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Burdale

X-Radiograph and Metallographic Analysis Report

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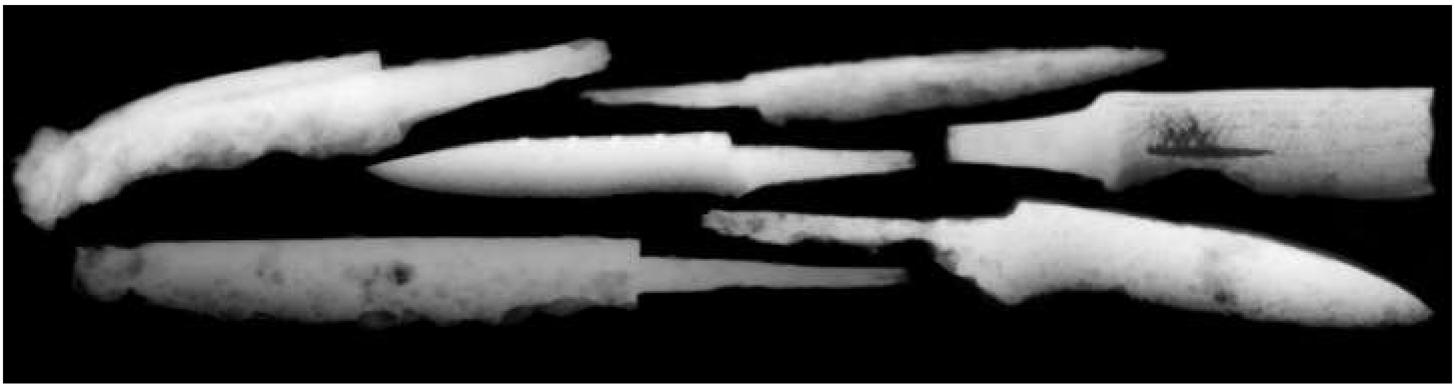


Burdale X-Radiograph and Metallographic Analysis Report

Introduction

During the 1990s intensive prospection by metal detectorists led to the discovery of many new Anglian and Anglo-Scandinavian settlements. Burdale is just such a site, identified on the Yorkshire Wolds valley-bottom where Anglian settlement features were identifiable from crop marks. Excavations in Burdale during 2006-2007 revealed a multi-phase Anglian farmstead. Traces of sunken buildings and refuse pits were excavated and there was evidence for the development of a number of enclosures. Preliminary dating places the settlement in the 8th and 9th centuries (Richards 2007).

A combination of metallographic and x-radiographic analysis of knives can reveal far more about iron technology in the Anglo-Saxon period than measuring and typology alone. Metallographic analysis is used to determine the iron alloys used, method of manufacture and heat treatments, and may even provide hints as to how the knife was used and repaired. Even so it is impossible to metallographically examine all iron knives from a site, therefore x-radiographs can be used to reveal the quality of preservation, the overall distributions of shapes, wear and manufacturing types of the entire assemblage (Blakelock & McDonnell 2007; Fell & Starley 1999; McDonnell 1992; McDonnell *et al.* 1991; Starley 1996).

In antiquity there were four different types of iron alloys that were used; ferritic iron which contained no alloying elements (less than 0.1%), phosphoric iron containing between 0.15% to 1% phosphorus and steel which contains carbon as the main alloying element. The fourth iron is termed piled or composite iron which incorporates two or more iron alloys, e.g. ferritic and phosphoric iron (McDonnell 1989). High-quality steel is characterised by homogenous high carbon contents (>1% carbon), has often been well heat treated, has high hardness values (*c*600HV) and few small spheroidal slag inclusions (Mack *et al.* 2000). The Saxon smith made good use of the different iron alloys properties by creating composite knives, i.e. using a hard steel cutting edge welded on to a soft and more flexible ferritic or phosphoric iron back. Tylecote and Gilmour's pioneering study (1986) of edged tools produced a typology of six different methods of manufacturing knives (Figure 1), which has since been simplified (Blakelock & McDonnell 2007; Tylecote & Gilmour 1986). To get the most out of the steel cutting edge heat treatments, such as quenching (the artefact is plunged into a liquid to cool it rapidly) and tempering (heating again to 500°C to remove some of the stress) would be carried out to create a much harder cutting edge (Pleiner 2006, 65-70; Samuels 1999, 5-37; Scott 1991, 31-32; Tylecote 1990).

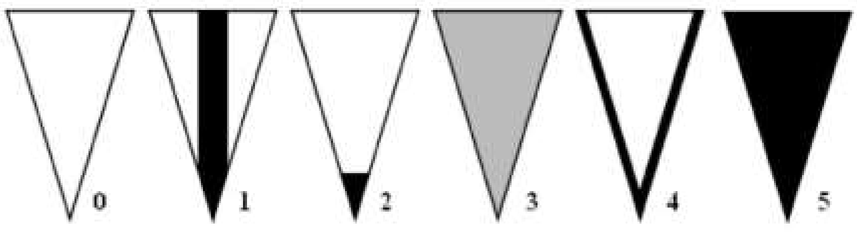


Figure 1: Knife manufacturing typology based on blade cross sections (adapted from Tylecote and Gilmour 1986). 0 = all ferrite (or phosphoric iron) with no steel cutting edge, 1 = steel core flanked by

ferritic or phosphoric iron, 2 = steel cutting edge butt-welded to the iron back, 3 = piled or banded structure throughout the section, 4 = steel forms a jacket around an iron core, 5 = all steel blade.

Methodology

A detailed examination of the knife x-radiographs was carried out to determine the condition of the knife assemblage. This study also provided the opportunity to investigate the overall distribution of manufacturing types and other features present (for full methodology see Appendix 1). In addition to this the size and shape, using a simple typology for both the back and tang interface (Figure 2), and of each knife was noted.

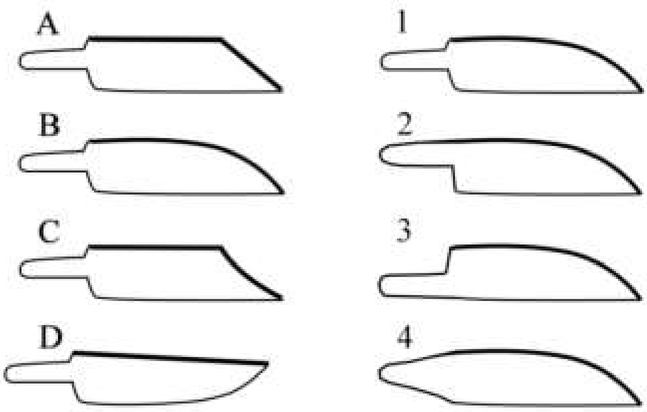


Figure 2: Archaeological typology based on the knife back shape (left), and the blade to tang interface (right). A knife with an angle-back and a distinct blade to tang interface on both sides would therefore be A1.

Samples were chosen for metallurgical analysis based on the state of preservation and features seen. Metallographic analysis was carried out on 13 knives and the pivoting knife. A list of the knives selected and the context details is provided in table 1.

Knife Number	X-Ray Number	Year	Context
4 (Pivoting Knife)	6633	2006	1000
200	6634	2006	6194
204	6633	2006	6197
208	6633	2006	I SE 8786 6196
218	6633	2006	E SE 8787 6196
64	6759	2007	1004
65	6759	2007	1004
67	6759	2007	
69	6759	2007	1019
70	6759	2007	1050
75	6760	2007	1157
76	6760	2007	1179
113	6760	2007	1018
190	6760	2007	
244	6779	2007	1472

Table 1: Samples selected for analysis showing their small find numbers, year of excavation, context details and x-radiograph numbers.

Prior to analysis photographs were taken of each knife. During metallurgical analysis the samples were closely examined using an optical microscope, in both the etched and un-etched condition. Each knife was tested using a Vickers hardness tester to establish the hardness and therefore quality of the iron alloys and heat-treatments used. A Scanning Electron Microscope with Energy Dispersive X-Ray Analysis (SEM-EDX) was then used to determine the elemental composition of the metal. A detailed description of the methodology is provided in Appendix 2.

Results

In total 30 knives were recovered during excavations at Burdale, including 1 pivoting knife. The majority (19) came from the excavations carried out in 2007 while the remainder were found in 2006. The x-radiographs for all 30 knives were examined. The results for each knife are available in appendix 3.

The x-radiograph analysis of knives from Burdale has shown that the most common knives deposited were curved-backed knives; this was closely followed by the angle-back knife (Table 2). Unfortunately many of the knives were found broken therefore many were un-diagnostic. The survey also revealed that the type of tang to blade interface was varied although the majority had a distinct tang to blade interface on one side only. There was a difference in knife shape between the two sites with a significant number of angle-backed knives recovered during the 2007 excavation. This may reflect a difference in date or in site function.

Burdale Site	***Number of Knives Examined***	***Good State of Preservation***	***Back Shape***					***Tang Interface***				
			A	***B***	***C***	***D***	***x***	***1***	***2***	***3***	***4***	***x***
2006	*10*	*6*		*5*			*5*	*2*	*1*	*5*	*2*	*0*
2007	*19*	*18*	*7*	*4*		*2*	*6*	*7*	*3*	*5*	*2*	*2*
Total	*29*	*24*	*7*	*9*		*2*	*11*	*9*	*4*	*10*	*4*	*2*

Table 2: A table showing the the general state of preservation and the archaeological typologies of the knives from Burdale. Note: x indicates were a knife was un-diagnostic or un-classifiable.This table excludes pivoting knife 4 which will be discussed separately.

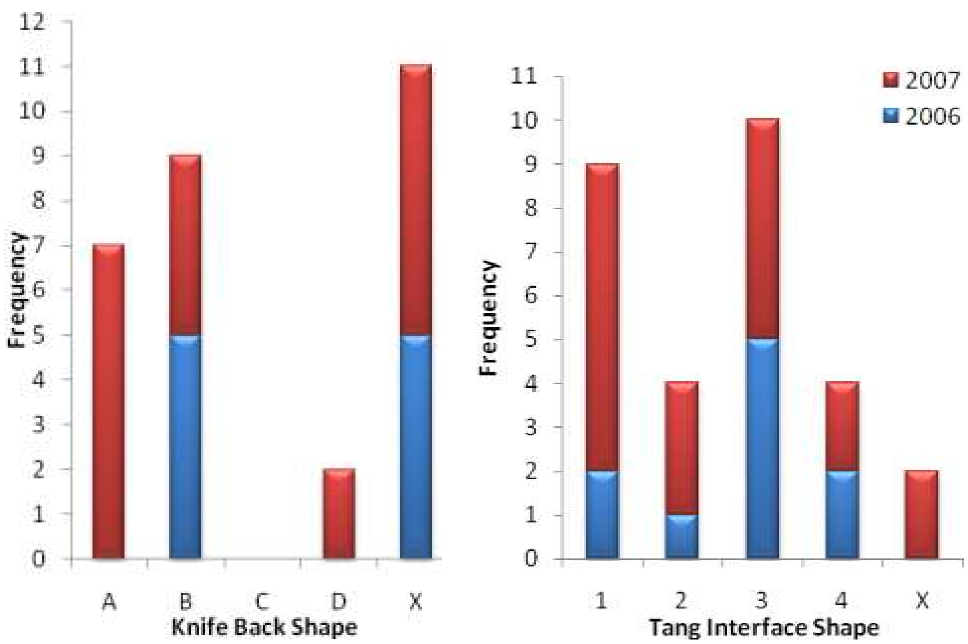


Figure 3: Histogram of knife typology

The full measurements from all knives from Burdale is available in appendix 3. Ten knives appear to have either broken blades or tangs therefore these were ignored, along with the pivoting knife, in the following analysis (Figure 4). The complete, or near complete, knives from Burdale ranged in size from 64mm to 148mm in length, with the average length 102mm. The length of the knife blade also varied dramatically from 32mm to 110mm, whereas the tangs were a more consistent in length from 17mm to 55mm. There seemed to be a direct relationship between the blade length and the tang length as blades in the majority of knives were twice as long as the tang. Even so caution must be used as the tangs are often the first thing broken during deposition and they may therefore have been much longer.

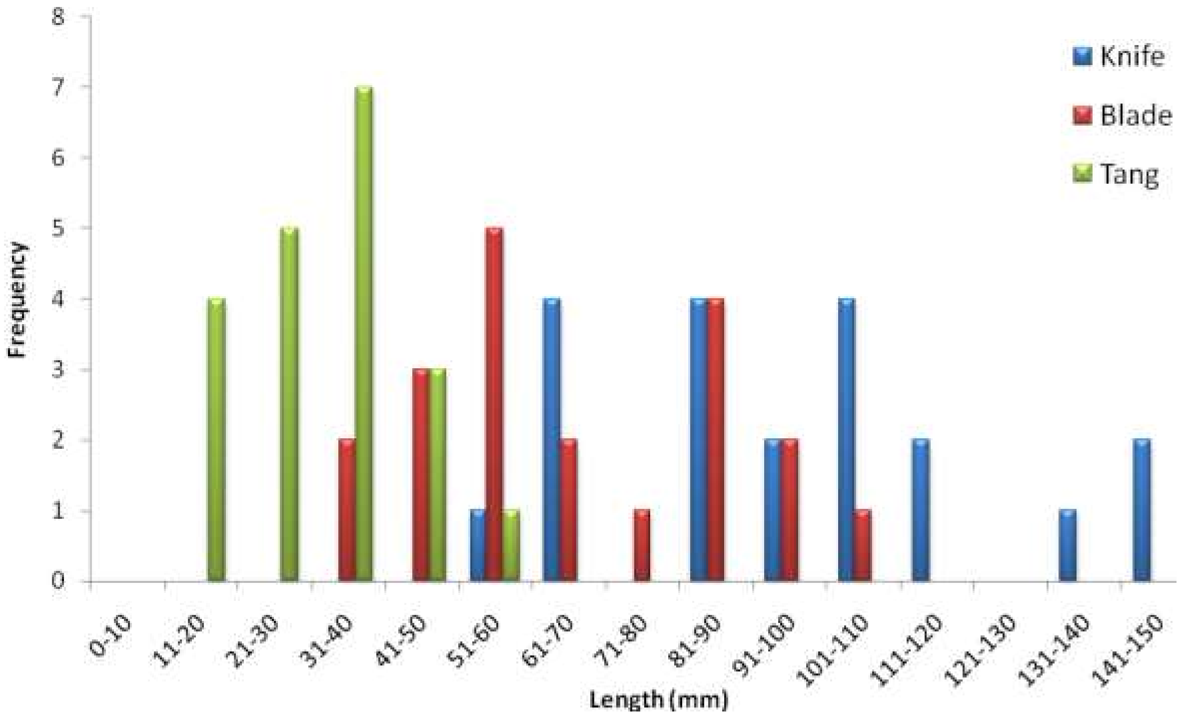


Figure 4: Histogram of knife sizes. This graph excludes some knives that appear to have been broken in antiquity.

The x-radiograph survey of the 29 knives revealed that 22 showed signs of some wear. The majority of which showed either an S-shaped curve (13) or slight (8) evidence of wear. Only one of the knives from Burdale showed signs of heavy wear. Ten knives had broken tangs or blades, this most likely occurred during deposition but in some cases the damage may have occured during use. The Burdale assemblage of knives was particularly unusual as five of the knives recovered from the 2007 excavations were bent (Figure 4). This type of damage could not occur naturally during deposition and therefore must have occurred during the life or just before deposition of the knives. Perhaps this act was related to the presence of a smithy on the site or even may represent ritual destruction prior to discard.

Burdale Site	***Wear Pattern***				
	None	*Slight*	*Moderate*	*Heavy*	*Unknown*
2006			*8*		*2*
2007	*1*	*8*	*5*	*1*	*4*
Total	*1*	*8*	*13*	*1*	*6*

Table 3: A table showing the amount of wear in the knives from each site.

Knife No	Wear	Type	Cutting Edge			Back			Heat Treated	Other Details
			Microstructure	HV	HV Range	Microstructure	Avg HV	HV Range		
4	Some									
200	Some	2	Tempered Martensite	671	386-701	Ferritic/phosphoric iron	140	94-168	yes	White weld line
204	Some	2	Tempered Martensite	441	303-441	Ferrite with pearlite/phosphoric iron	175	140-215	yes	White weld line
208	Slight	3	Ferrite with pearlite	286	196-412	Ferrite with pearlite(carbides)/ phosphoric iron	294	196-412	no	
218	Some	4	Tempered Martensite	549	232-549	Ferrite with pearlite (carbides)/ phosphoric iron	233	148-303	yes	
64	Very	2	Tempered Martensite	701	362-701	Ferrite with pearlite/phosphoric iron	130	91-187	yes	White weld line
65	Slight	2	Phosphoric iron	210	183-210	Phosphoric iron	209	161-244	no	
67	Slight	2	Tempered Martensite	549	143-549	Ferrite with some pearlite	109	91-137	yes	White weld line
69	Some	2	Pearlite	257	257-457	Ferrite and pearlite to pearlite	212	183-264	no	White weld line
70	Slight	2	Tempered Martensite	732	473-766	Ferrite	138	118-161	yes	White weld line
75	Some	2	Tempered Martensite	549	340-549	Ferrite with pearlite/ phosphoric iron	191	103-271	yes	
76	Some	2	Pearlite	272	244-321	Ferrite	184	137-221	no	
113	Some	3	Ferrite with pearlite	168	116-176	Ferrite with pearlite	148	116-176	no	
244	Slight	2	Tempered Martensite	766	441-927	Ferrite with pearlite (carbides)/ phosphoric iron	181	148-210	yes	White weld line

Table 4: Summary of the thirteen knives analysed. This includes the archaeological typologies assigned to the knives. It also shows the manufacturing typology, cutting edge and back microstructures along with their average hardness values and hardness ranges).

The vast majority of knives from Burdale (10 out of 13) are type two butt-welded knives, directly comparable to other Middle Saxon sites, e.g. Wharram Percy, Hamwic and York. The remaining knives consist of two piled knives (type 3) and a type 4 knife with steel wrapped around an iron core. Most of the type two knives (7 out of the 10) and the single type 4 knife had been heat treated to create a harder cutting edge. The backs of many knives consisted of more than one piece, and type, of iron alloy. There does not appear to be any difference between the technologies used to manufacture the knives in the two excavation areas.

The x-radiographs of the remaining 16 knives, that were not sectioned, suggested that there are as many as 10 butt-welded knives and 8 knives were identified as having steel cutting edges. Out of these knives 5 were identified as type 2 butt-welded knives with steel. This leaves up to 2 knives that could be type 1 'sandwich type' knives or homogenous steel knives.

Burdale Site	***Weld Line***	***'Spotted' Steel***	***Weld and Steel***
2006	*4*	*5*	*2*
2007	*4*	*3*	*3*
Total	*10*	*8*	*5*

Table 5: A table showing the features present in the knives not sampled.

At other Early Medieval sites such as Coppergate (Ottaway 1992a, 579-582) and Dublin (Blakelock 2007; Ottaway 1992a, 579-582) a number of different features present in the knives, Burdale was no different. One knife had a possible transversal notch but two, possibly three knives had indents in the back (Figure 6). The majority of knives from Burdale with notches and/or indents were angle-backed, this was also noted at Coppergate, York (Ottaway 1992a, 579-582) and Dublin (Blakelock 2007). None of the knives had any obvious form of decoration, eg pattern welding or non-ferrous inlays.

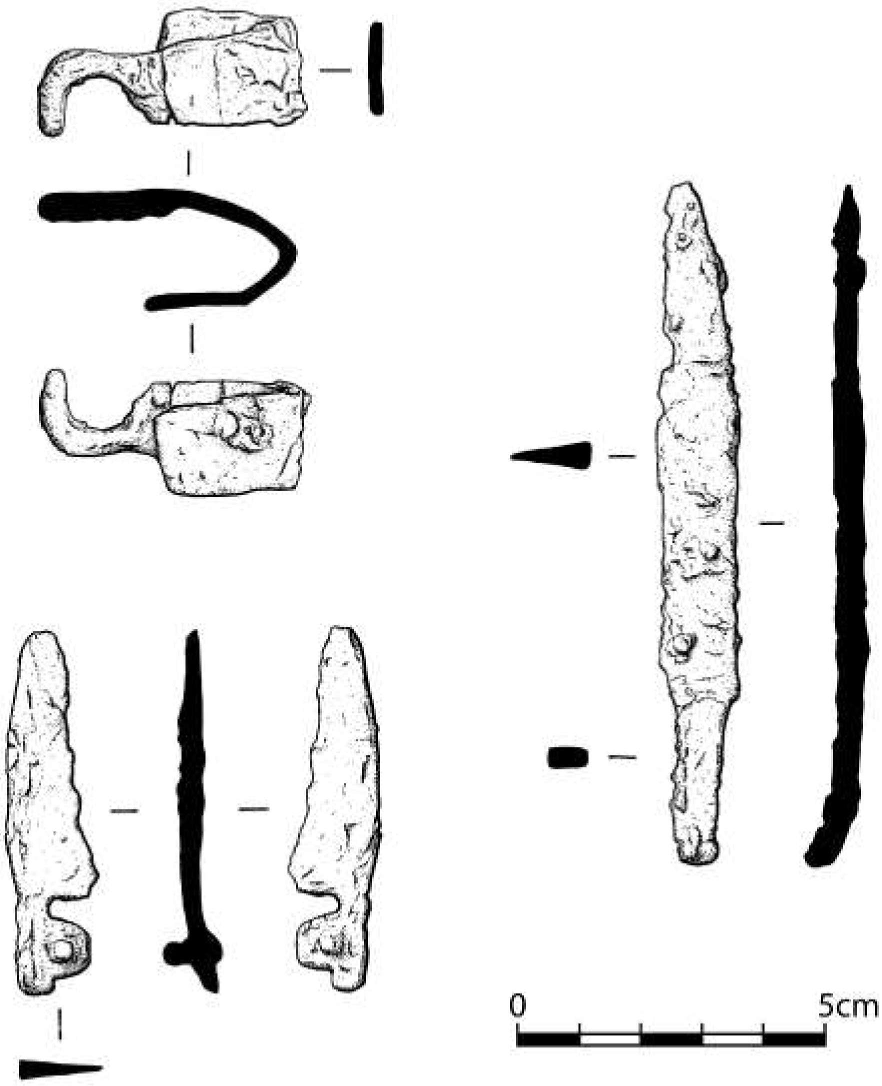


Figure 4: Sketches of three knives from Burdale. Right) typical knife with a curved back, Top Left) is an example of a bent knife and Bottom Left) is the broken pivoting knife (Illustration by Daniel Bashford).

Analysis of the assemblage revealed pivoting knife from the 2006 Burdale excavations (Figure 4). This knife had broken just beyond the pivoting pin. The x-radiograph revealed a clear groove in the back of the knife, similar to those seen at York. Very few, if any, pivoting knives have been examined in the past therefore the opportunity was taken to metallographically examine this one. The analysis revealed it was a type 2 butt welded knife. The knife back most likely ran the full length of the knife. The pivoting pin was made of a similar piled iron alloy to the back and was pushed through a hole premade in the knife.

Discussion

The survey of the knives from Burdale has shown that the most common knives deposited were curved-backed knives (Table 6 and figure 5); this was closely followed by the angle-back knife, this pattern is very similar to that at Hamwic (McDonnell *et al.* 1991), Fishergate and Coppergate, York (Ottaway 1992a). Unexpectedly the assemblage at Burdale is different than nearby Wharram Percy which had slightly more angle backed knives than curved knives. There is a clear difference in knife shape between the two Burdale excavation sites with a significant number of angle-backed knives (7 out of 19) recovered during the 2007 excavation while during the 2006 excavation none were recovered. This may reflect a difference in date or in site function.

Settlements	Date	Back Shape					Total	Reference
		A	B	C	D	U/C		
West Stow, Suffolk	5th-7th	14	18	-	6	12	50	(West 1985)
Poundbury, Dorset	5th-7th	3	4	-	1	1	9	(Green *et al.* 1987, 101)
Wharram Percy	7th-8th	6	3	-	-	3	12	(Stamper & Croft 2000, 133-135)
Burdale	8th-9th	7	9	-	2	11	29	
Six Dials, Hamwic	8th-9th	42	66	-	-	24	132	(McDonnell *et al.* 1991)
Fishergate, York	8th-9th	1	15	-	-	13	29	(Rogers 1993, 1273-1276)
Coppergate, York	9th	11	20	-	-	10	41	(Ottaway 1992a, 584)

Table 6: Knife back form for knives from a range of Early Medieval sites in England.

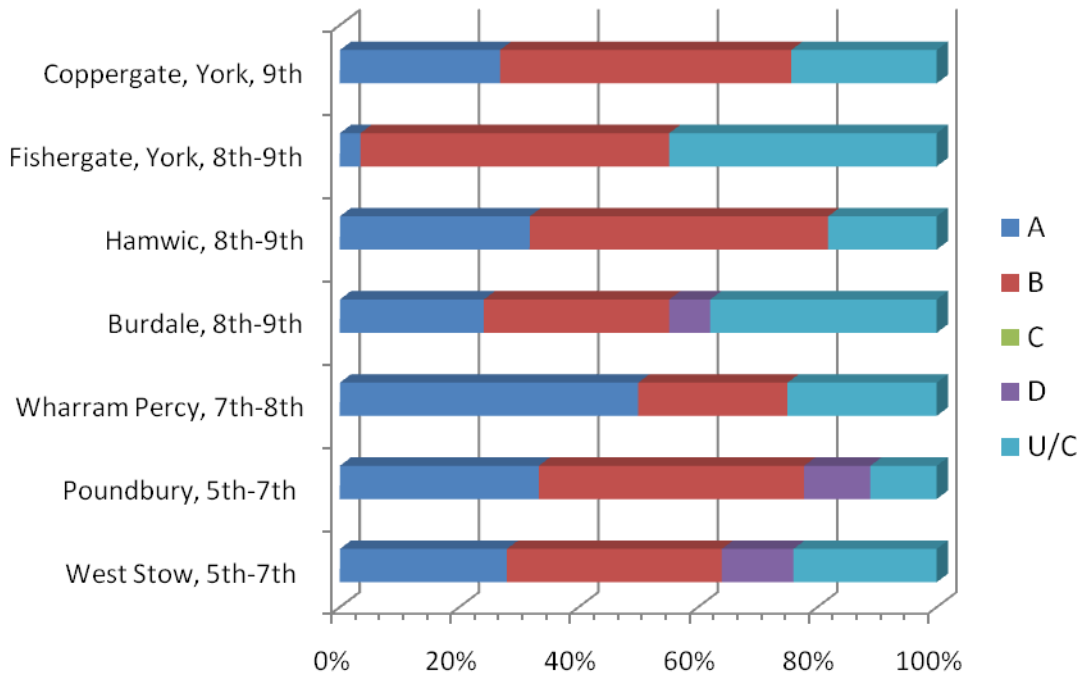


Figure 5: Bar chart of knife back shapes showing the percentage distribution using the table above of each knife back shape at Saxon and Anglo-Scandinavian sites across England.

As noted in the results Burdale like many Middle Saxon settlements was dominated by knives manufactured by butt-welding a cutting edge, often high quality steel, on to a ferritic or phosphoric iron back (Table 7). This pattern was further confirmed by the x-radiograph analysis of the remaining knives which suggests that there are as many as 10 more butt-welded knives, meaning that at least 19 out of 29 (66%) knives from the assemblage are of type 2 manufacture. The analysis also revealed 3 knives with what appeared a spotted texture suggesting steel but no weld line, suggesting that these knives could be type 1 'sandwich type' knives or homogenous steel knives i.e. type 5.

Sites		Manufacturing Typology and Cutting Edge Data						
		0	1	2	3	4	5	Overall
Poundbury, Dorset[1] 5th-7th	Number	1	1	4	1			**7**
	Avg HV	210	245	505	214			**384**
	Range HV	210	245	330-615	214			**210-615**
Wharram Percy[2] 7th-10th	Number	2		9	2			**13**
	Avg HV	185		281	248			**261**
	Range HV	171-199		121-524	182-275			**121-524**
Burdale 7th-9th	Number			10	2	1		**13**
	Avg HV			515	227	549		**473**
	Range HV			210-766	168-286	549		**168-766**
Flixborough[3] 7th -10th	Number	2		11		1		**14**
	Avg HV	204		556		479		**500**
	Range HV	139-268		379-650		479		**139-650**
Six Dials, Hamwic[4] 8th-9th	Number			12			1	**13**
	Avg HV			430			607	**444**
	Range HV			153-813			572-642	**153-813**
Fishergate, York[5] 8th-9th	Number			5				**5**
	Avg HV			445				**445**
	Range HV			314-630				**314-630**
Coppergate, York[6] 9th	Number		1	5		1		**7**
	Avg HV		407	708		309		**608**
	Range HV		407	244-927		309		**244-927**
Settlement Total	**Number**	**5**	**2**	**56**	**5**	**3**	**1**	**72**
	Avg HV	**198**	**215**	**477**	**233**	**446**	**607**	**437**
	Range HV	**139-268**	**245-407**	**121-927**	**168-314**	**309-549**	**572-642**	**121-927**

Table 7: Table showing the number of each knife manufacturing types at each of the different settlement sites including the Burdale. It also shows the average hardness value and the range of hardness values (HV) for the cutting edges for each manufacturing type at the settlement sites. [1](Tylecote 1987), [2](Blakelock 2006a; McDonnell et al. Forthcoming), [3] (Starley 1999), [4] (McDonnell 1987a, 1987b), [5] (Rogers 1993) and [6](Ottaway 1992a).

The good quality manufacture and heat-treatment of the knives from Burdale is reflected in the high hardness seen in table 7. The quality of type 2 knives from Burdale was particularly high and comparable in hardness to knives from Flixborough and far better hardness than those found at nearby Wharram Percy. This is mostly due to the absence of heat treatments at Wharram Percy compared to elsewhere, indicating that the poorer quality of the knives found at Wharram Percy could be a unique case.

Site	Knives Analysed	Average Hardness	Number of Butt-welded knives	Number of Heat Treatments	Number of White Weldlines
Wharram Percy 7th-10th [1]	13	281	9	1	3
Burdale 7th-9th	13	515	10	7	6
Flixborough 7th -9th [2]	6	473	4	5	4
Six Dials, Hamwic 8th-9th [3]	14	517	11	10	5

Table 8: Table showing the knife quality based on the average hardness of the cutting edge, the presence of heat treated steel and white weldlines for the Burdale knives compared to other knives from Middle Saxon sites. [1](Blakelock 2006a; McDonnell et al. Forthcoming) [2](Starley 1999) and [3](McDonnell 1987a, 1987b).

There were a number of features present in the knives from Burdale, similar to those found at Coppergate, York (Ottaway 1992a, 579-582). The presence of not only knives with notches and indents, but also pivoting knife is unusual and may be indicative of craft activities or a high status site. It is notable that at Wharram Percy no knives with transverse notches, indents or pivoting knives were identified (Blakelock 2006b).

Conclusion

Analysis of a 13 of knives from Burdale has revealed a trend in shape and manufacture similar to other Early Medieval settlements such as Hamwic and York, with 10 out of 13 knives butt-welded with an average of 515HV. Comparison with Wharram Percy on the other hand has revealed some interesting differences not only in the overall shape of the knives found but also the methods of manufacture, particularly notable in the heat-treatments carried out and therefore hardness (473HV at Burdale compared to 261HV at Wharram Percy). The other dramatic difference is the presence of surface features on the knives which may be an indicator of craft activity, since they mostly occur in craft orientated urban settlements, e.g. Hamwic and York.

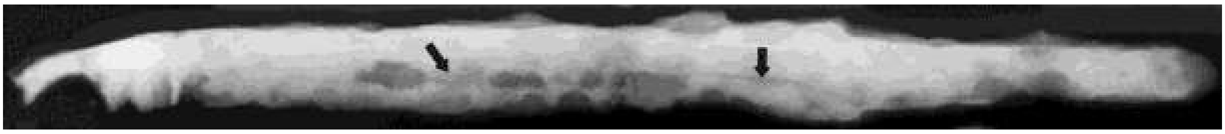
Appendix 1: Full X-Radiograph Methodology

X-radiography of all the knives was performed by Yorkshire Archaeological Trust during post excavation. For this study each X-radiograph was scanned in and saved using an Agfa FS50B scanner with Radview Workstation software with a pixel pitch of 50 microns. The scanner with its associated software allows detailed enhancement and examination of the x-radiographs providing better quality images that can be enhanced and processed.

The corrosion layers present on the knives can often mask the form of the knife, therefore the x-radiographs were used to determine the knife shape. The classification of knife forms encounters the usual problem of objects that are individually hand made, which is that no two will be identical. Classification becomes a question of grouping together similar objects that are similar (Blakelock & McDonnell 2007). There are three very different typologies, Evison, Ottaway and McDonnell. In the Evison typology knives were split into six groups based on whether the back was straight, curved or angled and whether the cutting edge was straight or curved (Evison 1987, 113-117). Classification using the cutting-edge shape has been shown in previous studies to be unreliable because the shape will have been changed during use and sharpening. For this reason Ottaway developed an alternative typology for his study of Anglo-Scandinavian ironwork from Coppergate, using the shape of the knife back as this is unlikely to alter through use (Ottaway 1992a). McDonnell (McDonnell *et al.* 1991) also created a typology, based upon an earlier version of Ottaway's criteria (Ottaway 1987, 86), that took into account the blade to tang interface. As all three typologies are different a new simpler typology has been created, one based solely on the shape of the knife back (Figure 2) (Blakelock & McDonnell 2007). A separate typology is used to examine the tang to blade interface, identifying distinct interfaces on both sides, one side only or blades with no interface (Figure 2). This allows objects to be classified even if a significant proportion of the knife has broken.

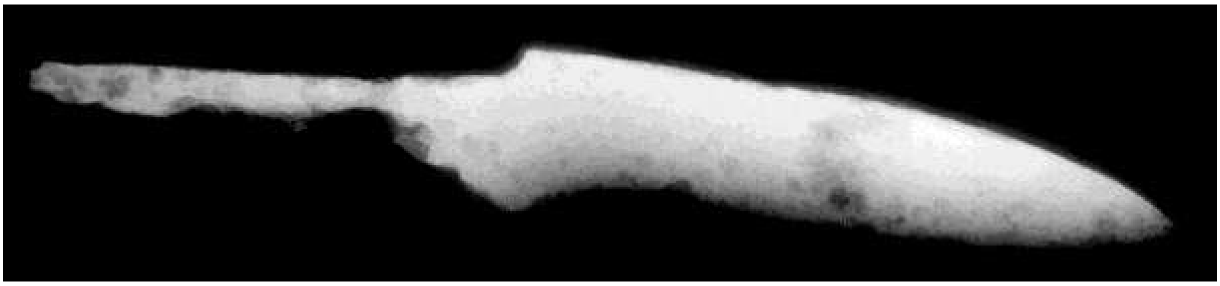
The state of preservation of the knife can be determined from the x-radiographs. This can also reveal areas of particularly bad corrosion, breakages or cracks in the knife. For this study, knives were given a number from 1 to 5, with 1 being execellent preservation and 5 being very heavily corroded. Particularly bad corrosion at the weld line was also noted.

X-radiographs of the knives were examined to assess whether steel edges and/or weld lines could be identified. Weld lines occur as distinct lines on x-radiographs. During the analysis of the Hamwic (McDonnell 1987a, 1987b) and Coppergate knives (McDonnell 1992) it became apparent that the high-quality steel edges had a characteristic x-radiographic image. This 'spotted' appearance was due to the presence of spheroidal slag inclusions, confirmed by metallography, which were enhanced by corrosion penetration; Figure 2 is a good example. This characteristic appearance has also been noted on x-radiographs by Fell and Starley (Fell & Starley 1999; Starley 1996). Therefore a Type 2 knife can be identified by the presence of a weld line, with (or without) the 'spotted' appearance. Type 1 and 5 knives are identified by the presence of steel with the absence of a weld line, although it is difficult to distinguish between them without analysis. Even though features seen in x-radiographs can be essential to the analysis of the assemblage as a whole, metallographic analysis is still required to provide other data eg HV, composition, heat treatment etc



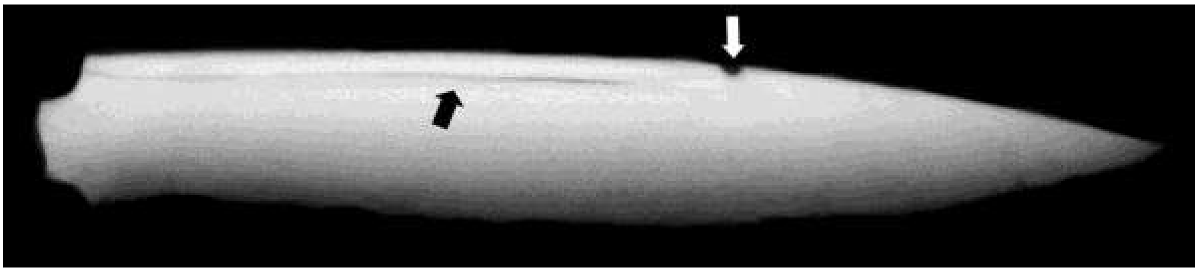
(Figure 6) X-radiograph of knife 75 (A1 type) from Burdale. Note the 'spotted' texture indicative of steel in the cutting edge (bottom strip) and a distinct weld line running along the blade (indicated by arrows).

The x-radiographs were also used to assess the amount of wear present in the knives, therefore assisting in the interpretation of knife use. Ottaway (1992a, 572-574) has suggested that the wear of knives depends on their method of construction. At Coppergate for example the type 1 'sandwich' knives frequently had an elongated S-shape (Figure 7) indicating they were heavily worn (Ottaway 1992a, 572-574). Other studies have shown that this is not always the case as type 2 knives have also been found heavily worn (Blakelock 2007).



(Figure 7) X-radiograph of knife 7695 (B1 type) from Fishamble Street, Dublin showing the distinctive S-shape curved cutting edge indicating wear.

X-radiographs can also reveal other details, which are often by masked by the corrosion products. Transverse notches (Figure 8) have been identified on a number of knives, most often at the shoulder; for example at Coppergate, Thetford, Portchester and Lincoln (Ottaway 1992a, 579-582). It is unknown whether they serve some function, perhaps for cutting thread during leather or textile working. One form of decoration found on some knives is an indented line along the back of each side of the knife (Figure 8). These grooves are most often found on angle-backed knives and are relatively common from the 5th-6th century onwards (Ottaway 1992a, 579-582). Another form of decoration is the inlay and use of non-ferrous metal; this can often be seen as distinct brighter areas on x-radiographs. The final form of decoration, also rather distinct is pattern welding, the pinnacle of the smith's art. The effect is created by forging, twisting and welding together strips of different metals including, ferritic iron, phosphoric iron and high carbon steels (Anstee & Biek 1961; Piaskowski 1964), these strips would then appear as light and dark bands which could be emphasised by etching or due to corrosion, as each metal would have a different resistance to corrosion (Ottaway 1992b, 481; Piaskowski 1964; Wilson 1981, 265-266). Pivoting or folding knives can also be identified using x-radiographs, as they always have a central rivet and tend to also have a specific shape.



(Figure 8) X-radiograph of knife 14725 (A1 type) from Christ Church Place, Dublin. This is an example of a knife with both a notch (white arrow) and an indent (black arrow) in the back.

Appendix 2: Metallographic Methodology

Sections from the knives were taken across the cutting edge of the blade and back, and where possible staggered to preserve the overall knife shape. The knives were secured in a vice, using paper tissues to protect the knife, and the sections removed by cutting with a jewellers piercing saw. In many cases the knives were fragile and some even broke during cutting therefore whole sections were removed using a slow speed wafering saw. The samples were mounted using mounting resin and prepared by grinding on successively finer paper before being polished to a 1-micron finish.

Metallographic examination using a Nikon Optiphot Reflected Light microscope with various objective lenses, ranging from x2.5 to x40, was carried out. Digital images were captured using a camera fitted to the Nikon microscope and FireI imaging software. The microscope was also fitted with a graticule eyepiece, which has 8 options of grain size for comparison at x100 magnification. Each sample was first examined in the as-polished state to investigate the distribution of slag inclusions and corrosion. The sample was then etched for approximately 5 seconds in a weak solution of acid (Nital, 4% nitric acid in alcohol) to reveal the microstructure of the metal.

The Vickers micro-hardness test was used to determine the hardness of different microstructures present in each sample. A load of 200g was applied and the indent measured. Approximately twenty measurements were taken per knife in various areas and the different microstructures present were noted.

The Scanning Electron Microscope with Energy Dispersive X-Ray Analysis (SEM-EDX) was used to determine the elemental composition of the metal. It was calibrated with a cobalt standard. Spectra were collected at 20kV accelerating voltage and 2nA filament curent for 100 seconds live time. The spectra were then quantified using the Oxford Instruments SEMQuant software. To allow for the heterogeneous nature of the metal an average of three or four analyses were carried out in each area of interest.

Appendix 3: Metallographic Results

Knife 64

The x-radiograph revealed a clear weld line but no evidence for a high-quality steel cutting edge. It also revealed that the back was most likely piled, as there were many dark striations clearly visible in the x-radiograph.

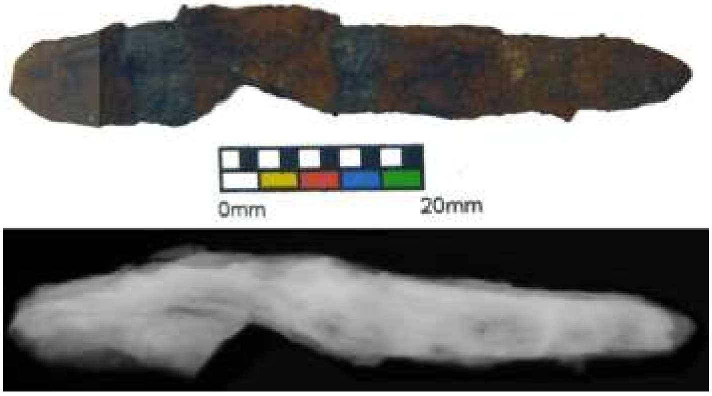


Figure 9: Photograph and x-radiograph of knife 64.

Metallographic analysis of the full section in the un-etched condition revealed a horizontal, slightly convex, weld line consisting of many small spherical single-phased slag inclusions. Below this weld line in the cutting edge there were some fairly large sub-angular single-phase inclusions. The back consisted of many bands of differing inclusion types, suggesting a piled iron back. Some of the bands consisted of small spherical voids while other areas contained sub-angular single- and multi-phased inclusions. Many of the bands of inclusions had some corrosion penetration which was clearly seen on the x-radiographs.

When etched the cutting edge consisted of predominately tempered martensite with some pearlite at the weld line (*Average* $490HV_{0.1}$, *Range* 362-$701HV_{0.1}$). At the very tip of the cutting edge there were areas that resembled martensite and the high hardness confirmed this ($701HV_{0.1}$). SEM-EDS analysis revealed the presence of small quantities of phosphorus in the cutting edge, up to 0.2%. The cutting edge also appeared to be separated by a faint vertical white weld line, although few, if any slag inclusions were present. There was significant carbon diffusion across the horizontal convex white weld line (*Average* $234HV_{0.1}$, *Range* 175-$264HV_{0.1}$). The white weld line was particularly enriched in Nickel in areas, up to 2.4% but arsenic was also present in high quantities (0.2-0.3%). The back consisted of many bands of ferritic and phosphoric iron. Just above the weld line the carbon diffusion had resulted in a mid carbon steel 0.3-0.4% carbon with grains of ferrite surrounded by pearlite, and some ghosting (*Average* $162HV_{0.1}$, *Range* 137-$187HV_{0.1}$). The rest of the back consisted of heterogeneous bands of iron; ranging from small grains of ferrite (*ASTM 7-8*) with ghosting, to ferrite and pearlite (mid carbon steels with up to 0.3-0.4% carbon) with no evidence for ghosting but Widmanstätten structures (*Average* $104HV_{0.1}$, *Range* 91-$116HV_{0.1}$). The bands which had many small voids had no grain boundaries but the ghosting present suggested phosphoric iron (*Average* $139HV_{0.1}$, *Range* 132-$148HV_{0.1}$). SEM analysis confirmed that some of the bands in the back contained significant quantities of phosphoric iron (0.2-0.3%), while others were clearly ferritic.

Figure 10: Mapped section of knife 64 in the un-etched (left) and etched condition (right).

Knife 65

The x-radiograph revealed a clear weld line present in this knife, below which there was also evidence for a high quality steel cutting edge.

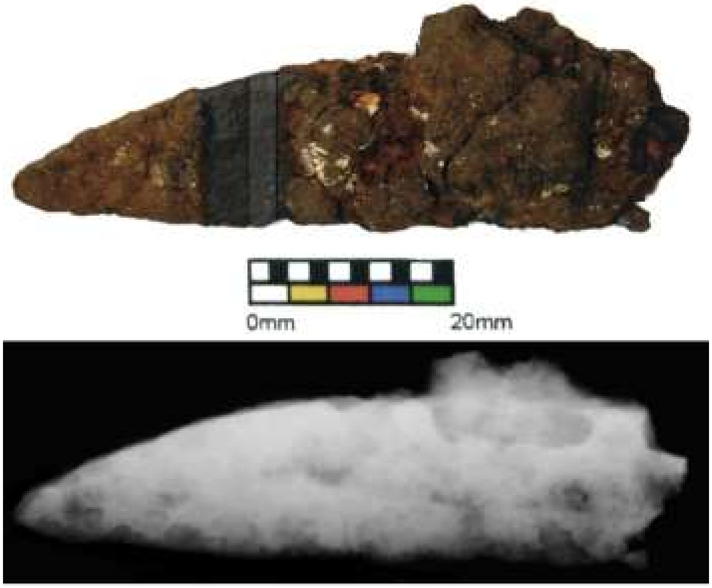


Figure 11: Photograph and x-radiograph of knife 65.

In the un-etched condition there was evidence for a horizontal scarf weld line consisting of sub-rounded mostly single-phased slag inclusions. The back had a range of slag inclusion types ranging from small elongated single-phased inclusions to large sub angular single- and multi-phased inclusions. In addition there was ghosting present particularly in the top left part of the back. The cutting edge seemed to have two different areas of inclusions; near the weld line there were few small single-phased inclusions, most of which were elongated. The other area closer to the tip of the cutting edge had both large, small, single- and multi-phased inclusions most of which appeared either sub-angular or elongated.

When etched the back had very large grains (*ASTM 1 and bigger*) with ghosting clearly visible (*Average 209*$HV_{0.1}$*, Range 161-244*$HV_{0.1}$), all these factors strongly phosphoric iron is present, confirmed by the extremely high phosphorus content detected during SEM Analysis (between 0.4-1%). There was no white weld line, instead the weld was very distinct with very little, if any, carbon diffusion, again supporting the presence of phosphoric iron in the knife back. The cutting edge was rather unusual as there were two different areas present. Just below the weld line there was an area of fine pearlite and tempered martensite, in areas there was even some lightly tempered martensite present (*Average 578*$HV_{0.1}$*, Range 362-766*$HV_{0.1}$). This area coincided with the small elongated single-phased inclusions, SEM analysis also revealed the presence of phosphorus (0.1-0.2%). Below this, near the tip of the cutting edge the microstructure changed dramatically from a well heat-treated blade to an area of phosphoric iron (0.2-0.3% phosphorus) with large grains (*ASTM 4-6*) and ghosting, this resulted in a lower hardness for the tip of the cutting edge (*210*$HV_{0.1}$*, Range 183-232*$HV_{0.1}$).

Figure 12: Mapped section of knife 65 in the un-etched (left) and etched condition (right).

Knife 67

Analysis of the x-radiograph revealed a clear butt-weld line with a spotted texture below suggesting a steel cutting edge.

Figure 13: Photograph and x-radiograph of knife 67.

In the un-etched condition the butt-weld line had many elongated multi-phased inclusions but was clearly visible due to its raised appearance suggesting enrichment from either phosphorus or arsenic. Below the weld line there were some small single-phased inclusions. The back consisted of two, maybe three, pieces of metal with different types of inclusions. Just above the weld line the inclusions were single-phased and elongated but further up into the back there were increasing numbers of single- and multi-phased elongated inclusions.

After etching the weld line was confirmed as a white weld line (*Average 178HV*$_{0.1}$*, Range 161-201HV*$_{0.1}$) which was enriched in arsenic (0.6-2.0%) but also in nickel up to (0.3%). Just below the weld the microstructure was pearlite with ferrite although some spheriodisation appears to have started to occur. About half way down the cutting edge the microstructure transformed into pearlite (*Average 178HV*$_{0.1}$*, Range 143-232HV*$_{0.1}$) and the very tip of the cutting edge was predominately tempered martensite (*549HV*$_{0.1}$*, Range 441-549HV*$_{0.1}$). There was some carbon diffusion across the weld line into the knife back. The back of the knife consisted of two different areas, possibly representing different pieces of metal. The first, closest to the weld line had small grains of ferrite (*ASTM 4-5*) with some grain boundary pearlite 0.1-0.2% carbon (*Average 111HV*$_{0.1}$*, Range 103-127HV*$_{0.1}$). Further in the back the carbon content decreases till there is no pearlite, in addition the grain size increases (*ASTM 2-3*), there is no evidence for ghosting and the low hardness suggests an absence of phosphoric iron (*Average 108HV*$_{0.1}$*, Range 91-137HV*$_{0.1}$), confirmed by SEM analysis.

Figure 14: Mapped section of knife 67 in the un-etched (left) and etched condition (right).

Knife 69

There was a clear weld line present in this knife in the x-radiograph. The cutting edge did not have a spotted texture.

Figure 15: Photograph and x-radiograph of knife 69.

The full section revealed a possible weld line of small spherical single-phased slag inclusions. Below this weld line, in the cutting edge the inclusions were small, single-phased and sub-rounded. The back consisted of bands of iron, some which had very few inclusions with those present sub-angular and single-phased while other areas had many angular and elongated multi- and single-phased inclusions.

When etched the entire knife appears to have been made from a mid to high carbon steel. The cutting edge is tempered martensite, with some areas of pearlite near the weld line ($257HV_{0.1}$, *Average* $377HV_{0.1}$, *Range* $183\text{-}457HV_{0.1}$). A white weld line (*Average* $223HV_{0.1}$, *Range* $187\text{-}244HV_{0.1}$) separates the cutting edge from the back. SEM analysis confirmed the presence of 0.2-0.3% As. There appears to have been some carbon diffusion over the weld line forming an area of roughly equal amounts of ferrite and pearlite (*Average* $206HV_{0.1}$, *Range* $201\text{-}210HV_{0.1}$). The inclusions had hinted at various bands of iron in the back which etching had confirmed. One band contained small grains of ferrite (ASTM 8) with some grain boundary pearlite 0.0-0.2% carbon (*Average* $187HV_{0.1}$, *Range* $183\text{-}187HV_{0.1}$), this coincided with the area with very few inclusions. Even so the predominate microstructure of the back consisted of pearlite with some grain boundary ferrite 0.6-0.8% carbon (*Average* $230HV_{0.1}$, *Range* $210\text{-}264HV_{0.1}$). Although there is a significant quantity of carbon in the back the presence of a clear weld line confirms that this knife is of type 2 manufacture. SEM analysis revealed no presence of phosphorus or other elements.


Figure 16: Mapped section of knife 69 in the un-etched (left) and etched condition (right).

Knife 70

Analysis of the x-radiograph revealed the presence of a clear weld line with a spotted texture suggesting a steel cutting edge particularly in the back of the knife.

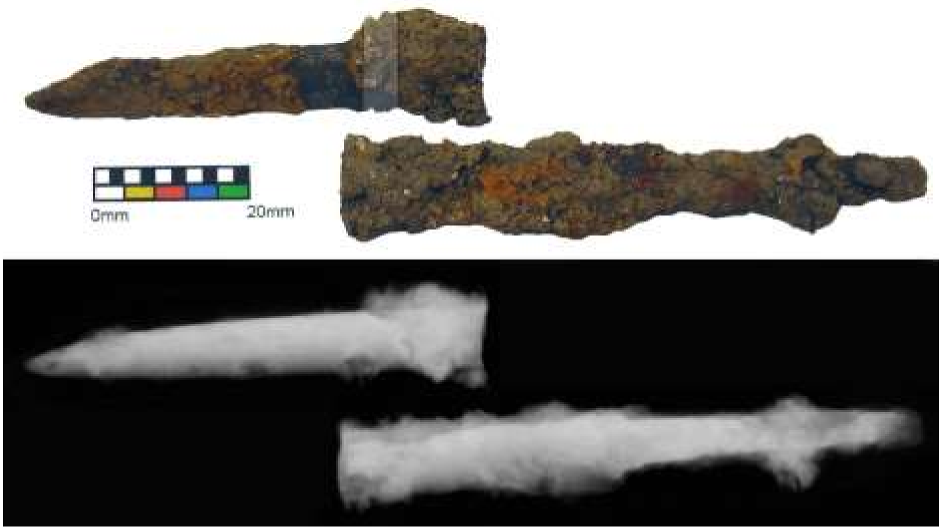


Figure 17: Photograph and x-radiograph of knife 70.

In the un-etched condition there was a clear horizontal, slightly convex line of small single-phased inclusions. The inclusions present in the cutting edge were predominantly small, single-phased and elongated. While those present in the knife back varied in shape and size but were mostly multi-phased. The inclusions in the back formed bands, some of which had heavy corrosion penetration.

After etching the cutting edge appeared far more complicated than the inclusions originally suggested. A white weld line enriched in both arsenic and nickel *($210HV_{0.1}$)* with some small, elongated, single-phased inclusions separated it into two halves. The microstructure varied, with decreasing carbon content, from a pearlite structure 0.8% carbon at the weld line to a ferrite with pearlite (0.4% carbon) structure at the edge of the knife (*Average $271HV_{0.1}$, Range 210-$362HV_{0.1}$*). The tip of the cutting edge consisted of a tempered martensite (732$HV_{0.1}$, *Range 473-$766HV_{0.1}$*). There was a thin yellow weld line separating the cutting edge from the back, and some carbon diffusion into the back. The inclusions in the knife back suggested a piled structure but the microstructure in the back was fairly homogenous with large grains of ferrite (*ASTM 3-4*) and no ghosting (*Average $137HV_{0.1}$, Range 118-$161HV_{0.1}$*). SEM-EDS analysis confirmed that the back was mainly ferritic iron.

Figure 18: Mapped section of knife 70 in the un-etched (left) and etched condition (right).

Knife 75

This knife was bent 30mm from the tip. The x-radiograph revealed the clear presence of a weld line and also the spotted texture that indicates a high quality steel. Two sections were removed from the knife, one near to the bent area while the second was taken from a straight section near the tang knife, this was to investigate the affect that bending the knife may have on the microstructure.

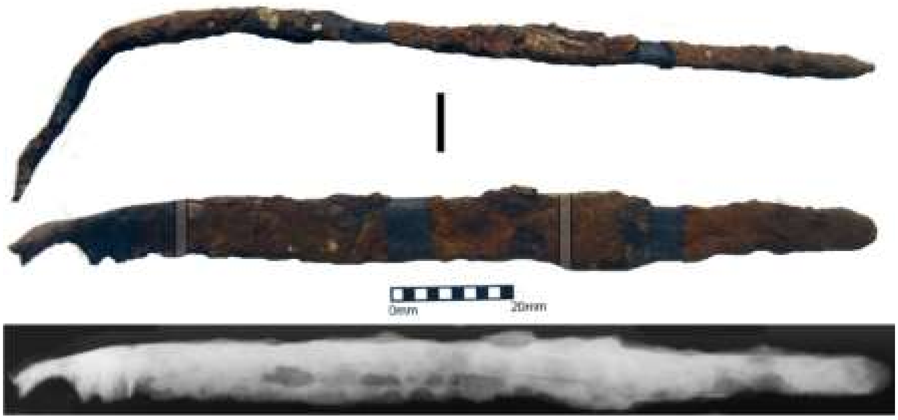


Figure 19: Photograph and x-radiograph of knife 75.

In the un-etched condition both sections were similar. There was a concave line of small slag inclusions concave in the section taken from the bent end but in the other section the weld was scarf. In the section furthest away from the bent tip there was particularly bad corrosion penetration, which was clearly seen in the x-radiograph. The cutting edge below was very clean with very few, very small spheroidal inclusions present. Just above the weld line the majority of inclusions were single- and multi-phased, but further in the back of the knife the inclusions present were much larger and angular, possibly suggesting that the back was constructed from two pieces of iron.

When etched there was no white weld line visible. The cutting edge in both knives was a high-quality, high carbon steel (1% carbon) as the grain boundary cementite was clearly visible in the corrosion products (Notis 2002). In the section closest to the bent tip the pearlite with cementite ($473HV_{0.1}$) transformed into tempered martensite at the very tip ($549HV_{0.1}$, *Range* $549HV_{0.1}$). The other section had very fine pearlite ($441HV_{0.1}$, *Average* $380HV_{0.1}$, *Range* $340\text{-}441HV_{0.1}$). The back of the knife consisted of two areas, corresponding well to the difference in inclusion types. Just above the weld line in both sections there was an area with medium to large grains (*ASTM 3-4*) with no pearlite or ghosting (*Average* $159HV_{0.1}$, *Range* $103\text{-}210HV_{0.1}$). The very back of the knife, with larger slag inclusions, had a microstructure consisting of small grains of ferrite (*ASTM 8*) with grain boundary pearlite 0.1-0.3% increasing to high carbon pearlite with ferrite 0.4-0.6% (*Average* $208HV_{0.1}$, *Range* $161\text{-}271HV_{0.1}$). SEM Analysis also revealed a difference between the two pieces of iron.

The act of bending the knife does not seem to have had an effect on the microstructure of the knife itself. There is no evidence for Neumann bands. Apart from tempered martensite at the tip of the knife the cutting edge has not been significantly heat treated, possibly the knife was possibly annealed prior to the bending suggested by the low hardness of the tempered martensite.

Figure 20: Mapped section of knife 75 in the un-etched (left) and etched condition (right).

Figure 21: Mapped section near the bent end of knife 75 in the un-etched (left) and etched condition (right).

Knife 76

Again this knife had been bent. The x-radiograph revealed a weld line, which through corrosion penetration and possibly the act of banding has caused the knife to split at the weld line. In addition to this the knife was very blunt and may represent a stage between the bar and the manufacture of a knife.

Figure 22: Photograph and x-radiograph of knife 76.

During cutting the section broke, leaving two pieces, due to the corrosion present in the weld line seen in the x-radiograph. One section represented the cutting edge and the other was the knife back. In the un-etched state the back appeared to be three, possibly four, pieces of iron. One area of the knife was incredibly clean of inclusions while the others areas had lots of small single and multi-phased slag inclusions. A band of inclusions with corrosion penetration were noted forming a possible weld line. The cutting edge consisted of mostly small single phased inclusions. There was also a crack in the cutting edge but this did not seem to delineate between different pieces of iron. SEM analysis revealed an absence of phosphorus in the knife back.

When the back section was etched it appeared to consist of varying sized grains of ferrite with little carbon. One area consisted of large grains (*ASTM 2-3*) this coincided with the area that had very few inclusions (*Average* $188HV_{0.1}$, *Range* 154-$221HV_{0.1}$). To the left of this area is a more heterogeneous region with medium to small grains (*ASTM 4-6*, *Average* $190HV_{0.1}$, *Range* 175-$221HV_{0.1}$). Below this area the grain size decreased (*ASTM 6, Average* $172HV_{0.1}$, *Range* 137-$201HV_{0.1}$). The possible weld line noted in the un-etched condition separated the above areas from a piece of metal which had medium sized grains (*ASTM 4, Average* $182HV_{0.1}$, *Range* 151-$201HV_{0.1}$). The cutting edge was predominately pearlite (*Average* $272HV_{0.1}$, *Range* 244-$321HV_{0.1}$) with a bit of pearlite with ferrite near one edge, presumably where the carbon had diffused over the weld line.

Figure 23: Mapped section of knife 76 in the un-etched (left) and etched condition (right).

Knife 113

Figure 24: Photograph and x-radiograph of knife 113.

This knife was very badly bent which meant that x-radiographs would not reveal anything about its manufacture. In the un-etched condition this knife had many elongated single- and multi-phased slag inclusions orientated vertically, suggesting a piled knife. When etched the microstructure consisted of bands of large grains of ferrite (*ASTM 3-4, Average 163*$HV_{0.1}$*, Range 158-168*$HV_{0.1}$), to bands of small grained ferrite with grain boundary pearlite (*ASTM 6-7, Average 148*$HV_{0.1}$*, Range 116-176*$HV_{0.1}$). In the back of the knife possible neumann bands were identified suggesting that this knife was significantly cold worked, most likely when it was bent. This knife had no obvious deliberate welds and therefore is a type 3 piled knife.

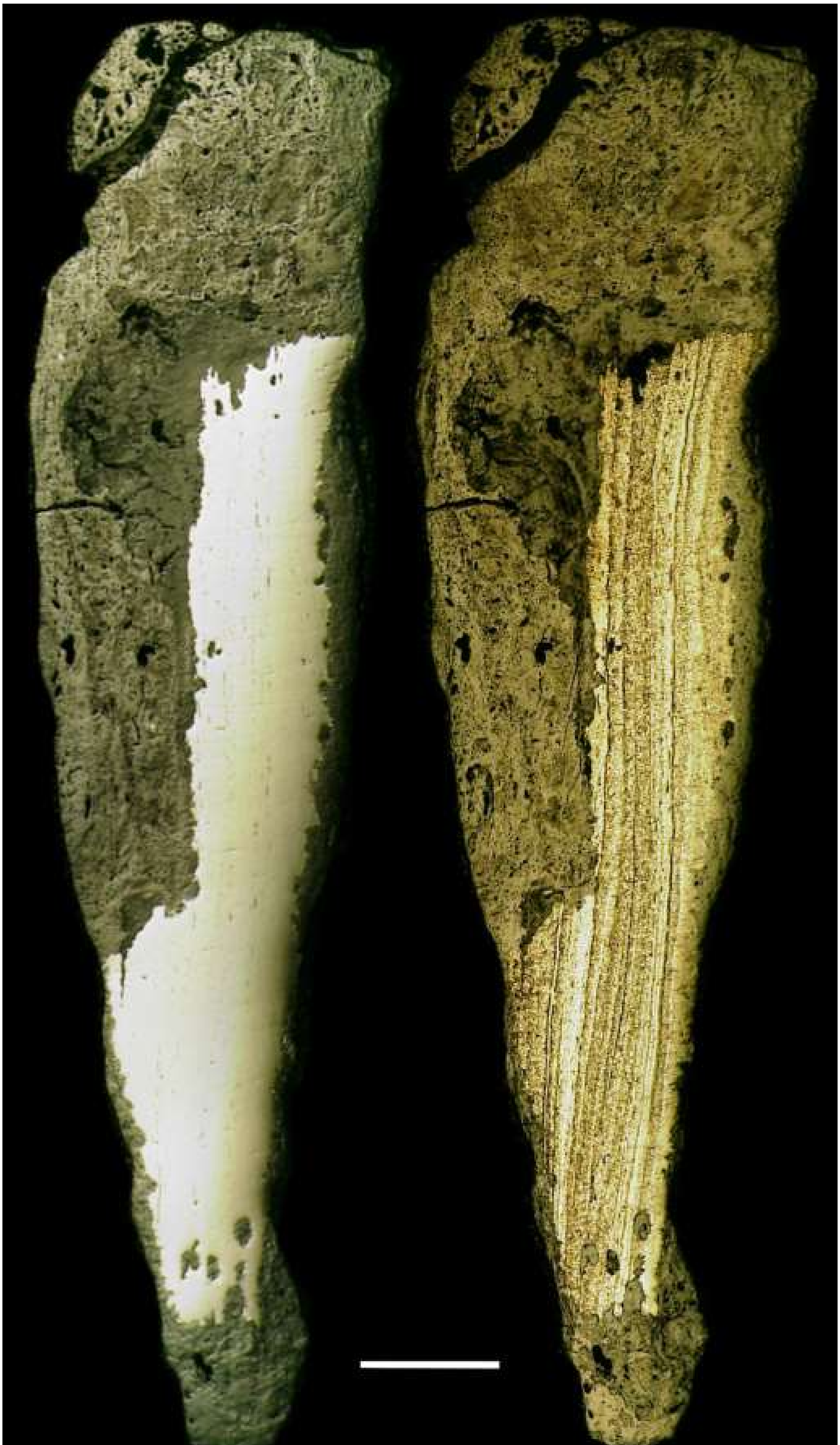


Figure 25: Mapped section of knife 113 in the un-etched (left) and etched condition (right).

Knife 200

X-radiography of this knife revealed that it was badly corroded, especially the cutting edge. There was a clear weld line near the tang and the texture below suggested a steel cutting edge.

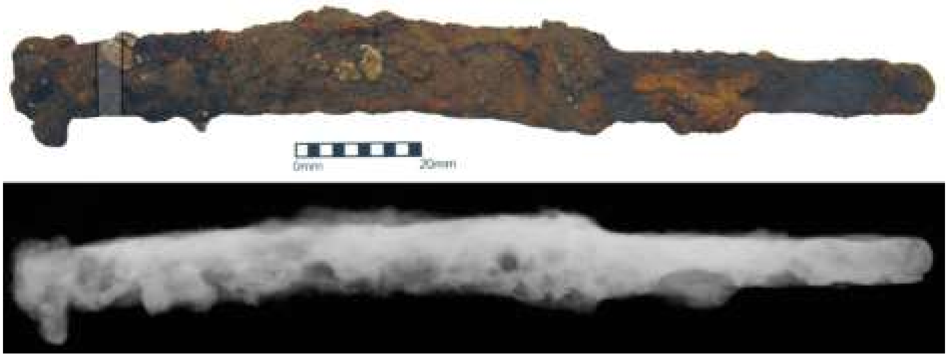


Figure 26: Photograph and x-radiograph of knife 200.

Un-etched the section revealed the full extent of the corrosion, not only had much of the outside and cutting edge corroded but there was corrosion penetration within the knife, most likely from a weld line in the back of the knife. Even with the bad corrosion a second weldline, presumably separating the cutting edge from the back was visible consisting of many sub-angular and spheroidal single-phased inclusions. Below this line in the cutting edge there were very few inclusions which were all single-phased and angular. Above the weld line in the back of the knife there was a range of inclusions from large angular ones to smaller sub-angular, both single and multi-phased. Above the corrosion penetration there were fewer single-phased sub-angular inclusions.

After etching a white weld line, enriched in nickel (0.3%) and arsenic (0.1-0.4%), separated what remained of the cutting edge from the knife back. The cutting edge consisted of tempered martensite, with some marteniste in areas (*671HV$_{0.1}$, Average 555HV$_{0.1}$, Range 386-701HV$_{0.1}$*). There was significant carbon diffusion across the weld line into the back resulting in small grains of pearlite, degrading to ferrite with pearlite (*Average 216HV$_{0.1}$, Range 196-232HV$_{0.1}$*). Above this the back consisted of very large grains with no pearlite (*ASTM 1-3*) and also no ghosting (*Average 155HV$_{0.1}$, Range 130-168HV$_{0.1}$*). Beyond the corrosion penetration the grain sizes decreased (*ASTM 3-5, Average 128HV$_{0.1}$, Range 94-164HV$_{0.1}$*). SEM analysis of the iron revealed an absence of phosphorus, suggesting ferritic iron.

Figure 27: Mapped section of knife 200 in the un-etched (left) and etched condition (right).

Knife 204

Analysis of the x-radiograph revealed the presence of a weld line half way up the blade, under this weld line the spotted texture suggested a steel cutting edge. There was also a possible indent in the back of the knife suggested by a line dark dense line.

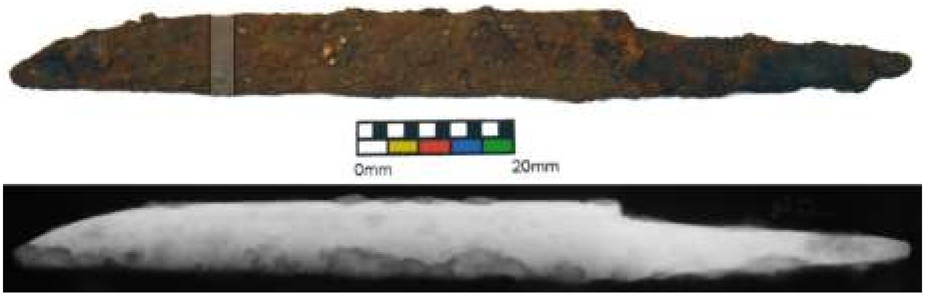


Figure 28: Photograph and x-radiograph of knife 204.

Before the sample was etched a horizontal, convex line of very small single- and multi-phased spheroidal inclusions was clearly visible splitting the knife roughly in half. Below this weld line in the cutting edge there were very few inclusions most of which were small, elongated and single-phased. The inclusions in the knife back revealed that at least two pieces of iron had been used; one formed a core with the other, possibly piled iron, wrapped around the outside. The core like the cutting edge had few small single-phased inclusions most of which were sub-rounded. The iron surrounding it had lots of elongated single- and multi-phased inclusions.

The cutting edge of this knife consisted of fine pearlite or bainite, with no evidence for heat treatment ($441HV_{0.1}$, *Average* $369HV_{0.1}$, *Range* $303\text{-}441HV_{0.1}$). This cutting edge was separated from the knife back by a white weld line (*Average* $239HV_{0.1}$, *Range* $201\text{-}271HV_{0.1}$) which was enriched in arsenic (0.2-1.3%), there was a limited amount of carbon diffusion across the weld line. The back of the knife was constructed of two pieces of iron, the core consisted of small grains (*ASTM 6*) of pearlite with grain boundary ferrite degrading to pearlite and ferrite, i.e. high to mid carbon steel 0.7-0.4% carbon (*Average* $172HV_{0.1}$, *Range* $140\text{-}183HV_{0.1}$). SEM analysis revealed the presence of some phosphorus in low quantities up to 0.2%. The iron surrounding this core was heterogeneous and appeared to be piled iron, but the microstructure was predominately large grains of ferrite (*ASTM 3-4*) with no evidence for ghosting even so it contained more phosphorus (0.1-0.3%) than the core (*Average* $178HV_{0.1}$, *Range* $143\text{-}215HV_{0.1}$).

Figure 29: Mapped section of knife 204 in the un-etched (left) and etched condition (right).

Knife 208

This knife had been broken in antiquity. The x-radiograph did not reveal the presence of any weld lines but did suggest that there may be some corrosion penetration.

Figure 30: Photograph and x-radiograph of knife 208.

The un-etched section revealed that the knife was badly corroded, on the outside but also within. There were no clear weld lines although vertical orientated elongated inclusions were present throughout. The inclusions present were mostly small single- and multi-phased inclusions. Many small spherical holes were identified, often forming bands across the knife section.

When etched there was no evidence for high-quality steel. There were occasional bands of pearlite which separated different microstructural areas; from small grains of ferrite with some pearlite and ghosting in areas (*ASTM 6, Average 380*$HV_{0.1}$*, Range 340-441*$HV_{0.1}$), large grains of ferrite (*ASTM 5-6)* to very small grains of ferrite with grain boundary carbides at the back of the knife (*ASTM 8, Average 341*$HV_{0.1}$*, Range 232-412*$HV_{0.1}$). SEM analysis revealed the presence of phosphorus throughout the section (0.2-0.4%)

Figure 31: Mapped section of knife 208 in the un-etched (left) and etched condition (right).

Knife 218

The x-radiograph did not reveal the presence of a weld line but did suggest the presence of steel in the cutting edge. There was significant corrosion visible, particularly in the cutting edge.

Figure 32: Photograph and x-radiograph of knife 218.

In the unetched condition there were no clear horizontal weld lines instead many of the inclusions were elongated and vertically orientated, most were single-phased but some had multiple phases. The inclusions in the back of the knife were small and single-phased.

After etching the knife was revealed to be a type 4, with an iron core and a steel cutting edge wrapped around it. The steel cutting edge mostly consisted of pearlite in areas but also carbides (*Average 327HV$_{0.1}$, Range 232-386HV$_{0.1}$*), but near the tip of the cutting edge this became tempered martensite suggesting the knife had been heat treated (*Average 529HV$_{0.1}$, Range 509-549HV$_{0.1}$*). There was no carbon diffusion from the cutting edge into the back most likely due to the presence of phosphoric iron, as noted by the large grains, ghosting and high hardness (*Average 192HV$_{0.1}$, Range 148-232HV$_{0.1}$*). Confirmed by SEM analysis which revealed phosphorus was present throughout the sample, ranging from 0.2 to 0.4%. The back was fairly heterogeneous as there were pearlitic areas particularly in the very back of the knife which had high carbon contents 0.3-0.7% carbon also had lower concentrations of phosphorus, 0.1-0.2% (*Average 269HV$_{0.1}$, Range 221-303HV$_{0.1}$*).

Figure 33: Mapped section of knife 218 in the un-etched (left) and etched condition (right).

Knife 244

Examination of the x-radiograph revealed the presence of a weld line and the spotted texture which suggests a high-quality high carbon steel.

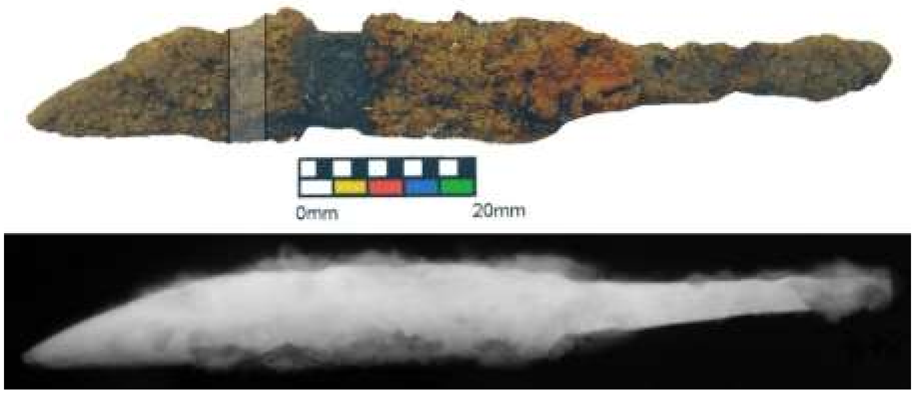


Figure 34: Photograph and x-radiograph of knife 244.

In the un-etched state there was a clear convex horizontal weld line of small multi-phased inclusions. The cutting edge below had both small and large single-phased inclusions. The back of the knife appeared piled with many vertically orientated elongated inclusions, these separated areas with different types of inclusions but the majority were sub-angular, single- and multi-phased inclusions.

A white weld line clearly separated the cutting edge from the piled iron back, when analysed it was found to be enriched in arsenic (0.4-0.6%) and nickel (0.1-0.4%). There was very little carbon diffusion across the weld line but in the cutting edge there was an area of low carbon ferrite with pearlite at the grain boundaries (*Average* $156HV_{0.1}$, *Range* $137\text{-}175HV_{0.1}$). The rest of the cutting edge appeared to be particularly good quality as it was predominately tempered martensite but there was also some martensite and retained austenite present near the tip of the cutting edge ($766HV_{0.1}$, *Average* $651HV_{0.1}$, *Range* $441\text{-}927HV_{0.1}$). The back of the knife was piled with bands of varying microstructures; large grains of ferrite with ghosting (*ASTM 3-4, Average* $159HV_{0.1}$, *Range* $148\text{-}168HV_{0.1}$), small grains of ferrite with ghosting or pearlite and/or carbides(*ASTM 6-8, Average* $201HV_{0.1}$, *Range* $183\text{-}210HV_{0.1}$) to medium sized grains with ghosting (*ASTM 5, Average* $175HV_{0.1}$, *Range* $168\text{-}183HV_{0.1}$). SEM analysis of the back revealed that phosphorus was present throughout the knife back (0.1-0.5%) but absent from the cutting edge, except in the area of low carbon ferrite which had 0.1% phosphorus.

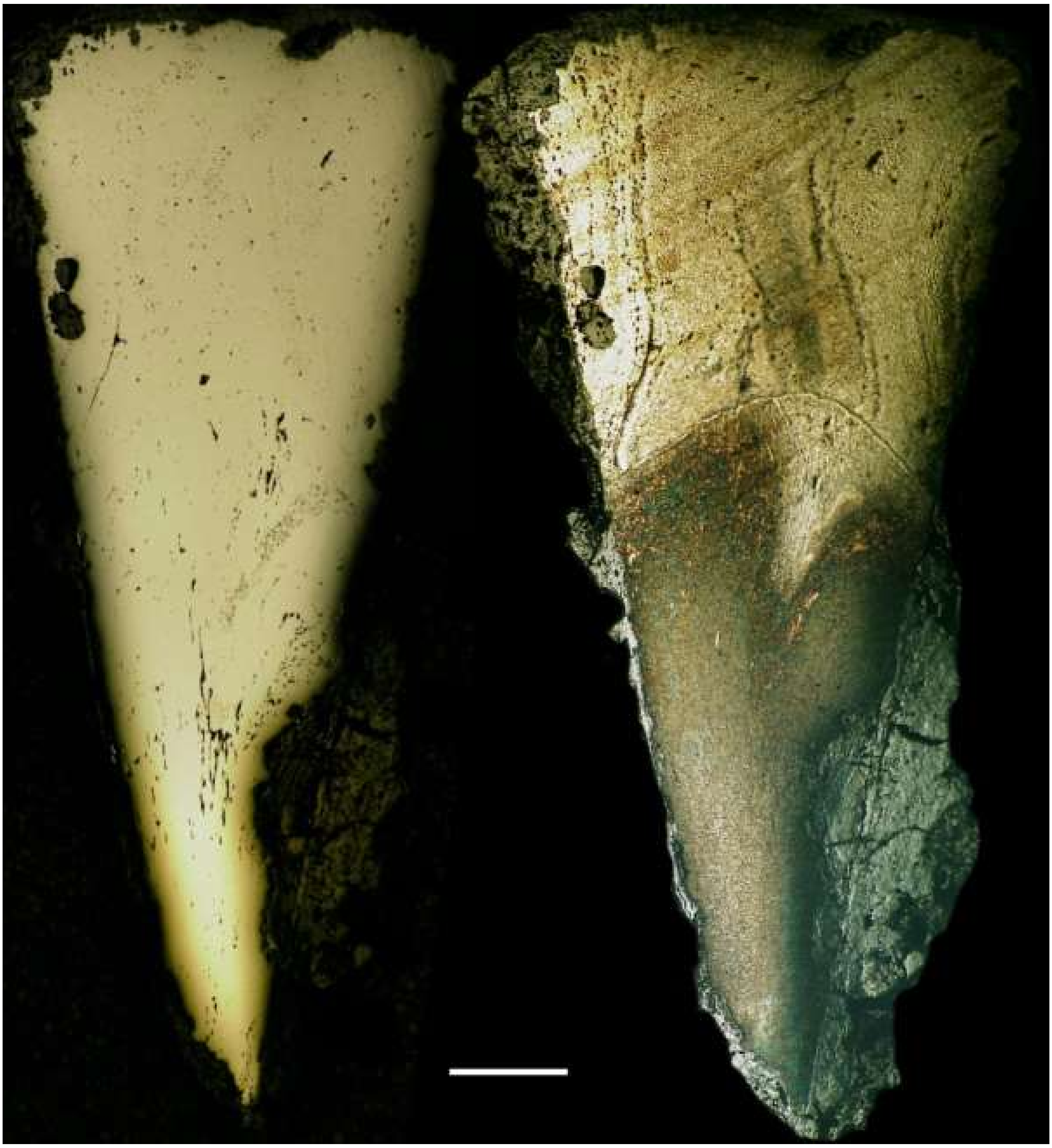


Figure 35: Mapped section of knife 244 in the un-etched (left) and etched condition (right).

Pivoting Knife 4

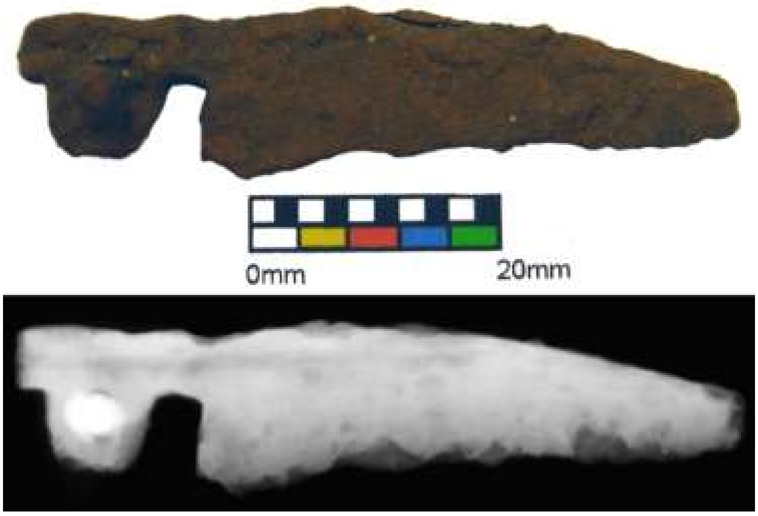


Figure 36: Photograph and x-radiograph of knife 4.

Pivoting knives are rare finds in Early Medieval Britain. Therefore this study offered the opportunity to analyse metallography of a pivoting knife. Sections were removed from both the knife back and the cutting edge, but also a section was taken from the pivoting point itself. The x-radiograph suggested a no evidence for a weld line, although the spotted texture was seen.

In the unetched condition there was a clear convex weld line made up of spherical single-phased slag inclusions. Below the weld line in the cutting edge there were very few inclusions all single-phased and angular. Above the weld line in the back there were two vertical bands of multi-phased inclusions, these bands also appeared raised in the un-etched condition. These separated three bits of iron with small single-phased inclusions, which were either elongated or sub-rounded.

When etched the cutting edge was revealed to be predominately a fine pearlite or bainite (*Average 631*$HV_{0.1}$*, Range 618-644*$HV_{0.1}$), in some areas tempered martensite was also seen (*Average 438*$HV_{0.1}$*, Range 386-473*$HV_{0.1}$). The weld line separating the cutting edge from the back was a white weld line (*Average 323*$HV_{0.1}$*, Range 303-362*$HV_{0.1}$) enriched in arsenic. The back was split into three pieces of iron by the two bands of inclusions which also turned out to be white weld lines. One piece of iron (left side) consisted of large grains of ferrite (*Average 129*$HV_{0.1}$*, Range 107-143*$HV_{0.1}$, ASTM 5-6) with grain boundary pearlite up to 0.2% or in some cases carbides. The other two pieces of iron had smaller grains of ferrite (ASTM 8) and also a higher carbon content up to 0.4% (*Average 186*$HV_{0.1}$*, Range 148-210*$HV_{0.1}$).

Figure 37: Mapped section of pivoting knife 4 in the un-etched (left) and etched condition (right).

The section of the pivoting point revealed that the whole of the back was constructed from the same piece of phosphorus free piled iron, This was particularly clear since both the two white weld lines and microstructures were the same, even with similar hardness for the large grained ferrite (*Average* $143HV_{0.1}$*, Range* $132\text{-}152HV_{0.1}$) and small grained mild steel (*Average* $170HV_{0.1}$*, Range* $148\text{-}192HV_{0.1}$). In the unetched condition the pin had similar inclusions to the knife back, with two clear bands of inclusions. When etched these bands appeared as white weld lines. The knife pin consisted of two different microstructures the first closest to the cutting edge consisted of a small grained (ASTM 7-8), mild steel with up to 0.4% carbon (*Average* $298HV_{0.1}$*, Range* $271\text{-}321HV_{0.1}$). The other was a large grained ferrite (ASTM 1-2, *Average* $206HV_{0.1}$*, Range* $183\text{-}232HV_{0.1}$). Unlike in the knife section the pin consisted of phosphoric iron with between 0.1 to 0.3% phosphorus. The pin was placed in a hole, which appears to have been pushed through from one side as the white weld lines in the knife back near the pivot have been distorted but this most likely while the iron was still hot as there are no neuman bands.

Figure 38: Mapped section of the pivot point in pivoting knife 4 in the un-etched (top) and etched condition (bottom).

Appendix 4: Summary Table

Knife No	Year	Context	Morphology		Length (mm)			Width (mm)		Thickness (mm)	Wear	Manufacture Details		Other details
			Back	Tang	Total	Blade	Tang	Blade	Tang			Weld Line	Spotted	
4	2006	1000	A	x	57	43	14	13	4	2	Some	x	y	Pivoting, Angle starts 15mm from tip
8	2006	1001	x	2	85	40	45	15	10	3	Some	x	y	
26	2006	1010	B	3	90	60	30	10	6	3	Some	y	y	
123	2006	1088	x	4	64	44	20	18	4	5	Unknown	y	y	Broken tip
200	2006	6194	x	3	148	93	55	18	10	3	Some	y	y	
204	2006	6197	B	1	115	87	28	11	7	3	Some	y	y	
205	2006	6197	B	4	67	45	22	11	8	3	Some	y	y	Angle starts 15mm from tip
208	2006	I SE	x	3	50	37	13	12	6	3	Slight	x	y	Broken
210	2006	H SE	x	3	60	25	35	14	6	2	Unknown	y	x	Broken
217	2006	F SE	B	3	110	82	28	12	6	3	Some	x	y	
218	2006	E SE	B	1	100	65	35	14	7	3	Some	x	y	Angle starts 15mm from tip
52	2007	1046	x	1	36	28	8	12	4	2	Unknown			Broken just after tang interface
64	2007	1004	B	4	64	32	32	10	8	2	Very	y	x	
65	2007	1004	B	3	62	60	2	15	15	2	Slight	y	y	Broken just after tang interface
67	2007	1018	A	3	87	53	34	14	7	3	Slight	y	y	
68	2007	1018	B	4	102	85	17	12	6	2	Slight	y	x	Angle starts 30mm from tip
69	2007	1019	D	3	109	78	31	14	8	4	Some	y	y	
70	2007	1050	B	1	140	100	40	12	7	2	Slight	x	x	Angle starts 10mm from tip
72	2007	1066	x	2	70	58	12	14	5	2	Unknown			Bent, but also tang bent
74	2007	1100	A	3	110	65	45	14	7	2	Some	y	x	
75	2007	1157	A	1	148	110	38	10	7	2	Some	y	y	Bent
76	2007	1179	x	3	70	50	20	8	4	2	Some	y	x	Bent
77	2007	1180	A	2	90	55	45	20	7	4	Slight	y	y	
112	2007		x	x							Slight	x	x	Broken
113	2007	1018	x	1	52	10	42	10	8	2	Some			Bent
125	2007	1054	D	x	74	74		12		3	Unknown			Broken
190	2007	1002	A	1	112	84	28	16	10	4	No wear	y	y	
226	2007	1443	A	2	75	65	10	11	4	4	Slight	y	y	Broken tang
244	2007	1472	A	1	97	60	37	12	5	3	Slight	y	y	Angle starts 15mm from tip
295	2007	1494	x	1	35	5	30	12	5	2	Unknown			Bent and broken

Table 9: Summary table of the knives from Burdale showing the measurements, typologies assigned and the results from the x-radiograph analysis.

Appendix 5: SEM Data

Sample	Area	Si	P	S	Mn	Fe	Ni	Cu	As	Total
64	Cutting Edge	*n.d.*	0.1	*n.d.*	*n.d.*	99.6	0.1	0.1	0.1	***88.4***
64	Cutting Edge	*n.d.*	0.1	*n.d.*	*n.d.*	99.8	*n.d.*	*n.d.*	*n.d.*	***88.0***
64	Cutting Edge	0.1	0.1	*n.d.*	*n.d.*	99.5	*n.d.*	0.2	0.1	***87.4***
64	Cutting Edge	*n.d.*	*n.d.*	0.1	*n.d.*	99.7	*n.d.*	0.2	*n.d.*	***85.8***
64	Back	*n.d.*	*n.d.*	*n.d.*	*n.d.*	99.9	*n.d.*	*n.d.*	*n.d.*	***114.6***
64	Back	0.1	0.1	0.1	0.1	99.3	*n.d.*	0.2	0.2	***110.4***
64	Back	*n.d.*	*n.d.*	*n.d.*	*n.d.*	99.7	*n.d.*	0.1	0.2	***106.8***
64	Back	*n.d.*	0.2	*n.d.*	*n.d.*	99.7	*n.d.*	*n.d.*	0.1	***103.5***
64	Back	*n.d.*	0.2	*n.d.*	*n.d.*	99.5	*n.d.*	*n.d.*	0.2	***97.0***
64	Back	*n.d.*	*n.d.*	*n.d.*	*n.d.*	99.5	0.1	0.2	0.2	***96.7***
64	Back	*n.d.*	0.3	*n.d.*	*n.d.*	99.3	*n.d.*	0.2	*n.d.*	***92.2***
64	Back	*n.d.*	0.1	*n.d.*	*n.d.*	99.8	*n.d.*	*n.d.*	*n.d.*	***91.4***
64	Back	*n.d.*	0.1	*n.d.*	0.1	99.8	*n.d.*	*n.d.*	0.1	***89.1***
64	White Weld Line	0.1	*n.d.*	*n.d.*	*n.d.*	96.4	2.4	0.3	0.8	***86.5***
64	White Weld Line	*n.d.*	*n.d.*	*n.d.*	*n.d.*	99.3	*n.d.*	*0.2*	0.5	***86.7***
65	Cutting Edge	*n.d.*	0.2	*n.d.*	0.1	99.6	*n.d.*	*n.d.*	*n.d.*	***112.6***
65	Cutting Edge	0.1	0.3	*n.d.*	*n.d.*	99.2	0.1	0.2	0.1	***112.8***
65	Cutting Edge	*n.d.*	0.1	*n.d.*	*n.d.*	99.7	*n.d.*	0.2	*n.d.*	***86.5***
65	Cutting Edge	*n.d.*	0.1	*n.d.*	*n.d.*	99.8	*n.d.*	*n.d.*	0.1	***92.7***
65	Cutting Edge	*n.d.*	0.1	*n.d.*	*n.d.*	99.9	*n.d.*	*n.d.*	*n.d.*	***97.9***
65	Cutting Edge	*n.d.*	0.1	0.1	*n.d.*	99.6	*n.d.*	*n.d.*	0.2	***84.7***
65	Cutting Edge	0.1	0.2	*n.d.*	*n.d.*	99.8	*n.d.*	*n.d.*	*n.d.*	***71.3***
65	Cutting Edge	*n.d.*	0.2	*n.d.*	*n.d.*	99.8	*n.d.*	*n.d.*	*n.d.*	***74.5***
65	Back	*n.d.*	0.8	*n.d.*	*n.d.*	99.1	*n.d.*	*n.d.*	*n.d.*	***80.6***
65	Back	*n.d.*	1.0	*n.d.*	*n.d.*	98.9	*n.d.*	*n.d.*	0.1	***82.5***
65	Back	*n.d.*	0.4	*n.d.*	0.1	99.3	*n.d.*	*n.d.*	0.2	***89.6***
65	Back	*n.d.*	0.4	*n.d.*	*n.d.*	99.3	*n.d.*	0.1	0.1	***94.9***
65	Back (Ghosting)	*n.d.*	0.9	*n.d.*	*n.d.*	98.9	0.1	*n.d.*	*n.d.*	***85.1***
65	Back (Ghosting)	0.1	1.0	*n.d.*	*n.d.*	98.7	0.1	0.1	*n.d.*	***86.2***
65	Back (Ghosting)	*n.d.*	0.4	*n.d.*	*n.d.*	99.5	*n.d.*	0.1	*n.d.*	***123.7***
65	Back (Ghosting)	*n.d.*	0.5	0.1	0.1	99.2	*n.d.*	*n.d.*	0.2	***130.4***
67	Cutting Edge	*n.d.*	0.1	*n.d.*	*n.d.*	99.8	*n.d.*	*n.d.*	0.1	***89.0***
67	Cutting Edge	*n.d.*	*n.d.*	*n.d.*	*n.d.*	99.7	0.1	*n.d.*	0.1	***88.2***
67	Cutting Edge	*n.d.*	*n.d.*	*n.d.*	0.1	99.8	*n.d.*	*n.d.*	0.1	***87.0***
67	Cutting Edge	*n.d.*	0.1	*n.d.*	0.1	99.8	*n.d.*	*n.d.*	0.1	***87.1***
67	Cutting Edge	*n.d.*	0.1	*n.d.*	*n.d.*	99.5	0.2	0.1	*n.d.*	***86.7***
67	Back	*n.d.*	*n.d.*	*n.d.*	0.1	99.5	0.2	0.1	0.1	***99.5***
67	Back	*n.d.*	*n.d.*	0.1	0.1	99.7	*n.d.*	*n.d.*	0.2	***101.5***
67	Back	*n.d.*	*n.d.*	*n.d.*	*n.d.*	99.8	0.2	*n.d.*	*n.d.*	***98.5***
67	Back	0.1	*n.d.*	*n.d.*	*n.d.*	99.5	0.1	0.1	0.1	***97.4***
67	Back	*n.d.*	*n.d.*	*n.d.*	*n.d.*	99.8	*n.d.*	0.1	0.1	***94.5***
67	Back	*n.d.*	0.1	*n.d.*	*n.d.*	99.5	0.1	*n.d.*	0.3	***93.5***
67	Back	*n.d.*	*n.d.*	*n.d.*	*n.d.*	99.7	*n.d.*	0.2	0.1	***92.1***
67	Back	*n.d.*	*n.d.*	*n.d.*	*n.d.*	99.9	*n.d.*	*n.d.*	0.1	***90.1***
67	Back	*n.d.*	*n.d.*	*n.d.*	*n.d.*	99.9	*n.d.*	*n.d.*	0.1	***90.3***
67	Back	*n.d.*	*n.d.*	*n.d.*	*n.d.*	99.8	*n.d.*	*n.d.*	0.1	***89.2***
67	White Weld Line	*n.d.*	*n.d.*	*n.d.*	*n.d.*	98.1	0.1	*n.d.*	1.8	***86.6***
67	White Weld Line	0.1	*n.d.*	*n.d.*	*n.d.*	98.0	0.3	0.1	1.5	***88.2***
67	White Weld Line	*n.d.*	*n.d.*	*n.d.*	0.1	97.7	0.2	*n.d.*	2.0	***86.4***
67	White Weld Line	0.2	*n.d.*	*n.d.*	*n.d.*	98.9	*n.d.*	0.1	0.6	***82.4***

Sample	Area	Si	P	S	Mn	Fe	Ni	Cu	As	Total
69	Cutting Edge	0.1	*n.d.*	*n.d.*	*n.d.*	99.6	*n.d.*	*n.d.*	0.2	***67.5***
69	Cutting Edge	0.1	0.1	*n.d.*	*n.d.*	99.7	*n.d.*	0.1	*n.d.*	***69.0***
69	Cutting Edge	0.1	*n.d.*	*n.d.*	*n.d.*	99.7	0.1	*n.d.*	*n.d.*	***75.9***
69	Cutting Edge	0.1	*n.d.*	0.1	*n.d.*	99.5	*n.d.*	0.1	0.3	***82.2***
69	Cutting Edge	*n.d.*	0.1	*n.d.*	*n.d.*	99.9	*n.d.*	*n.d.*	*n.d.*	***84.0***
69	Cutting Edge	0.1	*n.d.*	*n.d.*	0.1	99.8	*n.d.*	*n.d.*	*n.d.*	***89.5***
69	Back	0.1	*n.d.*	0.1	*n.d.*	99.7	*n.d.*	0.1	*n.d.*	***114.4***
69	Back	*n.d.*	*n.d.*	*n.d.*	*n.d.*	100.0	*n.d.*	*n.d.*	*n.d.*	***120.1***
69	Back	*n.d.*	*n.d.*	*n.d.*	*n.d.*	99.8	*n.d.*	0.1	0.1	***118.7***
69	Back	*n.d.*	0.1	*n.d.*	*n.d.*	99.6	*n.d.*	0.2	0.1	***118.3***
69	Back	*n.d.*	*n.d.*	*n.d.*	*n.d.*	99.7	0.1	*n.d.*	0.1	***111.2***
69	Back	*n.d.*	*n.d.*	*n.d.*	*n.d.*	99.9	*n.d.*	*n.d.*	*n.d.*	***84.0***
69	Back	*n.d.*	*n.d.*	*n.d.*	0.1	99.7	0.2	*n.d.*	*n.d.*	***81.1***
69	Back	*n.d.*	0.1	*n.d.*	*n.d.*	99.9	*n.d.*	*n.d.*	*n.d.*	***72.2***
69	Back	0.1	*n.d.*	*n.d.*	0.2	99.7	*n.d.*	*n.d.*	*n.d.*	***73.7***
69	White Weld Line	*n.d.*	*n.d.*	*n.d.*	0.1	99.5	*n.d.*	*n.d.*	0.3	***99.6***
69	White Weld Line	0.1	*n.d.*	*n.d.*	*n.d.*	99.5	*n.d.*	0.1	0.2	***107.1***
69	White Weld Line	0.1	0.1	*n.d.*	*n.d.*	99.4	0.1	*n.d.*	0.4	***115.7***
69	White Weld Line	0.2	*n.d.*	*n.d.*	*n.d.*	99.4	*n.d.*	*n.d.*	0.4	***117.9***
70	Cutting Edge	*n.d.*	0.3	0.1	*n.d.*	99.6	*n.d.*	*n.d.*	*n.d.*	***102.3***
70	Cutting Edge	0.1	0.1	*n.d.*	*n.d.*	99.5	0.1	*n.d.*	0.2	***102.5***
70	Cutting Edge	*n.d.*	0.1	*n.d.*	*n.d.*	99.7	0.1	*n.d.*	*n.d.*	***110.6***
70	Cutting Edge	*n.d.*	0.2	*n.d.*	*n.d.*	99.6	0.1	*n.d.*	0.1	***100.7***
70	Cutting Edge	0.1	*n.d.*	*n.d.*	*n.d.*	99.4	0.1	0.2	0.1	***100.8***
70	Cutting Edge	*n.d.*	0.1	*n.d.*	0.1	99.8	*n.d.*	*n.d.*	*n.d.*	***111.0***
70	Cutting Edge	*n.d.*	0.1	*n.d.*	*n.d.*	99.8	*n.d.*	*n.d.*	*n.d.*	***111.6***
70	Cutting Edge	*n.d.*	*n.d.*	*n.d.*	*n.d.*	99.8	0.1	*n.d.*	0.1	***111.3***
70	Back	*n.d.*	0.1	*n.d.*	*n.d.*	99.8	*n.d.*	0.1	0.1	***99.2***
70	Back	*n.d.*	0.1	*n.d.*	*n.d.*	99.8	0.1	*n.d.*	0.1	***98.1***
70	Back	0.1	0.1	*n.d.*	*n.d.*	99.8	*n.d.*	*n.d.*	*n.d.*	***116.5***
70	Back	*n.d.*	*n.d.*	*n.d.*	*n.d.*	99.9	*n.d.*	*n.d.*	*n.d.*	***117.7***
70	Back	0.1	0.1	*n.d.*	*n.d.*	99.3	0.2	0.1	0.1	***107.2***
70	Back	0.1	*n.d.*	*n.d.*	*n.d.*	99.8	*n.d.*	*n.d.*	0.1	***101.6***
70	Back	0.1	0.1	0.1	*n.d.*	99.6	0.1	*n.d.*	0.1	***110.5***
70	Back	*n.d.*	0.1	*n.d.*	*n.d.*	99.7	*n.d.*	*n.d.*	0.1	***108.2***
70	White Weld Line	0.1	0.1	*n.d.*	*n.d.*	97.1	1.8	*n.d.*	0.9	***114.7***
75 (Bent)	Cutting Edge	*n.d.*	0.1	*n.d.*	*n.d.*	99.7	0.1	0.2	*n.d.*	***109.3***
75 (Bent)	Cutting Edge	*n.d.*	0.1	*n.d.*	*n.d.*	99.4	*n.d.*	0.1	0.3	***111.3***
75 (Bent)	Cutting Edge	*n.d.*	*n.d.*	*n.d.*	*n.d.*	99.8	*n.d.*	*n.d.*	0.1	***117.8***
75 (Bent)	Back	0.1	0.1	*n.d.*	*n.d.*	99.4	0.1	0.2	*n.d.*	***105.5***
75 (Bent)	Back	0.1	*n.d.*	*n.d.*	*n.d.*	99.7	0.1	*n.d.*	0.1	***102.2***
75 (Bent)	Back	*n.d.*	0.1	0.1	*n.d.*	99.5	*n.d.*	0.3	*n.d.*	***99.3***
75 (Bent)	Back	*n.d.*	0.2	*n.d.*	*n.d.*	99.6	*n.d.*	*n.d.*	0.2	***99.5***
75 (Bent)	Back	*n.d.*	0.2	0.1	*n.d.*	99.6	0.1	*n.d.*	*n.d.*	***103.5***
75 (Bent)	Back	*n.d.*	0.1	*n.d.*	*n.d.*	99.8	*n.d.*	*n.d.*	0.1	***103.2***

Table 10: Full table of normalised results from SEM-EDS analysis. The total column shows the analysis total prior to normalisation.

Sample	Area	Si	P	S	Mn	Fe	Ni	Cu	As	Total
75	Cutting Edge	n.d.	0.1	n.d.	0.1	99.7	n.d.	0.1	n.d.	127.7
75	Cutting Edge	0.1	n.d.	n.d.	n.d.	99.5	0.1	0.2	0.1	129.4
75	Cutting Edge	n.d.	n.d.	n.d.	n.d.	100.0	n.d.	n.d.	n.d.	110.0
75	Back	n.d.	0.1	0.1	n.d.	99.4	0.1	0.1	0.2	126.1
75	Back	n.d.	0.1	n.d.	n.d.	99.7	n.d.	n.d.	0.2	115.4
75	Back	n.d.	0.2	n.d.	n.d.	99.8	0.1	n.d.	n.d.	100.5
75	Back	n.d.	0.2	n.d.	n.d.	99.7	n.d.	0.1	n.d.	77.4
75	Back	n.d.	0.1	n.d.	n.d.	99.9	n.d.	n.d.	n.d.	67.5
75	Back	0.2	n.d.	n.d.	n.d.	99.6	n.d.	n.d.	0.2	65.4
76	Cutting Edge	n.d.	0.1	n.d.	n.d.	99.7	n.d.	n.d.	0.1	86.5
76	Cutting Edge	0.1	n.d.	n.d.	n.d.	99.9	n.d.	n.d.	n.d.	83.9
76	Cutting Edge	0.1	n.d.	n.d.	n.d.	99.8	n.d.	n.d.	n.d.	84.0
76	Cutting Edge	n.d.	n.d.	n.d.	n.d.	99.9	n.d.	0.1	n.d.	85.0
76	Cutting Edge	n.d.	0.1	n.d.	n.d.	99.7	0.1	0.1	n.d.	82.4
76	Cutting Edge	n.d.	0.1	n.d.	n.d.	99.7	n.d.	n.d.	0.1	85.5
76	Back	n.d.	0.1	0.1	n.d.	99.7	0.1	n.d.	0.1	96.9
76	Back	n.d.	0.1	n.d.	n.d.	99.6	n.d.	0.2	0.1	100.6
76	Back	n.d.	n.d.	n.d.	n.d.	99.9	n.d.	n.d.	0.1	109.0
76	Back	n.d.	n.d.	n.d.	n.d.	99.9	n.d.	n.d.	n.d.	105.4
76	Back	n.d.	0.1	n.d.	n.d.	99.6	n.d.	0.2	n.d.	104.5
76	Back	n.d.	n.d.	0.1	n.d.	99.8	n.d.	n.d.	n.d.	106.6
76	Back	0.1	n.d.	n.d.	n.d.	99.8	n.d.	n.d.	n.d.	108.4
76	Back	n.d.	0.1	n.d.	n.d.	99.4	0.3	0.1	0.1	100.4
113	Back	n.d.	n.d.	n.d.	n.d.	100.0	n.d.	n.d.	n.d.	84.9
113	Back	n.d.	n.d.	n.d.	0.1	99.8	n.d.	n.d.	0.1	84.3
113	Back	0.1	n.d.	n.d.	n.d.	99.8	n.d.	n.d.	n.d.	95.2
113	Back	n.d.	0.1	0.1	n.d.	99.6	n.d.	0.2	0.1	99.0
113	Back	0.1	0.1	n.d.	n.d.	99.8	n.d.	n.d.	n.d.	97.9
113	Back	n.d.	0.1	n.d.	n.d.	99.8	n.d.	0.1	n.d.	96.8
113	Back	n.d.	0.1	0.1	n.d.	99.6	0.1	n.d.	0.2	96.8
113	Back	n.d.	0.1	n.d.	n.d.	99.8	n.d.	n.d.	0.1	96.2
113	Back	n.d.	n.d.	0.1	n.d.	99.8	n.d.	n.d.	n.d.	94.8
200	Cutting Edge	0.0	0.1	0.1	n.d.	99.8	n.d.	n.d.	n.d.	82.7
200	Cutting Edge	0.1	n.d.	0.1	n.d.	99.7	0.1	n.d.	n.d.	79.3
200	Cutting Edge	n.d.	0.1	n.d.	n.d.	99.8	0.1	n.d.	n.d.	80.8
200	Cutting Edge	n.d.	n.d.	n.d.	n.d.	99.8	n.d.	0.1	n.d.	78.9
200	Back 1	0.1	0.1	n.d.	n.d.	99.5	0.1	n.d.	0.1	112.0
200	Back 1	0.1	0.2	n.d.	n.d.	99.8	n.d.	n.d.	n.d.	115.9
200	Back 1	n.d.	0.2	n.d.	n.d.	99.6	0.1	n.d.	0.1	123.7
200	Back 1	n.d.	n.d.	n.d.	n.d.	99.8	0.1	n.d.	n.d.	125.6
200	Back 2	n.d.	0.2	n.d.	n.d.	99.6	0.1	n.d.	n.d.	93.6
200	Back 2	n.d.	n.d.	n.d.	n.d.	99.6	n.d.	0.1	0.1	92.7
200	Back 2	n.d.	0.1	0.1	n.d.	99.7	0.1	n.d.	n.d.	89.8
200	Back 2	0.1	0.1	n.d.	n.d.	99.4	n.d.	0.3	n.d.	88.7
200	White Weld Line	0.1	0.1	n.d.	n.d.	99.4	0.3	0.1	0.1	88.2
200	White Weld Line	0.1	n.d.	n.d.	0.1	99.4	0.3	n.d.	0.1	87.7
200	White Weld Line	n.d.	n.d.	n.d.	n.d.	99.3	0.3	0.1	0.2	77.1
200	White Weld Line	n.d.	0.1	n.d.	n.d.	99.0	0.3	0.1	0.4	85.1

Sample	Area	Si	P	S	Mn	Fe	Ni	Cu	As	Total
204	Cutting Edge	0.1	0.1	n.d.	n.d.	99.5	n.d.	0.1	0.2	111.1
204	Cutting Edge	0.1	0.2	n.d.	n.d.	99.7	n.d.	n.d.	n.d.	109.4
204	Cutting Edge	n.d.	n.d.	n.d.	n.d.	99.7	n.d.	0.1	0.1	109.8
204	Cutting Edge	n.d.	0.1	n.d.	n.d.	99.6	0.2	n.d.	0.1	109.5
204	Back	n.d.	0.3	n.d.	n.d.	99.2	n.d.	n.d.	0.4	107.4
204	Back	0.1	0.1	n.d.	n.d.	99.2	0.1	0.1	0.4	114.3
204	Back	n.d.	0.3	n.d.	n.d.	99.0	0.1	0.1	0.5	125.8
204	Back	0.1	0.3	n.d.	0.1	98.8	n.d.	0.1	0.6	115.7
204	Back	0.1	0.1	0.1	n.d.	99.1	0.1	0.2	0.3	111.1
204	Back	0.2	0.2	0.1	n.d.	99.2	n.d.	0.1	0.3	116.6
204	Back (Core)	n.d.	n.d.	n.d.	n.d.	99.4	n.d.	0.1	0.4	126.3
204	Back (Core)	n.d.	0.1	n.d.	n.d.	99.6	n.d.	n.d.	0.3	125.2
204	Back (Core)	n.d.	0.2	0.1	n.d.	99.4	n.d.	n.d.	0.4	115.2
204	Back (Core)	n.d.	0.1	n.d.	n.d.	99.6	n.d.	n.d.	0.3	114.0
204	White Weld Line	n.d.	0.1	0.1	n.d.	98.6	n.d.	n.d.	1.1	109.8
204	White Weld Line	n.d.	0.2	n.d.	n.d.	99.3	0.1	n.d.	0.4	109.8
204	White Weld Line	0.1	0.2	n.d.	n.d.	99.4	n.d.	n.d.	0.2	110.6
204	White Weld Line	n.d.	0.1	n.d.	n.d.	98.4	n.d.	0.1	1.3	110.0
208	Back	0.1	0.2	n.d.	n.d.	99.4	0.1	n.d.	0.2	94.4
208	Back	0.1	0.2	n.d.	n.d.	99.7	n.d.	0.1	n.d.	93.5
208	Back	0.1	0.2	n.d.	n.d.	99.6	n.d.	n.d.	0.2	93.3
208	Back	n.d.	0.2	0.1	n.d.	99.6	0.1	n.d.	n.d.	93.1
208	Back	0.1	0.3	n.d.	n.d.	99.5	n.d.	n.d.	0.1	92.5
208	Back	0.1	0.4	n.d.	n.d.	99.1	0.2	n.d.	0.2	100.7
208	Back	0.1	0.2	n.d.	n.d.	99.5	0.1	n.d.	0.1	93.9
208	Back	0.1	0.3	0.1	n.d.	99.4	n.d.	0.1	0.1	99.3
208	Back	0.1	0.3	n.d.	n.d.	99.4	n.d.	n.d.	0.1	97.0
208	Back	n.d.	0.4	n.d.	n.d.	99.4	n.d.	0.1	n.d.	99.4
218	Cutting Edge	n.d.	0.3	n.d.	n.d.	99.3	0.1	0.2	0.1	124.4
218	Cutting Edge	0.1	0.2	n.d.	0.1	99.6	n.d.	n.d.	n.d.	125.8
218	Cutting Edge	0.1	0.4	n.d.	n.d.	99.5	n.d.	n.d.	0.1	122.7
218	Cutting Edge	n.d.	0.3	n.d.	n.d.	99.6	n.d.	n.d.	0.1	124.1
218	Cutting Edge	0.1	0.3	n.d.	n.d.	99.5	n.d.	0.1	0.1	129.4
218	Cutting Edge	n.d.	0.3	n.d.	n.d.	99.6	n.d.	n.d.	n.d.	121.7
218	Back	n.d.	0.2	n.d.	n.d.	99.6	n.d.	0.2	0.1	98.6
218	Back	n.d.	0.3	n.d.	n.d.	99.6	n.d.	n.d.	n.d.	96.3
218	Back	n.d.	0.1	n.d.	n.d.	99.8	n.d.	n.d.	n.d.	113.9
218	Back	n.d.	0.2	n.d.	n.d.	99.7	n.d.	0.1	n.d.	120.0
218	Back	n.d.	0.4	n.d.	n.d.	99.6	n.d.	n.d.	n.d.	122.1
218	Back	n.d.	0.4	n.d.	0.1	99.4	n.d.	0.1	n.d.	122.1
218	Back	0.1	0.3	n.d.	0.1	99.2	n.d.	0.3	n.d.	130.9

Table 10 cont: Full table of normalised results from SEM-EDS analysis. The total column shows the analysis total prior to normalisation.

Sample	Area	Si	P	S	Mn	Fe	Ni	Cu	As	Total

Sample	Area	Si	P	S	Mn	Fe	Ni	Cu	As	Total

244	Cutting Edge	*n.d.*	*n.d.*	*n.d.*	*n.d.*	100.0	*n.d.*	*n.d.*	*n.d.*	***110.1***
244	Cutting Edge	0.1	*n.d.*	*n.d.*	*n.d.*	99.8	*n.d.*	*n.d.*	0.1	***105.2***
244	Cutting Edge	*n.d.*	*n.d.*	*n.d.*	0.1	99.9	*n.d.*	*n.d.*	*n.d.*	***107.9***
244	Cutting Edge	*n.d.*	*n.d.*	*n.d.*	*n.d.*	99.7	0.1	0.1	0.1	***111.5***
244	Cutting Edge	*n.d.*	*n.d.*	*n.d.*	*n.d.*	99.9	*n.d.*	*n.d.*	*n.d.*	***113.1***
244	Cutting Edge (Ferrite Area)	0.1	0.1	0.1	*n.d.*	99.7	*n.d.*	*n.d.*	0.1	***117.1***
244	Cutting Edge (Ferrite Area)	*n.d.*	0.1	0.1	*n.d.*	99.8	*n.d.*	*n.d.*	0.1	***118.7***
244	Back 1	0.1	0.2	*n.d.*	*n.d.*	99.7	*n.d.*	*n.d.*	*n.d.*	***107.2***
244	Back 1	*n.d.*	0.4	0.1	*n.d.*	99.5	*n.d.*	*n.d.*	*n.d.*	***109.8***
244	Back 1	*n.d.*	0.2	*n.d.*	*n.d.*	99.7	*n.d.*	*n.d.*	*n.d.*	***107.6***
244	Back 2	*n.d.*	0.3	*n.d.*	*n.d.*	99.4	0.1	*n.d.*	0.2	***111.5***
244	Back 2	*n.d.*	0.2	*n.d.*	0.2	99.3	*n.d.*	0.1	0.1	***108.7***
244	Back 2	*n.d.*	0.2	*n.d.*	*n.d.*	99.7	*n.d.*	*n.d.*	*n.d.*	***112.4***
244	Back 3	0.1	0.1	*n.d.*	*n.d.*	99.7	*n.d.*	*n.d.*	0.1	***113.0***
244	Back 3	*n.d.*	0.4	*n.d.*	*n.d.*	99.4	*n.d.*	*n.d.*	0.1	***111.1***
244	Back 3	0.1	0.3	*n.d.*	*n.d.*	99.5	0.1	*n.d.*	*n.d.*	***107.1***
244	Back 4	*n.d.*	0.3	*n.d.*	*n.d.*	99.4	*n.d.*	*n.d.*	0.2	***105.8***
244	Back 4	*n.d.*	0.5	*n.d.*	*n.d.*	99.3	*n.d.*	0.2	*n.d.*	***113.6***
244	Back 4	*n.d.*	0.3	*n.d.*	*n.d.*	99.5	0.1	0.1	*n.d.*	***105.4***
244	Back 4	*n.d.*	0.2	*n.d.*	*n.d.*	99.7	*n.d.*	0.1	*n.d.*	***114.5***
244	White Weld Line	*n.d.*	*n.d.*	*n.d.*	0.1	99.1	0.1	*n.d.*	0.6	***114.4***
244	White Weld Line	*n.d.*	*n.d.*	*n.d.*	*n.d.*	99.0	0.4	0.2	0.4	***114.9***
244	White Weld Line	0.1	*n.d.*	*n.d.*	0.1	99.3	0.1	*n.d.*	0.4	***116.1***
4	Cutting Edge	*n.d.*	0.1	*n.d.*	*n.d.*	99.8	*n.d.*	*n.d.*	*n.d.*	***96.3***
4	Cutting Edge	0.1	*n.d.*	0.1	0.1	99.3	0.1	0.1	0.3	***94.8***
4	Cutting Edge	*n.d.*	*n.d.*	*n.d.*	*n.d.*	99.6	*n.d.*	0.1	0.3	***93.0***
4	Cutting Edge	*n.d.*	0.1	*n.d.*	*n.d.*	99.7	*n.d.*	0.1	0.1	***89.2***
4	Cutting Edge	0.1	0.1	*n.d.*	*n.d.*	99.8	*n.d.*	*n.d.*	*n.d.*	***86.8***
4	Cutting Edge	*n.d.*	*n.d.*	*n.d.*	*n.d.*	99.7	0.1	0.1	*n.d.*	***85.0***
4	Back Large Grains	*n.d.*	*n.d.*	0.1	*n.d.*	99.7	*n.d.*	0.1	0.1	***70.2***
4	Back Large Grains	*n.d.*	*n.d.*	*n.d.*	*n.d.*	99.7	0.1	*n.d.*	0.1	***67.9***
4	Back Large Grains	0.1	*n.d.*	*n.d.*	*n.d.*	99.7	*n.d.*	0.1	0.1	***84.0***
4	Back Large Grains	*n.d.*	*n.d.*	*n.d.*	*n.d.*	99.9	*n.d.*	*n.d.*	*n.d.*	***81.9***
4	Small grains with P	*n.d.*	0.1	0.1	*n.d.*	99.7	*n.d.*	0.1	0.1	***78.5***
4	Small grains with P	*n.d.*	0.1	*n.d.*	*n.d.*	99.5	0.2	*n.d.*	0.2	***77.0***
4	Small grains with P	*n.d.*	*n.d.*	*n.d.*	*n.d.*	99.8	*n.d.*	0.1	0.1	***75.4***
4	Small grains with P	0.1	*n.d.*	*n.d.*	0.1	99.7	*n.d.*	0.1	*n.d.*	***73.7***
4	Small grains with P	*n.d.*	*n.d.*	*n.d.*	*n.d.*	99.8	0.1	0.1	*n.d.*	***91.5***
4	Small grains with P	*n.d.*	0.1	*n.d.*	*n.d.*	99.6	*n.d.*	0.1	0.2	***90.4***
4	Small grains with P	0.1	*n.d.*	*n.d.*	*n.d.*	99.8	*n.d.*	0.1	*n.d.*	***89.1***
4	Weld line 1 (Horiz)	*n.d.*	*n.d.*	*n.d.*	*n.d.*	99.7	0.1	0.1	0.1	***80.2***
4	Weld line 1 (Horiz)	0.1	0.1	*n.d.*	*n.d.*	98.5	0.2	*n.d.*	1.1	***76.9***
4	Weld line 2 (Verti)	0.1	*n.d.*	*n.d.*	*n.d.*	99.7	*n.d.*	*n.d.*	0.2	***94.0***
4	Weld line 2 (Verti)	*n.d.*	*n.d.*	*n.d.*	*n.d.*	99.4	*n.d.*	*n.d.*	0.4	***93.4***
4	Weld line 3 (Verti)	*n.d.*	*n.d.*	*n.d.*	*n.d.*	99.8	*n.d.*	*n.d.*	0.2	***80.1***
4	Weld line 3 (Verti)	*n.d.*	*n.d.*	*n.d.*	*n.d.*	99.7	*n.d.*	*n.d.*	0.3	***78.8***

4 Pivot	Pin Large Grains	*n.d.*	0.1	*n.d.*	*n.d.*	99.6	0.1	0.2	*n.d.*	***95.7***
4 Pivot	Pin Large Grains	0.2	0.3	*n.d.*	*n.d.*	99.2	*n.d.*	0.2	0.1	***82.9***
4 Pivot	Pin Large Grains	0.1	0.1	*n.d.*	*n.d.*	99.6	0.2	*n.d.*	0.1	***88.3***
4 Pivot	Pin Large Grains	*n.d.*	0.1	*n.d.*	*n.d.*	99.7	0.1	*n.d.*	0.1	***86.5***
4 Pivot	Pin Large Grains	*n.d.*	0.3	*n.d.*	0.1	99.3	0.1	*n.d.*	0.2	***83.6***
4 Pivot	Pin Large Grains	*n.d.*	0.2	*n.d.*	*n.d.*	99.3	0.2	*n.d.*	0.3	***82.6***
4 Pivot	Pin Small grains with P	0.1	0.1	*n.d.*	*n.d.*	99.5	0.2	*n.d.*	0.1	***81.1***
4 Pivot	Pin Small grains with P	0.1	0.1	*n.d.*	*n.d.*	99.7	*n.d.*	*n.d.*	0.1	***78.0***
4 Pivot	Pin Small grains with P	*n.d.*	0.1	*n.d.*	*n.d.*	99.6	*n.d.*	*n.d.*	0.3	***74.6***
4 Pivot	Pin Small grains with P	0.1	0.2	*n.d.*	*n.d.*	99.6	*n.d.*	*n.d.*	*n.d.*	***72.5***
4 Pivot	Pin Small grains with P	*n.d.*	0.2	*n.d.*	*n.d.*	99.4	0.1	*n.d.*	0.2	***69.8***
4 Pivot	Pin Small grains with P	*n.d.*	0.3	0.1	*n.d.*	99.6	*n.d.*	*n.d.*	0.1	***69.4***
4 Pivot	Back Large Grains	*n.d.*	*n.d.*	*n.d.*	0.1	99.7	*n.d.*	*n.d.*	0.2	***88.2***
4 Pivot	Back Large Grains	0.1	*n.d.*	*n.d.*	*n.d.*	99.7	0.1	0.1	*n.d.*	***88.2***
4 Pivot	Back Small grains with P	*n.d.*	*n.d.*	*n.d.*	0.1	99.5	0.2	0.1	0.1	***85.5***
4 Pivot	Back Small grains with P	0.1	*n.d.*	*n.d.*	*n.d.*	99.5	0.1	0.1	0.2	***84.0***

Table 10 cont: Full table of normalised results from SEM-EDS analysis. The total column shows the analysis total prior to normalisation.

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