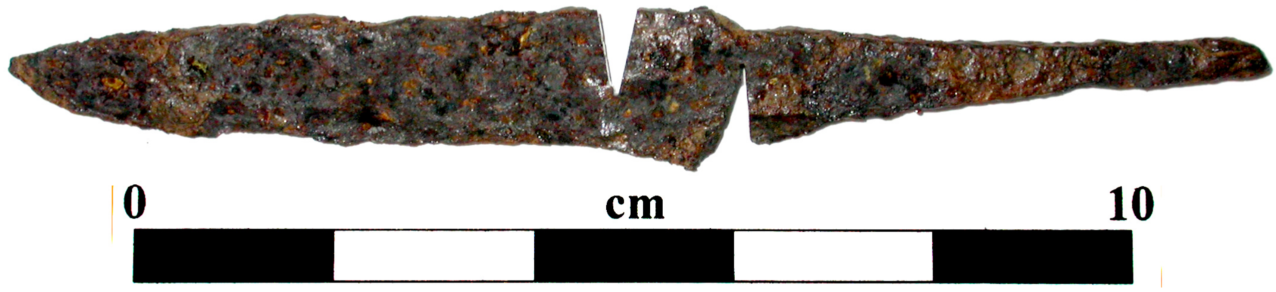


Figure 3, blade 1217/8 after sampling.

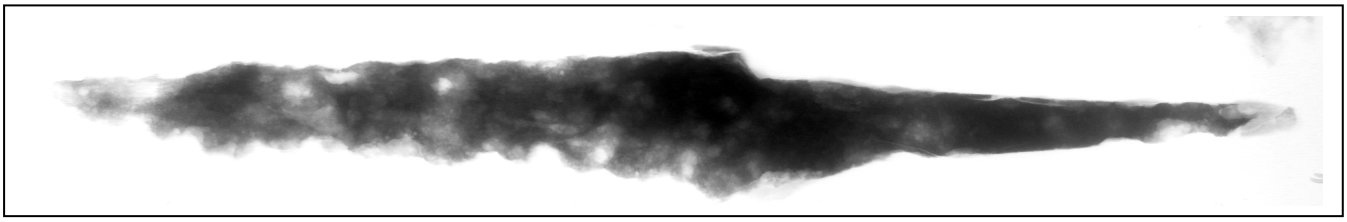
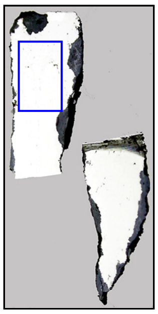
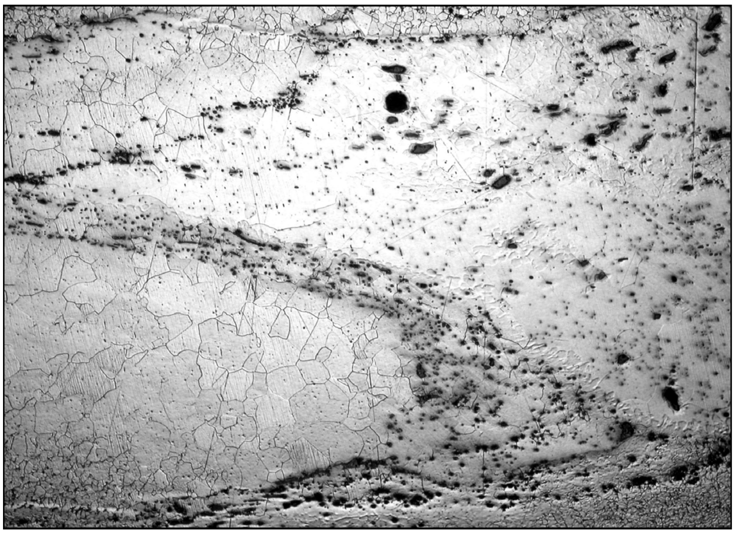


Figure 4. Detail of X-radiograph Plate 510.
During assessment classed as probable butt-welded steel edge, (Type 2).

Figure 5. Micrograph of sample AM2001. Etchant 2% nital, max. field of view 2.4mm



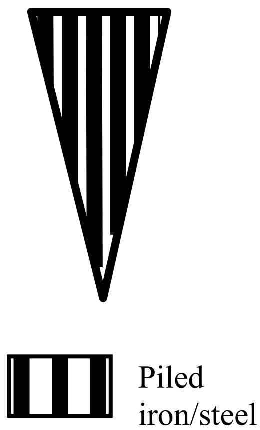


Two dissimilar metals: Slag-rich high phosphorus (ghosted) iron surround much cleaner ferrite.

Metallographic results

Unetched: Alignments of slag indicated a coarsely piled structure. The slag content varied considerably between different zones from negligible to as much as 5%.

Etched: Etching revealed an extremely heterogeneous structure, of complex and not easily interpreted origins. Within the section, regions of clearly phosphoric iron (HV 196.9, 198.7, 183.3, mean 192) adjoined apparently pure ferritic iron, but which also had elevated hardness (HV 188.1, 179.9, 155.7, mean 175), suggesting some hardening as a result of phosphorus, work hardening or rapid cooling, and some low carbon steel. Whilst some of the steel indicated rapid cooling, if not quenching, there was further evidence that edge of the blade had been cold worked, presumably to harden it. However, partial re-crystallization of this structure suggested further heating. Microhardness testing at the edge gave only modest readings of 191.6, 203.4, 209.3, mean 201 HV.



Interpretation

A very poor quality blade, corresponding to Tylecote and Gilmour's Type 3, not Type 2 as originally suggested from examination of its X-radiograph. The blade comprises a mixture of low carbon iron alloys, possibly the result of recycling from other artefacts, without any attempt at homogenisation. Despite the poor quality, a combination of rapid cooling, work hardening and the presence of phosphorus have resulted in a blade with hardness above that expected of pure iron.

1218/6 (Grave 6 Find 237). RA ref AM2002: Knife from inhumation, Phase 2d-3, 550-600AD.

Figure 6. Blade 1218/6 after sampling.

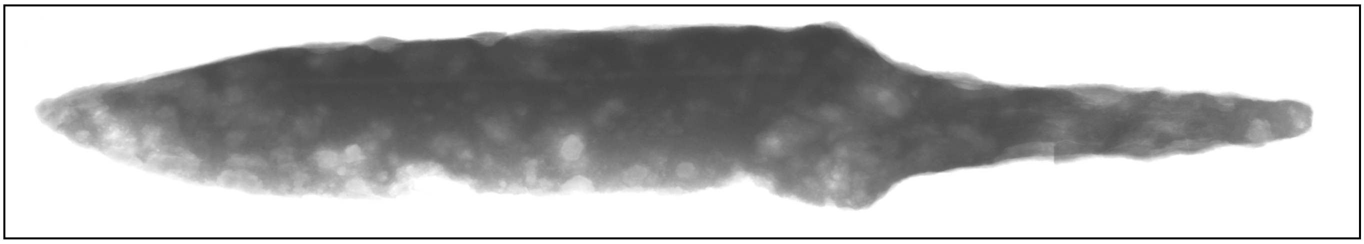


Figure 7. X-radiograph (Detail of Plate 511).
During assessment classes as probable butt-welded steel edge (Type 2).

Figure 8. Micrograph of sample AM2002. Etchant, 2% nital, max. field of view 2.4mm.

Etching has revealed the distinctive banded structure of the knife back.

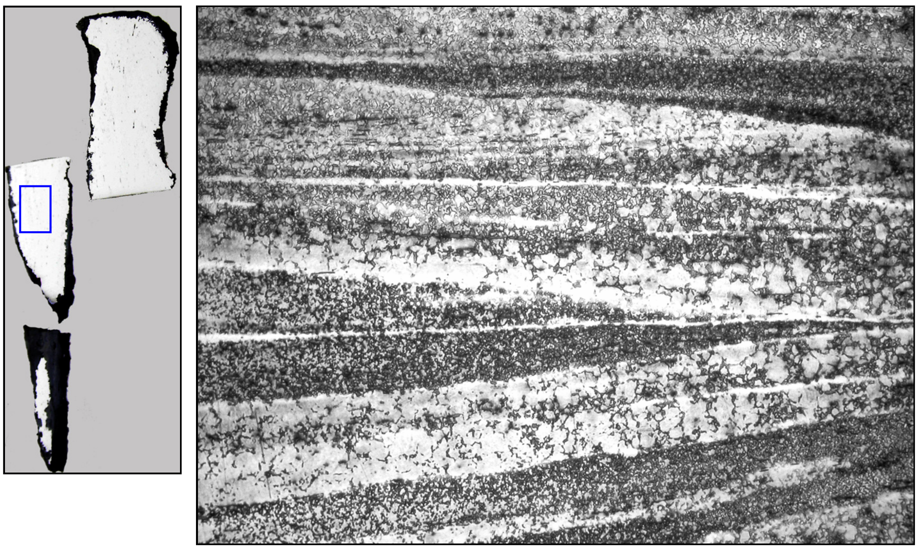
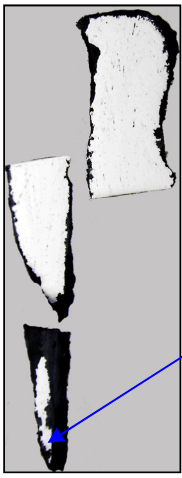
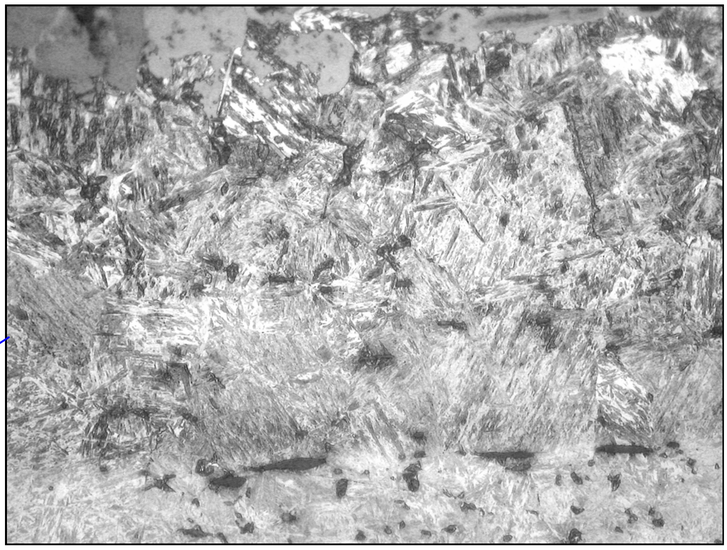


Figure 9. High magnification micrograph of the edge of sample AM2002. Etchant 2% nital, max. field of view 0.3mm.

At the extreme edge of the surviving metal core the structure is entirely tempered martensite. Note the presence of slag inclusions.

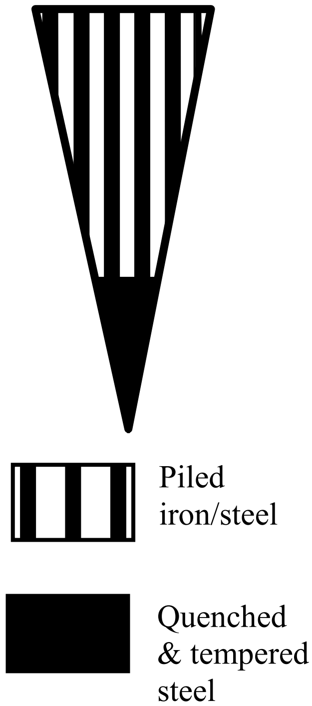




Metallographic results

Unetched: The section contained a high proportion of slag inclusions of elongated to stringer morphology, frequently fragmented from working at temperatures below which they remained ductile. Although the mean slag content was estimated at 5%, this was far from uniform.

Etched: The nital etch revealed very distinctive banding in the back of the blade. Apparently comprising iron with variable amounts of carbon although severe quenching, had led to the formation of bainite (HV 293.0, 144.7, 140.7, 210.2, 193.0, mean 178) and pearlite, preventing the actual content from being assessed. An exception to this was the centre of the back where slower cooling had resulted in a structure comprising approximately equal parts of ferrite (ASTM 8-6) and nodular pearlite, indicating a carbon content of about 0.4%. At the tip of the sample, i.e. the edge of the blade, more severe cooling rates and a higher carbon content gave much higher microhardness readings (HV649.3, 628.1, 570.4, 504.0, 579.4, 683.2, mean 602.4) and a tempered martensitic structure.



Interpretation

As suggested by the X-radiograph, a Type 2b blade in which a heterogeneous piled iron back has been butt-welded to a steel edge. Metallography also demonstrated that the blade had been heated, quenched and tempered to produce a tough and efficient cutting tool, the best quality construction seen in during this investigation.

1265/1 (Grave 34, Find 346). RA ref AM2003. Knife from inhumation, Phase 2c-3, 530-650AD.

Figure 10. Blade 1265/1 after sampling.

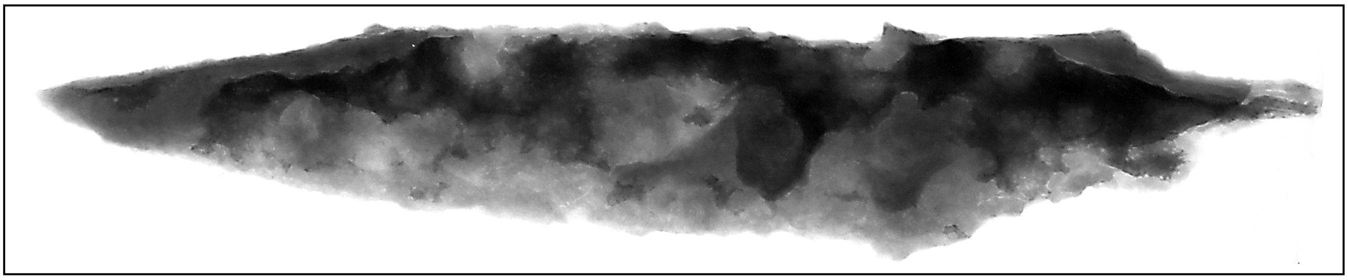


Figure 11. X-Radiograph (Plate 513 detail).
No technological classification made during assessment.

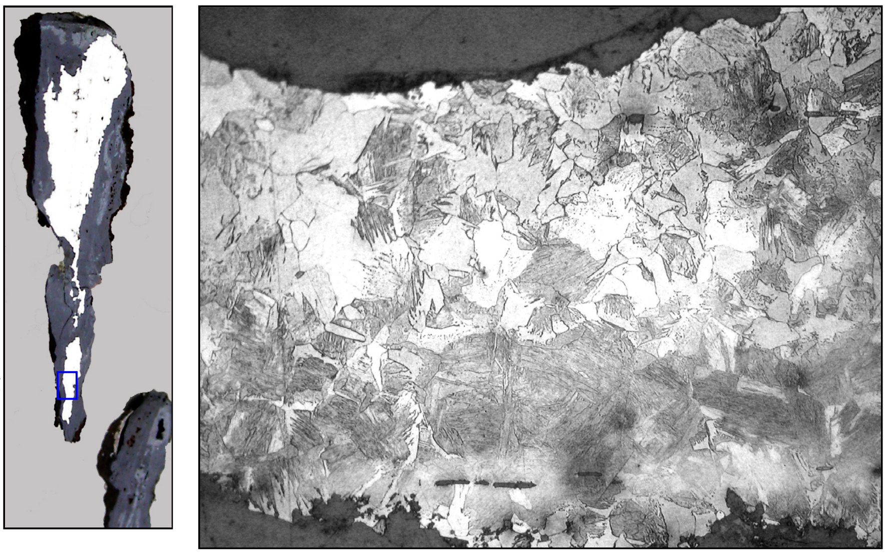


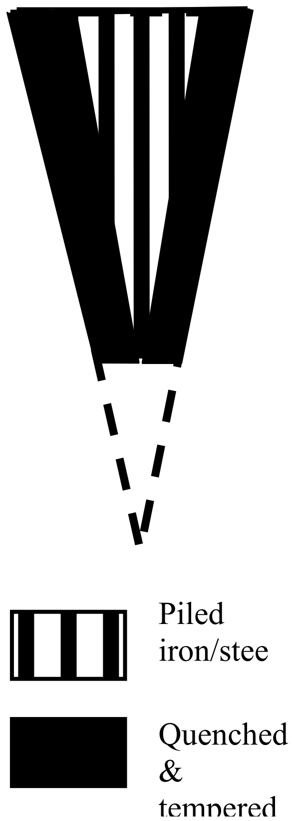
Figure 12. Micrograph of bottom of upper sample AM2003. Etchant, 2% nital, max. field of view 0.6mm.

Towards the base of the upper sample a mixture of bainite and martensite predominates, indicating that the edge was of quenched steel. Light-etching bands, as visible in the lower part of the micrograph, left, suggest the presence of nickel or arsenic in the metal, which has become concentrated at an exposed surface of the bar material due to preferential oxidation and loss of iron during hot working.

Metallographic results

Unetched: The alignments of slag inclusions at regular spacing indicated a piled structure. Between these alignments, slag content was unusually low, estimated at below 1%.

Etched: The nital etch revealed very distinctive banding in the back of the blade. The presence of quenched structures prevents visible quantification of the carbon content, but on the sides and base of the upper sample the presence of tempered martensite indicated a significant carbon content, giving usefully high hardness values (HV 414.8, 459.8, 450.3, 456.6, mean 445). Further towards the interior, the structure comprised bands of what appears to be lower (HV 338.5, 332.5, 328.5, 336.5, mean 342) and upper (HV 187.3, 203.4, 240.1, 268.0, 208.3, mean 221.4) bainite, although the difference in hardness content may reflect the carbon content more than the cooling rate. Unfortunately the section from the edge of the knife was entirely corroded, but given the distinct steel outer facings of the blade it is assumed these continue to the edge of the blade, where more rapid cooling would have given a harder cutting edge.



Interpretation

Most probably a type 4 blade in which steel was wrapped around a piled iron core and the whole heated, quenched and tempered.

2402/11 (Grave 73, Find 1077). RA ref AM2004. Knife from inhumation.

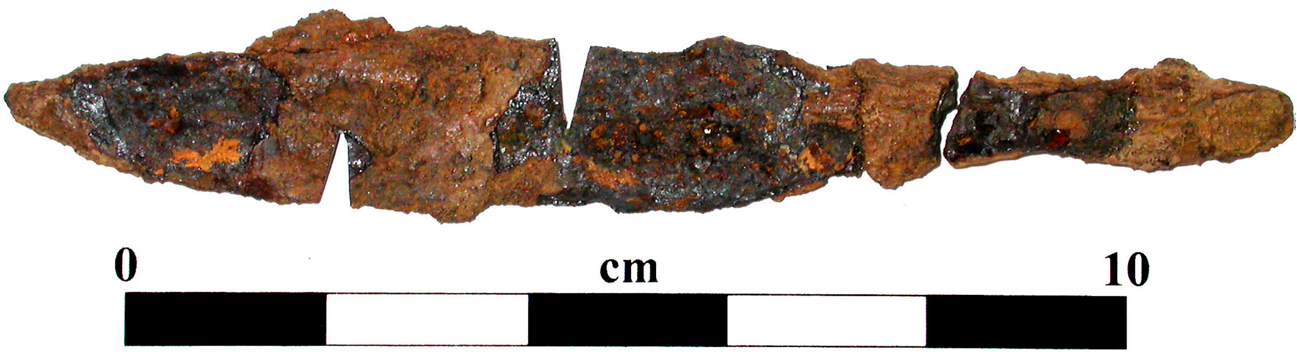
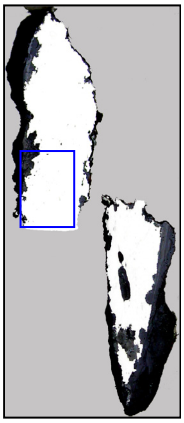


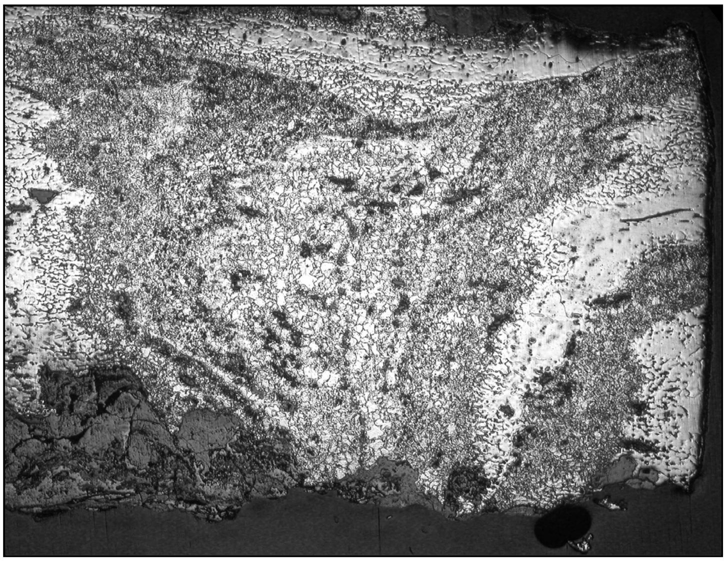
Figure 13. Blade 2402/11 after sampling.

Figure 14. X-radiograph (Plate 515 detail).
During assessment classed as probable butt-welded steel edge (Type2).

Figure 15. Micrograph of bottom of upper sample AM2004. Etchant, 2% nital, max. field of view 2.4mm.

Alternating bands of light and dark etching alloy reminiscent of pattern welding.

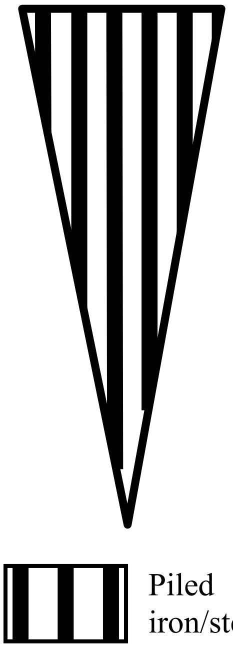




Metallographic results

Unetched: The alignments of slag indicated a coarsely piled structure. Between the weld lines, slag content was low, estimated at 0.5% to 1%.

Etched: The nital etch revealed a structure with light-etching bands of large (ASTM 3) ferrite grains with phosphorus ghosting (HV 207.3, 202.5, 225.0, mean 212) contrasting with an unusual feathery phase thought to be low carbon steel bainite (HV 250.2, 207.3, 200.6, mean 219 in the back and 266.6, 273.9, 313.4, mean 285 in the edge section), the greater hardness in the edge is probably due to the more severe quenching rate of the thin section.



Interpretation

It is possible that the contrast between the phosphoric iron and low carbon steel components would have shown a pleasing watery pattern on the sides of this knife, similar to deliberately pattern-welded blades. However, this may be fortuitous and, as the lack of a decent heat-treated steel edge suggests this is a poor quality blade, not the butt-welded Type 2 suggested by the X-radiograph. It must therefore be considered an inferior quality blade corresponding to Tylecote and Gilmour's Type 3, piled iron.

2404/5, Believed to be grave 75, not on original inventory. RA ref AM2005. Knife from inhumation Phase not known.

Figure 16. Blade 2404/5 after sampling.

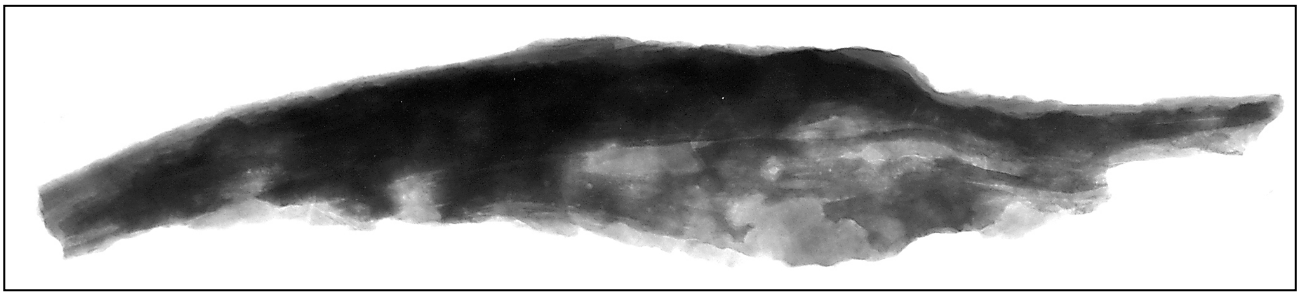


Figure 17. X-radiograph (Plate 515 detail).
During assessment classed as probable butt-welded steel edge (Type 2).

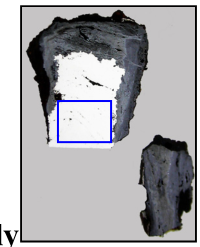


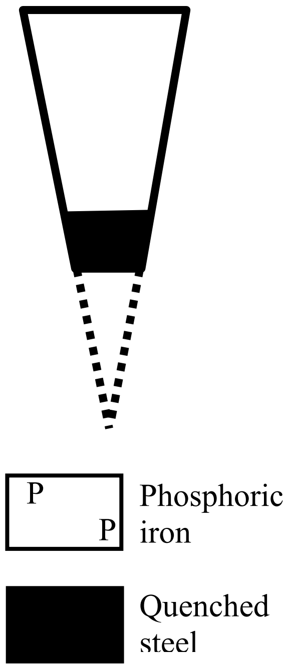
Figure 18. Micrograph of bottom of upper sample AM2005. Etchant, 2% nital, max. field of view 2.4mm.

Back section is predominantly of large, light etching grains with phosphorus ghosting and feathery structure at grain boundaries. Bottom of back sample shows darker etching region of much finer grain size with weld line between.

Metallographic results

Unetched: In the as-polished condition, major bands of slag in the back section showed that the blade consisted of a number of components welded together. Apart from these large stringers, slag inclusions were generally small and finely distributed, making up less that 0.05% of the surface of the section. Unfortunately the edge section was completely mineralised and no further examination of this was undertaken.

Etched: The nital etch revealed a clear transition between the lighter etching bulk of the back section and a darker, higher carbon region at its base. The weld between was sufficiently distinct to suggest a deliberate butt weld. In the back region, phosphorus ghosting was very evident and the variable microhardness values (HV 119.1, 179.1, 168.6, 182.3, mean 162) are typical of the uneven distribution of this element. An unusual feathery phase at the edges of the phosphoric iron grains may reflect a cooling regime that would have produced a bainitic structure had more carbon been present. In the lower region the most clearly recognisable austenite transformation product was bainite (HV 258.9, 246.2, 219.6, mean 238.2), but other areas were far from distinct and probably reflect the quenching of a material whose carbon content was insufficient to produce bainite.



Interpretation

Corrosion of the blade prevents absolute certainty, though it does appear that the smith intended to construct a Type 2b butt-welded blade by welding the highest carbon content ferrous material available to a phosphoric iron back, then quenching it to achieve greater hardness of this edge. The tool produced, however, was of relatively poor quality.

3792/6 (Grave 179, Find 3140). RA ref AM2006. Knife from inhumation. Phase not known.

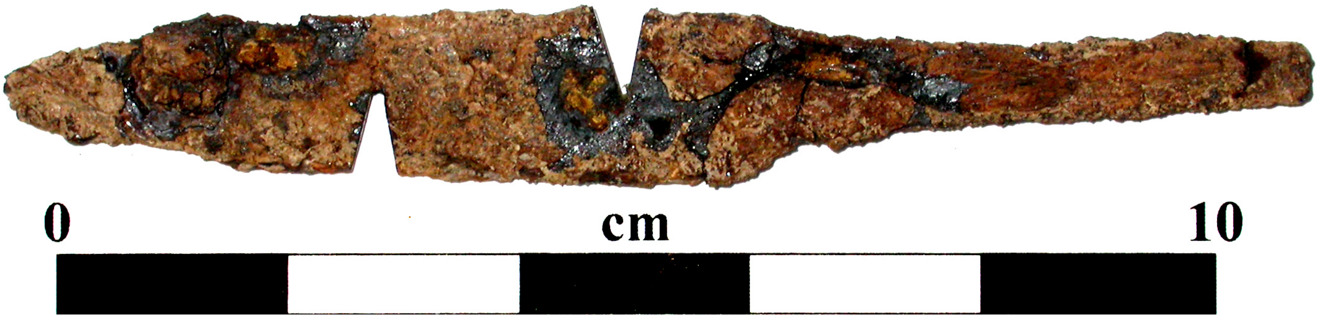


Figure 19. Blade 3792/6 after sampling.

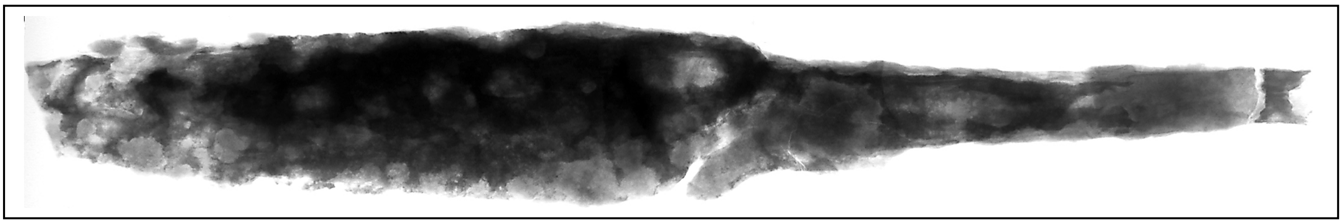
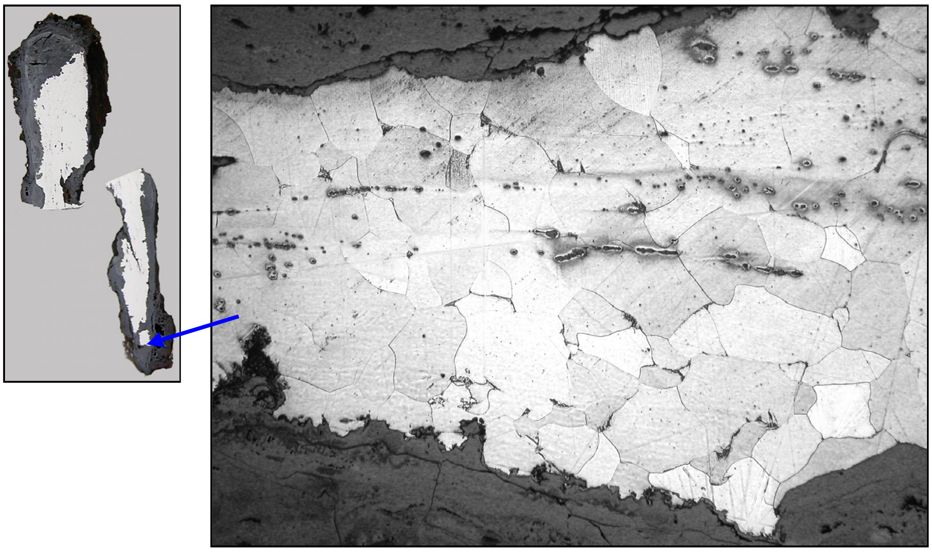
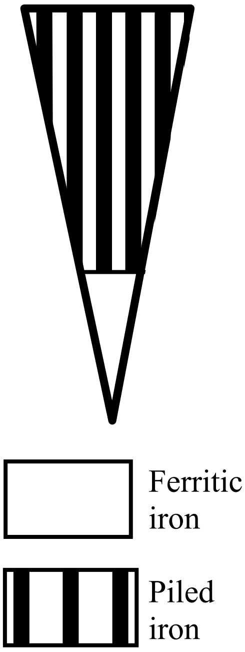


Figure 20. X-radiograph (Plate 514 detail).
No typological classification suggested by examination of X-radiograph.

Figure 21. Micrograph of edge of lower sample AM2006. Etchant, 2% nital, max. field of view 1.2mm.

The edge of the blade consists of equiaxial ferrite grains of large size.





Metallographic results

Unetched: In the as-polished condition, slag inclusions were seen to be concentrated in bands, suggesting a piled structure.

Etched: After etching in nital the back of the knife was seen to be coarsely banded with alternate light and dark etching phases. At higher magnification the light region was found to comprise large grains of ferrite, whose microhardness of 163.7, 188.1, 133.0, mean 167 HV suggested some hardening due to either low-level phosphorus, slight work hardening or rapid cooling. Between these bands, what was apparently a higher carbon material having smaller grains (ASTM 8) with a bainitic structure, giving microhardness readings of 121.7, 163.7, 147.2, mean 144.2 HV.

By contrast the edge section included very little of the higher carbon material and large (ASTM 2) ferrite grains predominated, particularly towards the cutting edge, which gave low hardness readings of 121.7, 163.7, 147.2, mean 144 HV.

Interpretation

A poor quality blade, whose structure is too illogical to be included in the Tylecote and Gilmour typology, though, it might be best considered as a piled type 3. Although apparently quenched it would have gained no improvement in properties as a result of this. It might be considered whether the blade once had an attached steel edge that has been lost by corrosion in the ground or wear during use, but this would seem unlikely give the near complete profile surviving.

Individual results: Fire steel

8280/8 (Grave 196, Find 3190). RA ref AM2007. Fire steel from inhumation. Phase unknown.

Figure 22. Fire steel 8280/8 after sampling.

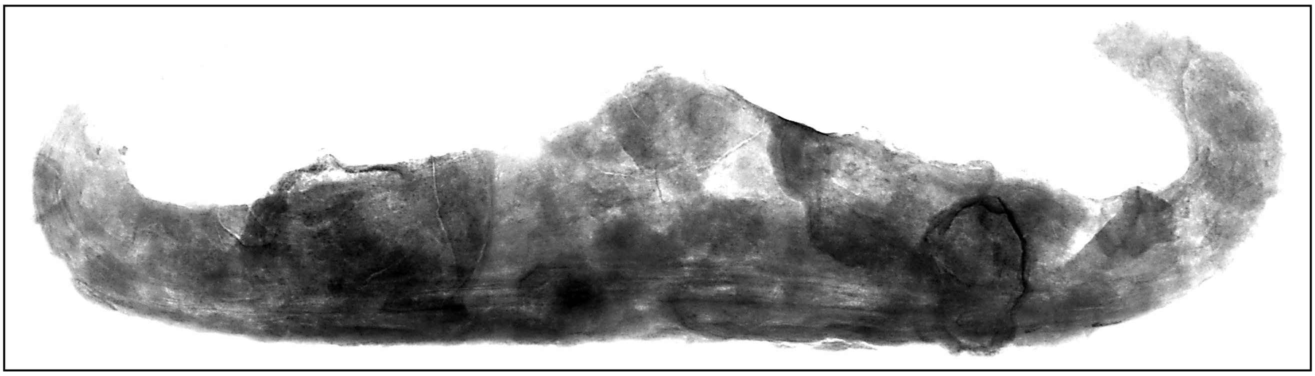


Figure 23. X-radiograph (Plate 512 detail), prior to re-adhesion of terminal. No typological classification suggested by examination of X-radiograph.

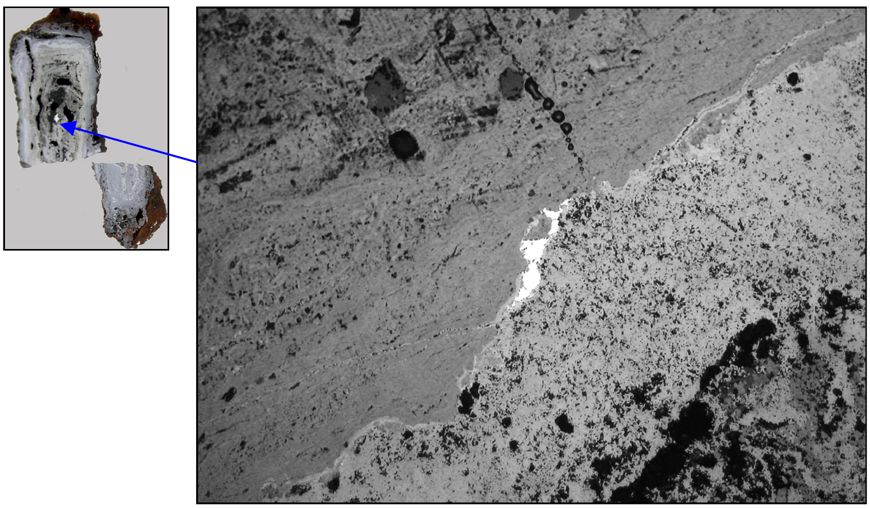


Figure 24. High magnification micrograph of centre of upper sample AM2007. Unetched. Max. field of view 0.3mm.

Sub-granular fragment of iron embedded in corrosion.

Metallographic results

Unetched: Only in very small isolated areas on the back section does any metallic iron survive and no relict structures were identifiable in the corrosion.

No further investigation undertaken.

Interpretation

Materials and method of construction unknown.

Individual results: Spearheads

1223/2 (Grave 22, Find 289). RA ref AM2008. Spearhead from inhumation. Phase unknown.

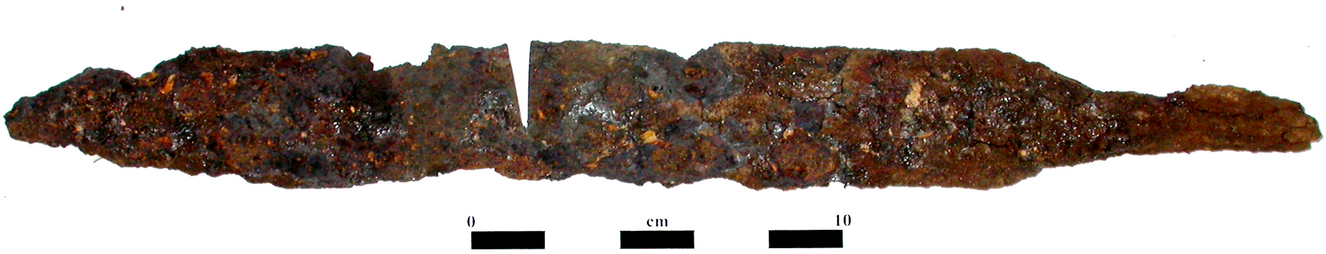


Figure 25. Spearhead 1223/2 after sampling.

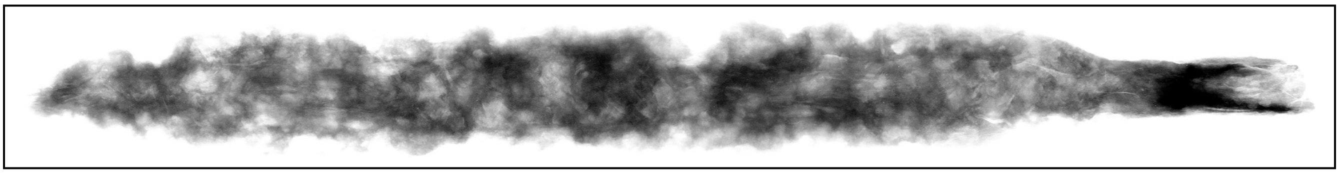
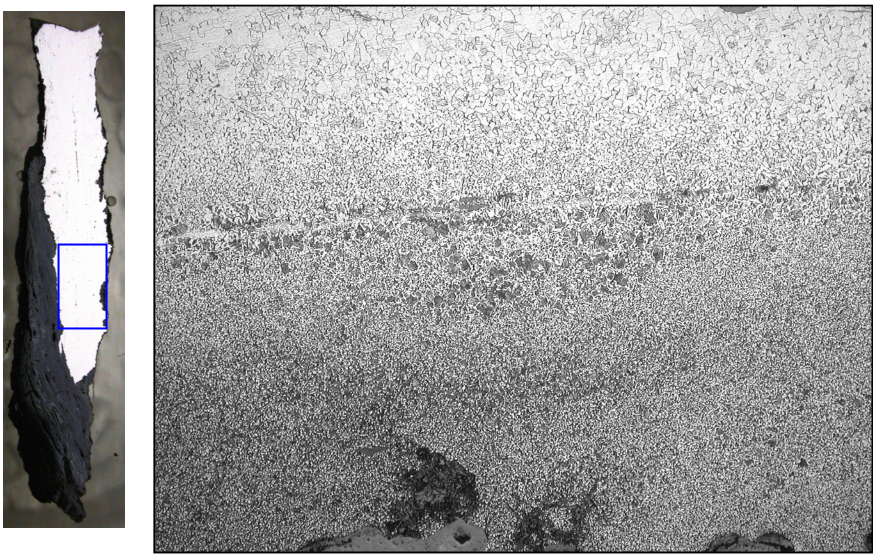


Figure 26. X-radiograph (Plate RA 22/06 detail).
Assessment based on X-radiograph suggested the body of the blade might be pattern welded, with no butt-welded edge.

Figure 27. Low magnification micrograph of centre of upper sample AM2008. Max. field of view 2.4mm.

A weld line separates two areas: ferritic iron (light etching) above and ferrite plus pearlite (darker etching) below. However, the differences between zones are not sharply contrasted.



Metallographic results

Unetched: In the as-polished condition, slag inclusions were almost entirely restricted to narrow bands, rather than evenly distributed through the section, which supported the assessment from the X-radiograph that the blade was pattern welded.

Etched: After etching in nital the section was seen to comprise a range of coarse ferrite (ASTM 5) and ferrite plus up to 50% pearlite microstructures (ASTM 8). Divisions between these areas were marked not only by entrapped scale but by light etching bands, of the type normally associated with nickel or arsenic enrichment, which occurs through preferential oxidation of iron at exposed surfaces during the working of the iron bar prior to incorporation into the artefact. Perhaps surprisingly, the areas demarcated by these weld lines showed no sharp compositional distinctions as would be expected of pattern welding. Microhardness testing of the ferrite produced values of 102.0, 146.6, 103.7, 99.0, mean 113 HV., suggesting an annealed structure without contamination with phosphorus. The pearlite was coarse without any attempt to harden and gave modest values of 228.0, 229.9, 214.5, mean 224 HV.

Interpretation
Although this spearhead might have been significantly hardened by quenching, this had clearly not been undertaken, nor was there any evidence of deliberate steeling of the edge. The presence of pattern-welding which might indicate a higher status artefact, was not entirely convincing, although it is possible that this had originally been a properly heat treated, pattern welded spearhead, but that long term heating and slow cooling, perhaps as part of a destruction ritual had largely removed these features.

1325/2 (Grave 44, Find 378). RA ref AM2009. Spearhead from inhumation. Phase 2b-2d, 480-600AD.

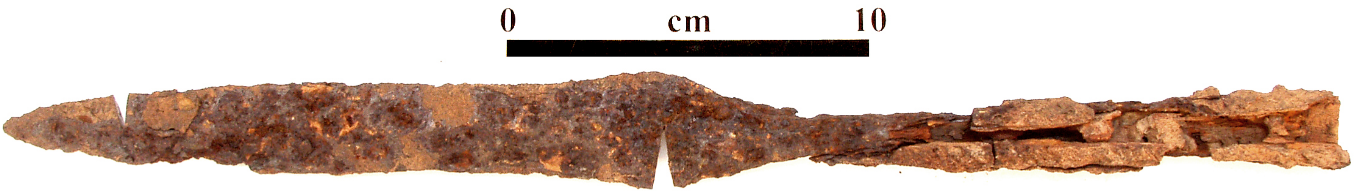
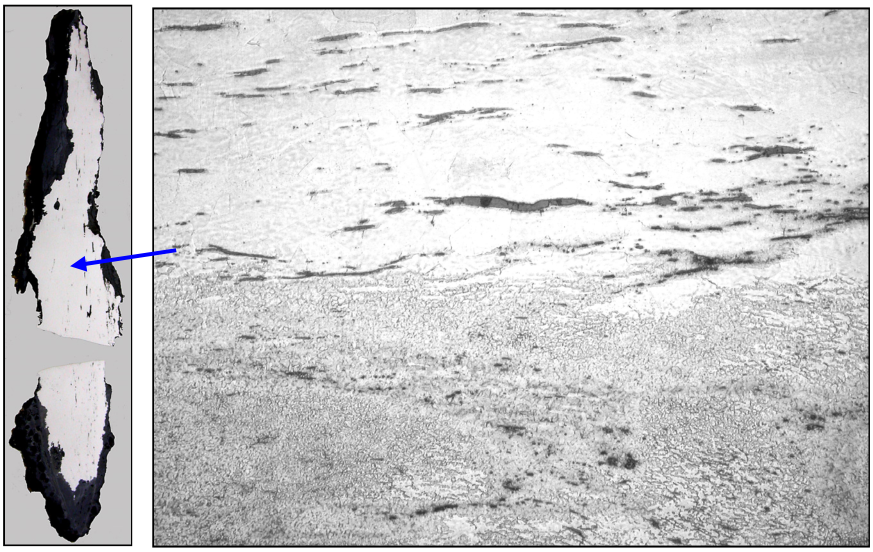


Figure 28. Spearhead 1325/2 after sampling.

Figure 29. X-radiograph (Plate RA 22/06 detail).
Assessment based on X-radiograph found no evidence of pattern welding or butt-welded edge.

Figure 30. Low magnification micrograph of centre of larger sample AM2009. Max. field of view 2.4mm.

Section predominantly of ferrite with phosphorus ghosting. Grain size varies greatly from ASTM 1 to ASTM 8.



Metallographic results
Unetched: Reasonably uniform distribution of slag inclusions of elongated or stringer morphology.
Etched: Etching revealed the section to be almost entirely ferrite with phosphorus ghosting (HV 155.8, 172.4, 168.2, mean 165). One isolated area was of near eutectoid pearlitic composition, but

this did not appear to be a deliberate addition to the blade and, instead of being hardened, had been over-heated with a consequent reduction in hardness (184.5, 173.3, 191.4, mean 183HV).

Interpretation

This spearhead was constructed of generally poor quality phosphoric iron; no attempt had been made to harden it.

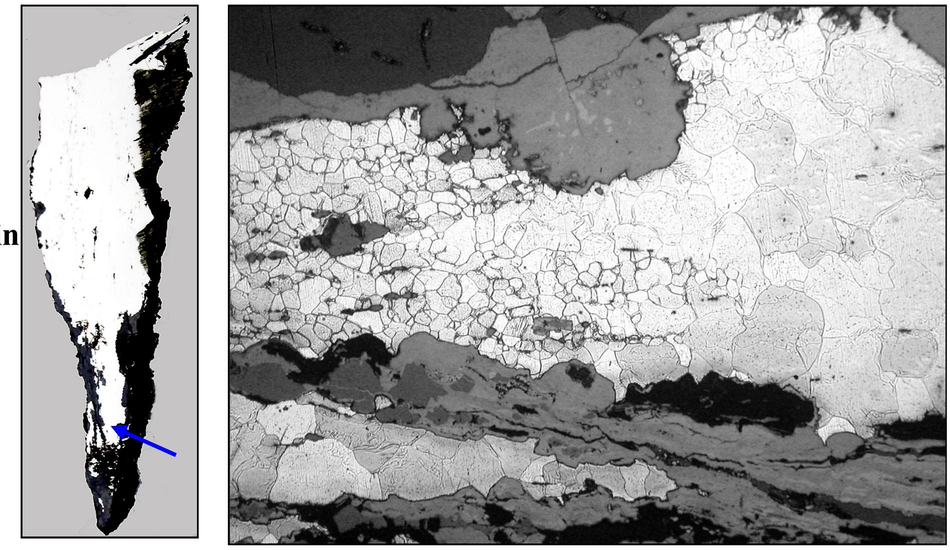
2300/1 (Grave 58, Find 1000). RA ref AM2010. Spearhead from inhumation. Phase not known.

Figure 31. Spearhead 2300/1 after sampling.

Figure 32. X-radiograph (Plate RA 22/06 detail).
Assessment based on X-radiograph found no evidence of pattern welding or butt-welded edge.

Figure 33. Micrograph of edge of single sample AM2010. Max. field of view 1.2mm.

At the extreme edge, the grain size is markedly smaller (ASTM 7 rather than 4). Possibly the result of re-crystallisation after cold working.



Metallographic results

Unetched: Uneven distribution of slag inclusions. Areas of large inclusions of elongated or stringer morphology up to 10% of the surface in some area. Elsewhere inclusion content is below 1% and these tend to be small, spheroidal or sub-round inclusions of single phase.

Etched: Etching revealed the section to be almost entirely ferrite with carbide precipitation within the grains. Although some phosphorus ghosting was evident, the effect of this on microhardness appears slight (121.9, 128.4, 128.3, 139.0, mean 129 HV).

Finer ferritic grains at the surviving edge may result from re-crystallisation after cold working.

Interpretation

A poor quality spearhead, constructed of fairly pure iron and probably re-heated prior to disposal. The effect of the latter was to further soften the blade by precipitating carbides within the ferrite and re-crystallizing the edge, thereby reducing the minor improvement in edge hardness that was attempted by quenching the blade and work-hardening the edge.

3139/1 (Grave 91, Find 1537). RA ref AM2011. Spearhead from inhumation. Phase unknown.

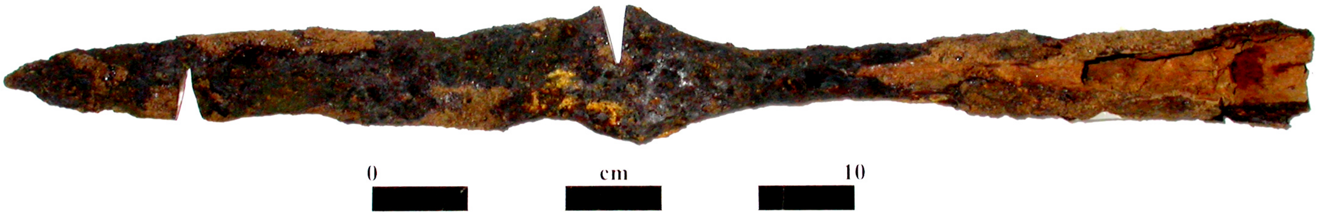


Figure 34. Spearhead 3139/1 after sampling.

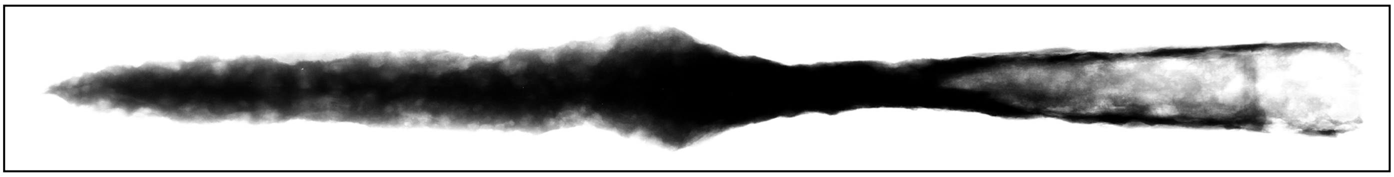


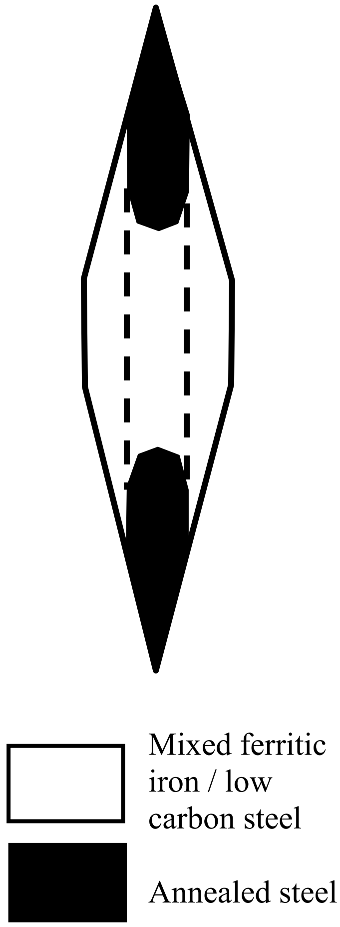
Figure 35. X-radiograph (Plate RA 22/06 detail).
Assessment based on X-radiograph suggested the possibility of pattern welding, but not a butt-welded edge.

Figure 36. Micrograph of sample AM2011. Max. field of view 2.4mm.

Weld line separating low carbon, ferritic, area from higher carbon, ferrite plus iron carbide region.

Metallographic results
Unetched: Areas of large inclusions of elongated or stringer morphology up to 20% of the surface, indicate the position of weld lines. Elsewhere inclusion content is very low from zero to 1% and these tend to be elongated inclusions of single phase.

Etched: Etching revealed the composite structure of the blade in which steel had been incorporated at the cutting edges, with coarse grains of ferritic iron (ASTM 3-6, HV 115.9, 119.9, 118.9, mean 116) or low carbon steel elsewhere. The quench-aged carbide precipitate within the ferrite showed that the spearhead had originally been rapidly cooled, but subsequently reheated. This reheating has also transformed the high carbon, presumably martensitic, structure into one of ferrite plus carbide particles (ASTM 8, HV 200.6, 193.3, 209.3, mean 201), the concentration of which suggests a near eutectoid (0.8% carbon) steel.



INTERPRETATION
Good quality composite construction with high carbon edges inserted into low carbon body. The side panels may have incorporated sufficiently variable alloys (iron and low carbon steel) to give the watery appearance of pattern welding. The spearhead was originally quenched to give hard edges that would retain a sharp edge. However, its metallurgical properties were subsequently drastically reduced by long-term heating, perhaps as deliberate damage prior to burial.

3214/1 (Grave 104, Find 1558). RA ref AM2012. Spearhead from inhumation. Phase unknown.

Figure 37. Spearhead 3214/1 after sampling.

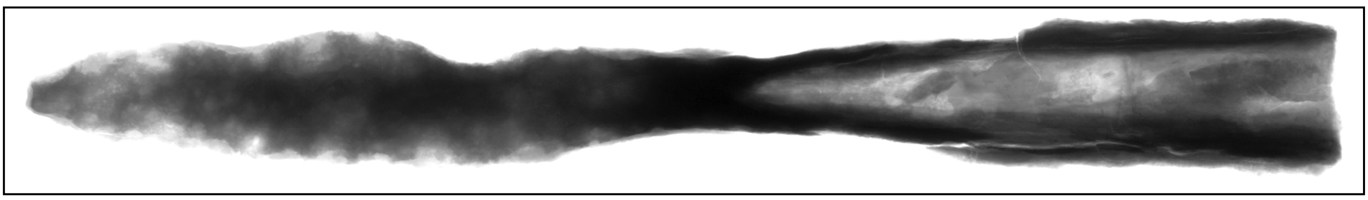
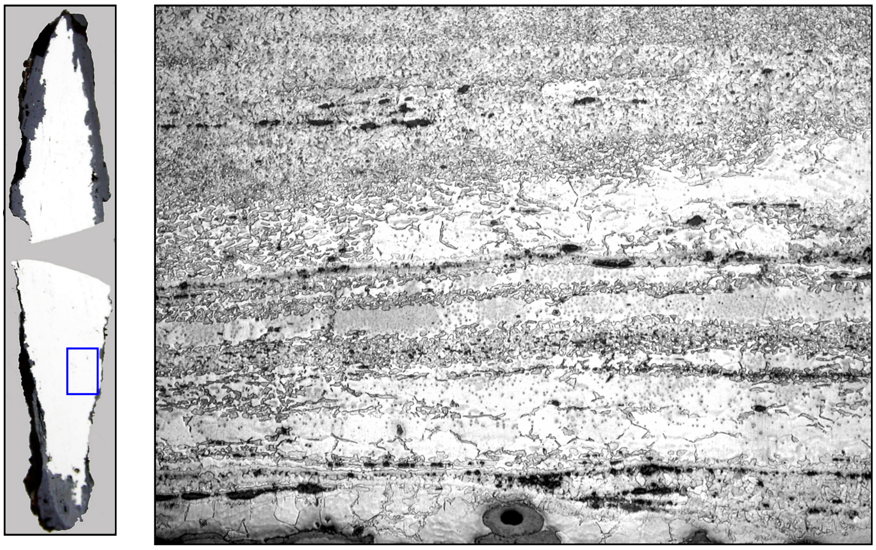


Figure 38. X-radiograph (Plate 512 detail).
Assessment based of X-radiograph found no evidence of pattern welding or a butt-welded edge.

Figure 39. Low magnification Micrograph of sample AM2012 after etching in nital.
Max. field of view 2.4mm.

Piled structure comprising bands ferritic iron, phosphoric iron and ferrite plus 10% pearlite.



Metallographic results
Unetched: Inclusions are concentrated in bands across the section, indicating a piled structure. At their densest these constitute about 10% of the surface area and are generally of single phase, sub-round to elongated morphology. Between these bands other areas were seen to be virtually slag-free.
Etched: When etched in nital the piled structure of the blade was clearly seen. Bands of ferrite (ASTM 6-7, HV 124.5, 113.1, 124.5, mean 120), ghosted phosphoric iron (ASTM 4-1, HV 163.3, 195.5, 162.3, mean 173.7) and low carbon iron were visible. In the latter a maximum of 10% pearlite was located at grain boundaries and had a coarse structure, partially agglomerated.

Interpretation
A poor quality spearhead manufactured from heterogeneous material that had been piled together. Even the higher carbon regions were below 0.1% carbon and therefore insufficient to be classed as steel. There was no evidence that any attempt to harden the blade had been made or that the spearhead had been re-heated to purposefully damage its effectiveness.

3217/1 (Grave 107, Find 1562). RA ref AM2013. Spearhead from inhumation. Phase not known.

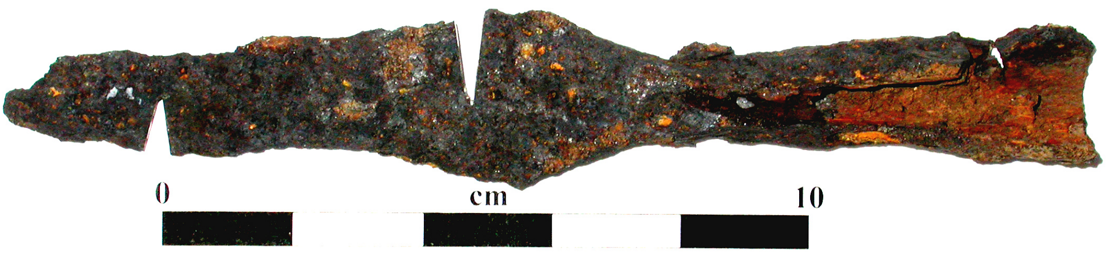


Figure 40. Spearhead 3217/1 after sampling.

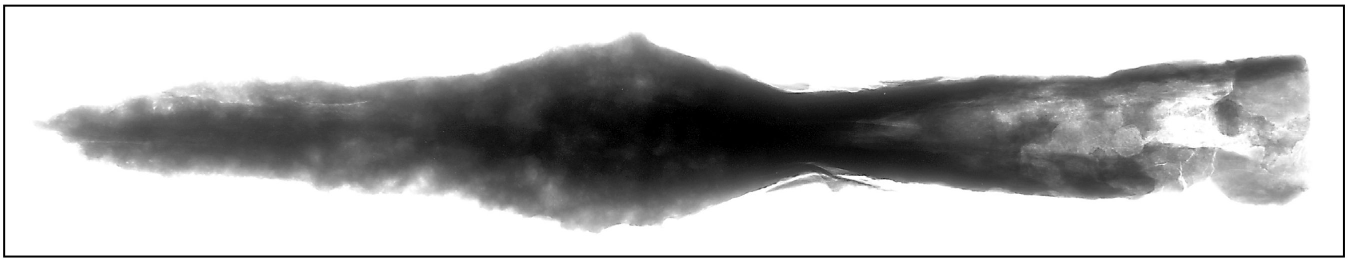


Figure 41. X-radiograph (Plate 512 detail).
Assessment based on X-radiograph found no technological information.

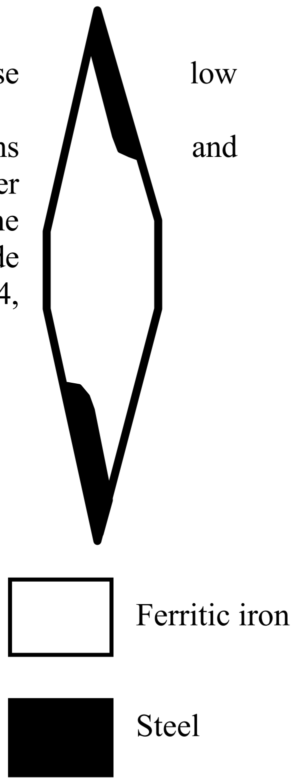
Figure 42. Low magnification micrograph of sample AM2013 after etching in nital.
Max. field of view 2.4mm.

Edge with dark etching steel Welded to lighter etching body.

Metallographic results

Unetched: Narrow bands of inclusions, single phase and elongated. Otherwise low inclusion content, less than 1% of sub-round to elongated morphology.

Etched: Etching revealed most of the section to be ferritic with large grains and low hardness (ASTM 3-6, HV 91.12, 86.98, 92.85, mean 90). However, on either edge a thin slip of steel had been added varying from 0.5 to 0.8% carbon). The microstructure of this phase was a coarse pearlite (ASTM 5-7), with the carbide beginning to agglomerate and having low hardness (HV 226.1, 220.6, 216.4, mean 221).



Interpretation

Some care had been taken to improve the effectiveness of this spearhead by giving it two steel edges. However, either no attempt to harden the blade had been made, or it had been subsequently reheated, possibly at time of deposition, which annealed the edges to a soft condition.

3228/1 (Grave 108, Find 1570). RA ref AM2014. Spearhead from inhumation. Phase 2d-c1, 550-580AD.

Figure 43. Spearhead 3228/1 after sampling.

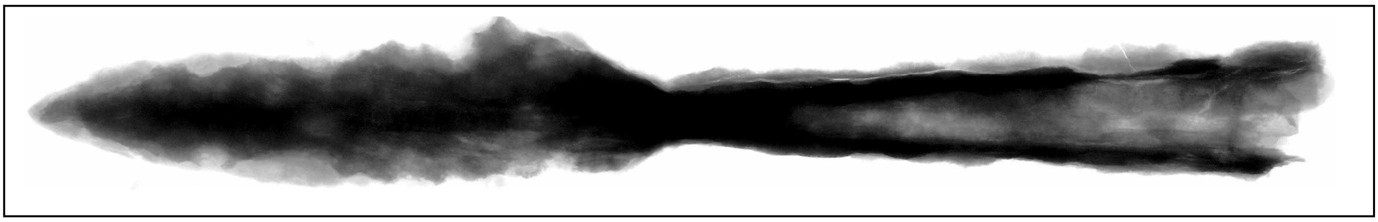
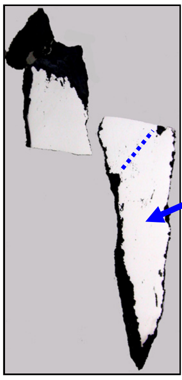
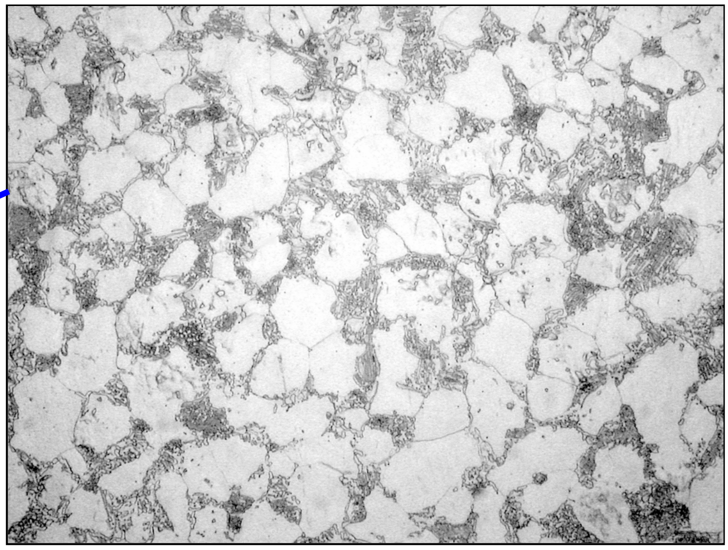


Figure 44. X-radiograph (Plate 518 detail).
Assessment based on X-radiograph found no evidence of pattern welding or butt-welded edge.

Figure 45. High magnifi-ication micrograph of sample AM2014 after etching in nital. Max. field of view 0.12mm.

Coarse agglomerated pearlite comprises up to 50% of the microstructure. The grains are homogenous and very fine (ASTM 8).

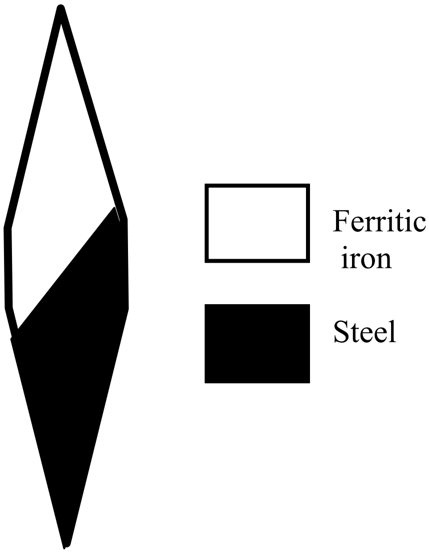




Metallographic results
Unetched: The low content of slag inclusions, generally below 1% and of single phase, sub-round to elongated morphology, indicates a carefully worked raw material.
Etched: Etching in nital revealed two zones, split obliquely through the centre of the blade. Both were unusually homogeneous and fine grained. On one side a lower carbon region comprised 10% agglomerated pearlite, 90% ferrite (ASTM 6, HV 110.2, 114.1, 117.1, mean 114). On the other similarly agglomerated pearlite constituted 50% of the surface and the structure was finer and gave greater hardness values (ASTM 8, HV 159.5, 177.7, 165.2, mean 167). There was no evidence that any attempt had been made to harden the edge by quenching, by contrast the structure was one of slow cooling, probably followed at some time by prolonged heating

Interpretation

Although this spearhead had been constructed using good quality materials, including a homogenous 0.4% carbon steel, the sections showed no attempt to capitalise on these by positioning the steel at the edges, or by quench hardening the structure. By contrast, later heating of the blade may have been undertaken with the intention of reducing its effectiveness.



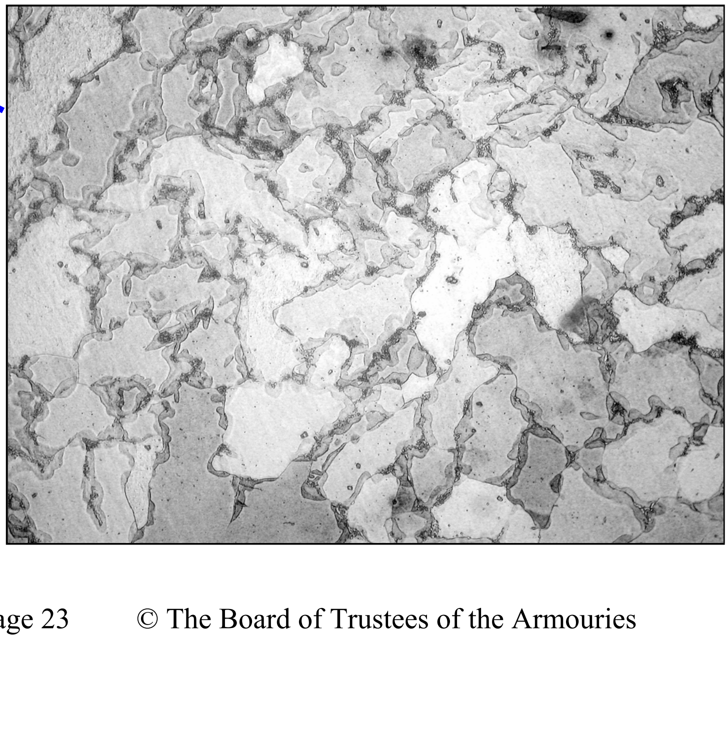
3315/1 (Grave 126, Find 3012). RA ref AM2015. Spearhead from inhumation. Phase unknown.

Figure 46. Spearhead 3228/1 after sampling.

Figure 47. X-radiograph (Plate RA 22/06 detail).
Assessment based on X-radiograph found no evidence of pattern welding or butt-welded edge.

Figure 48. High magnification micrograph of edge of sample AM2015 after etching in nital. Max. field of view 0.3mm.

An unusual structure towards the edge of the spearhead. A small amount of carbon is present as agglomerated pearlite / iron carbide particles at the ferrite grain boundaries. The microstructure is deformed, presumably from cold working and some ghosting is visible within the grains.



Metallographic results

Unetched: The bands of slag inclusions gave the first indication of the presence of piled iron. The slag inclusions are sometimes present in volumes of up to 15% of the sample surface, though almost absent from other areas. The elongated to stringer morphology of the inclusions, indicates a material largely worked at high temperature such that the slag remained ductile. Most were of multi-phase composition.

Etched: After etching, the presence of piled iron was confirmed. Three components were identified: Ferritic iron (ASTM5-6, HV 95.79, 94.92, 94.92, mean 95), phosphoric iron, which was often ghosted (ASTM 2-4, HV 183.4, 154.0, 170.0, mean 169) and a combination of ferrite with up to 20% pearlite, in an agglomerated form, at the ferrite grain boundaries. Particularly at one edge, and to some extent on the sides, deformed grains suggested that working had been carried out below the re-crystallisation temperature. This was possibly to harden the structure, though the lack of rapidly cooled microstructures show that no quenching was carried out. By contrast the agglomerated nature of the pearlite suggests that the spearhead was subjected to high temperatures, which would have softened the edges somewhat and measured microhardnesses gave relatively low values (HV 138.4, 126.4, 136.2, mean 134).

Interpretation

This spearhead had been constructed using a variety of alloys piled together, without the possibility of providing a good quality cutting edge, although localised cold working of the edge appears to have been attempted. In fact, the only heating regime to that can be identified was one of prolonged high temperature that would have diminished the qualities of the edge. This may have resulted from some deliberate damage prior to burial.

Table 1. Summary of samples examined and metallurgical results

Grave No.	Feature No.	Inventory No.	Armouries Metallography ref	Knife edge type	Edge microstructure	Edge hardness (HV)	Back microstructure	Back hardness (HV)	Work hardened	Heat damaged
Knives										
4	234	**1217/8**	AM2001	3	ferrite, phosphorus ghosting, pearlite	201	ferrite, phosphorus ghosting, pearlite	197 & 192	yes	no
6	237	**1218/6**	AM2002	2b	martensite	602	Ferrite, pearlite, bainite	178	no	no
34	346	**1265/1**	AM2003	4	tempered martensite	445	bainite	221 & 342	no	no
73	1077	**2402/11**	AM2004	3	bainite	285	ferrite/ phosphoric pearlite	212 & 219	no	no
75	1079	**2404/5-6**	AM2005	2b	bainite	238	phosphoric iron	162	no	no
179	3140	**3792/6**	AM2006	3	ferrite	144	Ferrite, possibly phosphoric iron, bainite	144 & 167	no	no
Fire steel										
196	3190	**8280/8**	AM2007		no info		no info			
Spearheads										
22	289	**1223/2**	AM2008		ferrite & pearlite	113 & 224	ferrite & pearlite. Pattern welded	113 & 224	no	possibly
44	378	**1325/2**	AM2009		phosphoric iron	165	phosphoric iron, some pearlite	165, 183	no	yes
58	1000	**2300/1**	AM2010		ferritic	129	ferritic	129	yes	yes
91	1537	**3139/1**	AM2011		annealed martensite	201	ferrite, some pearlite. Probably pattern welded.	116	yes	yes
104	1558	**3214/1**	AM2012		ferrite, phosphoric, some pearlite	120 & 174	ferrite, phosphoric iron, some pearlite	120 & 173.7	no	no
107	1562	**3217/1**	AM2013		pearlite	221	ferrite	90	no	yes
108	1570	**3228/1**	AM2014		ferrite, pearlite	114 & 167	ferrite, pearlite	114 & 167	no	yes
126	3012	**3315/1**	AM2015		ferrite, phosphoric iron & some pearlite	134	ferrite, phosphoric iron & some pearlite	95 & 169	yes	yes

Interpretation: Knives
Of the six knives, the most common manufacturing classification was Type 3, piled iron, without an additional steel edge and therefore of low quality. The metal used was of very variable composition. For these blades some enhancement of the hardness, compared to pure iron, might have been found from either low concentrations of the impurity phosphorus, or by work hardening the edge or by quenching the a blade which had low levels of carbon present. However, the overall impression is of poor quality, possibly re-cycled, metal being worked up into blades of indifferent quality.

Three knives were metallurgically superior. 1218/6 was clearly a blade of much higher quality, both in the materials used, in welding a steel edge to an iron/low carbon steel back, and in the heat-treatment used to capitalise on these materials. 1265/1 is less easy to assess, given its heavily corroded edge, but was probably also once an effective blade, though made using the unusual steel envelope technique. The final blade, 2404/5 is also butt welded, but it would appear that although an attempt to quench it was made, too little carbon was present to allow full hardening.

The question of deliberate "killing" by heating to reduce the hardness of the edge might be considered for 1217/8, for which the edge has re-crystallised, requiring re-heating to about 700^0C for a prolonged period.

Comparing metallographic results with those obtained from X-radiography, which had suggested clear evidence of Type 2 butt-welds in 3 blades and probable butt-welds in a further eleven cases, it is apparent that both probable Type 2s examined, (1218/6 and 2404/5), were correctly identified. However two of the three blades, (1217/8 and 2402/11), identified metallographically as being of piled iron, had also been predicted to be butt-welded.

This mis-identification was presumably due to welds from the piling being confused with butt-welds which joined a steel edge to an iron back. For the Type 4 envelope construction blade (1265/1), the X-radiograph had, predictably found no technological information. In general, X-radiography had provided useful information on the metallurgical structures, but piled iron welds were too easily mistaken for butt-welds. Additionally, X-radiography gave no indication of the materials or quality of the blades being examined.

Comparative knife data
As mentioned above, medieval knives are amongst the most thoroughly studied artefacts. The following sites provide comparative data:

Cemeteries:
Loveden Hill, Lincolnshire (C5th-C7th), (McDonnell 1989a)
Empingham II, Rutland (C5th-C7th), (Weimer 1996)
Edix Hill, Cambridgeshire (C6th-C7th), (Gilmour and Salter 1998)
Boss Hall and St Stephen's Lane – Buttermarket, Ipswich, Suffolk (6^{th} & C7th), (Fell and Starley 1999)
Mucking, Essex (C5th-7^{th}), (Starley 1996)
Cannington, Somerset (C4th-7^{th}) (McDonnell 1989b)
St Mary's Stadium, Southampton (C7th). (Reported in Blakelock and McDonnell, in press)

Settlement sites:
Coppergate, York (C9th) (Ottaway 1992)
Fishergate, York (C8th-C9th) (Ottaway and Weimer 1993)

Six Dials, Hamwih, Southampton (C8th-C9th) (McDonnell 1987a and 1987b)
Poundbury, Dorset (C5th-C7th) (Tylecote and Gilmour 1986, 37-42)
Wharram Percy (C7th-C8th) (Blakelock 2006)
Flixborough, Humberside (C9th-C10th) (Starley 1999)
Winchester (Anglo-Saxon) (Rulton 2003)
West Stow (Saxon) (Tylecote and Gilmour 1986, 42)
Ramsbury (Saxon) (Tylecote and Gilmour 1986, 42-44)

For most of the above sites metallographic examination was carried out, generally following X-radiography of the assemblage. Mucking artefacts were assessed only from the X-radiographs and although extensive may be less reliable.

An overview of the manufacturing typologies for most of the above sites has recently been undertaken by Blakelock and McDonnell (in press), for most of the above sites. They conclude that although no clear differences can be identified between the (non-metallurgical) types of knives found in cemetery and settlement sites, clear differences do exist when the manufacturing typologies were examined.

The strongest link is between settlements and Type 2, butt-welded blades, which made up 81% of the assemblages from these sites, but only 16 % of those from cemeteries, which show a broad range of manufacturing types. Sample biases are not discussed in the paper, but it might be worth considering the effect these would have on comparative overviews. Inhumation burials, with their associated grave goods, are known to become increasingly popular with time. Harder to assess is any bias associated with the metallographers' choice of blades for examination, which would almost certainly favour those which X-radiography suggested composite construction. Furthermore, it might also seem likely that settlement finds tend to be more heavily worn such that a certain proportion of type 2s might entirely lose their edge from extensive re-sharpening, which if true makes then the number of knives with surviving steel edges on settlement sites even more remarkable.

Blakelock and McDonnell also suggest that the hardness of edges on cemetery site is significantly lower, 363HV rather than 467HV. The question arises as to whether this could arise from deliberate softening of the blades as part of a process of ritual damage at the time of burial, even though the body itself was not cremated. A number of cemetery finds are singled out where, otherwise carefully constructed knives, contained softer, spheroidized structures, considerably inferior to what could have been achieved by quenching and tempering.

Comparison of Wasperton knives with other sites

Metallographic examination of the six Wasperton blades can now be compared with a corpus of about 100 other investigations of settlement and cemetery blades from England. Blakelock and McDonnell (In press) brought together 75 of these in their review paper. Their findings of low numbers of Type 2 blades for cemetery sites (16%), is not greatly at variance with the 2 of 6 for Wasperton. Similarly, their combined microhardness average for blade edges of 363HV is not far from the Wasperton mean of 319HV. It would seem likely that at Wasperton, as for other parts of Anglo-Saxon England, the quality of knives placed within burials generally, if not always, falls short of the quality of blades found in everyday use.

Interpretation: Spearheads

It is necessary to consider biases in the selection of spearheads for metallographic examination. The Wasperton samples were chosen primarily for the condition of the spearheads rather than metallurgical interest. However, it is possible that this policy favoured the selection of non-composite blades, which suffer less from bi-metallic corrosion brought about by the different electro-chemical properties of iron and steel. The original X-radiographic assessment of the 23 Wasperton spearheads suggested the presence of three possible pattern welded blades, two of which (1223/2 & 3139/1) were tested, and confirmed, by the metallographic study, though the quality of this decorative element was questioned. Generally, X-radiography proved effective in identifying pattern welding. The X-radiographic assessment only provisionally identified one butt weld (1328/1), for which the blade was not sampled, although other samples identified alternative means of adding steel edges, that are not so easily seen in X-radiographs (3139/1 and 3217/1). It is, therefore, clear that the X-radiographic assessment underestimated the number of steel edged weapons.

Even compared with the indifferent quality of the Wasperton knives, the eight spearheads from the cemetery examined by metallography were generally poorly crafted objects made of low quality materials. Only two (3139/1 and 3217/1) incorporated steel at the blade edges in a way that would have utilised its superior hardenable qualities to provide a hard, edge-retaining, blade. Apart from these two, some do show attempts to improve edge hardness, either by quenching, or cold working (2300/1, 3315/1), or possibly by deliberate selection of "phosphoric iron" (1325/2, 3214/1, 3315/1). However, the overall improvement is very low; mean microhardness measurements for the edges are only 163HV compared with 131HV for the body of the blade. This is due, at least in part, because all but one of heads, including the two steeled examples, but not the very poor quality 3214/1, gave the appearance of having been re-heated, at sufficient temperature and for enough time, to counteract the benefits which the earlier heat treatment or cold working had brought them. Similarly, spearhead 1223/2, which appeared to be pattern welded on its X-radiograph, was found to lack the clear divisions between high and low carbon materials, and it is possible that long-term annealing had allowed diffusion of carbon across the weld lies, blurring the divisions. Given the apparent high level of understanding of the principles of hardening in the Saxon period, it would seem unlikely that this damage was accidentally inflicted on the spearheads, but that deliberate "decommissioning" or "killing" may have been carried out prior to deposition.

If one ignores the later damage, it is clear that for a few of these spearheads care and expense had been undertaken in producing blades of distinctly better quality, either decoratively in the case of pattern welding (1223/2) or functionally for the steeled edge blades (3217/1) or both (3139/1). It might be thought that the function of the spearhead may be relevant here. Hill (2000), has undertaken a quantitative and literary analysis of nearly 200 later Saxon spearheads, and suggests criteria for considering whether a spearhead was primarily disposable, for throwing in battle, or would be retained as a thrusting weapon. Judging by length and socket size many of the Wasperton spearheads would be considered as javelins for throwing. Might these be expected to be of lesser quality? The findings show otherwise with the pattern-welded 1223/2 being the smallest examined at 16.9cm and having an internal socket size of 15mm and the pattern-welded, steeled 3139/1 being a modest 274mm, with 15mm socket. Spearhead 2300/1 was, at 530mm, the longest but also the worst quality. Whilst it is true that the pattern welded example, 1223/2 had a long blade, (recorded in the catalogue as 470mm, but fragmented by the time of metallurgical examination) and that its broad blade might well have appeared impressively pattern welded, it would appear that the use of steel was aimed more at an impressive appearance that at any fighting quality. Thus there is considerable reason to doubt whether, the Wasperton assemblage really represents the quality of weapons used in conflict rather than more token symbolic offerings accompanying the body to the grave.

Comparative spearhead data

Although less extensive than the data on Anglo-Saxon knives, a significant number of spearheads have been investigated technologically. However, the reporting of these is far less standardised than for knives, making comparison more difficult. The researcher is also faced with an almost total absence of analysed spearheads from contexts other than funerary.
As for knife studies, the most extensive study has been purely X-radiographic, (Starley, 1996) for Mucking, Essex, which looked at 65 spearheads. Just over half of these appeared homogenous, though pattern welding was identified in eight, whilst butt-welding, the favoured method of steeling knives in the Saxon period, was only suggested for one artefact.

Gilmour and Salter's (1998, 250-255) study of spearheads from the cemetery at Edix Hill (Barrington A), Cambridgeshire, provided the numerically largest metallographic study examining 20 spearheads. The authors stress the very different, much poorer quality, compared with knives from the same cemetery. The re-working of scrap iron was suggested for many, otherwise plain iron was used in 3 examples. Only 3 contained steel and for these the workmanship is unimpressive, with no mention made of any attempt to harden the steel.

Moir's (1990) study of Anglian spearheads from West Heslerton, examined 9 spearheads, with only one (sandwich construction) blade steeled and hardened with any significant increase in hardness. Fell and Starley (1999) examined 9 spearheads from Boss Hall and 2 from St Stephen's Lane, Ipswich. X-radiography of all these had suggested that they were of piled construction or contained extensive slag stringers. Metallography of 3 blades and one neck showed them all to be of soft iron sometimes with traces of carbon and or phosphorus. A single analysis found one fifth to seventh century, spearhead from Sancton (Gilmour 1999) to be of low carbon and unquenched.

All the above finds are from funerary deposits, presumably inhumations. Data from non-funerary contexts are rare. A single spearhead from Thetford (McDonnell 1987), for which the context is unfortunately not mentioned, was identified from its X-radiograph to be pattern welded. Metallography subsequently identified a rare instance of a quenched and tempered steel edge giving hardness measurements up to a max.imum of HV 519. Ottaway (1992, 715-716) reports the metallographic examination of a possible Anglo-Scandinavian spearhead tip from Coppergate. This was made of piled phosphoric iron and low carbon steel without quenching or cold working. A definitely non-cemetery find, although debatably also a ritual deposit, was a spearhead from the Thames at Kempsford in Gloucestershire (Tylecote and Gilmour, 86, 110-115). The dating on this artefact is only approximate at seventh to eleventh century AD. Although this was reported to contain up to 0.4% carbon, no attempt had been made to harden it, more probably the object had been annealed giving even lower edge hardness.

Comparison of Wasperton spearheads with other sites

In comparing Wasperton spearheads with those from other sites mentioned above, it is again necessary to be aware that many researchers do not explicitly state their sampling criteria and it is possible that selective biases occur between data sets. Despite this many of the larger, interpretive, studies do come to similar conclusions.

Firstly, the metallurgy of spearheads from cemeteries is generally poor, for a period when the working of ferrous materials is generally of a very high standard. Studies including Wasperton, which have examined both knives and spearheads from cemeteries have shown that the spearheads are metallurgically inferior, even though knives from cemeteries themselves are of lesser quality than those found on settlement sites.

Typically, most blades are produced by piling together a range of low quality ferrous alloys, of high slag and low carbon content. The heterogeneity of these shows not only that the smith had little interest in producing a strong functioning artefact, but also suggests that much of the material was recycled.

Butt welding, the favoured method for edging knives, particularly for non-funerary use, but also widely used for those appearing in cemeteries is rarely, if ever, used in funerary spearheads. The examination of Saxon spearheads from anything other than cemetery sites is so limited that valid comparison cannot be undertaken.

All but one of the Wasperton spearheads were considered to have been deliberately heated, to soften and presumably reduce their effectiveness. Similar treatment can be seen from the results of previous published studies, although the authors have not always been explicit in suggesting the systematic, deliberate nature of this. As for physical damage, such as the 14% of spearheads that Hill (1990) presumed to have been damaged in battle, it is perhaps time to recognise that spearheads rarely entered the grave in pristine condition.

Conclusions

X-radiographic examination and selective metallographic sampling have provided an effective means, not only of studying the materials and construction techniques of the Wasperton knives and spearheads, but of their effectiveness. For the knives at least, these can be shown to be inferior to those from contemporary non-funerary contexts. At present there is insufficient data to make similar comparisons between spearheads from graves and those deposited elsewhere, but the poor quality of the spearheads is evident in comparison with all other classes of Saxon edged tools and weapons. Whilst such poor quality might be considered acceptable for a lightweight throwing spear, it would appear that larger weapons, were no better. There seems to have been no difficulty in obtaining a range of iron, phosphoric iron and steel. However, these alloys have not been worked and selectively used in a way to maximise there qualities, as might me expected during a time where the skills of a blacksmith were highly regarded.

There appears to be a sound case for suggesting that most, if not necessarily all knives and spears found at Wasperton were manufactured grave goods, produced to a lower standard than would be expected of a functional tool or weapon. Although the number of sites examined is low, this would appear to be common practise for all contemporary Anglo-Saxon cemeteries.

The metallographic investigation of the assemblage from Wasperton has also provided further evidence that the grave goods, particularly the spearheads were further compromised by an act of heating prior to burial, at bonfire type temperatures followed by slow cooling, a process which would surely have been known to damage their effectiveness.

It is unfortunate that the object considered to be either a purse fitting or fire steel was too heavily corroded to allow its composition, and possibly therefore its function to be determined. However, considering the presence of apparently purely funerary objects in the graves, it may be that this too would have been made without requiring functionality.

References

Blakelock, E. (2006) *Analysis of Knives from the Rural Settlement of Wharram Percy, Yorkshire.* University of Bradford, unpublished undergraduate dissertation.

Blakelock, E and McDonnell, J.G. (In press) A review of the Metallographic Analysis of Early Medieval Knives. *Journal Historical Metallurgy Society*.

Fell, V. and Starley, D. (1998) *Metallographic Examination of Seven Medieval Knives from Eynsham Abbey, Oxfordshire* (Ancient Monuments Lab. Report **70/98**).

Fell, V. and Starley, D. (1999) *A Technological Study of Ferrous Blades from the Anglo-Saxon Cemeteries at Boss Hall and St Stephen's Lane - Buttermarket, Ipswich, Suffolk* (Ancient Monuments Lab Report **18/99**).

Gilmour, B. (1993) Spearhead. In Timby, J. Sancton I. Anglo-Saxon Cemetery: Excavations carried out between 1976 and 1980. *Archaeological Journal,* **150,** 243-365.

Gilmour, B and Salter, C. (1998) Ironwork: Technological examination of the knives, spearheads, and sword/weaving batten. In Malin, T. and Hines, J. *The Anglo-Saxon Cemetery at Edix Hill (Barrington A), Cambridgeshire*. CBA Research Report **112**, Council for British Archaeology. 250-256.

Hill, P. (2000). The Nature and Function of Spearheads in England c.700-1100 A.D. *J. Arms and Armour Soc.* **XVI, 5.**

McDonnell, J.G. (1987a) *Metallurgical Analyses of Six Iron Knives from Hamwih, Southampton.* (Ancient Monuments Lab. Report **93/87**).

McDonnell, J.G. (1987b) *Metallurgical Analyses of the Thetford Spearhead (SFN 261).* (Ancient Monuments Lab. Report **4/87**).

McDonnell, J.G. (1989a) *Metallurgical Analyses of Iron Artefacts from Lovedon Hill, Lincolnshire.* (Ancient Monuments Lab. Report **132/89**).

McDonnell, J.G. (1989b) *Metallurgical Analyses of Fourteen Iron Knives and Three other Artefacts from Cannington, Somerset.* (Ancient Monuments Lab. Report **9/89**).

McDonnell, J.G. (1987) *Metallurgical Analyses of six Iron Knives from Hamwih, Southampton.* (Ancient Monuments Lab. Report **93/87**).

McDonnell, J.G. & 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

Moir, D. (1990) *The Metallographic and Scanning Electron Microscope Analysis of Nine Spearheads from the Anglian Cemetery at West Heslerton, North Yorkshire*. Unpublished MA thesis, University of Bradford.

Ottaway, P. (1993). *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.

Rulton, S. (2003) *An Investigation into the Metallurgy of a Group of Anglo-Saxon and Medieval Knives from Winchester*. Unpublished BSc Dissertation, University of Bradford.

Starley, D. (1996) *A Technological Study of Knives and Spearheads from the Excavations at Mucking, Essex.* (Ancient Monuments Lab. Report **37/96**).

Starley, D. (1999) *The Analysis of Middle Saxon Ironwork and Ironworking Debris from Flixborough, South Humberside* (Ancient Monuments Lab. Report **35/99**).

Starley 2005. *The Assessment of Ferrous Grave Goods from Wasperton Anglo-Saxon Cemetery MN80-85*. Unpublished Royal Armouries Technological Report **3/05.**

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

Weimer, K. Metallurgical Analyses of Iron Knives (1996) in Timby, J. *The Anglo-Saxon Cemetery at Empingham II, Rutland*, Oxbow Monograph **70,** Oxford**,** 76-85.

