The metallurgy, development, and purpose of pattern welding

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ABSTRACT: Surface patterns resulting from welding together iron and/or steel pieces were probably recognised soon after bloomery smelting began, long before the technique was exploited for its decorative potential in the mid to late Iron Age. People have speculated on when, why and how the technique was developed, long before the term was formally adopted in 1948 to differentiate weld patterns from those that originate from the casting of steel. Before much metallographic research was done on relevant material, pattern-welding was generally assumed to have been an ancient technique that was used to improve the physical properties of the objects – only swords before about the 7th century AD – for which it was used. However research, particularly over the past 40 years, has increasingly shown that pattern-welding was primarily a decorative technique designed to demonstrate excellence in the exploitation and welding together of different iron alloys this being judged by their appearance.

Introduction and background

Pattern welding has been thought for a long time to represent the peak in iron smithing. However the technique has been little understood: its metallurgy, when it started, how it developed, why it was used and by whom, what the patterns might represent, whether it had a structural purpose or not – this having been previously assumed to be the case – and also the cultural framework into which it fitted, together with the implications for specialised manufacture, and so on. Consequently much mythology and misinformation has grown up around it, even in scholarly circles. Until recently the main reason was that there was too little archaeometallurgical data to use as a basis for tackling the subject in a systematic way that looked at all the issues surrounding this technique of manufacture. But over the past 30 years much new evidence has come to light and although various implications arise from this it is now possible to reassess and explain the technique much more convincingly than was hitherto the case. The interpretation of the early written evidence for pattern welding, whether the patterns were visible to the owners or other people familiar with the weapons, and how it is possible to show this, is has recently been discussed in detail (Gilmour 2014).

What is pattern-welding?

Welding – in this case the joining of pieces of iron by hammering them together when sufficiently hot to allow this to happen – is inherent to the successful production of a lump or bar of iron made by the bloomery process, the method by which as far as we know all early iron, including steel, is likely to have been made in Europe until the later Middle Ages. For this reason welding is likely to have developed into a specialised skill early in the transitional Bronze Age/Iron Age phase when many of the main developments in iron-working are likely to have occurred. It is also likely that the bloomery process itself soon became specialised for the production of different types of iron, the most important of these being steel and, although very little material has yet been examined in detail, already we can see the production of specialised composite welded iron/steel objects, such as knives and swords, in south-east Europe and the Middle East by the late 2nd millennium BC. For example a dirk from Cyprus made of an iron core around which was welded a outer layer of steel to form the blade (Lang 1991, 95, fig 4) and a sword blade from Luristan in western Iran, in which the blade was made as a sandwich with a piece of steel between two pieces of iron (Maxwell-Hyslop and Hodges 1966, 168-9; Allan and Gilmour 2000, 41-3).

Not only must the welding together of pieces of iron have become a specialised skill early in the Iron Age, but the marks left by the welding must soon have been noticed and, perhaps not long after, to have begun to be exploited for their decorative potential. Once this process started, it then inevitably led to specific decorative welded styles – that is early forms of pattern-welding – which were influenced by the culture of the time. Thus

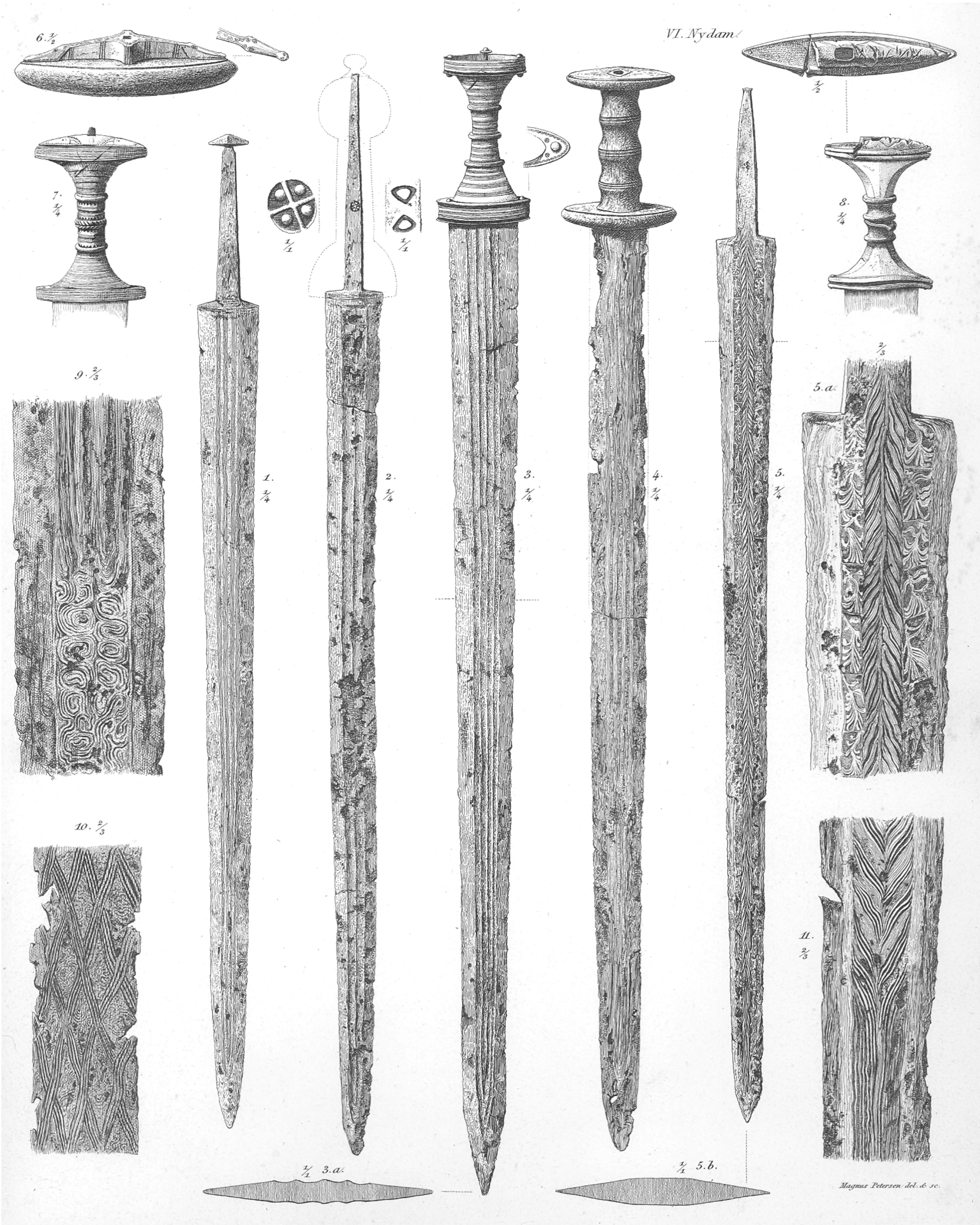

Figure 1: Swords from the large votive bog/pool deposit at Nydam, Jutland, showing a variety of patterns etched into the surfaces of the blades. These show different construction methods: twist patterning (11), straight banding (1), coil/concertina (9), lattice (10) and block/floral (5) (illustration from Engelhardt 1866, Plate VI).

by this time (whenever it was) composite construction would have been used not only simply for utilitarian purposes, say the welding of a steel edge onto a softer iron core for the blade of a knife to give a more durable sharp edge, but also exploited for its decorative potential.

At present the earliest evidence for decorative techniques such as pattern-welding in Europe would appear to date from about the mid-first millennium BC and, although the database of examined material is still small, this technique appears to have been developed primarily for long swords, possibly specifically the archetypal 'Celtic' long swords of northern and central Europe (Pleiner 1993, 117-8, 122-3, 146-7).

Pattern-welding is the name given by Maryon (1948) to define the technique used to create the decorative patterns first noticed on the blades of early swords and other weapons found in Europe in the early to mid-19th century (Fig 1). The name pattern welding was given as a way of identifying swords or other weapons with surface patterns originating from welding techniques (cf Anstee and Biek 1961, 71). This identification was introduced to differentiate between swords whose surface patterns derived from the forge welding together of a variable number of different parts, and those steel weapons whose surface patterns resulted from the structure of the cast steel ingots from which they were made. Previously all these iron or steel weapons tended to be misleadingly referred to as damask or damascene by (late medieval and) later Western observers, these terms still being ingrained in many people's minds. The mistaken links with Damascus have tended to confuse the study of pattern-welded weapons with those made of watered crucible steel, which also has been mistakenly linked to Damascus as the principal manufacturing source. This problem has been discussed elsewhere (Allan and Gilmour 2000, 76-9).

Iron alloys, welding, composite construction and its decorative potential

Early iron alloys, particularly steel, are still poorly understood both in terms of how they were exploited, viewed and to some extent – particularly in the case of steel – how they were made. Added to this, swords are perhaps the least well understood class of iron artefacts. Swords made of iron or steel have long been known to be an important symbol of rank and a cultural icon in early Europe and elsewhere. Less clear however, certainly until recently, has been how these weapons were made or the extent to which they were actually used as fighting weapons. Fortunately we can investigate the large number of surviving early swords and other weapons with their excellent potential for recovering evidence of manufacturing history by technological study: using a combination of radiography, detailed metallographic study together with compositional analysis and elemental mapping. Research of this kind is now beginning to reveal the full extent of the skills of early smiths: the range of iron alloys they were exploiting, as well as the ways in which these were used either alone or in combination.

The recovery (either by archaeological excavation or accidental discovery) and dating of groups of objects has shown that bronze swords became a common form of weapon – however they might or might not have been used – during the Bronze Age. However it was not until the Iron Age that a great diversity of different methods of sword construction began to be used, this being a consequence of the very different properties of iron and its alloys. It also seems clear that during the later Iron Age a distinctive form of long bladed sword became common in northern Europe and that in this region outside the Roman Empire welded construction techniques, which leave a decorative surface on the blades, were exploited for some of them (Stead 2006, 46-7).

Many pattern-welded weapons have been found in parts of the world as far afield as Ireland and Indonesia although they have been popular at different times over the past 2000 years in different areas. In recent times the technique of pattern-welding has been most popular in Indonesia, Malaysia and the surrounding areas of south-east Asia although it was used to a lesser extent elsewhere including the Ottoman Empire and other Islamic parts of southern and western Asia. Most surviving pattern-welded weapons from these parts of the world date from the 16th century although the earlier development of the technique in these areas is not yet known. Recent research has shown that, in Northern Europe at least, pattern-welding had developed into a more formal decorative technique, (seemingly) used only for swords, by some time in the early first millennium AD.

Several studies have looked at how patterns can be developed by twisting laminated pieces of iron (*eg* Lang and Ager 1989; Ypey 1982) but less attention has been paid to other patterns and how they might have been created and, perhaps equally if not more importantly, what iron alloys were actually used to create the patterns, and how this changed or developed over time.

Figure 2:The blade of a very well preserved late Iron Age sword from Orton Meadows, Cambridgeshire, with visible stamps and a typologically early or 'free-form' variety of pattern-welded blade (length of sword 98.0cm).

Pattern welding in Iron Age Britain

The origins of pattern welding are likely to lie in the early Iron Age with the consolidation of the spongy and often fragmentary lumps produced by the early direct reduction (bloomery) furnaces. It may have developed from the observation of weld lines on the corroded surface of blades made from several small pieces of bloom iron welded together. Recent research suggests that, in the West at least, pattern welding began to be exploited in central Europe during the last half of the first millennium BC (Pleiner 1993, 117 no68). As yet it is not known exactly how it developed from the early accidentally-visible weld patterns to the range of formal patterns which were being used for a large proportion of swords in Europe during the last half of the first millennium BC.

In Britain the best evidence so far for a 'prototype' form of pattern-welding is on an exceptionally well-preserved Late Iron Age (1st century BC to 1st century AD) sword, found in 1980 during gravel extraction in a former bed of the River Nene at Orton Meadows, near Peterborough, Cambs (Stead 2006, no97; Fig 2) – one of what would possibly have been a much larger group of swords deposited as a series of votive river offerings. Unlike later European pattern-welded swords with a more formal composite construction, which almost always includes separately welded-on cutting edges, X-radiography showed this sword to have the same structure right across the blade. The blade had been very heavily etched down its centre, exposing the distorted fibrous pattern that is still almost as clearly visible as the day it was put in the river (Fig 3). This pattern did not extend to the edges of the blade the margins of which must have been protected from the etching liquid by wax or grease acting as a resist agent.

Were it not for the exceptional preservation of the sword, the identification of this form of pattern welding with its use of resist protection would be much less certain. It is the earliest known example where we can be certain that patterns like this were intended to be seen. This long sword was clearly not a one-off example, and this early less formal form of pattern-welding seems likely to have been both common and widespread for this kind of high status object by this time. A similar but slightly less well-preserved late Iron Age long sword – where the flowing fibrous pattern along the middle is just still visible on the surface, as are the raised protected margins along the edges – was found nearby (Stead 2006, 46-7, no122, pl 6). Traces of a similar central pattern is also still just visible on another late Iron Age long sword found in 1987 at Shepperton, Surrey, in another former river channel exposed by grave quarrying (Stead 2006, 46-7, no127, pl 6).

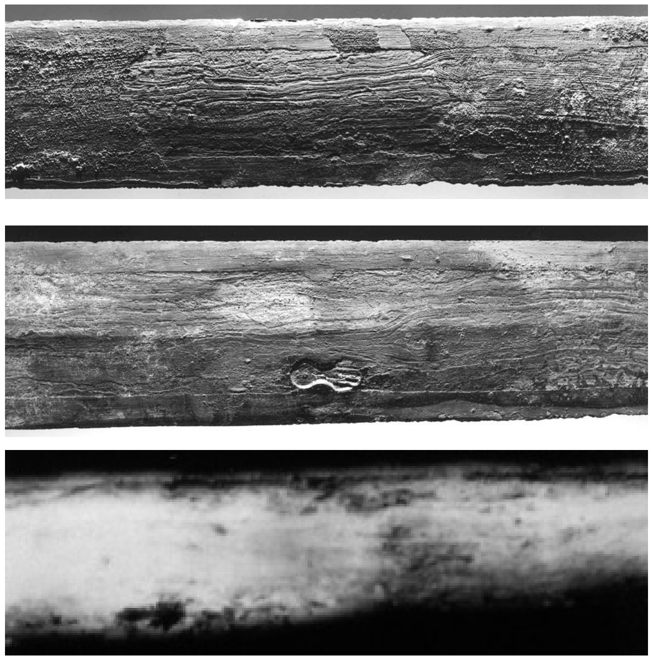

Figure 3: Both sides of the Orton Meadows sword blade showing the resist-protected margins along the edges, and the heavily etched, pattern-welded detail in the centre, strongly resembling flowing water. The distinctive 'dumb-bell' shaped maker's punch-mark is visible near one edge. Below, X-radiograph showing the structure runs across the full width of the blade.

Hints of this form of composite construction, involving the welding together of a bundle of iron rods to give a similar appearance on an X-radiograph, has been examined in a section from a fragment of another sword blade of suspected late Iron Age date recovered from the Thames at Little Wittenham, Oxon (Tylecote and Gilmour 1986, 162-4). Hints of a distinctive fibrous pattern was still clearly visible on an X-radiograph of a totally corroded example from Guernsey which suggests that this early, less formal form of pattern-welding was widespread, at least in Britain in the late Iron Age (Gilmour 1996).

In total, the remains of perhaps 11 swords were found in a votive, watery (bog) deposit at Llyn Cerrig Bach in Anglesey, NW Wales (Savory 1976, 57, 59, 94-5; Fox 1946, 5). Fragments of only four have been examined (McGrath 1968). In one example several rods, each occupying the full thickness of the sword, were found to have been welded side-by side (Fig 4). The carbon contents of the rods varied across the width of the blade although none of the rods seems to have consisted of much more than a low carbon iron (much like modern mild steel). Structurally this would not have been a particularly effective weapon but would have given a very clear banded or striped visual appearance when polished, and etched and this seems the most likely intention.

Composite sword construction and pattern welding in Roman Britain: indigenous production or Barbarian import?

By the 2nd century AD in Europe (if not earlier), simple forms of composite construction were giving way to more complex and formal varieties of pattern-welding usually with welded-on cutting edges. Weld patterns were first noted on archaeological iron swords from waterlogged sites in northern Germany and Scandinavia in the mid-19th century, in particular the great votive peat bog (or pool) deposits of Jutland. In the (mainly) mid-2nd to late-4th century votive deposit at Nydam alone, 93 of 106 swords found are recorded as being pattern-welded (Todd 1975, 192-5). The acid water of the peat bog had (further) deeply etched the surface leaving the patterns easy to see (Engelhardt 1866, pl 6-7; Fig 1). This is typical of anaerobic waterlogged

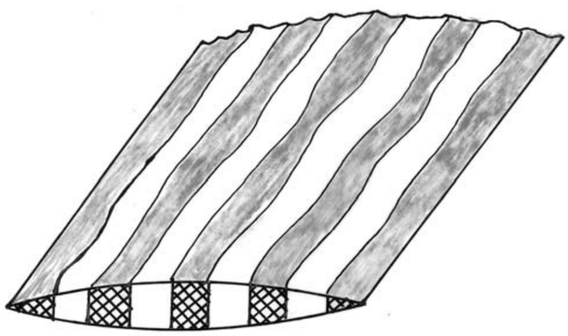

Figure 4: Perspective view of the structure of one of the late Iron Age sword blades from Llyn Cerrig Bach with its simple, slightly sinuous banded structure made of plain iron rods (white) welded between others of low carbon iron (cross-hatched in section but grey on the surface). (after McGrath 1968, fig 2, no4 and Tylecote 1986, fig 92d).

burial conditions whereas burial in drier ground leaves pattern-welded weapons badly corroded and the patterns virtually impossible to see, except by X-radiography. This kind of large votive deposit cannot have been that unusual in the Jutland area to judge from the more recent find of similar material from Illerup (Biborski and Ilkaer 2007). However the great popularity of these weapons during the first millennium AD has begun to be fully appreciated only during the last 50 years with the application of X-ray techniques to archaeological iron objects.

Although little detailed technological work has yet been done on surviving European pattern-welded swords of the 2nd-4th centuries, it is clear from what is visible on the surface of the swords from Nydam, that this was a great period of experimentation in different forms of pattern-welded sword construction. Swords with a banded construction, similar to that already described for the late Iron Age sword from Llyn Cerrig Bach, have been identified from the Nydam deposit and have been reported on other roughly contemporary European sword blades from further east (Rosenquist 1971, 188, fig 22). Other swords from Nydam include straight and simple chevron type twist patterns very similar to those found on two long swords (*spathae*) from Canterbury and two of the roughly contemporary pattern-welded swords excavated at the Roman fort of *Arbeia* (South Shields).

Structure and context of the Canterbury pattern-welded swords

The two long swords from Canterbury were evidently buried hastily in a shallow irregular pit, the swords having been thrown on top of their owners who would appear from their equipment (datable on stylistic grounds to the late 2nd century) to have been German officers in the Roman army (Webster 1982, 185). The circumstances of their disposal would suggest these men were murder victims, the killing perhaps linked to a mutiny by part of the Roman army in SE Britain in 186 (Gilmour 2009, 260). This could explain why the accompanying pieces of equipment, especially the two long swords, were buried in this particular way (to hide incriminating evidence) at this time.

These two long swords have now been both X-radiographed and metallographically examined and both were of complex pattern-welded construction, not as was reported in the initial assessment (Watson *et al* 1982, 189). One of these blades would have had a single chevron or herringbone pattern running down the centre on either side of the blade, while the other would have

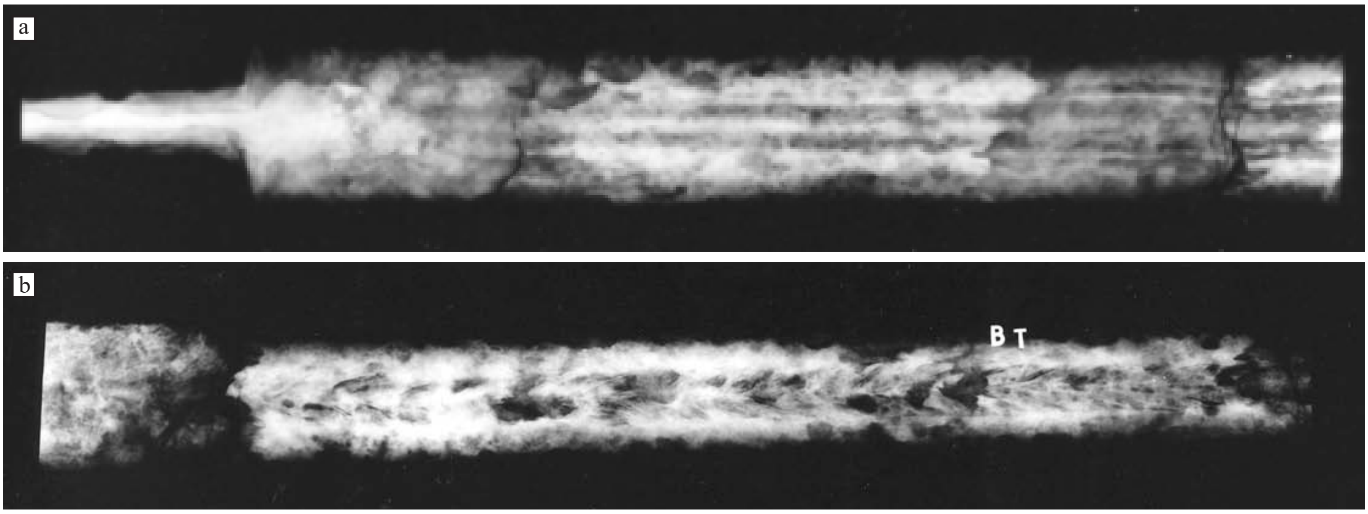

Figure 5: X-radiographs of two 2nd-century long swords from Canterbury. a) Longitudinal-banded structure to the central part of one sword, and b) Coarse herringbone or chevron pattern along the central part of the other sword. Traces of the welds between the cutting edges and the composite cores of each sword are visible in places as narrow dark shadows.

had a series of laminated bands running down the central part of the blade (Fig 5). Both these forms of decorative construction have a series of parallels from Nydam and other sites in northern and Eastern Europe. There are also two shallow grooves or narrow fullers – so called from the forging process used to form them which also results in the grooves being in opposing pairs on either side of the blade – running down the central pattern-welded part on both sides of each of these swords.

Although the surface patterns on these two swords are different, in section the two blades are similar in appearance and structure (Fig 6). In both cases separate steel edges have been welded on to a pattern-welded central part, in each case the pattern was accentuated and slightly distorted by the forging of the grooves. Also clear in section is that the finely-banded patterned parts of each sword are made of alternate laminations of phosphoric and low carbon iron, a feature which is typical of swords of the Anglo-Saxon period, but which was clearly already present in Britain and well developed as a decorative technique by about 200.

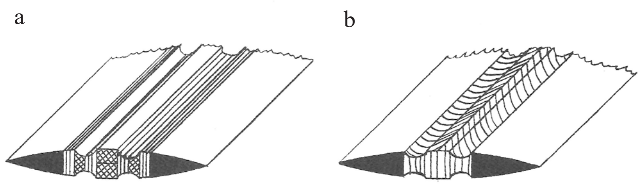

Figure 6: Simplified perspective views of the structure of the two swords from Canterbury. They show the composite pattern-welded construction in section and give a general idea of the form of the patterns that would have been visible on the surface of each. The welded-on cutting-edges are made of heat-treated medium to high carbon steel (black in section), with narrow pattern-welded bands and additional medium carbon steel rods (cross-hatched in section of sword a).

A back scattered electron image of the section of sword a (Fig 7a) shows the surviving metal, and the EPMA phosphorus map shows its original distribution right across both metal and the corroded and mineralised surface. It is clear from this that the phosphorus from the laminated bars survives well, both in its original position and concentration in the mineralised corrosion crust (formerly the surface metal of the blade) as well as in the surviving metallic core of the sword (Fig 7a). Thus this is an excellent way of demonstrating the original phosphorus content and distribution in the laminations of any object, provided the corrosion crust can be kept in place.

When corrosion goes too far through the middle of the sectioned part it is difficult to prevent the sample breaking up, as happened with the other sword. However some of the mineralised surface crust survived in the area of the laminated pattern-welded rods, and here too the EPMA phosphorus mapping (Fig 7b) showed the phosphorus left in its original position in the mineralised remains where no iron metal survived. In both swords corrosion had been too rapid for any relic grain structure of the iron to survive, but since the phosphorus survives well, this technique of elemental mapping offers the potential for retrieving useful metallurgical information even where a sample may be mostly or even completely corroded, without any surviving relic grain structure.

Pattern-welded swords from the Roman fort of *Arbeia*

Two pattern-welded swords from *Arbeia* (South Shields) were part of a group of possibly three or four swords, surviving (and possibly buried) as fragments with other equipment forming a votive or foundation deposit of military material under a new section of rampart built in 205-207 as part of an extension to the fort, the main supply base for the Hadrian's Wall region, to be ready for the visit of the Emperor Septimus Severus in 208 and his subsequent campaigns across Hadrian's Wall (Croom 1995, 50).

Preliminary examination of the surviving fragments, mainly by X-radiography, suggests that at least two of these swords were pattern welded and shows that one at least was also decorated with copper-alloy inlays near the hilt (Allason-Jones and Miket 1984, 296-8; Tylecote 1986, 171-2; Fig 8a). Tylecote (1986, fig 112) includes a radiograph from one sword which shows both copper alloy inlay and complex pattern welding, but also illustrates (1986, fig 114) photographs of a different sword (most probably from continental northern Europe although the provenance remains to be identified) which has very similar copper alloy inlays on both sides near the hilt, plus slight hints of pattern welding along the four parallel, centrally placed fullered grooves on both sides though this remains to be clarified. On one side, the copper alloy inlay – suspected to be brass – shows a figure of Mars with a spear held upright in one hand with the other hand holding a shield propped up on the ground, while on the other side the inlay shows a winged victory in the form of an eagle flanked by two standards (Fig 8b). The radiograph of this sword shows a double

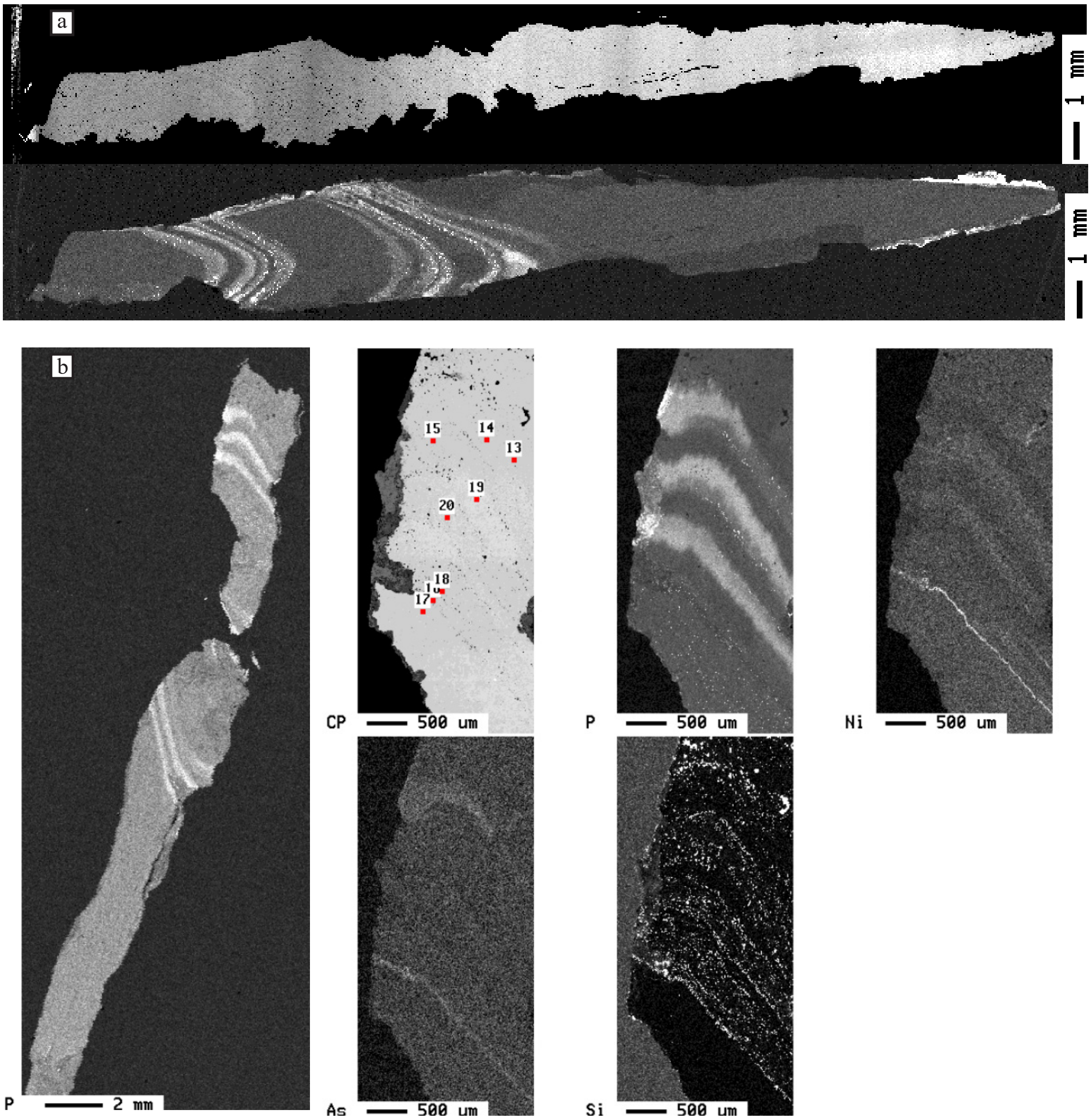

Figure 7: a) EPMA images of the section shown in Fig 6a. Above: surviving metal in a back-scattered electron image, below a phosphorus map of the same section (white areas are phosphorus-rich). b) EPMA elemental maps for the section shown in Fig 6b. Left: nearly complete map for phosphorus, right: detailed area maps for the metal plus corrosion crust (CP), showing nickel and arsenic enrichment mainly at some weld boundaries and the differential presence of silicon (in small entrapped slag inclusions), virtually absent in one central component..

chevron or herringbone pattern running down the blade, which from its initial appearance seems likely to be very similar in structure, although more complex, compared to the herringbone patterned sword from Canterbury (Fig 5b). The black lines picking out the details on the two inlays have been identified as niello and the almost cartoon-like character of the figures has been described as 'amateurish and uninspired' (Allason-Jones and Miket 1984, 296), which is totally at odds with the quality of the blade which, even from X-radiography, can be seen to be excellent. Although this sword is more complex, the single herringbone design seen on the X-radiograph of the second pattern-welded sword from South Shields (Croom 1995, 46, fig 1) would appear to be almost identical to that seen in the equivalent sword from Canterbury.

A series of very similar swords, probably of much the same date, have been found in several places in NE Europe, all with excellent quality pattern-welded (or similarly composite) blades, together with crude examples of copper alloy inlays copying the same general design of the figure of Mars on one side and the winged victory symbol on the other. In some examples

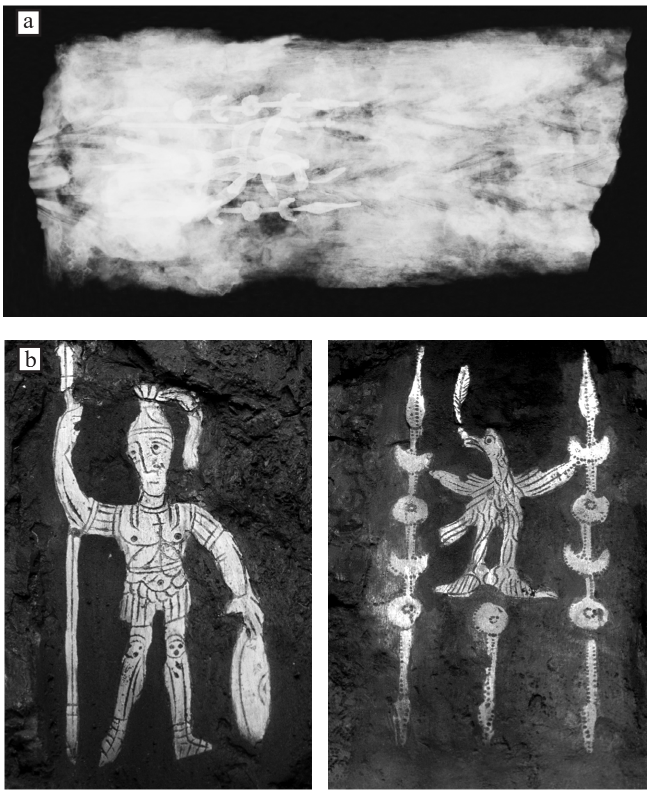

Figure 8: a) X-radiograph of one of the fragmentary swords buried at South Shields in c205-207, showing a double herringbone pattern running along the central part of the blade plus the overlapping images of two copper-alloy (?brass) inlays on either side near the hilt. b) The two inlays, representations of Mars as a Roman soldier on one side and a winged victory in the form of an eagle between two standards on the reverse.

the figures are barely recognisable, which for such a clearly high status and well-made sword blade, would seem inconceivable for a Roman military workshop. These designs are relevant to the Roman army but their crude appearance would suggest copying by craftsmen unfamiliar with the symbolism, and indicates a non-Roman (*ie* barbarian) origin for the swords and the inlays. So far the closest parallel to the South Shields inlaid sword would seem to be an almost identical example found in Hromowka in the Ukraine (Croom 1995, 46) a long way from the Roman Empire but probably not quite so far from a possible common point of origin somewhere in between.

If the recently considered evidence of military tombstones, altars and memorials does indicate a large (and continuing) Germanic element to the Roman army units posted to Hadrian's Wall (Clay 2007, 47-61) then one might see these swords as having belonged to regular army officers of Germanic origin, rather than being associated with federate or auxiliary units. Much the same could be said of the swords from Canterbury. These examples are simply the chance finds that have come to light so far but they suggest that a great many more existed, some of which may yet be found.

Yet more complex examples of herringbone and other twist patterns were also found among the Nydam swords as were other pattern-welded forms such as the rare lattice pattern found in a sword fragment until recently on display in the Ashmolean Museum, Oxford (Fig 9). This sword fragment, the find site of which is not recorded in the inventory for this part of the museum collection, is unlike any known later pattern-welded types but is so closely similar to another sword fragment from Nydam (Engelhardt 1866, pl 6, 10 (Fig 1); Maryon 1960, 32, fig 7) that it most probably originates from the same votive deposit, if not from the same sword, and again a date somewhere around the 2nd or 3rd century seems most likely. Its pattern-welded structure occupies the full width of the blade and the lattice framework is made of laminated rectangular section rods into which diamond-shaped lozenges have been hammer welded, each of these having been cut from a composite pattern-welded bar with a herringbone pattern showing on the surface.

The variety of pattern-welded designs found on long swords in the later Roman period, and the few technical studies so far done on them, suggests both that this was a period of great experimentation in this kind of design and construction for sword making, and also when skills had reached their peak. If the example of Nydam was typical then we can perhaps expect some 90% of long swords to have been pattern welded, and at present it seems reasonable to conclude that they were of north European barbarian origin. Also, because of Roman recruitment policy, these weapons found their way into the later Roman army along with much other military equipment, but essentially they belong to a non-Roman culture. The examples noted above come from chance discoveries at either end of eastern Roman Britain but one wonders (in the absence of cemeteries with accompanied burials) how many more remain to be found in the regions in between.

Technology and purpose of pattern welding

It has been suggested that pattern welding was developed as a method of combining the conflicting properties of the hardness of steel with those of the softness of iron to give a more resilient product. Scientific examination of surviving swords, especially those of Anglo-Saxon England (5th–11th centuries), however, indicates that it was actually developed for reasons of display rather than for any structural purpose. A combination of metallographic and scanning electron probe micro-analysis (EPMA), for the mapping of phosphorus concentrations and elemental analysis, suggests that the majority of the pattern-welded central parts of swords and other weapons of this period actually consist of a simple alternating or laminated structure which includes nearly all the different designs which are found (Gilmour 1990). This is a banded structure consisting of pieces of iron high in phosphorus (approx 0.5–1.0% P) and pieces of iron with a low but even carbon content (up to approx 0.2%, but generally less).

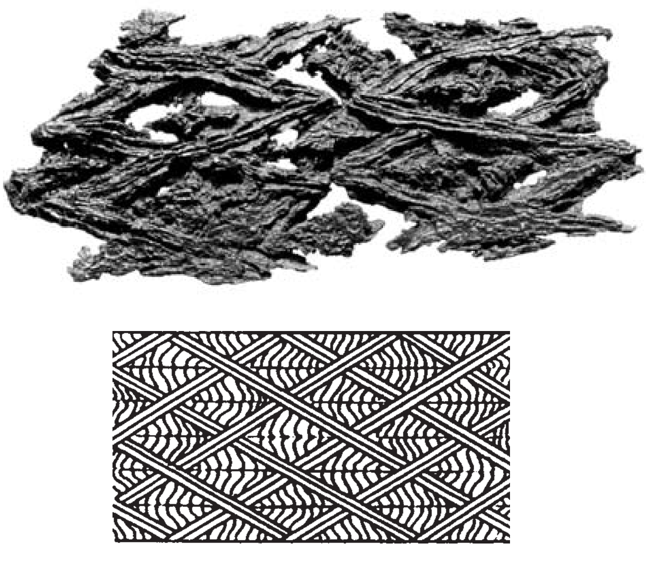

Figure 9: A corroded sword blade fragment (Ashmolean Museum, Oxford) probably from Nydam (cf Fig 1, 10) and below a reconstruction of its very unusual and complex lattice form of composite pattern-welded structure.

This is especially well illustrated in the twisted pattern found in a *seax* (a stray find) from Dorset dating approximately to the 10th century (Fig 10). In this example the alternate high phosphorus and low carbon iron construction of the composite pattern-welded strip welded into the blade, running parallel to the back, shows up exceptionally well both under optical microscopy (Fig 10b) and in an EPMA map for phosphorus (Fig 10d). In the map, the low carbon iron of the pattern-welded parts shows as black areas nearer the middle of this section. The larger rectangular black areas at either end represent the medium to high carbon steel edge and back parts of the blade, between which the patterned strip was welded. This example shows very clearly (Fig 10b) the optical contrast that is the result of making the pattern-welded parts of a weapon in this way. Much the same very clearly contrasting pale and dark bands would have been visible after this *seax* was originally polished and etched. The high phosphorus content of the pale-etched pattern-welded parts of weapons such as this also had the effect of preventing carbon diffusion across the welds during manufacture thereby ensuring that the patterns were clearly visible as contrasting pale and dark areas with sharp edges.

The edges of pattern-welded swords are usually composite in construction, but in contrast to the pattern-welded central parts, the edges tend to consist of a combination of plain iron (with hardly any carbon or phosphorus in it) and medium to high carbon steel (with approximately 0.5-0.8% carbon) which is welded in such a way that it forms the tip of the cutting edges, although even here steel is often found not to have been used. The great complexity in construction with the very sparing use of steel is well illustrated in the case of a snake-pattern sword from a 6th-century grave at West Heslerton, Yorks (Gilmour 1999; Fig 11), and four swords from a 6th/7th-century cemetery at Croydon, Surrey (Fig 12). The diagrammatic reconstruction of these illustrates how Kindī's description in his sword treatise, written in 832-841, of types of iron in use in northern Europe (Hoyland and Gilmour 2006) can be applied to earlier material as well.

Detailed analysis of swords and other weapons from Anglo-Saxon contexts has shown that four distinct iron alloys, including plain iron, were used quite specifically in the manufacture of the different main parts of these weapons (cf key to Fig 12). This in turn means that

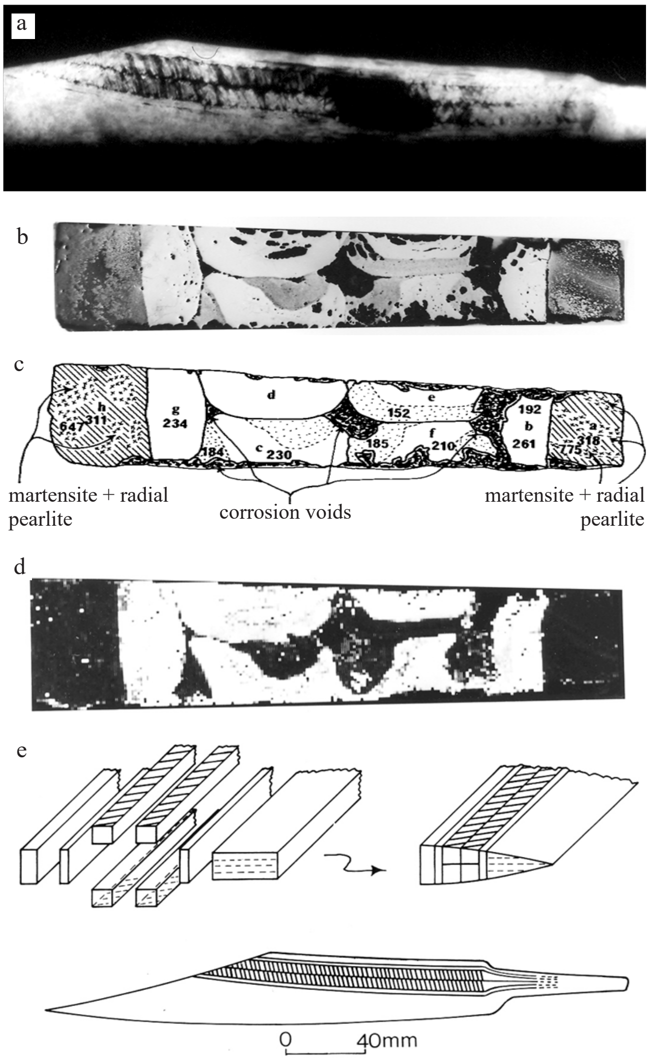

Figure 10: 10th century pattern-welded seax from Dorset. a) X-radiograph, b) Photo-macrograph (etched 2% nital), c) Sketch section showing welded structure and Vickers micro-hardness values, d) EPMA elemental map for phosphorus (P content up to 1% in white areas), e) Diagrammatic reconstruction views.

sword smiths of this period were skilled in using a variety of iron alloys and also means the iron and steel industry was actually very well developed and organised in terms of the metals produced, traded and used, during what has traditionally been thought of as the Dark Ages in Europe.

Middle Eastern written sources, particularly Kindī's 9th century sword treatise, describe swords with a visible patterned surface as being 'watered'. The use of low carbon iron in combination with phosphoric iron to produce the pattern welded parts of swords had already been developed by the end of the 2nd century – as is well illustrated by the structure of the long swords from Canterbury (see above) – and this technique must have been very well established by the mid-5th century and is found repeatedly to have been used for swords over the following two centuries. When etched the darker grey tones (resulting from the fine grain structure of low carbon iron) would have contrasted well with the pale or whitish appearance of the phosphoric iron (resulting from its very large grain structure), and the effect of (faster) flowing water would have been emphasised with a herringbone or chevron pattern. The effect of water flowing between two banks is an obvious interpretation for the effect seen on the well preserved late Iron Age sword from Orton Meadows (Fig 3), and this effect may have been intended for pattern-welded swords, at least in a more stylised form, for the great majority of the most complex later ones, those made before about the mid (and possibly later) 7th century.

*c*450-650: The peak of pattern-welded design and use for swords?

Whatever the origin of a particular blade, we can expect that the optical properties of different types of iron would have been exploited to show off or enhance the visual appearance of any pattern-welded sword. The quality of blades like these would have been judged by their appearance, and so the best combinations of iron alloys will have been deployed to enhance it. The structure of the many 5th- to 7th-century sword blades already examined analytically indicates strongly that the actual manufacture, exploitation and probably also the trade in the iron alloys developed significantly from earlier centuries. Technological studies suggest that it was at this period that this decorative style of composite welded manufacture reached its peak in terms of complexity and skill, in both the development of the iron alloys used and the way they were put together.

Quite what the patterns displayed on the swords meant to people in the millennium leading up to the mid-7th

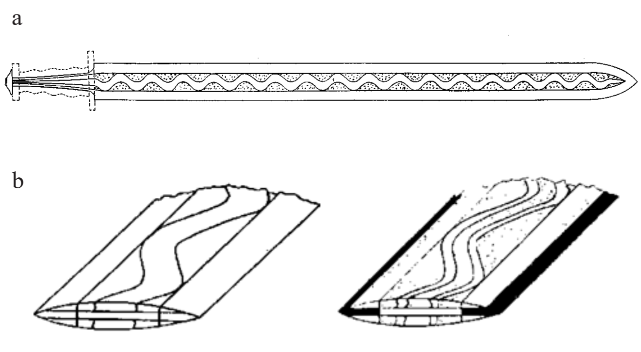

Figure 11: a) Simplified view of a very unusual snake pattern found on both sides of a sword from West Heslerton. b) Views of the structure of the sword. Left: the main parts of the blade, right: the more complex structure of the individual components and the effect of final polishing and etching of the sword blade (the white central bands are pale-etching phosphoric iron, the stippled areas grey-etching low carbon iron, and the black edges steel).

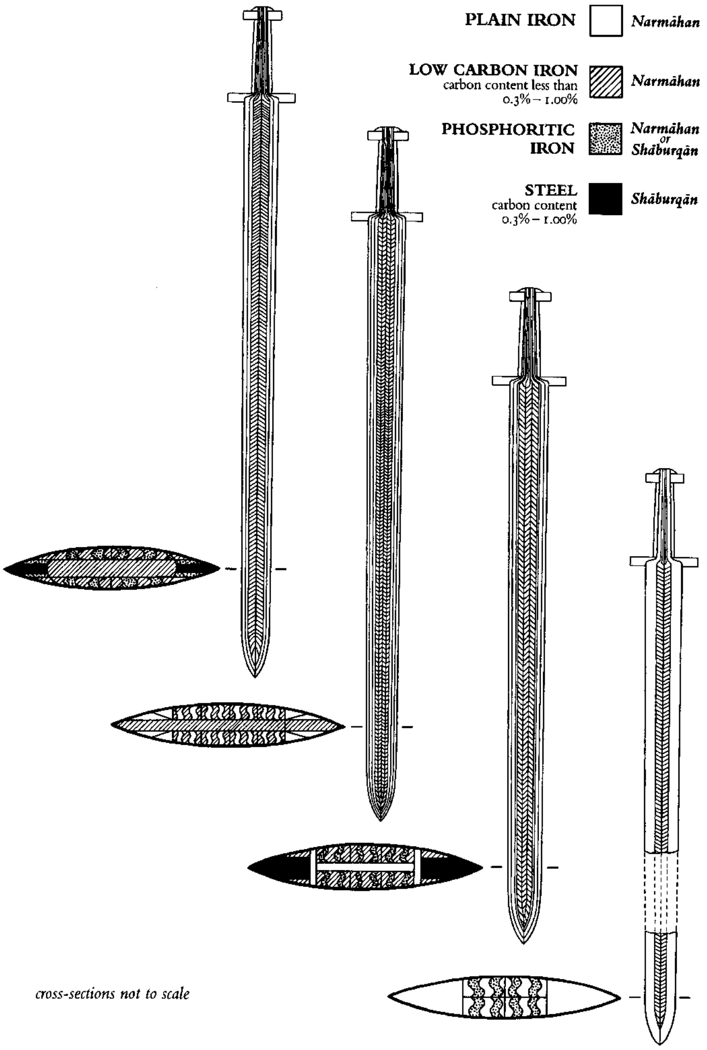

Figure 12: Reconstruction of swords from Croydon, showing their very complex, but typical, pattern-welded structures. Note the different structure of each sword in section, how little steel has been used (none in two cases) and how the final patterns involve the full width of the blade in three cases. The key shows the equivalent terms discussed by al-Kindī for the manufacture of composite European sword blades.

century is at best uncertain but several suggestions can nevertheless be made. There seem to be two main strands of meaning or purpose, one clearer than the other. The sword blades are clearly exhibition pieces, designed to demonstrate the very best in a smith's skill in combining the finest iron alloys in such a way as to produce precise visible surface patterns. The very best quality swords, as judged by their complexity and precision of patterns, are also found to have utilised the very best iron alloys available at that (or almost any other) time. The composite rods, whether twisted or not, from which the pattern-welded components were made required alternate laminations of low-carbon iron and phosphoric iron which had to be more or less homogeneous to enable the required optical contrast to be achieved.

What the smiths (and the polishers) had discovered was that a piece of iron whose carbon content was a consistent 0.1–0.2% (or even slightly less) produced a grey finish when polished and etched, as a result of the fine grain size that this small amount of carbon will induce in iron. Small quantities of phosphorus induce exactly the opposite effect, so that an increasing percentage of phosphorus will produce an iron with an increasing grain size and a much more bright white effect when polished and etched. Combining these two different alloys of iron to produce laminated bars for making composite rods, and using both twisted and straight rods, for a contrasting optical effect, was a technique that was already being exploited by the late 2nd century (Gilmour 2009).

Analysis carried out so far suggests that the phosphorous content of the iron used in the composite central rods incorporated into these much earlier pattern-welded swords was typically around 0.2–0.3%, but by the 6th century, at least in an Anglo-Saxon context, it was more typically within the range 0.5–1.0%. Thus phosphoric iron had become a highly specialised product, perhaps only smelted in a few production centres, which may well have been specially developed during the intervening period for its use in the making of pattern-welded swords; accordingly it may possibly also have been traded widely. Low-carbon iron may also have been developed and traded in this period for similar purposes.

Not only did this period see the peak in development in the combined use of low carbon iron and phosphoric iron for pattern-welded swords, but also the use of steel reached a minimum for sword blades such as these, and is nearly always found to only form the tip of the cutting edges. The cutting edges themselves are usually quite complex, and made in some kind of sandwich arrangement which would have intentionally formed part of the overall pattern-welded design (Gilmour 2003, 97-100; Fig 12). Steel here refers specifically to hypo-eutectoid steel (the lower end of the carbon content for this iron alloy) which for practical purposes is iron alloyed with approximately 0.3–1.0% carbon. Hyper-eutectoid steel (carbon content approximately 1.0–2.0% carbon) can be expected to be found in some artefacts made in the central southern Asian region but is almost unknown on finished objects in Europe although it has been found (and is to be expected in this region) for unused steel billets, partially processed bars of bloomery steel. For a definition and discussion of the varying exploitation of steel see Allan and Gilmour (2000, 41-79 and glossary entries pp 543, 548, 553).

It is much less easy to be sure of why swords were decorated in this way, although we can be fairly certain that it was only used for swords until approximately the mid-7th century. This appears to indicate that the patterns relate to specific pagan symbolism. Earlier medieval descriptions of analogous patterns seen on swords in the Middle East suggest that an association with water is implied, with the patterns themselves being described as watering. It is possible that by the 6th century we are seeing a highly stylised form of the kind of pattern seen on some later Iron Age long sword blades, where the resemblance to flowing water is much more obvious (Hoyland and Gilmour 2006, 15 n). It may be that the patterns were seen as imbuing the blade with some kind of special property. The rare form of snake pattern described in Thiðriks Saga, and seen in a 6th-century sword from West Heslerton, Yorks (Gilmour 1999; Fig 11), can be interpreted as a more obvious good luck charm; the watered patterns may have had a similar significance.

Whatever its significance, by the early 7th century, pattern welding had evolved into a highly formalised or stylised form of decorative composite-welded construction and was used for the great majority of swords that have been found in Anglo-Saxon England. Almost all these swords have been recovered from burials which can be dated approximately to the period 450 to 650, when the pagan custom of burial with objects such as weapons (for male burials) was common, particularly in eastern England. The patterns on the swords from these burials are almost invariably found (by X-radiography) to be either a single or multiple herringbone design. The simple herringbone or chevron designs are the result of welding two twisted rods with opposing spirals side-by-side: that is, with the twists running in opposite directions.

Multiple herringbone patterns were built up by welding more alternating twisted rods alongside each other. Designs based on two, three or four rods are the most common, but multiple designs based on five or even six twisted rods are occasionally found. In all these cases the adjacent composite rods were continuously twisted along their entire length before they were welded together. In nearly every case it has been found that the twisted composite herringbone pattern visible on one side of each of these swords is independent of the pattern visible on the reverse side. In other words these patterns are formed from two separate layers of adjacent twisted composite rods, either welded back-to-back to give two separate but usually indistinguishable herringbone patterns, or each welded, in a single operation, to a separate plain 'backing' piece running through the centre of the sword.

Sometimes an alternating design is found where the simple herringbone form is mixed with straight-grained elements. Occasionally the adjacent, alternately twisted and straight, composite rods were welded side by side so that the twisted portions of one rod were next to the straight portions of the next, so that the consequent pattern alternated across the blade as well as up and down. In all the cases of alternating patterns, the pattern could only work if the alternating portions of each twisted rod were very accurately forged. If they were not the correct length, then the pattern would not work, or at best would be untidy. Inaccuracies would magnify the problem along the whole length of the blade.

Thus the skill of the sword smith in being able to make very accurate variations in the pattern was demonstrated by how good the pattern was seen to be on the surface of the blade. But another way, in which his skill in making blades like these was shown, was by the appearance of their herringbone elements. If the herringbone design was undistorted then it meant that the smith had achieved a near-perfect finish on the surface of the blade without having to resort to grinding the blade's surface to achieve a flat finish which could then be polished and etched to reveal the pattern. As soon as any of the surface was ground away, then the pattern became progressively more distorted (Fig 13). Thus a near perfect herringbone

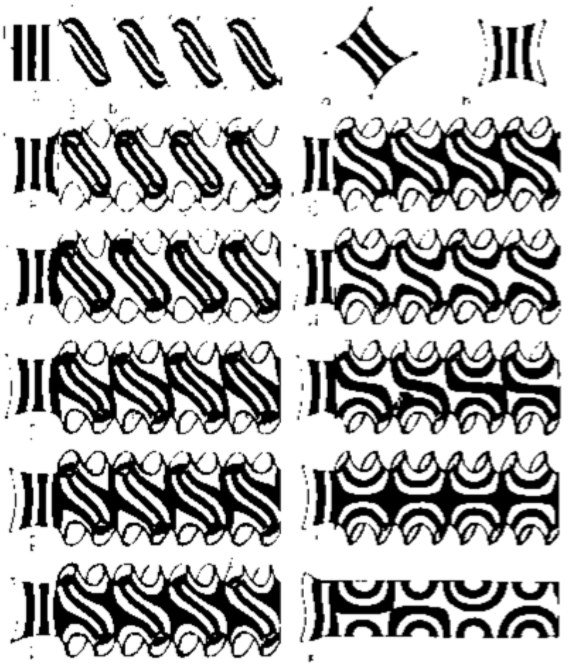

Figure 13: Progressively grinding away a twisted laminated bar will result in the original diagonal (spiral) pattern (upper left) becoming more and more distorted the more that is removed until the half way point is reached and a looped pattern results (lower right) (after Ypey 1982, 184).

design was another indication of both the skill of the sword-smith and of the quality of the blade, and this may have been one of the main ways in which the quality of an indigenous Anglo-Saxon sword blade was judged. This is in complete contrast to the pattern-welded design seen on a probable 6th century Frankish sword blade from the cemetery at Saltwood Tunnel, Kent, where the looped design depended on the careful matching and welding together of the adjacent continuously twisted composite rods, followed by the grinding away of half the thickness of each rod (Gilmour 2010, 61-5; Fig 13).

Interest in pattern-welding in Europe waned later in this period and, although pattern-welding for swords seems to have more or less disappeared before the 12th century, the technique appears to have persisted for a time in making knives but seems to have disappeared altogether in this region before the end of the 14th century. It must have continued in use in the Islamic areas to the east as well as further afield, and it would appear that, up to a point, pattern-welding was reintroduced to Europe in the later 18th century following contacts with the technique then being used by arms makers in the Ottoman Empire in the eastern Mediterranean. Between the late 18th and early 20th centuries in Europe, pattern welding was used for swords to only a very limited extent, a striking example being a sword made in Italy at Naples by the Neapolitan Royal Arms Factory (Fig 14). It bears the monogram PL and was made *c*1790 probably for Pietro Leopoldo, Grand Duke of Tuscany, who briefly became Emperor of Austria before he died in 1792. However, all the techniques and materials (different iron alloys) used by sword-smiths of the Anglo-Saxon era were no longer understood and this sword is crude by comparison, however striking it might look.

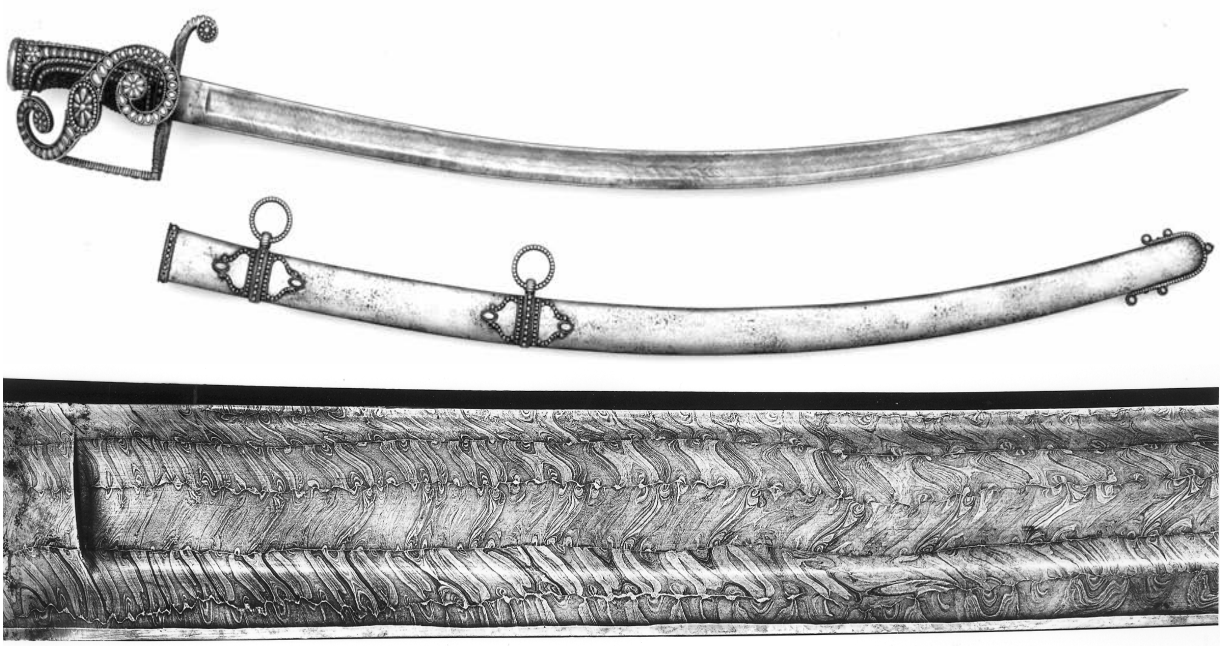

Figure 14: Neapolitan sword made in c1790. Note the uneven pattern-welded structure seen on this single-edged blade plus the use of a resist agent to protect a narrow margin along the cutting edge from the effects of the acid used to bring out the heavily etched pattern along the rest of the blade, curiously similar to the sword from Orton Meadows (Fig 3).

Acknowledgements

Fig 8b is reproduced by courtesy of the British Museum, Fig 9 is by Jeremy Hall and Fig 14 reproduced by courtesy of the Royal Armouries.

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