Developments in iron smithing and decorative welding techniques found in Anglo-Saxon swords and related edged weapons.

~~**The Technology of Anglo-Saxon Edged Weapons**~~

Brian J. J. Gilmour

Thesis submitted for the degree of Doctor of Philosophy in the Faculty of Arts of the University of London

VOL I

University College London
Institute of Archaeology
November 1990

Abstract

The subject of this study is the manufacture of edged weapons of the Anglo Saxon period in England, c.AD 400-1100.

The central part of the study consists of the technological examination of a reasonably large sample of the surviving weapons mainly by X-ray and metallography. The main aim was to gather sufficient evidence from such analysis to allow conclusions to be drawn about (a) the methods of manufacture in use at particular times; (b) the development of these methods during the period; and (c) why these developments took place.

The study deals mainly with swords, both double-edged longswords and scramasaxes (single-edged swords or daggers) but includes a few spearheads. To supplement the evidence from technological examination, the study is introduced by summaries of the typology and archaeology of these weapons (Chapter 1) and of the documentary evidence (Chapter 2). Such evidence tells much, not only about their formal history, but also about their use and significance, especially how far they were ceremonial and how far working weapons. This is important when assessing the aims and effectiveness of the smithing.

Chapter 3 describes the techniques of examination employed in this study, although the study is primarily concerned with the smithing of the weapons it was also necessary to consider, at least in outline, the sources and types of ores, and the smelting processes used to produce the metal for them. This information is summarised in Chapter 4 with a discussion of the more relevant aspects such as the possible direct product of bloomery steel.

To understand what information the metallurgical structures frozen in the surviving weapons yield about their smithing, Chapter 5 sets out the relevant aspects of the metallurgy of iron. This chapter includes a description of the methods of physical examination used here.

The bulk of the study (Chapter 6) consists of detailed analytical reports of the main sample of weapons examined both by X-ray and metallography. These reports have been grouped chronologically by period; a provisional grouping is suggested when few distinguishing characteristics survived with the blades.

In Chapter 7 the principal results of the analyses are set out and conclusions are drawn and discussed in the light of the preceeding chapters (and the Appendices I and II). Comparisons are made with analyses of some earlier and later weapons to help put these results in perspective.

During the study many other weapons were X-rayed only and these results are given in Appendix I. Appendix II provides a parallel for the decorative use of iron and steel in edged weapon manufacture, that of the near eastern so-called 'damascene' technique for making watered steel blades.

Acknowledgements

My greatest debt of thanks is owed to the late Professor Ronnie Tylecote without whose frequent encouragement, advice and, sometimes cajoling, this project might never have been completed. I also owe much to the encouragement and advice of Dr Nigel Seeley. The project, derived from an undergraduate dissertation which he supervised and he also supervised the present study in both its initial and final stages. I am grateful to Dr David Scott and Jim Black who also supervised the work at various stages and I would also like to thank other members of the Institute of Archaeology for their interest in the work. I must also thank Dr Helen Clarke of University College who read my earlier dissertation and suggested I pursue this study.

I would like to thank the Master and staff of the Royal Armouries and especially Bob Smith and the rest of the members of the Conservation Department for all their encouragement and support and to Mark Harrison and Chris Gravett for discussing various ideas and helping with the Anglo-Saxon literature sources. Also I would like to thank the Director and staff of the Lincoln Archaeological Trust who provided practical help and encouragement through the earlier stages of the work with particular thanks to Mick Jones, Elizabeth Nurser, Rob White and especially Kate Foley, now with English Heritage.

The project would not have been possible without the enlightened help of various museums in providing me with suitable material for the study and in particular I must thank David Kelly of Maidstone Museum, Leslie Cram of Reading Museum, John Clark of the Museum of London, Mike Stone of Swindon Museum and Roger Peers of the Dorset County Museum and Andrew White and the City and County Museum of Lincoln. I must also thank the British Museum especially Barry Ager and Leslie Webster for letting me look through all their material. Particular thanks are due to Janet Lang for x-raying all the B.M. medieval swords and scramasaxes and for all her help in making these and related information available to me. I must also thank Arthur Macgregor and Mark Norman of the Ashmolean Museum, Oxford for similar help in examining and x-raying their early medieval weapons, and, in particular, to Chris Salter of the University of Oxford, Dept. of Materials Science for his EPMA work and helpful comments.

I owe a great deal to the generous help given to me by Susan Amberton and Sandra Morris who made the final typescript possible.

Lastly, but definitely not least, I would like to thank Rod Clough, my fellow researcher who gave me much specialist advice as well as daily, friendly encouragement; also Lauren, my wife, my brother Anthony and my mother who have given me much practical advice and personal support and encouragement on the project right from the early stages, and also other friends who have asked after the work (and wondered when it was going to be finished). Finally I must thank Dr Martin Henig who read a draft and advised on various points, for his help and encouragement.

The Technology of Anglo-Saxon Edged Weapons

Table of Contents

Acknowledgements

Page

Introduction 1

Chapter 1. Types, origins, development and survival of the weapons studied

1.1 Change from bronze to iron 5
1.2 Manufacture of iron swords 6
1.3 Source of weapon finds: 8
1.3.1 Early Anglo-Saxon Period (5-7th centuries) 9
1.3.1.1 Swords from cemeteries; their condition and potential for metallographic analysis 9
1.3.1.2 Sword blade types and origins 9
1.3.1.3 Manufacture of sword blades and fittings 10
1.3.2 Middle Anglo-Saxon Period (7th-9th centuries) 11
1.3.3 Late Anglo-Saxon Period (9th-11th centuries) 11
1.3.3.1 Blade types, dating and origins 12
1.3.3.2 The effects of waterlogged burial conditions 14
1.4 Scramasaxes 14
1.5 Spearheads 17

Chapter 2. Evidence for the manufacture of edged weapons from literature, historical and pictorial sources

2.1 Descriptions of contemporary observers 18
2.2 Sword mentions in epic poems or sagas 26
2.3 Conclusions 31

Cont ....

		Page
Chapter 3.	**Techniques of examination employed**	
3.1	Visual examination	32
3.2	X-radiography	32
3.3	Metallographic analysis	34
3.3.1	Cutting and mounting of specimens	34
3.3.2	Microscopy	35
3.3.3	Hardness Testing	36
3.3.4	Photomacrographs	36
3.4	Electron probe micro-analysis (E.P.M.A) and other methods of examination	37
Chapter 4.	**Some aspects of the physical metallurgy of iron and iron-carbon alloys**	
4.1	Allotropy of iron	38
4.2	Solid solubility of carbon in iron	38
4.3	Wrought iron, steel and cast iron	38
4.4	Hypo- and hyper-eutectoid steels	40
4.5	Cast iron	40
4.6	Calculation of the carbon content in a hyper-eutectoid steel	40
4.7	Heat treatments of carbon steels:	41
4.7.1	Annealling and normalising	41
4.7.2	Full annealling	41
4.7.3	Normalising	41
4.7.4	Overheating during annealling and normalising : Widmanstatten effect	41
4.7.5	Subritical annealling	42
4.7.6	Quench hardening	42
4.7.7	Effect of cooling rate	42
4.7.8	Martensite	43
4.7.9	Nodular troostite or radial pearlite	43
4.7.10	Bainite	44
4.7.11	Tempering	45
4.7.12	Gradient Quenching	46

Cont ....

		Page
Chapter 5.	**The early production of iron and steel**	
5.1	Introduction	47
5.2	Outline of the direct or bloomery process:	47
5.2.1	Selection and exploitation of ores	47
5.3.1	Carbonate ores:	48
5.3.1.1	Sedimentary deposits	48
5.3.1.2	The nodular carbonate form	48
5.3.2	Haematite ores	48
5.3.3	Limonite ores	49
5.3.4	Other ore sources	49
5.3.4.1	Magnetite	49
5.3.4.2	Bog iron ore	49
5.3.4.3	Sulphide Ores	49
5.3.4.4	Phosphorus containing ores	50
5.3.4.5	Quality of ores and reasons for selection	50
5.4	Pre-smelting treatments - ore dressing:	51
5.4.1	Washing	51
5.4.2	Weathering	51
5.4.3	Roasting	51
5.5	Smelting	52
5.5.1	Fuel	52
5.5.2	Reduction of ore to metal	52
5.5.3	Furnace types	53
5.5.4	Fluxing	54
5.5.5	Formation and consolidation of an iron bloom	55
5.5.6	Effects of phosphorus and sulphur	55
5.5.7	Iron bloom	56
5.6	Natural steel	56
5.7	Nickel enriched iron	57
5.8	Bloomery steel, direct process	58
5.9	Cast iron	60
5.10	Carburisation of iron	61
5.11	Effects of phosphorus on carburisation and other properties	62
5.12	Forging, welding and piling	63

Cont ....

		Page
5.13	Oxidation during welding	64
5.14	Minor element enrichment at weld seams	65
Chapter 6.	**Analyses of the edged weapons examined**	
6.1	Sword S32, from Reading	66
6.2	Sword S27, from the Thames at Little Wittenham	69
6.3	Sword S29, from the Thames at Little Wittenham (?)	71
6.4	Sword S39, from Whittlesey	73
6.5	Sword S17, from Sarre	75
6.6	Sword S49, probably from Bifrons	79
6.7	Sword S51, from Sarre	81
6.8	Sword S52, from Sarre	82
6.9	Sword S53, from Sarre	84
6.10	Sword S54, from Sarre or Bifrons	86
6.11	Sword S55, from Sarre or Bifrons	88
6.12	Sword S56, from Bifrons	91
6.13	Sword S12, from Wickhambreux	93
6.14	Sword S13, from Kent, possibly Bifrons	96
6.15	Sword S14, from Eastrey	98
6.16	Sword S15, from Holborough	102
6.17	Sword S18, from Aylesford	105
6.18	Sword S19, from Wickhambreux	109
6.19	Sword S20, from Lenham	112
6.20	Sword S1, from Lovedon Hill	115
6.21	Sword S40, from Chesterton	118
6.22	Sword S10, from Mitcham	122
6.23	Sword S45, from Mitcham	125
6.24	Sword S16, from Sarre	128
6.25	Sword S31, from Caversham	130
6.26	Sword S46, from Brentford	134
6.27	Sword S7, ? from the Thames near London	137
6.28	Sword S8, ? from the Thames near London	139
6.29	Sword S43, from the Thames	141
6.30	Sword S48, from Rochester	145

Cont ....

		Page
6.31	Sword S23, ? from the Thames near Reading	148
6.32	Sword S47, from the Thames at Waterloo Bridge	151
6.33	Sword S24, from the Thames at Cleeve	154
6.34	Sword S41, from the Thames at Vauxhall	157
6.35	Sword S25, from Reading (? Thames)	161
6.36	Sword S44, from the Thames at Brentford	164
6.37	Sword S26, from the Thames at Wallingford Bridge	167
6.38	Sword S28, no provenance	168
6.39	Sword S30, from Sunbury Weir Stream	170
6.40	Scramasax S50, from Barham Down	172
6.41	Scramasax S22, from the Thames at Reading	174
6.42	Scramasax S34, from Kempsford	177
6.43	Scramasax S37, from Kempsford	181
6.44	Scramasax S42, from the River Lea at Leyton	184
6.45	Scramasax S4, from Dorset County Museum	187
6.46	Scramasax S9, from the Thames at Hampton	190
6.47	Kris S57, probably from Malaysia	192
6.48	Spearhead S38, from Kempsford	194
6.49	Spearhead S35, from Kempsford	196
6.50	Spearhead S36, from Kempsford	198
6.51	Spearhead S33, from Kempsford	202
Chapter 7.	**Discussion and conclusions on Anglo-Saxon edged-weapon technology**	
7.1	Swords	205
7.2	Scramasaxes	213
7.3	Spearheads	216
7.4	Pattern-welding	218
7.4.1	Background and reconstruction experiments	218
7.4.2	Origins and development of pattern-welding in Europe	220
7.4.3	Selection of iron alloys for pattern-welding	224
7.4.4	Pattern-welded blade types	228
7.4.5	Methods for varying the patterns and for producing the final surface appearance	229
7.4.6	Eastern pattern-welding	231

Cont ....

		Page
Appendix 1 :	**Catalogue of edged weapons examined by X-radiography**	235
Appendix 2 :	**South Asian watered crucible steel**	275
A2.1	Introduction	275
A2.2	Origin and use of the term 'damascening' for watered crucible steel sword or dagger blades	276
A2.3	Wootz and the manufacture of watered crucible steel in India, Sri Lanka and Persia	280
A2.4	Early Arab accounts of watered crucible steel	284
A2.5	The production of wootz ingots	286
A2.5.1	Early European accounts of the methods used	286
A2.5.1.1	Wootz produced by the carburisation of bloomery iron with dried wood	287
A2.5.1.2	Wootz produced by the carburisation of bloomery iron with cast iron	290
A2.5.2	Discussion of the methods described for making wootz:	292
A2.5.2.1	The bloomery iron/wood method	294
A2.5.2.2	The bloomery iron/cast iron method	296
A2.6	Producing the watered pattern	297
A2.6.1	Dendritic segregation	301
A2.6.2	Grain boundary distribution of cementite	302
A2.6.3	A layered distribution of cementite particles	303
A2.6.4	Three dimensional distribution of cementite needles	304
A2.6.5	Varieties of pattern and final polishing and etching	304
A2.7	Conclusions: The origin and purpose of watered crucible steel and its comprarison with pattern-welding	305
Bibliography		307

Vol 2

Figures

1 Wheel and hand grinding and polishing of sword blades; from the Utrecht Psalter c AD 820

2 Variation of micro-hardness with load

3 i) Iron-carbon equilibrium diagram
ii) Expanded steel portion of the iron-carbon diagram

4 Continuous cooling time/temperature transformation (TTT) diagram: the transformation effects of different cooling rates for eutectoid (0.8% carbon) steel

5 Isothermal TTT diagram for eutectoid steel

6 Superimposed continuous cooling and isothermal TTT diagrams

7 Variation of hardness with carbon content for different transformation products produced by different rates of quenching

8 Variation of hardness with tempering temperature for a 0.4% carbon steel tempered for 30 minutes

9 Variation of depth of carburisation with temperature

10 Outline of swords with positions of sections

11 Outline of scramasaxes with positions of sections

12 Outlines of kris with position of section

13 Outlines of spearheads with positions of sections

14 Sword blade S32

15 Sword blade S27

16 Sword blade S29

17 Sword blade S39

18 Sword blade S17

19 Sword blade S49

20 Sword blade S51

21 Sword blade S52

22 Sword blade S53

23 Sword blade S54

24 Sword blade S55

Cont ...

25	Sword blade S56
26	Sword blade S12
27	Sword blade S13
28	Sword blade S14
29	Sword blade S15
30	Sword blade S18
31	Sword blade S19
32	Sword blade S20
33	Sword blade S1
34	Sword blade S40
35	Sword blade S10
36	Sword blade S45
37	Sword blade S16
38	Sword blade S31
39	Sword blade S46
40	Sword blade S7
41	Sword blade S8
42	Sword blade S43
43	Sword blade S48
44	Sword blade S23
45	Sword blade S47
46	Sword blade S24
47	Sword blade S41
48	Sword blade S25
49	Sword blade S44
50	Sword blade S26
51	Sword blade S28
52	Sword blade S30

Cont ...

53 Sword blade S50

54 Sword blade S22

55 Sword blade S34

56 Sword blade S37

57 Sword blade S42

58 Sword blade S4

59 Sword blade S9

60 Kris S57

61 Spearhead S38

62 Spearhead S35

63 Spearhead S36

64 Spearhead S33

65 Summary of cross-sectional structures found

66 Methods of combining iron and steel to make blades

67 Main structural types found in pattern-welded blades

68 Acklam sword: reconstruction of both sides of the blade, drawn from a radiograph

69 Variations in pattern through the thickness of a twisted laminated rod (after Ypey 1982)

70 Pieces from different stages in Anstee's 1959 pattern-welding experiments

71 Peterborough sword: surviving surface detail heavily etched structural pattern with resist protected edges and remains of inlaid makers mark

72 Peterborough sword: surviving surface detail; pattern enhanced by oblique lighting

73 Peterborough sword: radiograph showing the coarse-grain pattern running across the full width of the blade.

74 Simple (Stage 2b) pattern-welded structure seen in a sword blade from Lyn Cerrig Bach

75 3rd-century pattern-welded swords from Canterbury: (i) blade with a non-twisted pattern; (ii) blade with a twisted pattern; radiographs of Canterbury blades (i) and (ii)

76 Development of pattern-welding

77 Some unusual forms of pattern-welding found on sword blades.

78 Combinations of weld pattern found on scramasaxes and/or spearheads of the Late Saxon Period

Cont ...

79 Aldersgate scramasax or knife: conjectural method of construction for this individual - toothed type of weld pattern.

80 Gilling sword: herringbone pattern partially distorted by grinding

81 An eleventh-century Anglo-Saxon manuscript illustration showing barbed spearheads

82 A comparison between a typical form of Late Saxon pattern-welded spearhead (6.50 from Kempsford) and one of the spearheads shown in the eleventh-century illustration (Fig 81).

83 The wootz to watered crucible steel process.

84 Two wootz ingots and a bar forged from a wootz ingot

Tables

1 Effect of carbon on the average hardening temperature and the critical cooling rate of plain carbon steel

2 Variation of temper colour with temperature

3 Effect of phosphorus on the diffusion of carbon

4 Effect of temperature on the thickness of the carburised layer after two hours

5 Effect of carbon and phosphorus on the hardness of iron

6 Colour changes of iron with temperature

7 Summary of metallographic analyses

8 Electron probe micro-analysis (EPMA): Results, percentage of minor elements by weight.

INTRODUCTION

The present study deals mainly with the changes and development in smithing practices, particularly with respect to the use of different combinations of iron and steel, in the manufacture of sword blades and other edged-weapons during the Anglo-Saxon (or early medieval) period between c. AD 400 and 1100. The study arose from a general survey of sword-smithing technology, undertaken for an undergraduate dissertation for the University of London, Institute of Archaeology, completed in 1975.

Hilda Ellis-Davidson has stated that 'A study of the swords of Anglo-Saxon times must begin with the practical questions: What were the swords like, and how were they made?' (1962, 1). A great deal of valuable information on the archaeology and contemporary literature concerning these weapons is contained in her book, but information about the actual structure, manufacture and appearance of the sword blades was not available. She was unable to answer the questions posed in the absence of any physical analysis of the weapons.

In Britain several hundred swords, scramasaxes and spearheads of the Anglo-Saxon period survive, mainly in museums in England. The present study sets out to show that a careful study of the blades of these weapons, both by radiography and metallographic analysis, can reveal much concerning their structure, appearance and particular smithing techniques such as heat treatments even when the blades are very badly corroded. With the virtual absence of written records this is the only approach possible in attempting to reconstruct this important early industry.

The work presented here, with one exception devoted to material from Britain, was undertaken to provide some of this missing information. The scope of the study was extended to include some Roman and earlier material, and a little later medieval material, for comparative purposes. A 19th-century pattern-welded Malayan kris (dagger) has been included to show how a typical, although more recent, example of south-east Asian decorative welding and etching might compare with earlier European pattern-welded weapons.

In this study the main emphasis has been concentrated on swords and to a lesser extent on the single edged weapon, the scramasax, with a few spearheads included to compare the metallurgy and smithing techniques used. The reason for this emphasis is that the general survey of swordsmithing, already mentioned, suggested that the most complex smithing techniques were concentrated on swords and scramasaxes. It seemed that a study concentrating on the weapons would be most productive in tracing developments and changing fashions in this more specialised branch of Anglo-Saxon iron smithing. Some spearheads have been included in the study in order to show how and when techniques such as pattern-welding and heat treatments were applied to this class of edged-weapon.

The study of iron from archaeological contexts in general, and swords in particular, is made more difficult because, unlike other metals in antiquity, it was produced in the solid state, from its ores, as a spongey iron bloom. Steel (in Europe) was made either directly by the same bloomery process or produced (probably more usually) by the carburisation of bloomery iron (for a discussion of the methods, see Chapter 5). As a result all iron and steel artefacts produced in Europe before the late medieval period were made by forging and welding processes from metal which had never been molten and are therefore heterogeneous in contrast to non-ferrous objects produced from the liquid state which are more homogeneous. Identification of metals by techniques such as chemical analysis, X-ray fluorescence and Atomic absorption spectroscopy is much less useful for iron artefacts as these methods do not allow for differentiation between the parts of a heterogeneous structure.

The nature of early iron means that the analytical study of iron artefacts is dependent upon metallographic analysis using optical microscopy and hardness testing. This, backed up by detailed techniques such as Electron Probe Micro-Analysis (EPMA) where possible, forms the basic method of the present study.

Interest in iron artefacts, particularly from a typological and technological viewpoint, has tended to lag behind the study of copper alloy objects and particularly those made of the more precious metals. This must in part be the result of the unpromising appearance of most archaeological iron objects. It may also be because iron artefacts have tended to be viewed as utilitarian, and, therefore perhaps, not as worthy of study as objects with a more obvious 'antique' appeal.

An obvious exception to this view is the interest in weapons and armour which have long been considered as items of value and usually feature prominently in any collection of metal artefacts. In more ancient times this was also the case; for example swords were sometimes specifically mentioned in the wills of wealthy Anglo-Saxons and also by early writers.

Until recently little analytical work had been done on the structure and manufacture of iron tools and implements. It is mainly due to the pioneering work of Professor R.F. Tylecote in this country and Professors Piaskowski and Pleiner, in Poland and Czechoslovakia respectively, that research into the technology of iron has become established. Also until recently there has been little analytical research work done on the structure and manufacture of iron weapons and this is possibly more surprising given the greater interest or value attributed to these objects.

The main interest in the study of Anglo-Saxon iron smithing over the past forty years has tended to focus on the technique of decorative welding known as 'pattern-welding'. This term was introduced by Maryon and first appeared in print in 1948 (Maryon 1948, 73-76). Weld patterns in swords of archaeological origin became a subject of wider interest following the discoveries, in the mid nineteenth century, of the great votive deposits of weapons in the peat bogs of the Jutland peninsula (see Chapter 1.2). In the largest of these, at Nydam, approx 90% of swords were found to have clearly visible patterns etched into the corroded surfaces of the blades.

In the following half century or so many swords with visible weld patterns were found in waterlogged deposits particularly Viking period weapons in Scandinavia (Lorrange 1889). Before 1948 the decorative technique observed on these blades was described as a form of 'damascening' (for instance Baldwin Brown 1915, 273), a name used to describe a wide variety of inlay techniques used in metal working as well as the production of the special kind of Near Eastern watered steel, made from an early form of crucible steel called Wootz, for which Damascus was a reputed centre according to some later European writers (Appendix 2).

Surviving swords and daggers of this type date from about the sixteenth century onwards and can be found in many major museum and private collections (for instance The Wallace Collection, Victoria & Albert Museum and Royal Armouries). They have often survived in almost perfect condition with their intricate 'watered' patterns marked by pale and darker grey highlighting on the blades (for instance Smith 1960, 16-19). The technique used to produce these Near Eastern blades has sometimes been referred to as true damascening so as to separate it from the pattern-welded technique

The present study examines both techniques and explores the suggestion made by Tylecote (1976, 76) that while the techniques were very different in many ways, they may not always have been as fundamentally different as has sometimes been supposed, for example by Maryon who said that there was no technical relationship whatever between the two processes (Maryon 1960, 52). The crucible watered steel or so-called damascene process is described and compared with pattern-welding in Appendix 2.

Chapter 1

Types and origins of weapons studied and main manufacturing techniques

1.1 Change from bronze to iron

Bronze Age weapons were homogeneous having been made from molten copper-alloy cast into moulds, with a typical alloy composition of about 90% copper and 10% tin with small proportions of other alloying elements such as lead, arsenic, antimony and nickel (Tylecote 1962, Table D, 324-41). Sword blades produced in this way would have ranged in hardness between about 150 and 250 HV depending on the alloy composition and degree of work hardening. Bronze blades could only be hardened by cold working which also increased their brittleness.

Iron began to be regularly used in the Eastern Mediterranean around 1200 B.C. although earlier iron artefacts are found, for instance the iron knife from the tomb of Tutankhamun (d.1350 B.C.) (Aitcheson, 1960, 94). Early iron weapons occur mainly in tombs of the 12th century B.C. in Syria, Palestine, Cyprus and parts of Greece. These include a long sword of a type known at the same time in bronze from a period 1 tomb at Hama in Syria. (Waldbaum 1980, 82-3).

Hallstatt period finds from cemeteries in Central Europe show how iron and bronze swords of the same types existed at the same time in a transitional period during which iron displaced bronze as the metal used to make weapons and implements (Sievers 1982). One such sword (Chap 6.1) was examined in the present study. This is likely to be an iron copy of a Thames type bronze rapier. No other British examples of bronze sword types copied in iron have so far been noted although good parallels have come from Hallstatt C and D1 contexts in Europe (Sievers 1982, Tafel 4, No 17; Tafel 14, No 84; Table 15, No 92).

1.2 Manufacture of Iron Swords

Iron weapons were made from solid bloomery iron which involved a very different technology and working methods. Blades and iron fittings had to be forged from pieces of white hot iron of a thick pasty or dough-like consistency. At the beginning of the Iron Age the new weapons of iron were made in the the same style as their Late Bronze Age counterparts, for example the decorated Luristan sword hilts of about 1000 B.C. (Maxwell-Hyslop and Hodges 1966). These illustrate how fashion in weapon styles dominated changes in technology. The earlier designs were suited to the casting of bronze but not to the forging of solid iron. Conforming to such Bronze Age styles must have been both difficult and unnecessarily inconvenient.

In the present study are included two weapons which appear to belong to the transitional Late Bronze Age - Early Iron Age phase. One already mentioned, is an iron copy of a Late Bronze Age sword blade (Chap. 6.1) and the other an iron socketed spear head (Chap 6. 48) similar to Bronze Age types. The Iron Age spread to Britain, from Europe, probably during the seventh century BC (Cunliffe 1974, 30) and so it seems reasonable to conclude that these transitional weapons are not much later than approximately 600 B.C.

Long swords were common by the Late Iron Age and graves in both France and Britain have produced iron swords up to about 1m long (Todd 1975). From Roman accounts of battles with the Gauls it seems clear that Gallic long swords were too long and not rigid enough for close quarter fighting (Lang 1988, 199-201).

At the time of the Claudian occupation of Britain Roman the short sword, the *gladius*, was a standard item of equipment (Hazell 1981). Most *gladii* were no more than about 50 cm in length and had fairly thick rigid blades which were suitable as a stabbing weapon in hand-to-hand combat. The Roman gladius would appear to be a derivative of a shorter form of Early Iron Age sword adapted to suit the method of warfare developed by the Roman army in which the sword was a standard infantryman's weapon and not a sign of rank.

In the Later Roman army the long sword or *spatha* became part of the equipment of the auxiliaries and because of its greater length, was better suited as a slashing weapon although it would have been more prone to bending than the shorter, comparitively thicker, *gladius*. The *spatha* (usually 80-100 cm long) can be distinguished from the *gladius* (usually 40-60 cm long) by its length and the comparative thinness of its blade. Few examples of either type of sword have been found from sites within the Roman Empire.

The survival and distribution of Iron Age, Roman and later weapon finds reflects changing burial practices. Many weapon finds also come from rivers particularly near river crossings and these in most cases are likely to represent ritual deposition rather than the loss of equipment (Bradley 1990). In the Roman and post-Roman Iron Age this practice can be seen more clearly. This practice seems not to have been confined to the Celts but is also found amongst the peoples of north-west Europe of the Roman and post Roman Iron Age in the great votive deposits of the Danish and North German peat bogs such as those at Illerup and Nydam. It would seem that large quantities of military equipment such as swords or spearheads are not found on the sites of battlefields. These would probably have been carried off for use as scrap metal, spare weapons or perhaps trophies which may, themselves, have become votive offerings.

Weapon finds in Roman Britain are rare although two *spatha*_ were found in Canterbury, each accompanying a male skeleton in an isolated pair of third-century burials (Webster and others 1982). It is possible that these were the burials of Germans mercenaries or members of a Roman auxiliary unit. These two long swords are similar to others found on the northern frontier zone of the Roman Empire (Rosenquist 1968) and may be imports from this area. Both have been X-rayed but not metallographically examined. One was shown to have a fairly simple twisted, pattern-welded central structure and the other a straight grained pattern-welded structure (Appendix 1. 34 and 35, Fig 75).

A series of sword blades, datable by associated material to between 197 and 205 AD, was found buried under part of a rampart at the Roman fort at South Shields. This would appear to be military equipment discarded or lost, possibly during alterations to the fort (Richmond 1953) before its possible use, as a supply base for Septimus Severus' British campaigns of 208-211. Amongst these were fragments of a *spatha* incorporating simple pattern-welding similar to one of the Canterbury blades and contemporary swords from Germany (Rosenquist 1968). A very fine example of a shorter, thinner *spatha* was found in 1965, during small-scale excavation work at Funtham's Lane, Whittlesey in Cambridgeshire, under stratified material dating between the second and fourth centuries A.D. (Howe 1978, 23) and it would appear likely that the sword is a stray find relating to the nearby late first-century fort at Longthorpe. The Whittlesey sword (Chapter 6.4) is so far the only Roman *spatha*_ in Britain to have been metallographically examined but six examples of the Roman short sword (*gladius*), all dating to the late 1st or early 2nd century A.D. have recently been analysed in this way (Lang 1988, 199 - 216).

1.3 Source of Weapon Finds

1.3.1 Early Anglo-Saxon Period (5-7th centuries A.D.)

The great majority of weapons found during this period were interred in graves usually in one of the many pagan Anglo-Saxon cemeteries of eastern and central England (see Meaney 1964). Early Anglo-Saxon cemeteries are noted for the wide variety of personal possessions especially weapons which accompany the dead. The proportion of weapons to burials and of swords to spearheads (scramasaxes being uncommon during this time) is very variable with much the highest proportion in each case occuring in Kent especially at Sarre (Davidson 1962, 7-13; Swanton 1974)..

At Sarre in Kent 26 graves out of 272 were found to contain swords. Two of these were only small fragments, one a pommel and one part of a hilt, giving rise to the possibility that swords may often have been damaged or fragmentary when buried. One further grave contained part of a scabbard. Thus 27 graves were furnished with swords (or parts of swords) out of a total of 66 graves which contained weapons of all kinds (Brent 1863-5) . It would seem from this that nearly half the armed men of that community carried swords. Some from Sarre have been metallographically examined in the present study (see Chapter 6).

In common with other burial goods swords were sometimes damaged or fragmentary when buried. In some cases it is difficult to say whether the damage was intentional or not. Some of the breaks visible in the swords from Sarre were not recent and could be the result of cracking and breakage during use (graves 8 and 54). Fragments of a sword were, however, scattered through one grave (3) and the damage clearly could not have been accidental. The deliberate damaging or 'ritual killing' of earlier swords has been noted (Rosenquist 1968). This was practised on swords and other objects from Anglo-Saxon cemeteries, for example the sword (Chapter 6.33) and four copper alloy bowls from a grave in the cemetery at Lovedon Hill, Lincolnshire (Fennell 1957, 170) and the Sutton-Hoo helmet, (Bruce-Mitford 1978).

Extensive corrosion in the ground means that it is often impossible to tell in what condition a sword (or almost any other iron object) was before burial.

1.3.1.1 Swords from cemeteries; their condition and potential for metallographic analysis

The condition of swords found in different cemeteries varies between completely mineralized to fairly heavy, but mainly surface corrosion . Early Saxon cemetery sites are usually situated on fairly well drained, higher ground resulting in aerobic corrosion which has often removed much of the iron. The Early Saxon swords selected for sampling and metallographic analysis in this study tended to be those in poor condition in museum reserve collections. This was partly because such objects are usually more accessable to researchers, but also because it was the aim to show that by using metallographic analysis much smithing history can be recovered from poorly preserved objects such as swords. The results below demonstrate that this is indeed the case, good results can be obtained and unnecessary damage avoided provided a systematic approach is adopted.

1.3.1.2 Sword blade types and origins

The swords found in Early Anglo-Saxon cemeteries in England vary in length between about 75 and 100 cm. The edges tend to be roughly parallel sided or slightly tapering towards the point. In profile the blades are usually found to be of a flat or flattish convex shape and mostly vary between about 4.5 cm and 6.0 cm in width. This form of blade would appear to be standard in England during this period, although other forms of blade are occasionally reported.

The grooved or fullered form of sword blade is uncommon in England during this time. However, two similar swords were found in the cemetery at Abingdon, Berks (now Oxon), each one with a wide shallow groove or fuller on one side and two narrower grooves on the other (Leeds and Harden 1936, 59 and Plate XIX). Many of the long swords, of the 3rd-5th century, found in the peat bogs of Jutland have two or, three or four grooves on either side.

A single wide groove or fuller became very common on swords found in Britain from about the eighth century or later although it appears to be very unusual earlier. It is more common earlier on mainland Europe where examples of blades with single fullers from about the fourth century onwards have been noted (for instance Behmer 1939, Plate 1, 6 and 28).

Fullers are a feature of Celtic swords and may have originated as the linear decoration on bronze swords and daggers especially those made in Hungary (Webster 1982, 187). Wider grooves and fullers possibly developed from early attempts to recreate the narrow grooves or lines in cast bronze weapons or may also have been introduced to reduce blade weight without sacrificing strength. Some sword blades of Roman date exhibit a corrugated appearance in profile (Rosenquist 1968).

One of the two third-century Canterbury swords was found to have a double groove on one side. The two Abingdon swords, on the basis of sword blades found in England, would appear to represent a transitional kind of form between the long swords of the Roman Period and those blades of the Mid-Late Saxon period which usually have a single fuller on either side. The unusual form of the Abingdon sword might indicate that these were imported blades. It has been suggested, on the basis of one of the scabbard chapes, that these two swords originated from the area of Namur in Belgium (Leeds and Shortt, 1953), a central part of the Frankish Kingdom during the 6th century (Treharne and Fullard 1969, 4).

The unusual form of the Abingdon swords may indicate that these blades were imported from mainland Europe where grooved or fullered sword blades are commoner before the eighth or ninth century.

The forms of continental Migration Period sword blades appear to vary rather more than is the case in England, with fullered and grooved blades occurring at the same time as the flat backed or slightly convex profile blade which appears to be almost ubiquitous in Early Anglo-Saxon England.

1.3.1.3 Manufacture of sword blades and fittings

The early generations of Anglo-Saxon settlers are likely to have imported much in the way of iron tools and weapons from their homelands in north Germany. However, once the larger population groupings had become established it seems likely that major industries such as iron working soon became established locally even if on a relatively small scale. This process has recently been shown to be the case in the late ninth-century Viking settlement of Lincoln, where an industrial quarter was established in the city within about twenty five years (Perring 1980, 36).

The highly decorated non-ferrous mounts, found on many swords, seem likely to have been made by different craftsmen to the sword smiths who produced the blades which required the skills associated with the forge welding of iron and steel. Other craftsmen are also likely to have been involved. Recent work, particularly by Jaqui Watson of the Ancient Monuments Laboratory, has shown how different perishable organic materials were used for parts of sword fittings. Horn and occasionally ivory was used for the guards and normally wood for the grips (see Acklam sword, Agar and Gilmour 1988, 14) and fleece lined wood was probably fairly standard for the scabbards possibly with additional iron or decorated copper alloy strapping or chapes. It would appear that, after the forging of the actual sword blade some co-ordination between different craftsmen would have been necessary before a complete sword with a matching scabbard was produced.

1.3.2 Middle Anglo-Saxon Period (7th - 9th centuries)

For the period after the pagan custom of burying weapons in graves stopped in about the mid seventh century and before the ritual deposition of weapons became common again in about the mid ninth century very few weapons have been found. For the study of the developing techniques of weapon technology and the progressive use of different alloys this is unfortunate as the supply of objects available for investigation all but ceases during this time. In the present study the two swords tentatively placed within this period were both found in the Thames and may represent examples of the custom of depositing weapons in rivers which occurred before the main Late Saxon phase of river deposition.

1.3.3 Late Anglo-Saxon Period (9th - 11th centuries)

Although a few weapons are found in graves, the great majority of weapon finds of this period come from rivers, the largest concentration having been found in the Thames, in or near London. These finds seem to represent the ritual deposition of weapons in rivers (Bradley forthcoming) in a similar way to the great votive deposits of weapons in the peat bogs of the Jutland peninsula in the late Roman and post Roman period (Todd 1975). This pagan practice of throwing weapons in rivers was practiced in pre-Roman Iron Age (and earlier) and re-emerged in Late Saxon England. Most of the swords reported in the present study came from in or near the river Thames or one of its tributaries.

1.3.3.1 Blade types, dating and origins

Unlike earlier swords, those of the Late Saxon period were usually fitted with iron guards and pommels, which are sometimes no more than flat bars forming an upper guard. These parts are often found to be decorated with gold, silver, niello and copper alloys. The style of decoration can often provide evidence for both date and origin of manufacture, either in England or abroad though it is always possible that the decoration was added later.

The ornament of the Abingdon sword hilt, for example appears to be of Anglo-Saxon workmanship while others show styles such as Ringerike which appear to originate in Scandinavia (Davidson 1962, 63) but may have been copied in England. Some swords must have come from Scandinavia although the extent of the import of weapons compared with home production is not clear. Future metallographic work as well as typological studies should shed further light on this problem.

Large numbers of swords and other weapons of this period have been found in Scandinavia and Petersen (1919) set out the main typology of these weapons. Wheeler (1927) grouped and gave dates to some of the main sword finds of the Late Anglo-Saxon Period from England. By this time the commonest form of blade appears to be one with a deep wide groove or fuller on either side although flat-back backed and convex forms are still found. Examples of all these examined in the present work. Blades of this period also tend to be more sharply tapered towards the tip than the more parallel-sided early Anglo-Saxon examples.

Most of the sword blades examined in the present study either lacked any applied decoration or were fragmentary thus making close dating impossible. As far as possible they were given an approximate date using Petersen's or Wheeler's typologies.

The function of the fuller, according to some writers (Cowen 1934, 171), was to enable the blade to be thicker without extra weight or loss of flexibility. This may be true although the flexibility must have been dependent as much on the varying physical properties metal of the blade as the profile.

The occurrence of pattern-welding on swords of the Anglo-Saxon period is discussed in a separate section dealing with development and purpose of pattern-welding (Chapter 7.1.4). The basic technique continued largely unchanged through the period but appears to have gone out of fashion for sword blades during the eleventh century.

A new fashion which became popular during the ninth century was the inlaying of iron pieces in sword blades, to form either letters or a design. The individual pieces are sometimes twisted in the manner employed in pattern-welding and often form recognisable words the most common being ULFBERHT and INGELRII with some variations to the spelling (Davidson, 1962, 48). The Ulfberht form is found as far afield as East Prussia and Ireland (Jankuhn 1951, Fig 28) Jankuhn considered that they were distributed from a centre in the Middle Rhine from the late ninth to the eleventh centuries. The names perhaps refer to sword makers but may also have been extensively copied and therefore may not be a guarantee of a place of origin even if that were known.

The question of where swords were made is as much of a problem for the Late Anglo-Saxon period as it is for the earlier periods. Charlemagne's capitulary of AD 779 banned the export of swords (Loyn and Percival 1975) although Salin considered that the illegal export of arms continued and this ban on the export of swords was repeated in another capitulary of 803 (Easton and Wieruszowski 1979). This may have affected the export of swords from certain larger scale production centres but there seems no reason to suppose that skilled swordsmiths were not working in other parts of Europe, including England, throughout this period. Skilled smithing techniques must have been fairly widely known and it would seem to have been in the interests of any major political group to encourage indigenous weapons production. There seems to be no reason to suppose that techniques such as pattern-welding were closely guarded secrets known only in a very few places.

Areas of production may eventually be identified once large enough numbers of swords from different places have been metallographically examined as well as typologically grouped and the results compared and plotted.

1.3.3.2 Effects of waterlogged burial conditions

The extent of corrosion on swords recovered from rivers or similar, waterlogged conditions varies a great deal, although the physical survival of the iron is usually much better than from cemetery sites (which are usually well drained) as corrosion is largely anaerobic and much slower. The more corroded examples often lack any non-ferrous applied decoration or inlays, probably the result of a combination of electrolytic corrosion of the iron in the contact with the more noble metals and physical movement under water causing the decoration to fall away. Corrosion is sometimes very uneven with some parts of one blade showing just a light patination on the surface while other parts are corroded right through. A pattern-welded sword from Gilling Beck in Yorkshire (Gilmour 1986. 93) showed a black patination over a well preserved surface on parts of one side while the other side was heavily pitted. It had probably lain on the less corroded side for a long time preventing access of oxygen and thus providing cathodic protection to this side of the blade at the expense of the other.

The pattern-welding of the Gilling sword was visible even on the very lightly patinated parts of the blade as slightly raised parts in the centre of the blade. This is probably the result of final surface polishing and etching during manufacture rather than the effects of burial or submersion which are far more likely to be less even.

On several of the blades examined for the present study uneven corrosion had left the positions of welds and pattern-welding clearly exposed. On some swords, including ones without obvious signs of weld patterns, a fibrous or wood grain effect could be seen running down the blades. Again this must be the result of differential corrosion promoted by differences in metal composition and the presence of non-metallic slag inclusions. These differences may have been exploited by ancient sword smiths or sword finishers far more than has so far been suspected, as they were by medieval and later Japanese sword smiths.

1.4 Scramasaxes

The single-edged weapon known both as the *seax* and scramasax was popular during the Anglo-Saxon period. These weapons vary greatly in size, ranging from single-edged swords down to small daggers. Size and burial circumstances can be used as very general criteria to divide smaller examples into weapons, and knives used for other purposes. The two classes merge one into another, the weapons being mostly larger than the knives. The term scramasax is used here to cover the whole range of these single-edged weapons.

The origin of the scramasax can be traced back to the later Hallstatt period when, in central northern Europe, the sword seems to have sharply diminished in importance. Its place was taken by a single-edged knife, sometimes termed a kampfmesser, which could be used in close combat. This change in weapons is indicated by variations in the proportions of different weapons found in graves although the total of weapon finds from this period is small (Todd 1975, 163).

This may indicate a change of tactics favouring close quarter infantry warfare to the use of cavalry. There seems also to have been a considerable regional variation in the use of different weapons. For example axes are commoner in Eastern Germany while further west in Mecklenburg daggers some 20-25 cm in length are more prominant (Todd 1975, 163). This situation appears to have remained much the same for the rest of the Pre-Roman Iron Age in Northern Europe. The war equipment found in the large votive deposits at Hjortspring and Kragsbolle (in Jutland) features mostly spears, some short kampfmesser, 20-40 cm long, and a few swords (Todd 1975, 164-6).

A more recognisable example of the single-edged scramasax came from the second century B.C. wagon-grave at the Langa on Fyn and it remained a characteristic German weapon during the Roman period as is seen by examples from the Vimose votive bog deposit in Jutland (Todd 1975, 169). One of these Vimose weapons is a clear forerunner of the Wheeler's Type I or 'Frankish' type of scramasax, such as the example from a grave at Barham Down, Kent (Chapter 6. 40).

According to Wheeler these are first found in Merovingian Gaul in the late sixth century A.D and, in England, are found in a few graves dating to the early seventh century (Wheeler 1935, 176-7). Scramasaxes were still fairly uncommon here by the mid seventh century when the pagan practice of burial with graves goods ceases. In contrast to swords of the Early Saxon period scramasaxes appear to have been plain, functional weapons and so far no decorated examples have been found in England nor have any been noted from the continent.

By the Later Saxon period (ninth - eleventh century) the scramasax had became a more popular weapon to judge from the large numbers which have been found in rivers with swords and other weapons. Unlike the scramasaxes of the Early Saxon Period these later blades are usually decorated either with grooves or pattern-welded strips near the back and sometimes with copper alloy or silver inlays. The non-ferrous inlays can take the form of twisted wires, small panels and occasionally letters. Non-ferrous inlays are usually found on smaller blades, a notable exception being a runic inscription, still not understood, on a longer scramasax from the Thames at Battersea (Wilson 1964, p 144 and pl XXII). A smaller scramasax from Sittingbourne in Kent bears a non-runic inscription which records both the owner and the maker of the weapon (Page 1964, 86). Some of these non-ferrous inlays, particularly those employing twisted wires, appear to be copying forms of pattern-welded decoration found on many of these blades. Sometimes pattern-welding and non-ferrous decoration are found on the same object, for example the small scramasax, included in this study (Chapter 6, 47) which has a sine-wave form of pattern-welding alongside a mixed copper alloy, twisted wire inlay which appears to mimic a standard herringbone pattern-welded design.

A straight or flat-backed, long form of scramasax is common in Scandinavian graves of the seventh and eighth centuries. Wheeler called this his Type II or 'Norwegian' type and dates it to this period. This more-or-less corresponds to the Middle Anglo-Saxon Period, during which grave finds mostly cease and before river finds become common again, which may explain why this type is very rare in this country.

The long bladed scramasaxes usually found in England are variations of Wheeler's Type III or Hurbuck type for which he gives an eighth-tenth century date range although the Hurbuck hoard from Co. Durham can be assigned to c A.D. 900 (Wheeler 1927, 178-9). This type has been found in various parts of England, several examples in the British Museum and Museum of London having come from the river Thames in the London area (see Appendix 1). As with other weapons of this period scramasaxes are usually found in or near rivers although one long bladed Hurbuck type scramasax (now on display in Scunthorpe Museum) was found with a double-edged sword in a ninth-century grave at Kirton-in-Lindsey, Lincolnshire. A long single-edged Hurbuck type blade from Kempsford, Near Swindon, was examined in the present study (Chapter 6. 43. Without specific datable features most of these Wheeler Type III or Hurbuck type scramasaxes can only be given an approximate ninth or tenth-century date.

The other main form of scramasax is a shorter bladed weapon, usually no more than about 30 cm long, with a fairly sharply angled back. Wheeler called this his Type IV or 'Honey Lane' type after a blade found in the City of London at Honey Lane Market with coins of Ethelred II (978 - 1016). On this basis he placed this type to around the tenth or eleventh centuries (Wheeler 1927, 178-9). The presence of the coins may suggest a hoard, and that consequently the Honey Lane weapon was buried with the intention of retrieving it. Most of the shorter scramasaxes (that is those less than about 45 cm long) found come from rivers, without any independent dating evidence. They usually vary in form between Wheeler Types III and IV and in the absence of specifically recognisable forms of decoration, they are mostly only roughly datable between about the ninth and eleventh centuries although Wheeler thought that the angled form was probably no earlier than tenth century (Wheeler 1927, 180).

1.5 Spearheads

A fuller discussion of the evolution of the spearhead is beyond the scope of the present work and just a few general points are included here. It appears to have been the standard fighting weapon most of the time from the Early Iron Age and before and, as such, can be compared to the bayonet of more modern infantrymen . Some 2000 or more have been found in Early Anglo-Saxon burials alone and even sites such as Sarre with its many swords have produced more spearheads (Swanton 1974, 28-90). Swanton listed nearly all the known examples from the pagan period and divided these into a series of types. Spearheads from the Late Saxon period can often be identified by reference to Petersen's (1919) work or by comparison to known continental types although only very approximate dating is usually possible.

A few spearheads were included in the present study to allow some general comparisons to be made between the structures of different weapons as well as their development. Apart from one transitional Bronze Age-Iron Age weapon the remaining three spearheads examined are probably all of Mid-Late Saxon date. One (Chapter 6. 51) was a clear example of a Petersen Type H which he attributes to the tenth century (Petersen 1919). The examples included in the Catalogue of radiographs (Appendix 1) confirm reports from the continent (such as Ypey 1982, 241-275) that pattern-welding was used on spearheads by the Late Saxon period.

Chapter 2
Evidence for the manufacture of edged-weapons from literature, historical and pictorial evidence

Most of the various mentions of swords in Anglo-Saxon Literature and other written sources has been extensively described and discussed, mainly by Davidson (1962). In the present study attention is concentrated on the practical aspects of the information which the written sources provide; it is concerned with reliability and with any deductions that can reasonably be made concerning the appearance, composition and quality of the weapons as well as the methods by which they were made. These have long been sources of speculation and various early references have been interpreted in different ways. To assess the main references for this study possible eye witness accounts are considered first followed by other written sources.

2.1 Descriptions of contemporary observers

In A.D.507 Cassiodorus, secretary to the Ostrogothic king Theodoric the Great, sent a letter to the king of another German tribe, the Warni, thanking him for his gift to Theodoric of several swords. The text has been translated as follows:

> Together with musical instruments of pitch-black wood and
> boys with the fair skin of their race, Your Fraternity has
> chosen for us swords capable even of cutting through armour,
> which I prize more for their iron than for the gold upon
> them. So resplendent is their polished clarity that they
> reflect with faithful distinctness the faces of those who
> look upon them. So evenly do their edges run down to a point
> that they might be thought not shaped by files but moulded by
> the furnace. The central part of their blades, cunningly
> hollowed out, appears to be grained with tiny snakes, and
> here such varied shadows play that you would believe the
> shining metal to be interwoven with many colours. This metal
> is ground down by your grindstone and vigorously burnished by
> your shining dust until its steely light becomes a mirror
> for men; this dust is granted you by the natural bounty of
> your land, so that its possession may bestow singular renown
> upon you. Such swords by their beauty might be deemed the
> work of Vulcan, who is said to have perfected his craft with
> such art that what was formed by his hands was believed to
> have been wrought by power not mortal but divine. (Davidson 1962, 105-106)

Cassiodorus speaks as one who actually saw the swords and provides a clear description of fullered (or grooved) and pattern-welded blades. It would seem likely that these blades were made by weapon smiths of the Warni whose kingdom, appears to have been in the area east of the Rhine, possibly as far east as the Elbe basin in central northern Germany (Davidson 1962, 108). It would be useful to know whether pattern-welded blades without fullers or non pattern-welded blades were also being made by these weaponsmiths in the late fifth or early sixth century. A future detailed survey of weapon finds may go some way to answering this.

The description of tiny snakes is a clear reference to pattern-welding running down the central fullered part of the blade. The passage which follows refers to finishing treatments intended to display the weld pattern to its best advantage as well as to give a smooth, even finish to the blade. The grindstone and shining (polishing) dust must have been used successively to give a progressively finer finish to the blade before it was etched to reveal the pattern-welded structure 'Varied shadows ..... interwoven with many colours' are effects which could only be brought about by etching the polished surface of the blade. The shining dust, or sand as it could be read (Davidson 1962, 106, note 2), was used for burnishing. It is difficult to identify this material as many compounds could have been used for this purpose (for instance finely ground iron oxide, jewellers rouge, or clay compounds). One suggestion is that it could have been Kieselguhr, a form of diatomaceous silica which is used in mildly abrasive polishing compounds and one of the few places where it is known to have been worked in early times is one area near the Elbe; an area thought to have been occupied by the Warni in the fifth and sixth centuries (Davidson 1962, 108-9).

This may be a further clue to the origin of the swords described by Cassiodorus as being capable of cutting through armour and prized more for their iron than the gold upon them. It is impossible to know to what extent Cassiodorus is merely complimenting the king of the Warni on his swords and to what extent the functional properties of the blades matched the apparent claim.

Two other early descriptions also refer to patterned blades (Smith 1960, 14). The pre-Islamic Persian poet Imru irlquais, who died in c. A.D.540, refers to a blade as having wavy marks like tracks of ants. A younger contemporary of his, Asn b. Hajar, describes blades as follows:

It has a water whose wavy streaks are glistening .... It is like a pond over whose surface the wind is gliding .... The smith has worked out in it a grain as if it were the trail of small black ants that had trekked over it while it was still soft.

These descriptions may well refer to 'watered' or 'damascened' blades probably being made in Persia or northern India at this time, rather than the western pattern-welding that was being used for sword blades and which is described by Cassiodorus. The eastern technique and its comparisons with western pattern-welding is further discussed in Appendix 2.

In the late eighth century Offa, King of Mercia is recorded as having received a sword of 'Avar workmanship' from the King Charles the Great although no further detail is recorded (Davidson 1962, 109). A sword which had belonged to Offa was still in the possession of the Wessex royal family over two hundred years later when it is mentioned in the eleventh-century will of Prince Athelstan (Whitelock 1930, 46), although there seems to be no way of supporting Akerman's suggestion that this might have been Offa's 'Hunnish' sword (Akerman 1855, 50).

It would appear, in any case, that a sword belonging to Offa had become a family heirloom. This may often have been the case with swords so that date of burial and date of manufacture may differ greatly. Blades may sometimes have been re-hilted so that dating on the stylistic grounds of the fittings could also be misleading.

The reference to Offa's gift from Charlemagne would suggest that swords made by the Avars of the middle Danube region were of some renown. Salin (1957) thought that the Frankish centre of production was somewhere in the middle Rhine area whereas the Avars occupied the north side of the middle Danube region. It would thus appear that in the late eighth to early ninth centuries we may be able to identify at least two areas where documentary sources suggest that the manufacture of swords took place.

A ninth-century Monk of St Gall tells of how the Emperor Louis (813-40) tested swords sent by the 'King of the Northmen' as a mark of submission.

> Louis took one by the hilt and tried to bend the tip of the blade right back to the base; but the blade snapped between his hands which were stronger than the iron itself. Then one of the envoys drew his own sword from its sheath and offered it like a servant to the Emperor's service, saying 'I think you will find this sword as flexible and strong as your all-conquering right hand could desire'. The the Emperior ... bent it like a vine-twig from the extreme point back to the hilt, and then let it gradually straighten itself out again. (Davidson 1962, 113-4).

Davidson suggests that this passage implies that swords were made in Scandinavia at this time but that they were not of very good quality. It is, however, hard to see how the tests on the Scandinavian swords could actually have taken place as described.

The known examples of ninth century swords from north-western Europe are mostly fairly heavy, broad bladed weapons more often than not with a central fuller on either side. The size and form alone would indicate that these blades can never have been as flexible as that belonging to Louis. There may have been instances where a particular combination of iron and steel together with quenching and the correct degree of tempering led to the production of a blade with properties approximating to modern spring steel. A blade like this however would have been difficult to flex more than a little and reports such as this must be examined carefully. The strength of the Emperor must have been greatly exaggerated and the account may have been repeated a number of times before reaching the ears of the monk. This does not mean the account is without foundation as tests on the physical properties of sword blades may well often have been carried out and these would be likely to have included flexibility, and the ability to keep a sharp cutting edge (that is, hardness). It seems highly improbable that this particular description was an eye-witness account.

From the ninth century onwards there are several interesting accounts by Arab writers of swords from north-western Europe carried further east by Vikings. The traveller Ibn Fadlan, who visited the Scandinavian settlers on the Volga in 922 (Foote and Wilson 1970, 399), mentions the value placed on the sword by these people, the Rus. He reports that every man presents a sword to his son at birth and describes the swords as slender, with a furrow running down the centre, and of Frankish workmanship (Davidson 1962, 114).

An envoy of the arab caliph Muktadir recounts in A.D.921 or 922 that swords of the Vikings were broad and pattern-welded (Salin 1957, 107). A ninth-century Arab historian, Al-Kindi describes two kinds of swords, which he calls Frankish and *Slimanish* or *Suleymanish*_ (Allen 1979, 83 and 138). The Frankish swords he describes as tapering to a rounded tip with a broad channel running down the centre of the blade, which resembles a stream of water (Davidson 1962, 115). This is a clear reference to fullered, pattern-welded blades. The patterns he compared to those of Tabaristan cloth or to rings of chain-mail. They are, he says, of whitish colour, and when the treatment of the blade is completed the background is red. He reports that some of the blades are marked in the upper part with half moons or crosses of bronze or gold, and sometimes a nail of gold or bronze is hammered into a hole in the blade. He also gives us information on construction and says that both Frankish and *Slimanish* swords are of soft iron and steel, forged together, the patterns being formed by this mixing of metals. The *Slimanish* swords, he says, have smaller decoration and the blades are brigher, the points are less rounded and the blades taper less than the Frankish ones, while the hilts are not so richly decorated, and the swords are not marked with crosses (Davidson 1962, 115).

Al-Kindi does not mention blades inlaid with iron pieces such as the well known Ulfberht or Ingelrii blades which have been found as far afield as Ireland and northern Russia near Novgorod (Davidson 1962, Figs 28 & 29). Novgorod was one of the centres of Viking influence in the East and part of the Viking trade network based on the great rivers which included the Volga (Foote and Wilson, 1970, 220-229 and Fig 25). This may mean that these inscribed blades were more common later and had not been seen by Al-Kindi in the ninth century.

Al-Kindi's descriptions of pattern-welded blades are very useful and give us some idea of the variety of welded patterns which were seen on sword blades in his day. A pattern resembling a stream of water would appear to have been common. This would seem to be a description suitable for a single herringbone type of decoration formed by welding together two adjacent rods; twisted in opposite directions.

This simple pattern-welded design is very common on fullered blades of the Late Saxon period (see Appendix 1). The descriptions of patterns compared to Tabaristan cloth and to rings of chain mail indicate other variations of weld patterns.

Some of these may be variations of twisted and straight grained designs such as are frequently found on swords and scramasaxes of this period elsewhere in north-western Europe. For instance the looped pattern found on some scramasaxes (see Appendix 1) can be compared with the rings of chain mail.

The variations in colour and treatment described by Al-Kindi must refer to an etching process intended to bring out and accentuate the weld patterns and the differences in the metals which he also mentions. The non-ferrous inlays mentioned may be smiths marks but this form of inlay is not commonly found on sword blades found in this country or elsewhere in north-western Europe. This may mean that Frankish swords of this kind (made possibly in the Rhineland) were carried east by Viking traders but did not find their way to Britain although this might have been expected.

The *Slimanish* swords mentioned by Al-Kindi are difficult to identify with any precision. Another Arab writer, Ibn-Rustah, calls the swords of the Rus *slimaniya* (Davidson 1962, 116). It would seem that the term *Slimanish* refers to sword's carried by the Scandinavians which were thought to have come from other sources of manufacture than the Frankish weapons. Further research may clarify this point.

The anonymous author of the eleventh-century Persian Geography 'Hudud al-Alem' refers to swords of the Rus. He says he knows of blades used by one branch of the Rus which may be bent double and when loosed they go back to their original position (Davidson 1962, 116). This is much the same as the account given earlier by the Monk of St Gall and may be a repeat of an earlier claim rather than a contemporary eye witness account. Another eleventh-century writer, Nasireddin al Tusi, describes swords of the Franks, which he says are of soft iron, but so sharp that iron cannot resist their stroke, and so pliable that they can be bent like paper (Davidson 1962, 116). This sounds a variation of the same, probably exaggerated account but suggests that Frankish swords had a good reputation at least as far as their sharpness was concerned.

The origin of Frankish swords in the eleventh century seem most likely to have been the middle Rhine region of Franconia in the Kingdom of Germany (Treharne and Fullard 1963, 10 and 11). Salin considers that the various documentary mentions suggest that the Frankish arms factories must be in the Rhine area near Cologne (Salin 1957, 107). He goes on to mention the 'Gesta Dei per Francos' as speaking highly of the length and sharpness of the Lorraine swords, Lorraine (or Lotharingia) being the name for the area to the south and east of the lower Rhine from the tenth century (Treharne and Fullard 1969, 9, 10, 11, 16, 20).

Al-Biruni, an Arab living in Afghanistan in the eleventh century, gives details on the structure of Western pattern-welded swords (Davidson 1962, 116). He says that the patterns were welding phenomena produced by welding soft iron (*nermahan*) and steely iron (*saburaqan*). He also says that these pattern-welded swords were made not only by the Franks but also by the Rus (Vikings) and the Saqaliba which have been interpreted as all the Northern Europeans with fair hair and blue eyes (Salin 1957, 95). Al Biruni goes on to report that the quality of the steel was a function of its refining which caused a loss of metal and involved much forging as well as a preliminary treatment. This apparently involved the purifying passage of iron through the intestines of a starving bird. We are told that after reducing the iron to small pieces there were then mixed with flour and fed to ostriches in Asia, and ducks by the Rus. On collection from the excrement the metal was then refined or purified (Salin 1957, 95-96). Salin (1957, 96n) reports that this curious story appears as far afield as China and the earlier German sagas but a modern experiment repeating the procedure with a duck produced no noticeable effect on the iron.

Al Biruni thought that the smiths who produced the European pattern-welded blades were copying the watered patterns of the Eastern crucible steel swords which he reports could not stand up to the cold winters of the Rus (Davidson 1962, 116). Present evidence, however, suggests that pattern-welding developed independently of the manufacture of watered crucible steel although this ultra high carbon steel is very likely to have become embrittled in very cold weather (see Chapter 7.4.2).

There seems little doubt that during the ninth to eleventh centuries a large number of pattern-welded swords were possessed by the Rus or Vikings. Davidson (1962, 117) suggests that if some workshop in the Baltic region produced (many of) them this would account for the distinctions, in al-Biruni's account, between the swords of the Rus and those of the Franks. However, there seems to be no particular reason for thinking that production of these swords was confined to one particular area and Al-Biruni's account would in fact seem to suggest that there may have been more than one other area producing pattern-welded blades.

To judge from the various reports, the Arab writers evidently thought highly of the swords carried by the Scandinavians. Ibn Miskawaih, who died about A.D.1043 records that, following the loss of their power in one district ' the Moslems disturbed their graves and brought out a number of swords, which are in great demand to this day for their sharpness and excellence'. (Davidson 1962, 117).

The eleventh-century arab writer Nasireddin al-Tusi, says that no iron could resist the shock of the Frankish swords and reports that they arrived illegally across Islamic lands as their export was banned (in 779 and 803 - see Chapter 1.3.3.1) and each one was worth 1000 Egyptian dinars (Salin 1957, 97).

In most of these reports it would seem that fairly reliable accounts of contemporary events are being mixed with stories, for example of the reputation of particular swords, which probably owe more to legend rather than to first hand knowledge.

2.2 Sword mentions in epic poems or sagas

Legendary references to swords in these sources are not as useful a source of information as those of contemporary observers but can provide some useful hints suggestive of the manufacture or appearance of swords or other edged weapons. Compound words with *'mael'*, which refer to swords, appear in many places in the eighth-century poem Beowulf and other poems and the term *malswurd* occurs in one Anglo-Saxon will and appears to refer to a specific type of weapon. Davidson discusses various occurences of the term *mael* or its Old Norse equivalent mal and convincingly argues that the poets were describing the visual effect of pattern-welding when using this term . *'Brogdenmael'* is translated as 'blade with woven patterns' (p. 122). *'Brogdenmael'* is found in Beowulf (lines 1616 and 1667 - see Klaeber 1941) and also in the Anglo-Saxon poem Elene in the passage 'the hard edged blade with its woven patterns quivers and trembles; grasped with terrible sureness, it flashes into changing hues' (Davidson 1962, 120-153).

Sceadenmael, also from Beowulf (line 1939) has been translated as 'ornamented with distinctive and branching patterns'. It has been linked with *wundenmael*, used in Beowulf, to describe the sword Hrunting of which the words *stio* and *styleag* (hard and steely edged) are also used (Davidson 1962, 123). This sword has several descriptions referring to it:-

'This sword which Hrothgars' *thyle* lent to Beowulf in his need was by no means the least powerful of allies. That *haeftmece* bore the name of Hrunting; it was among the foremost of ancient treasures. Its edged blade was made of iron, gleaming with twigs of venom (*atertanum fah*) and hardened by blood of battle; never yet had it failed any man who grasped it in his hands in warfare' (line 1455f).

..... He swung his sword of battle with a mighty rush, and his hand did not fail in the stroke, for the sword with curving patterns (*hringmael*) sang a greedy song of battle upon her head .... (line 1519f).

..... The enraged warrior flung down the sword with twisted patterns (*wundernmael*) and bound ornaments (*wraettum gebunden*), hard and steely-edged, so that it lay upon the earth. (line 1531f - Klaeber 1941).

Here are fairly obvious references to a pattern-welded blade. The different mentions firstly of curving, and then twisting patterns for one sword blade may indicate that different descriptions were used to describe one overall patterned effect, or, alternatively, these could be more specific references to variations of patterns. Davidson suggests that twigs of venom is probably another way of describing snake-like patterns, the description used by Cassiodorus to describe pattern-welded blades two hundred years or more earlier. However, as we can see from the West Heslerton sword (Appendix 1.306) as well as continental examples (Ypey 1982, 381-388), the snake-like pattern is unmistakeable and contrasts with the much more common twig like herringbone patterns. A clear description of the snake-like effect is given in Thidrick's Saga in which the sword Ekkisax is said to have been made by the dwarf Albrich:

> 'He hid it down in the earth before it was completed. He searched also through nine kings' realms before he found the water in which he could harden it. ..... The blade is well polished and marked with gold, and if you set the point down on the earth, it seems as if a snake runs from the point and up to the hilt, gleaming like gold. But if instead you hold it upwards, then it seems as if the same snake runs from the hilt and up the point, and it moves as if were alive'. (Davidson 1962, 162 and 166 Bertelsen 1905-11, 179).

Davidson also proposes (1962, 132) that 'hardened by the blood of battle' could be interpreted as a reference to a quenching solution and similar descriptions may have a similar explanation.

The word *graegmael* is used (line 2682) to describe Beowulf's own sword, Naegling. This has been translated as grey-coloured but Hatto (1957, 152) considers that a metallic, silvery gleam similar to hoar frost would be more accurate. This may be another reference to pattern-welding. The sword Naegling is also described as being an ãncient heirloom as is another pattern-welded sword in the poem which is described (line 2036f) as the 'treasure and ancient heirloom of the Heathobards, hard and ring patterned (*hringmael*)' (see Davidson, 1962, 125).

The various references to heirlooms would suggest that prized weapons were often passed down, in some cases, possibly though several generations. This possibility must always be borne in mind by the student who should not assume that a weapon is necessarily dated closely through associated finds. Conversely, a weapon datable by stylistic or other means cannot necessarily be used to date associated contexts, for example a burial without any other datable finds.

One reference which illustrates the problem of heirlooms, as well as the use of the term *mal* also describes how sword blades were sometimes re-used. In Gisla Saga (ix) the spear Graisida was made from a broken sword of the same name which was said to have had a particularly fine blade:

> 'Now the broken Graisida was taken, and Thorgrum made a spear from it, and it was ready by evening. There were patterns (*mal*) on it". (Davidson 1962, 127; Johnson 1964).

The same spear is later referred to in Sturlunga Saga (iv, 26; vi, 17) as a *'malaspjotr'* or patterned spear and it appears that it was still in use at the battle of Orlygstadt (21st August 1238) about 270 years later:

> 'Sturla defended himself with the spear called Graisida nimbly and well; it was a great malaspjotr, old and apt to bend. He thrust so vigorously with this that men fell before him continually; but the spear bent and he straightened it out under his feet several times'. (Davidson 1962, 127; McGrew 1974).

It would appear from these references that the weapon Graisida was in use for at least 270 years in its re-used state although the age of the sword from which the spear was made is not mentioned. This spearhead seems have been fashioned from a fragment of a broken and possibly old sword sometime in the mid tenth century. Very few examples of sword blades fragments refashioned into spearheads have so far been found (or recognised) in this country although one good example was found in the Thames at Standlake (Oxon; Ashmolean Museum, 1949; 960). It has been electrolytically stripped of any corrosion products leaving a clearly visible pattern-welded structure (see Appendix 1.141)

This spearhead has been made from a sword fragment which has been re-forged leaving it thinner than any comparable sword blades. It is now about 0.2 cm thick and even allowing for surface loss from corrosion it is unlikely to have been much thicker than about 0.25 - 0.30 cm thick which contrasts with contemporary sword blade thicknesses which seem to vary between 0.40 and 0.50 cm. This thin blade would clearly have been quite prone to bending with a form quite unlike the much thicker purpose-made contemporary spearheads. The flat bladed pattern welded form and the non-abraded, pattern welding is most typical of sword blades belonging to the Early Anglo-Saxon period which may roughly date the original sword. This spearhead may have been made out of a broken sword fragment at roughly the same time as the one mentioned in Sturlunga Saga and looks to have been just as prone to bending.

A close parallel to the Standlake spearhead was found in the Early Anglo-Saxon cemetery at Broadstairs in Kent (see Appendix 1.319). The Broadstairs example was fashioned from a broken fragment of pattern-welded sword no later than the 6th or 7th century, the time of burial. The Standlake spearhead was forged from a fragment of similar flat bladed pattern-welded sword which was not fullered whereas nearly all pattern welded swords of this type appear to have been fullered in the Late Saxon Period.

This strongly suggests that the Standlake weapon was made in the Late Saxon Period from a fragment of a much older sword (possibly of 6th-7th century date). Alternatively, it is possible that; like the spear Graisida in Sturlunga Saga, it was itself made much earlier and that it survived for a long time, possibly as an heirloom, before being deposited in the Thames. Although earlier, the circumstances surrounding the Standlake spearhead seem very similar to those described for the spear Graisida in Sturlunga Saga and provide an interesting confirmation of a situation otherwise only known (at least in this country) from literary sources.

Thidrick's Saga was compiled in Norway in the thirteenth century but contains some material from earlier legends, particularly concerning three famous swords, Naegling, Mimming and Ekkisax. The making of the sword Mimming is described. An initial sword blade was forged and the king who had ordered it was well satisfied but the smith Velent (Weland) said:

'It will have to be better before I have finished'.... Then
Velent went to the smithy and took a file and filed the sword
down to dust. He took the filings and mixed then with meal,
and then he took poultry, starved them for three
days, and took the meal and gave it to the birds to eat.
Then he took the birds' droppings and brought them to the
forge and worked out all the soft parts of the iron; and from
it he made a sword which was not as big as the first one.

Before the king could take possession of the sword Velent the
smith rapidly made an inferior sword which was similar in
appearance and this he gave to the king instead
(Davidson 1962, 159 - 160).

The story of feeding small pieces of iron to birds is found as far afield as eastern Europe and China. There seems no reason to believe that such a process could have any noticeable effect upon the metal. Given the difficulties of filing and subsequent welding it seems very unlikely that a smith would ever have ground down a complete sword blade in this way although experiments of this kind with small pieces of iron may have been made.

The nearest we seem to have of any actual illustrations of sword manufacture during the Anglo-Saxon period is the plan of the ninth-century monastery of St Gall which shows a factory with a number of rooms for particular tradesmen including one room for blacksmiths and another for grinders or polishers of swords (Horn and Bron 1980, Fig 1). This suggests that the final grinding and polishing of sword blades was a specialised occupation. Two manuscript illustrations of about AD820 from the Utrecht Psalter (Fig 1) show sword blades being ground down before polishing (Wormald 1953).

2.3 Conclusions

The various examples included here show that literary or documentary sources have much to contribute concerning the manufacture and structure of sword blades in the Anglo-Saxon or early medieval period. Much care must clearly be taken in assessing any early account; to try to separate fact from fiction or legend, and to determine how close to being a primary or eye witness account any early description might be, or how reliable the writer himself can be expected to be.

Early accounts are of particular value in suggesting the original appearance of weapons, particularly swords, as surviving examples of Anglo-Saxon or earlier weapons are all corroded. Examples from modern collections of Middle-Eastern (watered crucible steel) and Japanese weapons dating from about the thirteenth century seem to be the earliest ironwork of any kind which survives in anything approaching its original condition and appearance.

Documentary sources where they exist should always be borne in mind when assessing the results of modern analysis although modern analytical results and early accounts should be compared with care and possible pitfalls borne in mind.

Chapter 3
Techniques of examination employed

The examination of the weapons reported in this study was divided into:

3.1 Visual and binocular examination of the complete object
3.2 X-radiography
3.3 Metallographic analysis of a transverse section across all or part of the object
3.4 Electron probe micro-analysis of selected sections.

3.1 Visual Examination

This was carried out by eye and sometimes also by using a low power binocular microscope. This provided a visual assessment of the general condition and completeness of each object. The decayed remains of non-metallic attachments, such as scabbard parts and grip mounts for swords, was noted although the analysis and identification of these parts was beyond the scope of this work. The extent and nature of the corrosion of the iron was also noted at this stage, and in some cases the position of welds and (sometimes clear) hints of weld patterns could be seen preserved in the corrosion products approximately at the original surface of the artefact. This was useful in assessing whether the information gained at the next stage (x-radiography) was representative of the original structure of the blade of the weapon.

3.2 X-radiography

Each object was radiographed using either a Faxitron screened cabinet machine where the size of the objects permitted or, alternatively, a larger machine in a screened room. A standard (kilovoltage and milliampage) X-ray beam was used for each machine and the exposure time was varied depending on the exposure that was found to give the best overall results. Sometimes this required several exposures, especially in some spearheads where the object tapered and therefore had parts of greatly varying thickness.

In most cases Kodak Industrex CX pre-screened X-ray roll film was used for very long objects such as swords, and shorter objects were X-rayed side by side, in the cabinet machine, using standard (readypak) sheets of film placed between lead screening sheets to cut down the secondary back scatter effects of the X-rays inside the machine. The finer grain Kodak Industrex MX film was used in some cases but the improvements to the definition of the X-ray images were found to be not significantly greater. Industrex CX film was also more readily available and was used in most cases.

Radiography was mainly intended to locate and provide information on welding techniques such as pattern-welding and ferrous inlays. Non-ferrous inlays were recorded where they occured but mostly, where possible, objects with non ferrous inlays were not selected for radiography. X-raying was carried out with the flat face of the blades laid at right angles to the path of the X-ray beam. Because of the (relatively) flat form and possible complex welded structures of these blades it was clear that only in this plane could any sort of useful interpretable information be gained. It was hoped that an indication, even in non pattern-welded blades, of the overall structure down the full (surviving) length of each blade would be obtained. For those blades selected for sectioning the results of X-radiography (vertical plane) were later combined with the results of metallography (transverse or horizontal plane) to allow a three dimensional reconstruction of the heterogeneous structure of each blade to be made.

The main problem encountered was the interpretation of the double images, obtained by the passage of the X-rays through the unevenly corroded surfaces on either side of the blade. The images were often very unclear especially in cases where complex, pattern-welded, structures were present as well as heavy surface incrustation..

The structures revealed by radiography show up because of uneven corrosion at the surface and along the welds joining the various parts of the blades. The different densities to the passage of X-rays show up on the film. An uncorroded pattern-welded sword would not be expected to show much detail when X-rayed. The same may be true for totally corroded pattern-welded swords especially where these are still encased within the encrusted and dense remains of their scabbards. When a totally mineralised blade is reported to show no structure when X-rayed this does not necessarily mean that it did not have a complex (pattern-) welded structure and this possibility should always be borne in mind. The state of corrosion and presence of dense incrustations which can screen the passage of X-rays are both important factors to consider when attempting to interpret radiographs especially of Anglo-Saxon sword blades.

In the present study it did not prove possible in most cases to remove dense incrustations so as to facilitate more effective X-ray analysis. However the central part of the very corroded Wickhambreux sword blade S19 (Chapter 6.18) was X-rayed with and without the encrusted remains of its scabbard. A far clearer and more interpretable image was obtained once the encrusted outer parts were removed. The reconstructions from X-ray analysis included here are in some cases rather tentative owing to the problems of interpretation.

Careful study of the radiographs especially of the more corroded examples enabled sectioning to be carried out where the network of surviving metal was at its thickest. This enabled the maximum amount of metal to be obtained, for metallographic analysis, with the least damage to the object and meant that wasted cutting was avoided. Also the position of cuts was determined so as to study specific parts of weld structures which showed up on X-ray. The only really unsuccessful section cut (Chapter 6.46) came about because it was not possible to choose the cut position using X-ray evidence.

3.3 Metallographic Analysis.

3.3.1 Cutting and mounting specimens

Transverse sections for metallographic analysis were cut from each blade and set in polyester mounting resin. In a few cases complete transverse sections were taken from the broken ends of blades (for instance Chapter 6.20) but these were found to be rather cumbersome to deal with, and particularly difficult to keep flat across the whole width during polishing. Where complete sections were not possible, narrow wedge-shaped sections were cut from half of the blade. In some cases two wedge-shape sections were cut from one blade, so as to obtain a complete composite transverse section, the positions of the cuts being staggered so as not to weaken the object too much. The positions of the cuts were determined from careful study of the radiographs. The study of the complete transverse sections, both continuous and composite, of several double-edged swords soon revealed that these blades were more-or-less symmetrical in structure on either side of the central axis. It was therefore decided that for most double-edged swords a wedge-shape section would only be taken from one half of the blade. Two sections were occasionally taken from the blades to act as a control.

The cutting of the sections was done with either a hacksaw or a diamond cut-off wheel depending on the condition of the object. Fast setting polyester resin was used for most of the mounts. The maximum temperature reached by the setting process was no more than 100°c and then only for a short time - not sufficient to affect even fully hardened martensitic structures. Initial polishing was done with progressively finer carborundum discs; grades 120, 320 and finally 600. Final polishing was carried out using polishing wheels with 6 micron then 1 micron diamond pastes.

3.3.2 Microscopy

Most microscopic examination was carried out using an Olympus binocular metallographic microscope at magnifications of between x50 and x1000. An initial examination was carried out on each specimen, after final polishing to make a visual assessment of the slag content and distribution across the section.

Each section was then given a light etch using 2% nital and the whole section was examined. It was found necessary to use the full range of lenses to carry out both a macroscopic and microscopic study to deduce the general structure of each section, the number of parts it was made from, as well as the composition of each part. The presence and position of welds, the total number of components that had been welded together were determined and in many cases the main components could be subdivided as well. The presence, distribution and percentages of carbon in different parts was noted as well as the grain structure of both iron and steel parts, the evidence for heat treatment, cold working and other visible traces such as the presence of nitride or carbide 'needles'.

A sketch was made of each section and as much detail as possible was noted on the drawing which was accompanied by a series of descriptive notes referring to each part of the section. The sketches and notes formed the basis for the transverse sectional diagrams and accompanying reports which appear in Chapter 6. Photomicrographs were taken at varying magnifications to record specific structures.

3.3.3 Hardness testing

A series of Vickers micro-hardness tests were carried out on specific points across each section so that the different parts of each section were tested. The sections were found to be so heterogeneous, and some of the parts so small, that to get an adequate and even coverage it was most practicable to use a Vickers micro-hardness tester with a 100 gram loading. The appropriate British Standards expression for each result is the figure obtained followed by HV 0.1 to reflect the loading. To simplify the reports here, results using the 100 gram loading are expressed as HV and only where a different loading was used does the result include a figure (for example, 1000 gram loading - HV1.0). A small metallographic microscope using a Vickers pneumatic, lens mounted micro-hardness testing attachment was used and found to be the quickest and easiest method to carry out the hardness tests. The use of micro-hardness testing with low loads has been shown to give hardness readings which tend to increase as the loading decreases (Fig 2). The micro-hardness tester was used on a control sample of standard hardness, 98 HV, and this gave results of 112 HV on the tester using 100 gram loading. This is consistent with the graph (Fig 2) and means that the results obtained are probably between about 10 and 15% higher than the true Vickers hardness values. The results given in the reports below are the uncorrected values obtained on testing and the likely error factor should be borne in mind.

3.3.4 Photomacrographs

Each section was given a heavier etch so that low magnification (below x 10) photomacrographs could be taken of the complete section to show the overall welded structure and distribution of iron and steel parts. The only satisfactory way found of doing this was by using a Vickers projection microscope with a low magnification 'macro' lens. Even and adequate lighting of the sections was found to be difficult to achieve.

Overetching gave undesirable effects such as staining, highlighting, and left a a relief map effect. The correct level of etching was found difficult to achieve because the metal of the sections was so heterogeneous so that, with many sections, one part ideally required a much different degree of etch to another to bring out all the detail.

In practice a compromise had to be sought and the results were more successful for some sections than others. The macrographs have been reproduced at the same scale as the diagrams so that each could be related to the other and the visible structures more clearly explained.

3.4 Electron probe micro-analysis (EPMA) and other methods of examination

The available methods of examination were restricted by the heterogeneous nature of the iron or access to the instrument in the case of the electron probe micro-analyser. In a few cases an alternative etchant, Heyn's reagent (cuprous ammonium chloride), was used to test for the presence of phosphorus where apparently anomalous hardness readings strongly suggested that this might be present in the iron especially where a very large ferrite grain structure was observed. Usually this was confirmed by the selective deposition of copper on the phosphorus rich areas.

Electron probe micro-analysis (EPMA) was used to produce X-ray maps for selected sections and to get an estimate of the percentage of phosphorus, sulphur, cobalt, nickel, copper and arsenic present in the main range of structures observed (Table 8). The purpose of the X-ray maps was to illustrate the varying distribution and concentration of phosphorus in some of the composite blade structures metallographically examined and to show how the hardness values of the ferrite structures were directly affected by their phosphorus contents. For ease of comparison the X-ray maps are reproduced at the same scale next to the corresponding photomacrographs.

Chapter 4

Some Aspects of the Physical Metallurgy of Iron and Iron-carbon alloys

4.1 Allotropy of Iron

Iron as a solid exists in different allotropic crystalline forms. The most important are alpha and gamma iron. The crystal lattice arrangement of alpha iron is a body centred whereas that of gamma iron is a face centred cubic arrangement (Scott 1987, 4). The iron-carbon equilibrium diagram (technically the iron-iron carbide diagram) shows the temperature ranges in which each form of iron is most stable as well as the effect of different proportions of carbon (Fig 3 i).

4.2 Solid solution solubility of carbon in iron

The great importance of the two crystalline forms of iron lies in the difference of the solubility in solid solution of carbon between the two. Carbon is virtually insoluble in the body centred alpha form the lattice structure of which will only accept a maximum of 0.04% of carbon. The face centred cubic lattice will accept carbon atoms more readily and up to about 2.0% carbon is soluble in alpha iron. The solid solution of carbon in alpha iron is known as ferrite and that of carbon in gamma iron as austenite.

4.3 Wrought iron, steel and cast iron

Iron in its pure state has a melting point of 1535°C. This is much higher than the temperatures reached in early furnaces or hearths which are likely to have operated at about 1200°C (Tylecote 1962, 191, Clough 1986, 24). For this reason iron had to be worked in its solid state.

The expanded 'steel' portion of the iron-carbon diagram (Fig 3-ii) is the more useful in the study of early iron artefacts as this covers the full range of bōth temperatures and carbon contents which are likely to be encountered (in Western Europe). This shows the different crystalline states that are stable at different temperatures. When the body centred cubic form of iron, ferrite is heated above 910°C it simply changes into the face centred cubic form, austenite, and when the temperature is allowed to fall below this figure it changes back into the ferrite form.

The solid solution austenite however, behaves differently when the carbon content is above 0.04%. In austenite containing up to about 0.8% carbon the temperature at which any change takes place is depressed, as the proportion of carbon present rises, down to a minimum of 695°C.

If a solid solution of austenite containing about 0.4% carbon is cooled it will remain unchanged until a temperature of about 800°C is reached. This is the upper critical (Ar3) point at which the austenite separates out into ferrite with its maximum solid solution carbon content of 0.04%, and austenite with a higher solid solution carbon content. When the temperature of this solid solution is allowed to fall a further major change takes place at 695°C, the lower critical temperature (Ar1). At this temperature the eutectoid reaction takes place, in which the ferrite remains unchanged but the austenite breaks down as the face centred cubic structure of iron is not stable below this temperature. The austenite decomposes into ferrite and cementite (iron carbide) dispersed in a eutectoid stucture known as pearlite because of its appearance which resembles mother of pearl. Pearlite consists of alternating thin layers of ferrite and cementite (iron carbide), this being the most stable configuration that the carbon, ejected from solid solution, and the ferrite can take up. The pearlite forms between the existing ferrite grains.

For an alloy containing 0.8% carbon the upper and lower critical points (Ar3 and Ar1) coincide at 695°C when a cooling solid solution of austenite will break down into a eutectoid structure consisting entirely of pearlite.

In alloys containing between 0.04% and 0.8% carbon the proportion of pearlite to ferrite present below 695°C is proportional to the carbon content of the alloy. The proportion of pearlite present can therefore be used to calculate the carbon content of the alloy.

The proportion of pearlite is most accurate as a gauge of carbon content, in a steel in the normalized condition, that is one which has been cooled in still air from above the upper critical point (Greaves & Wrighton 1957, 88; Rollason 1973, 177). Steels cooled much faster than this through the critical range, that is quenched, behave differently and these are dealt with below. As a general rule the pearlite is coarser if the cooling rate has been slower and finer if the cooling rate has been faster.

When austenite containing between 0.8 and 2.0% carbon is cooled through the critical range (Fig. 3 ii) it will first of all separate into a mixture of austenite and cementite and then at the eutectoid temperature (695°C) the austenite will break down to give pearlite within a matrix of cementite (Greaves and Wrighton 1957, pt 22a).

The temperatures so far quoted are those which refer to iron and iron carbon alloys on cooling. The same critical points on heating occur at slightly higher temperatures. The lower critical point on heating an iron carbon alloy, (Ac1), is reached at 723°C and the upper critical point of pure ferrite (Ac3), at 937°C. The iron-carbon diagram looks much the same in both cases. In this study the temperatures obtained on cooling are used as these seem most relevant to the study of ancient artifacts whose structures can often allow the researcher to deduce much information concerning the final heating and subsequent cooling.

4.4 Hypo - and Hyper - eutectoid steels

An iron-carbon alloy containing up to about 0.8% carbon is known as hypo-eutectoid whereas one containing more than 0.8% carbon is known as hyper-eutectoid. A plain carbon steel is an alloy of iron containing up to about 2.0% carbon .

4.5 Cast Iron

Iron-carbon alloys containing between about 2 and 5% carbon are classed as cast irons. Much of the carbon is either present in its combined form, iron carbide or cementite (white cast iron) or as free carbon, graphite flakes (grey cast iron) present in a matrix consisting of varying proportions of the eutectoid pearlite or ferrite.

4.6 Calculation of carbon content in a Hypo-eutectoid steel

The proportion of ferrite to pearlite in a hypo-eutectoid steel that has been cooled in still air (normalised) can be used to estimate its carbon content by applying the following formula.

% Carbon = % pearlite x 0.008

A similar visual estimate of carbon content can be obtained for hyper-eutectoid steels although these are rarely encountered in ancient artefacts.

4.7 Heat treatments of Carbon Steels

4.7.1 Annealing and Normalising

Annealing is a general term applied to several softening operations which have a different effect on the grain size and cementite structures within a particular steel. Microscopy of a sample of the metal will reveal which operation has taken place.

4.7.2 Full Annealing is carried out on modern steels in order to obtain grain refinement in combination with high ductility (Bailey 1972, 43). For hypo-eutectoid steels the steel is heated to about 50°C above the upper critical point and for hyper-eutectoid the temperature is 50°C above the lower critical point (Fig 3 ii). The steel is held for a while at this temperature, depending on thickness, followed by very slow cooling, usually in the furnace. This produces a softer steel than normalising.

4.7.3 Normalising involves heating both hypo- and hyper-eutectoid steels to about 50°C above the upper critical point (Fig 3 ii), again for a time depending on thickness, and then allowing the metal to cool in still air. This will produce maximum grain refinement and consequently the steel is slightly harder and stronger than a fully annealed steel.

Both these processes are likely to have been experimented with by early iron smiths. As all early iron and steel was worked by hot forging, any steel which was air cooled was almost automatically produced either in a normalised or fully annealed condition, except where parts of the metal were overheated. The results of this study would suggest that air-cooling of early steel was probably very common.

4.7.4 Overheating during annealing and normalising : Widmanstatten effect

Overheating during full annealing or normalising can occur if the conditions are not closely controlled. If a steel is heated above the correct temperature or if the correct temperature is maintained for too long then austenite grain growth will occur. Where this has happened, upon cooling, ferrite is deposited first at the grain boundaries and then along certain crystallographic planes. Upon further cooling pearlite will form around the ferrite. This gives rise to the phenomenon, is known as the Widmanstatten structure (see Samuels 1980, 255 and Fig 68). It derives its name from the man who first observed this structure in meteorites and it has, under the microscope, a very distinctive columnar or acicular appearance. The Widmanstatten structure is a cause of brittleness in steel.

The results of this study show that this structure is often to be observed in the steel or steeled iron portions of early artefacts. It seems to occur only in patches which indicates that localised overheating took place during forging reflecting variations in temperature within the furnace which would have been very difficult to control completely.

4.7.5 Subcritical Annealing

Subcritical (process or spheroidising) annealing is a low temperature treatment carried out on modern steels to relieve internal stresses caused by cold working and to soften the metal. (Rollason 1973, 175). The steel is heated to about 500-650°C, just below the temperature at which pearlite re-dissolves as austenite. It is held for a time, for up to several hours, within this temperature range during which time the pearlite lamellae 'ball up' or spheroidise (Samuels 1980, 226-228 and Fig 54). The ferrite grains also gradually increase in size. The longer this process is continued the greater the increase in ductility (softness) of the steel with a corresponding decrease in tensile strength and hardness.

This is a secondary heat treatment that may often have been applied to early artefacts in order to soften the steel parts. The softening effect is in direct contrast to the hardening induced by the heat treatments involving quenching which are described below.

4.7.6 Quench Hardening

Hypo-eutectoid steels of varying carbon contents can be hardened to differing extents by heating the metal above the upper critical point (Fig 3 ii) and then quenching in liquids of differing thermal capacity. For each quenching liquid the two main variables are the carbon content and the rate or speed at which the quench occurs, which varies with the thermal capacity of the quenching liquid. Early iron smiths would have estimated the correct temperature from which to quench a steel by gauging its colōur (Table 7).

4.7.7 Effect of cooling rate

Very slow cooling of a hypo-eutectoid steel from above the upper critical point results in large ferrite grains and thick pearlite lamellae. An increase in the cooling rate increases the number of points from which change starts resulting in a smaller ferrite grain size and thinner pearlite lamellae.

4.7.8 Martensite

Very rapid cooling such as is obtained by quenching a steel in water will produce a supersaturated solution of carbon in alpha iron called martensite. During very rapid cooling the points at which austenite transforms is greatly reduced from the points shown in the iron-carbon diagram (Fig. 3 ii). The austenite is not retained down to room temperature and at 150 - 350°C it transforms to martensite. The carbon of the retained austenite does not have time to separate as cementite and the distorted lattice structure of martensite results. Its distorted structure means that it is very hard and non ductile. The higher the carbon content, the greater the distortion to the lattice structure and hence the greater the hardness of the martensite. The hardness increases most markedly for steels with a carbon content of up to about 0.7% but the effect is rather less thereafter (Davies and Oelmann 1983, 111). Martensite appears acicular or needle-like as a result of the diffusionless precipitation of carbon as plates or laths along certain crystal planes. It etches rather slowly and gives a pale colour with nital as the etchant.

The cooling rate above which martensite will be formed is known as the critical cooling rate. The critical cooling rate differs for steels of different carbon contents. This is shown in Table 1 from which it can be seen that steel of 0.2% carbon has to be cooled about twice as fast as a steel with a carbon content of 0.6%. In practice steels with less than 0.3% carbon cannot be hardened effectively (Rollason 1973, 185).

4.7.9 Nodular Troostite or radial pearlite

The continuous cooling diagram, Fig 4, shows the resulting transformation effects of different cooling rates on a eutectoid steel. Above the upper critical cooling point pearlite of increasing coarseness is formed. Very close to the critical point a mixed formation can occur in which some martensite is formed but mixed with it is a dark etching nodular looking constituent which is often known as troostite. This can only be resolved at high magnifications when it is found to be a radial form of pearlite consisting of laminations radiating from a central nucleus. The term troostite is out of fashion in some quarters (for example Samuels 1980) but this distinctive radial form of pearlite is sometimes found in edged weapons and other archaeological ironwork for example Tylecote and Gilmour 1986, p96, Fig 42), and therefore deserves some attention. The term nodular troostite (Rollason 1973, 183) can be used to describe this formation and the term is used in this way for this study.

4.7.10 Bainite

The above structures do not cover all the microconstituents which can be observed in ancient steels which have been rapidly cooled from the austenite range. In this study one such structure has been found in medium-high carbon steels (about 0.5 - 0.8% carbon). This has a feathery appearance which is also laminated and so resembles pearlite. The structure would appear to be upper bainite. Bainite is normally only observed in alloy steels or carbon steels that have been isothermally transformed from above the upper critical point. The time/temperature transformation (TTT) diagram for eutectoid steel (Fig .5) shows the structures obtained when the steel is quenched in various liquids at specific temperatures and then held at each temperature for varying times.

Fig 6 shows the cooling curve from the continuous cooling TTT diagram (Fig. 4) superimposed on the isothermal TTT diagram (Fig 5) for the same eutectoid steel. Although strictly speaking it is incorrect to superimpose these curves, the continous cooling TTT diagram only differs slightly from the isothermal TTT diagram which is easier to construct (Davies & Oelmann 1983, 125). The cooling curves illustrate the different transformations which take place under different rates of cooling. Curves 1 and 2 show transformations to pearlite, and 4 and 5 the transformations to martensite under very rapid cooling.

The intermediate curve 3 represents a rate of cooling where a split transformation occurs. In some cases this results in the formation of the radial form of pearlite already referred to as nodular troostite mixed with martensite. In other cases a structure resembling the feathery upper bainite is observed. It has been pointed out that in some instances bainite is formed under continuous cooling conditions (Samuels 1980) although the reason for this does not seem clear. A fast dark etching acicular constituent similar to martensite is sometimes observed. Both lower bainite and tempered martensite (see 4.7.11) give this appearance but lower bainite is less hard and this can be used to distinguish between the two (Fig 7).

It would seem most likely that, for a medium to high carbon steel, when a troostite or bainitic structure is observed an intermediate cooling rate (slower quench) has been applied to the steel under examination. This may have involved the use of a quenching medium with a lower thermal capacity, such as oil, to give a 'slack' or slow quench.

Results from the present study would suggest that when a bainitic structure has been observed the carbon content has usually been higher, fairly near the eutectoid. Conversely, when a troostitic structure has been observed the carbon content has been slightly lower, usually about 0.4-0.6% by visual estimate. The early iron smith worked empirically so he was not aware of the different microstructures that he produced by subjecting a piece of steel to varying cooling rates. On the other hand he must have soon learnt what effects the different treatments had on the physical properties of the metal. Similar treatments may have produced nodular troostite and bainite in different steels and these structures may represent deliberate efforts by an early smith to produce a steel of intermediate hardness and brittleness. Bainite varies in hardness between about 200 and 400 HVwhereas nodular troostite can be rather harder, about 450 HV (Fig 7).

4.7.11 Tempering

Steel in its fully hardened, martensitic state is in a highly stressed condition, very hard but also brittle and liable to cracking. This problem can be lessened by tempering. The objectives of tempering are to both, a) relieve internal stresses caused by quenching and, b) to toughen the steel. This is carried out by warming the steel below the lower critical temperature (below about 700°C).

Warming for a time at 100 - 200°C is sufficient to relieve internal stresses while leaving the martensite in an acicular form, although this becomes very fast and dark etching (with nital). This 'black' martensite is called tempered martensite and resembles lower bainite although it is much harder than lower bainite.

Between 200 and 450°C the martensite decomposes into ferrite and a precipitation of fine particles of carbide. This structure is tougher but less hard than martensite. At higher tempering temperatures, 450 - 650°C the carbide particles coalesce producing fewer but larger carbide particles in a spheroidal form known as sorbite (Bailey 1972, 51). In this condition the steel is yet tougher but less hard. Fig 8 shows the variation in hardness with tempering temperature. Quenching and tempering are used in modern carbon steels to product metal that is both tough and springy.

The temperature ranges used to be gauged by the 'temper colours' of the oxide film which formed on the surface of the clean metal upon reheating (Table 2). By treating steels in this way varying degrees of hardness and toughness can be obtained depending on the use to which it is to be put.

It would appear that quenching as a means of hardening steel only gradually came into use during the Iron Age, Roman and early medieval periods. Early iron smiths must soon have discovered the effects of quenching steel but may often have found the results too brittle for practical use. There is not much evidence for the deliberate tempering of quench hardened artefacts even among the earlier medieval weapons dealt with in this study. One of the earliest examples of quench hardening so far found by metallographic analysis was an unused axehead from Egypt (Tylecote 1976, 51) which had a martensitic edge which had been softened by a process known as autotempering. The axehead must have been quenched from the austenitic range, probably in water, but removed from the quenching liquid before the whole body of the object had time to cool right down. The result was that heat flowed from the still hot centre of the axehead to the edge thereby tempering the newly formed martensitic structure and rendering it tougher and less brittle. This was almost certainly accidental and the smith unaware of what he had achieved. Accidental autotempering is more likely to have occured on thicker objects such as this rather than thinner examples such as the weapons of the present study. However, tempered martensite was observed in several cases and autotempering resulting from ineffective quenching may be as likely a cause as the intentional re-heating of the quenched blades.

4.7.12 Gradient quenching

This occurs when part of a steel object is protected from effects of the quenching medium by a clay envelope which prevents that part of the object from cooling so quickly. Medieval and later Japanese swordsmiths practised this technique by coating a blade with a mixture of wet clay and charcoal, then scraping most of this away along the edge which was to be hardened (Yumoto 1958, 99 and Pl44). The blade was then heated above the upper critical temperature then quenched in water. To judge from the gradient microstructure seen on certain blades (Gilmour 1975, 94-95; Tylecote 1976, 66) the blades must have been held in the quenching liquid long enough (mostly) to prevent autotempering. The result, for example, for a steel cased blade would have been a hard martensitic edge and a tough unhardened back.

The gradient structures observed progressively away from the fully hardened edge are very similar to those produced for plain carbon steels in the modern Jominy end-quench test for hardenability (Rollason 1973, 202-3). It is not known if this technique of partial quench hardening was used in Europe before the post-medieval period. It would have been possible for single edge blades although impractical for double-edge weapons such as most medieval and earlier swords. This technique does not seem to have been used for any of the weapons examined in this study.

Chapter 5

The Early Production of Iron and Steel

5.1 Introduction

Much has been written about the early production of iron and the bloomery process (see Tylecote 1962, 1976 and 1986). The processes involved have recently been re-examined and evaluated in detail (Clough 1986) and are therefore only covered in brief outline here. The production of steel from iron or it's ores and various smithing techniques are covered in more detail.

The techniques outlined include the selection of ores, their preparation and smelting. These cover the main methods of production used from the beginning of the Iron Age until the late medieval period when the manufacture of iron and steel by the indirect or blast furnace process was introduced into this country and mainland Europe.

5.2 Outline of the Direct or Bloomery Process

5.2.1 Selection and exploitation of Ores

The two most obvious factors affecting the exploitation of iron ores from the beginning of the Iron Age and on through the early medieval period were their availability and quality - how easily iron with the desired properties could be smelted. Iron ores are found in most parts of Europe and are fairly widespread in Britain often in fairly limited deposits which may once have been exploited although they would not now be large enough to be commercially worthwhile recovering. Many of these minor deposits are likely to lie as yet undetected (Tylecote 1962), and so the true extent of the use of iron ores until well into the medieval period in Britain is not known. Because of the ease with which it is smelted iron is often likely to have been exploited on a very small scale.

The main British sources of iron ore before the Industrial Revolution have been located (Tylecote 1962, 176, Table 43). The plotting of the minor sources known to have been used is more difficult and tends to show the often (unavoidably) haphazard distribution of archaeological survey or research. In the absence of written evidence the pin-pointing of such sites has depended on the identification of nearby ore roasting and smelting sites which on a small scale, are easy to miss and are easily confused with smithing sites as the waste products are similar. It has been estimated that at one time or another iron ores have been worked in twenty nine out of forty-one (pre 1974) English counties with the likelihood that the actual total is higher (Tylecote 1962, 175-6). In Britain the main ore sources were the carbonate, haematite and limonite ores although other ore sources are likely to have been exploited as well.

5.3.1 Carbonate ores

These are by far the most common and occur as follows:

5.3.1.1 Sedimentary deposits, for instance those found along the north-west face of the Jurassic ridge running from the Cleveland Hills in the north down through Northamptonshire and Lincolnshire to Oxfordshire. These deposits are made up of a group of ironstones, the Middle Lias (Limestone) or Marlstone (Trueman 1971) and consist of sideritic, chalybite or spathic iron ore, each essentially ferrous carbonate ($Fe\ C0_3$). When exposed this weathers to one of the iron oxides.

5.3.1.2 The nodular carbonate form which is sometimes known as clayband or clay ironstone. It is found in the Wealden series of ironstone beds and at the coal seams it underlies coal in shale beds (Tylecote 1962, 177 and Fig 43; Trueman 1971).

5.3.2 Haematite ores

These consist of anhydrous ferric oxide ($Fe_2\ 0_3$). The ores from West Cumberland and the Furness district of Lancashire were much sought after during the Industrial Revolution as they were very low in certain impurities particularly phosphorus. These sources are now more or less exhausted and most haematite ores come from the Jurassic scarp and contain appreciable amounts of phosphorus.

5.3.3 Limonite ores

These consist mainly of the crystalline, hydrated ferric oxide, Goethite ($Fe_2O_3H_2O$ or Fe0.0H). They occur in the Forest of Dean and along the edge of the south Wales coalfield between Rudry and Llanharry.

5.3.4 Other ore sources

5.3.4.1 Magnetite or Lodestone (Fe_3O_4) is the magnetic, combined form of oxide which is rare in any quantity (Hodges 1964, 81) and therefore is unlikely to have been much used as a source of ore although there are some indications that it may have sometimes been used (Schubert 1957, 16).

5.3.4.2 Bog iron ore by contrast is likely to have been a more important source of iron ore because of its wide availability in particularly in northern and western Britain. It has been found associated with Iron Age contexts in various part of Britain (Tylecote 1962, 179). Bog iron ore is a loose, porous earthy form of limonite and does not occur as a sedimentary deposit or rock. It is formed particularly under arctic or subarctic conditions where iron bearing surface waters meet organic matters, these being the conditions most suitable for the precipitation of iron oxides.

It is formed in a similar way in boggy moorland conditions in Britain where it occurs in layers resembling peat, a few inches thick, just below the surface (Tylecote 1962, 179). This was an important source of ore in northern Europe in the pre-Roman Iron Age and the post Roman Migration period particularly for countries such as Denmark with few other indigenous ore sources. Bog ore was still used for the small scale production of iron until recently in Ireland (Clark 1952, 202 & Coghlan 1977, 11).

5.3.4.3 Sulphide ores

The sulphide ores, iron pyrites (pyrite, marcasite, pyrrhotite) have generally been avoided as source of iron because of their sulphur content. Sulphur is very detrimental to the properties of iron (see below) although it can be removed by efficient roasting and so become a viable source of iron (Clough 1986, 124). It does not, however, appear to have been much used by early iron smelters who may mostly have avoided it because of its sulphur content. Sulphur along with phosphorus is easily reduced with the metal.

5.3.4.4 Phosphorus containing ores

Phosphorus is common in most iron ore deposits in Britain and occurs in varying proportions (see Tylecote 1962, 180-1, Table 64; Greensmith 1978). Like sulphur but unlike most other elements that commonly occur in these ores it reduces easily with iron in which it forms a solid solution affecting its properties.

Phosphorus is usually present in the ore as Vivianite (3 Fe . P 0 .8H 0) and when reduced it makes the iron harder (Table 5) but more brittle when cold (cold shortness). A proportion of phosphorus from a phosphorus bearing ore will be removed in the slag during smelting and the rest will be left in the iron bloom. As we have already seen, the low phosphorus haematite ores were greatly preferred in the Industrial Revolution and the sources of these in northern England are now mostly exhausted. The results of this study show that far from being rejected as being of little value high phosphorus iron may sometimes have been exploited for properties considered beneficial. Early ironsmiths may not have been aware of what phosphorus was although they must soon have discovered the varying properties of the metal smelted from different ore sources and learnt where these could be best utilised and when they were not suitable.

5.3.4.5 Quality of ores & reasons for selection.

Iron was most economically produced by the smelting of ores which had a high iron content and which needed the least pre-smelting treatment (mainly roasting) and also which contained the smallest proportion of unwanted minerals (gangue) which could not be removed in this way. This was especially true of iron produced by the early bloomery process which was not efficient; much iron being lost in slag during smelting. Judged on this basis the haematite from Ulverston, Lancs, is a good ore with only 8% unwanted minerals to be removed as slag during smelting compared with 25% in bog iron ore from Weardale (Tylecote 1962, 182). However, unlike haematite the bog ore is very porous and therefore apart from drying requires no roasting. The carbonate ores contain a lower proportion of iron but this is soon increased upon roasting which also makes the ore more porous and therefore suitable for smelting.

5.4 Pre-smelting treatments - ore dressing

5.4.1 Washing, by which earth and clay were removed from the ore, was practised in different parts of Britain in the seventeenth and eighteenth centuries (Schubert 1957, 215).

5.4.2 Weathering. Ore was dug up and left exposed in the open air, for example in 1541 at Rivaulx in Yorkshire where ore was left to weather like this to lose its earthy parts (Schubert 1957, 215).

5.4.3 Roasting (calcining) was an important preparatory treatment for iron ores before smelting. Most ores are too hard and dense to be suitable for smelting in which free access to carbon monoxide gas is required for more efficient reduction to iron. The purpose of roasting was to make the harder ores easier to break up and to make them more porous, and at the same time, to remove impurities such as carbon dioxide, water (including water of crystallization) and sulphur which comes out as sulphur dioxide. The conditions necessary to achieve this are a moderate temperature and an oxidising atmosphere.

Before about the middle of the seventeenth-century nearly all ore roasting appears to have taken place in the open air by burning heaps consisting of interleaved layers of fuel and ore starting with fuel at the bottom. The fuel was mainly wood, peat or charcoal with decreasing amounts of fuel from the bottom towards the top. Ore burning took between twenty-four hours and several days depending on the weather. An ore to fuel ratio of 2 : 1 appears to have to be suffient for the roasting of most ores. There are several sixteenth and seventeenth century accounts describing ore roasting (Schubert 1957, 216-7 notes).

The main chemical changes to the ore that occur during roasting may be summed up as follows:

$FeCO_3$ on heating → FeO + CO_2
decomposes (Ferrous Oxide) (Carbon dioxide)
(Carbonate ores)

$4\ FeO + O_2$ oxidation → $2\ Fe_2O_3$
(ferric Oxide)

$Fe_2O_3 \cdot H_2O$ on heating → $Fe_2O_3 + H_2O$
(limonite or hydrated ferric oxide)

$S + O_2$ oxidation → SO_2
(Sulphur) (Sulphur dioxide)

5.5 Smelting

To obtain iron from the ore, the iron oxide of the ore must be reduced to metal and the lowest temperature at which this can be achieved is about 800°C, whereas the melting point of pure iron is about 1540°C

5.5.1 Fuel

Until the development of coking during the Industrial Revolution the chief source of fuel for the reduction of iron ore was charcoal. Raw wood must have been tried but found to be unsatisfactory - because of its oxygen content and the need to have it in small pieces intimately mixed with the ore. Coal must have been tried from time-to-time, (Tylecote 1962, 190-1) but found to be unsuitable because of its sulphur content. Peat is also unsuitable owing to its burning characteristics.

5.5.2 Reduction of ore to metal

In the bloomery process the fuel provides the heat necessary for the reducing reaction and also provides the reducing agent. For the reduction of iron oxide to be possible the temperature in the part of the furnace where reduction is to take place must be maintained above 800°C and the atmosphere must be sufficiently reducing for this to happen. Carbon monoxide gas is required to reduce the ore to metallic iron. Under reducing (limited draught) conditions charcoal (carbon) burns to form carbon monoxide. Above 800°C carbon monoxide dissociates to form nascent carbon which reacts with the iron oxide, reducing it to metallic iron with the evolution of carbon dioxide. the process can therefore be divided into two stages and summed up as follows:

$$C + O_2 \xrightarrow{\text{reducing conditions}} CO$$

(Charcoal) (Oxygen) partial oxidation (Carbon monoxide)

$$\xrightarrow[\text{complete oxidation}]{\text{oxidising conditions}} CO_2$$

(Carbon dioxide)

$$Fe_2O_3 + 3\,CO \xrightarrow{\text{reduction}} 2\,Fe + 3\,CO_2$$

(Ferric oxide) (Iron)

To maintain a high enough temperature for reduction an induced draught of air was produced by bellows and introduced via nozzles (tuyeres) although the draught kept low enough for reduction to take place. Both carbon monoxide and carbon dioxide will be produced from the fuel in these conditions. If the ratio of carbon monoxide to carbon dioxide gets too low, which will happen if the blast of air is too strong, then reduction of the metal oxide stops. Also, unless the ore is porous enough it will not be reduced efficiently and, if the particle size of the charcoal is not small enough, too little carbon monoxide maybe evolved for reduction to take place. However, the particle size of both ore and charcoal should not be too small or there will not be a sufficiently free passage for the air blast and the reducing gas and reduction will be inhibited.

Under the conditions so far described iron oxide will partially reduce to metallic iron but still be intimately mixed with the gangue or unwanted mineral constituents of the ore as well as cinders from the fuel. Much of the unwanted mineral constituents will be in the form of silica which will combine with iron oxide from the roasted ore to form fayalite (iron silicate). This slag or gangue is therefore formed without the need to add a separate flux. To be separated from the iron bloom the free running temperature of this gangue must be exceeded. This was usually about 1150°C although this varied depending on the composition of the gangue and if fluxes had been added. (Tylecote 1962, 187 and Table 67).

The free running temperature was critical and when it was exceeded the slag liquified to form a pool at the bottom of simple hearths or flowed into slag tapping pits outside more advanced hearths or furnaces. The free running temperature must have been fairly easily attainable by smiths from the beginning of the Iron Age as liquid copper (mp 1083°C) was produced from the beginning of the Bronze Age.

5.5.3 Furnace Types

The earliest furnaces or hearths used for iron smelting appear to have been the simple 'bowl' type, consisting of a small hemispherical depression in the ground (about one foot in diameter by about one foot deep), primitive (animal hide) bellows being used to maintain an air blast. There was no provision for slag tapping and slag appears to have run to the bottom of the furnace and been absorbed by a bed of charcoal (Tylecote 1962, 219).

By the 2nd century A.D. in Britain these early hearths had been developed into the 'shaft' furnace with a superstructure standing up to about 6 feet high and provided with slap tapping pits (for example Ashwicken, Norfolk; Tylecote 1962, 218 - 221). Shaft furnaces may have been in use elsewhere in Europe as early as the 6th century B.C. and it has been suggested that an intermediate type, the 'domed' furnace with a hemispherical superstructure, may have been in use in Northern Europe in the pre-Roman Iron Age (Coghlan 1977, 27).

However, no examples of this type have been definitely identified in Britain although this form has been suggested for the reconstruction of a furnace in Minepit Wood, Sussex. (Cleere 1972, 14). Shaft furnaces were undoubtedly the most important and possibly the only form of bloomery furnace that developed from the simple bowl type. It was these that were ultimately enlarged and developed into the blast furnace.

5.5.4 Fluxing

To produce a usable iron bloom most of the gangue must be removed as a fusible slag. Iron oxide will work as a flux and react with the silica (and other minerals) present to form a glass-like slag, consisting mainly of fayalite ($2FeO.SiO_2$, with a free running temperature about 1170°C). There seems to be little evidence before the late medieval period for the use of additional fluxing agents such as lime to lower the free running temperature and improve the yield of iron. Lime may occasionally have been added and this reduces the free running temperature by about 50°C up to maximum of 12% CaO above which the free running temperature rises again (Tylecote 1986, 130).

The absence of fluxes on archaeological iron smelting sites does not necessarily rule out their use altogether; it is possible that in some cases a water soluble flux may have been used but has become leached out of the slag during burial. Potash, for example, would have been readily available from wood ash and to some extent must have been an inevitable constituent of the charcoal used for smelting. Other mineral impurities in the ores such as the oxides of manganese, magnesium and aluminium, Mn 0, Mg O and $Al_2 0_3$, also act as fluxing agents but again do not reduce the slag free running temperature by more than about 50°C. The temperature within the reducing part of the furnace must be maintained by means of the air blast, above that of the free running temperature of the slag formed by the fusing of the gangue. In practice this appears to usually have been within the range of 1050 - 1200°C.

5.5.5 Formation and consolidation of an iron bloom

During reduction solid particles of iron are formed and these gradually coalesce to form a spongy lump or bloom after the slag has run to the bottom of the furnace or been tapped away. The spongy bloom thus obtained still retains some slag and most of this was removed by gently hammering the bloom while still hot or after re-heating (above about 1050°C) until the slag became fluid enough to be squeezed out. A bloom carefully consolidated in this way could result in a clean, almost slag free, piece of iron although the results of the present work would suggest that the care take over consolidation was rather variable.

Most other impurities present in the ore, such as the oxides of manganese, magnesium and aluminium, will be lost in the slag since they are far less readily reduced than the iron oxides.

5.5.6 Effects of phosphorus and sulphur

If phosphorus and sulphur are present in the furnace they will be reduced and will combine with the iron as it is formed. Sulphur has a particularly deleterious effect on iron, making it very brittle both when hot and cold (hot and cold shortness). This is caused by the formation of a film of ferrous sulphide (Fe_2S) around the ferrite grains of the metal. Very careful forging can result in the break-up of this film thereby making the metal more malleable (Clough 1986, 121) but this must either have been beyond the scope of the earlier ironsmiths or not worth their while and consequently high sulphide irons seem to have been avoided.

Phosphorus, on the other hand; has less serious effects on the properties of iron. It has little effect when hot although the metal becomes harder and more brittle when cold (cold shortness) although for many purposes a perfectly usable iron is produced.

During the Industrial Revolution low phosphorous ores were sought where possible and subsequently phosphorus was removed during refining of iron because of the brittle properties it imparted. More recently, however, phosphorus has increasingly been actually added to refined iron to improve corrosion resistance and strength (Tylecote pers. comm; Clough 1986, 54).

5.5.7 Iron bloom

The furnace conditions and bloom consolidation described above usually left a fairly pure lump of iron except for the remaining slag and any phosphorus that may have combined with the metal. Sometimes iron artefacts have a patchy and very low carbon content which is likely to have resulted from the accidental absorption of carbon during smelting. The absorption of more than a very small amount of carbon is unlikely in the reducing conditions described especially where phosphorus is present (see carburisation of iron below).

5.6 Natural steel

According to some writers iron ores containing manganese were deliberately exploited so that a natural alloy steel with greater toughness and elasticity was produced on smelting (Forbes 1956,8,33). This was said to be the reason for the reputation of the iron produced at the Roman iron works in the province of Noricum. It has been stated that these ores were first discovered and exploited for this property by the Iron Age tribes of that part of the eastern (Austrian) Alps, and also that this method of producing steel directly from manganese bearing ores was continued in Roman Britain as part of the Wealden iron industry near Battle in Sussex (Schubert 1957, 29 and 54).

Unfortunately this claim appears to have been based almost entirely on analyses of the various ores rather than the steel that is supposed to have been produced (Schubert 1957, p54 and note 3). The oxides of manganese and of many other metals in modern alloy steels are far more stable than those of iron (see Clough 1986, 48) and, therefore, these are most unlikely to have been reduced with the iron in the vast majority of medieval or earlier bloomery smelting furnaces unless under very exceptional conditions. The reducing conditions and the higher temperatures required would have been beyond the scope of these furnaces even if the early iron maker was aware of the properties of a 'natural' alloy steel which is unlikely. In any case the proof of the manufacture of early alloy steels would have to come from the objects themselves and so far this evidence is lacking. Occasionally an iron object with an appreciable manganese content (0.1 - 1.0%) is reported. (Coghlan 1977, 83) but in the absence of metallographic analyses it is possible that the manganese may occur as part of the slag from smelting still entrapped within the metal and not as an alloy with the iron. Since iron is produced and worked in the solid state it is heterogeneous and bound to contain impurities in varying amounts depending on the quantity of slag left in the metal after consolidation and subsequent forging, as well as the chemical composition of the slag. Reports of 'natural' alloy steel must, therefore, be treated with extreme caution and carefully examined.

5.7 Nickel enriched iron

Nickel is occasionally found in small quantities in archaeological iron objects (Photos 1989, Table 3). It is reducable to the metal much more easily than manganese although in Europe iron ore deposits with nickel are rare. There has been much debate as to whether the nickel that has been found in some iron objects is of meteoric, telluric (native) origin or whether it came from the smelting of nickel bearing iron ores. The occurence of nickel in archaeological iron objects has recently been listed and divided up according to whether they are likely to be of meteoric or smelted in origin (Photos 1989, 406-410). The criteria for judging the origin of nickel bearing iron has been discussed, one important factor being the retention of the Widmanstätten structure, characteristic of nickel/iron meteorites, even after working and annealling at comparitively low temperatures (Buchwald and Mosdel, 1985).

Localised iron ores with a relatively high nickel content would seem to be the source of the nickel found in a series of spade shaped 'ingots' or 'currency' bars from central and northern Sweden and which must represent only a small proportion of similar objects produced in this region (Thalin 1973, 39). Two other spade shaped 'currency' bars and a similar socketed axe have been examined using electron probe micro analysis (EPMA) and metallography which have identified narrow pearlitic or martensitic bands with nickel contents mostly varying between 1.4 and 9.3% (Hansson and Modin 1973).

Other early medieval scandinavian blades with nickel banding have also been reported (Tholander 1979) and it would seem that there are two possibilities for the formation of the nickel-rich banding. Firstly the making of a laminated piece of metal by welding and piling a piece of non-nickel bearing iron and a piece of nickel enriched iron. This was undoubtedly the method used for the manufacture of many South-East Asian kris, the very common type of dagger with a blade almost invariably made by a relief map form of pattern-welding (see Chapter 7.4) in which alternate laminations were often made using nickel rich iron (Bronson 1979). In one case these laminations have been found to contain approximately 3% nickel (Tylecote and Gilmour 1986, 147).

The second possibility also involves piling but not the intentional combination of dissimilar pieces of iron. In this case a single piece of iron with a fairly low but detectable nickel content might be folded and welded a number of times (piled). Oxidation at the weld surface would lead to formation of a thin nickel enriched band in a similar way to the formation of arsenic enriched bands at the weld surfaces, an effect which has been reported for early welded artefacts (Tylecote and Thomsen 1973). This may be the origin of much of the banding reported in the early medieval Swedish artefacts for which there seems to have been no obvious decorative purpose comparable to the South-East Asian kris blades and nor do they bear much comparison to contemporary pattern-welded weapons. The nickel banding in the Swedish artefacts may be an accidental by-product of forging and piling local nickel bearing ores although the metal made from these ores may have been forged and piled because they were found to product iron with improved qualities. In the present study the blades examined by EPMA were uniformly low in nickel with the exception of one high phosphorus pattern-welded band of a small scramasax or knife, (Chapter 6.42) which was found to have a nickel content of 0.59% (Table 8). The nickel content in another of the high phosphorus bands was low and it is fairly clear that it was the high phosphorus content of these bands that was important for the pattern-welding (see Chapter 7.4). The single high nickel value of the one pattern-welded band may be a rogue result or it may represent part of a batch of nickel rich, high phosphorus iron imported specially for pattern-welding unless this knife was made near one of the localised areas, such as Sweden, where these ores appear to have been exploited.

5.8. Bloomery Steel, Direct Process

There seems little doubt that the metal of a bloom normally produced at a smelting site consisted of ferrite (alpha iron) with perhaps a very small and patchy carbon content, below about 0.1% at most. It does, however, appear that a steel, with a carbon content above about 0.2 or 0.3% was sometimes produced if only as patches within a generally ferritic bloom. A Roman bloom from Woolthorpe, Lincs, is reported as having zones containing between 0.2 and 0.5% carbon (Schubert 1957, 55 n.1). Others reported from Arundel in Sussex and Corstopitum on the Tyne are reported containing between about 0.5 and 1.5% carbon (Smythe NNS, vol 17 (1936-7) 197-203; Tylecote 1962, Table 80 - p243).

The degree of carburisation achieved was very uneven, Similar results have been obtained during smelting experiments (Pleiner 1969) and these have showed that bloomery steel can be intentionally produced although the carbon content of the bloom is always likely to have been very uneven.

To produce carburised iron or steel directly in this way, the furnace conditions have to be much more reducing than is necessary for the production of a low carbon iron bloom although the temperature still has to be above the free running temperature of the slag (ie. normally between about 1100 and 1200°C). A higher charcoal to ore ratio is required and control over the air blast is more critical. These factors make it a more difficult and expensive operation. The choice of a low phosphorus ore is critical to the success of smelting steel in this way as the presence of even a small proportion of phosphorus slows down the absorption of carbon considerably (Table 3).

The manganese bearing ores from which the Norican 'natural' steel was reputedly smelted would have been suitable for the production of a steely iron bloom, but not for the reasons given by Forbes and others. Manganese oxide will preferentially combine with silica in the ore during smelting and therefore a higher proportion of iron will be reduced. The onset of carburisation will be reached at an earlier stage (Clough 1986, 49) and the bloom will have a higher percentage of carbon, hence a more steely structure.

During the nineteenth century bloomery iron and steel was produced in two distinctly different furnaces in the iron smelting town of Tendukera in India. The steeled iron was produced in a much taller furnace narrowing at the top. (Percy 1864, 258).

The direct carburisation or steeling of the iron in a bloomery furnace must always have had uneven results and been difficult to control. Until we can analyse sufficient of the steeled blooms or cakes produced by bloomery furnaces it is rather difficult to assess the actual success of this process at various times or how it developed or how much directly produced steel was made rather than produced by the carburisation of wrought iron.

Different hot forging characteristics of the metal after the smelting of the bloom would soon have been realized by smiths, as well as the varying properties when cold and the potential of hardening by quenching.

5.9 Cast Iron

Cast iron was not intentionally produced in Europe until the introduction of the blast furnace for the indirect production of iron and steel from its ores, between approximately the twelfth and fourteenth centuries, although the blast furnace was not in use in Britain until the late fifteenth century (Clough 1986, 9; Cleere and Crossley 1985, 219). It was a larger version of the bloomery shaft furnace which had already developed into the high (Stuckhofen type) bloomery furnaces. Bloomery iron production was only gradually displaced by the indirect process as the technology improved and the production of different grades of iron and steel became possible and economical. In China, however, cast iron was being used for tools and moulds from the fourth century BC (Needham 1958, 5).

Bloomery smelting experiments have produced some cast iron under very reducing conditions (Wynne & Tylecote 1958; Clough 1986, Plate 5). Solidified lumps of cast iron are also sometimes found on archaeological sites, for instance at the Roman smelting sites of Wilderspool and Tiddington where their production was fairly clearly unintentional as they appear to have been discarded (Tylecote, 1962, 243 and Table 80).

The cast iron must have been produced in the parts of the furnace with a very reducing atmosphere and where the temperature was above 1130°C, the melting point of the carbon-iron eutectic. The iron, as it was reduced, would have absorbed carbon until the maximum carbon content in the austenite solid solution was exceeded at which point some of the liquid carbon-iron eutectic (4.3% carbon - see Fig 3i) would have formed. If the conditions permitted this would continue until enough droplets were formed to coalesce and flow to the bottom of the furnace and eventually form a small pool of cast iron.

Cast iron is very hard and brittle and cannot be forged and is virtually unusable, except where castings are required, unless the carbon content is reduced. This is done by fining where the molten cast (pig) iron is oxidised by blowing air through it or by the addition of iron oxides (as ore) or a combination of both.

By these means steel and carbon free iron (m.p. 1535°C) can be indirectly produced. The technology relating to these processes followed the introduction of the blast furnace in Europe in the late Medieval Period and so does not concern us here.

The conditions required to produce steel directly in the bloomery furnace are very similar to the conditions which can accidentally produce cast iron and these conditions must have been quite difficult to control. It is not surprising that the less heavily reducing conditions required to produce low carbon iron were normally employed especially as these were more economical on fuel (charcoal) and were suitable for phosphorus containing ores.

5.10 Carburisation of Iron

The availability of directly produced steel probably increased with the developments of the more specialist types of bloomery furnace, the Osmund in Scandinavia, the Stuckhofen in Austria and the Catalan in Spain. Steel was being imported into Britain from both Spain and Scandinavia during the thirteenth and fourteenth centuries (Salzman 1967, 286-288) and may have been produced in this way.

Before the development of these more specialised bloomery furnaces steel or steeled iron must usually have been produced by the carburisation of bloomery iron. Very reducing conditions are necessary but the free running temperature of slag does not have to be exceeded although a greater depth of carburisation is achieved if the temperature is higher (Table 4). It can and undoubtedly was carried out in the reducing part of a smith's charcoal hearth.

In the reducing part of the smith's hearth carbon monoxide gas is produced. On decomposition this forms nascent carbon atoms which are absorbed at the surface of iron in this part of the hearth. The process is, however, slow and sufficiently reducing conditions have to be maintained throughout. Even carburisation is also difficult to achieve under these conditions and only really possible with quite small pieces of iron. The difficulties of carburisation have recently been discussed with the conclusion that a minimum temperature of 900°C was necessary for the process to have been successful (Rehder 1989).

The heat and carburising medium may sometimes have been separated, for instance, by the packing of pieces of iron and charcoal in sealed containers which were heated for long enough for carburisation to take place.

This method is similar to one of the main ways in which *wootz* (the South Asian crucible steel) was produced possibly as early as the 6th century A.D. (see Appendix 2). In the sixteenth century, Biringuccio (1966, 67-71) described a method where pieces of iron were soaked in liquid cast iron until lumps of steel resulted. This was similar to the early Chinese 'co-fusion' method of making steel with cast and wrought iron which was in use in China from about the 6th century A.D. or earlier (Needham 1958, 24) and has been reproduced under modern laboratory conditions and the extent of carbon diffusion at different times monitored (Whitaker and Williams 1969). This was similar to the iron/cast iron crucible methods of making *wootz* ingots (Appendix 2).

5.11 Effects of Phosphorus on the carburisation and other properties of iron

The presence of phosphorus in iron has the effect of slowing down or preventing carburisation. Phosphorus atoms in the face-centred cubic lattice of alpha iron inhibit the passage of carbon atoms through the lattice, and the effect is greater as the proportion of phosphorus is increased. (Table3). Consequently, the attempted carburisation of iron with an appreciable phosphorus content is much more likely to fail if attempted in an ordinary smithing hearth. Early smiths must soon have become aware of this problem and learnt which types of iron it was possible to carburise.

An increasing content of phosphorus in iron also has the effect of increasing the hardness (Table 5) and tensile strength or elasticity of the iron . The increasing brittleness (cold shortness) of higher phosphorus irons is therefore partly compensated for, by the properties of increased tensile strength and hardness. Iron objects low in carbon and phosphorus have to be work-hardened or carburised to equal the hardness achieved by equivalent objects in bronze. However, phosphorus containing iron without any carbon will produce objects with physical properties as good as, or better than their bronze counterparts. The wide availability of phosphorus containing ores and the readiness of the phosphorus to reduce with the iron would have made their use attractive where the properties of the resultant iron were suitable.

One notable effect of phosphorus in iron with some carbon present is that a banded structure may result from the segregation of the phosphorus and carbon containing areas, which is accentuated by subsequent forging. This banded effect can be very noticeable on an etched transverse section through such a piece of metal. It can easily be confused with a piled structure which will usually (but not always) be identifiable by bands of slag inclusions trapped along the welds.

5.12 Forging, Welding and Piling

Until the techniques of hot forging and the solid-phase hammer welding of iron were mastered the Iron Age proper could not have got underway. Small iron objects have been occasionally found in Bronze Age contexts (Coghlan 1977, 39-41) but the iron was almost certainly produced accidentally, probably during copper smelting, and then cold worked into a small piece often treated more as a curiosity and perhaps prized as such. Once the techniques of gently hammering the hot spongy iron bloom to remove most of the still liquid slag and consolidate the metal had been mastered then iron objects could easily be made.

It must soon have been discovered that two pieces of white hot iron will fuse when hammered together, this being just an extension of what happens when the spongy bloom is consolidated. Fusion or pressure welding was in use before the Iron Age (Tylecote 1968, 1-17) and so the technique was not new.

Unlike bronze, iron cannot be cold worked to any great extent as it soon becomes hard, brittle and unworkable. It can however be very successfully hot worked. When iron or steel is hot worked or forged above the upper critical point the austenite deforms but immediately re-assumes an equiaxed crystalline shape and in this way it is self-annealling.

Prolonged hot forging of iron was often carried out mainly in one direction which resulted in the remaining slag entrapped within the iron being stretched out into long fibres or ribbon-like inclusions. To some extent a fibrous slag content may have added strength (stiffness) to an iron weapon such as a sword, although on the whole the poor mechanical properties of slag probably would not have greatly added to the quality of the iron. However, dispersing it in long thin strands may at least have reduced the weakening effect at any one point.

The extensive forging of a piece of iron will usually result in a long rod or bar. This can be folded and forged out again to the same length and this procedure repeated on a number of times. This process is known as piling (or faggotting) and tends to result in a layered structure even in objects consisting of fairly homogeneous low carbon iron. It is an obvious way of combining pieces of iron and steel so as to produce a structure where the carbon of the steel was fairly evenly dispersed throughout, especially after prolonged subsequent heating to more completely disperse the carbon. In some cases the mixed properties (of toughness) hardness and flexibility of a multi-decker sandwich or laminated structure, combining a higher carbon steel with wrought iron, may have been preferred to those of a more homogeneous medium-carbon steel.

Piling was used for the production of steel for a Japanese sword blade during the medieval and post-medieval periods. (Chikashige 1936). Sometimes the metal is said to have been folded and forged out as many as twenty times, thus producing about one million layers of steel which if skilfully done would have resulted in a nearly homogeneous structure (Gilmour 1975, 90). The results of the present work show that composite rods used to make the decorative bands of pattern-welded swords most commonly consist of between six and eight bands of alternating composition made by welding together and piling two dissimilar pieces of iron, one usually (similar to modern ultra-mild steel) containing a small amount of carbon and the other often with phosphorus content of between 0.4 and 0.8% (see Chapter 7).

5.13 Oxidation during welding

The main problem encountered during the welding together of pieces of iron or, iron and steel would always have been the tendency of the surface of the iron to oxidize at welding temperatures. This results in the formation of a layer of ferrous oxide (hammer-scale) at the surface of the hot metal. The effect of this layer of ferrous oxide can be lessened by the use of a flux which will reduce the free running temperature of the oxide by the formation of a slag which will flow away during welding, allowing the two iron surfaces to fuse together when hammered. The presence of a solid oxide film will prevent fusion causing serious weakness and even partial welding failures are clearly very undesirable.

The results of this study have shown that the inclusion of some slag along the weld seams of archaeological objects must have been very difficult to avoid. This is usually visible in section as small inclusions of the pale grey ferrous oxide (FeO), wüstite, in a darker grey matrix of fayalite ($FeO.SiO_2$) or a similar glassy constituent. These inclusions are noticably different to entrapped inclusions of smelting slag which usually appears to contain little wustite and, therefore, usually appear as a rather featureless dark grey colour upon etching. The visible occurance of wustite in lines of entrapped slag 'spots' in a transverse section across an iron object is usually a clear indication of the position of a weld. These inclusions can be very small and difficult to see and along very high quality welds can be virtually undetectable. By looking for the different types of inclusion, slag created during smithing (smithing slag) can often be differentiated from slag created during smelting (smelting slag).

Fine sand seems the most likely fluxing medium to have been used on the surfaces to be welded and this may account for the mixture of wustite and fayalite or glassy constituent observed in the slag inclusions at some weld seams.

Several of the analyses reported here (for instance Chapter 6.25 and 6.42) show a narrow but pronounced grey line of pearlite superimposed on the line of slag inclusions along a weld seam. This may suggest that finely ground charcoal, either as powder or a paste was also used to help maintain reducing conditions at the weld.

In some of the examples reported below voids had been left near the centres of the objects during the welding together of several components and where this had occured the void had been filled with smithing slag. Fig 58/9 shows the surviving remnants of a large inclusion of entrapped smithing slag at the centre of the Dorset scramasax (6.45). Dendrites of paler wustite can be seen against a darker grey background probably of fayalite, with a darker grey glassy constituent present. The dendritic pattern shows that the slag was liquid during welding. This can be compared with Fig 59/c which shows a larger, rather featureless dark grey, entrapped inclusion of smelting slag within the ferritic metal of the back part of the Hampton scramasax (6.46). Paler grey wustite was observed in a few cases in some larger inclusions of smelting slag but proportionally was always a small constituent/proportionally. In most cases there was a fairly clear and obvious difference in appearance between the two types of slag which together with the distribution of the inclusions gave a good indication of the presence of a weld seam which otherwise wasn't very clear. Sometimes forging may leave inclusions of smelting slag in a piece of iron distributed in such a way as to give a misleading suggestion of a weld.

Oxidation must have been a particular problem both with the welding of steel components into an artefact, and the forging out of a single piece of steel. Any oxidation at the surface would result in decarburisation and extensive decarburisation would seriously impair the properties of the steel. Of the examples reported here where steel pieces had been used there was relatively little evidence of decarburisation during forging and welding which shows that considerable care was taken to avoid this happening.

5.14 Minor element enrichment at weld seams

The occurence of 'white lines' along weld seams in iron and steel artifacts has been reported and discussed (Tylecote and Thomsen 1973). On a polished and etched section these appear as narrow, bands segregated along a weld seam. Analysis has shown these bands often to be enriched in arsenic and phosphorus. It would appear that, during welding, these elements become more concentrated in the remaining metal after some of the iron is lost by oxidation at the welding surface.

Chapter 6

Analyses of the edged weapons examined

6.1. S32: Sword from Reading Museum, 131:61

The surviving blade of a short sword which was broken just below the hilt. Its distinctive leaf-shaped blade is very similar in shape and size (its length being 38.6 cm and its width 3.7 cm) to leaf-shaped sword blades of the late Bronze Age. The condition of the blade was characteristic of river finds of iron that have been immersed and buried in sediments for a long time (possibly the River Thames in this case). Parts of the blade survived with only a little surface pitting whilst other parts, particularly in the centre, had been corroded almost right through and the corrosion appeared to have spread slowly outwards from focal points attacking different parts within the blade selectively so as to reveal what appeared to be a distinctly layered structure to the blade. There appears to be no particular reason to doubt that this blade is anything other than an early Iron Age copy of a late Bronze Age form of sword. Transitional Bronze Age/Iron Age objects, forged from bloomery metal so as to look like traditional forms previously only made from cast bronze, are occasionaly found (see also 6.48).

X-radiographic Examination

A radiograph of the sword showed little internal structure to the blade and therefore it has not been reproduced here.

Metallographic Examination

A wedge-shaped transverse section was cut from the central, wider, part of the blade (Fig 10). Unetched, the areas of the section nearer the surface of the blade gave a striated appearance caused by many broken lines of slag filaments and spots running parallel to the surface on either side. Fairly extensive corrosion had taken place around some of the larger filaments. The slag was mostly two phase, light and dark in appearance (?wustite and fayalite). The central area of the section was fairly slag-free with only a few small flattened inclusions present.

When etched with nital, three fairly clear zones were visible although the divisions between these zones were rather blurred. (Fig 14a). Most of the lower half of the section was occupied by zone (a) which consisted of very large grained ferrite with much two phase slag distributed as parallel broken lines along the length of the section. This banded or striated appearance is suggestive that piece (a) was piled as well as extensively forged before the final assembly of the blade. A little pearlite occurs in places along the slag lines and also near the junction with area (b) where it is probably a result of carbon diffusion from (b) to (a) during the final forging of the blade.

Part (c) was very similar to (a) although the parallel lines in (c) were a little less marked in appearance. It also consisted mainly of very large grained ferrite with lines of slag with a little pearlite present near the weld boundary with (b), again probably the result of carbon diffusion from (b) to (a) during final forging of the blade. Slightly more carbide was present along some of the slag lines within area (c) than was the case with (a) but the carbon content was still very low, hardly more than 0.05%. The outer parts of the blade (a) and (c) represent strips of well forged, possibly piled wrought iron of a high slag content.

The central area (b) however, was fairly slag free and consisted of a fairly even distribution of pearlite and with a low carbon content of about 01%. The ferrite was fairly large grained with a fairly marked tendency towards a non-equiaxial Widmanstatten type of distribution. The contrast between the parts suggests that area (b) was a separate and differently prepared core piece of very low carbon steel that was sandwiched between the outer pieces (a) and (c), the whole assembly then forge welded together.

The three main parts of the blade, identified as (a), (b) and (c) in the section, gave hardness values of 112, 125, and 129 HV respectively (Fig 14c).

The more markedly ferritic areas inside the boundaries of (b) with (a) particularly near the cutting edge where very little pearlite remained, show that considerable decarburisation must have taken place before or during the final assembly of the three separate parts of the blade. Some carbon diffusion appears to have taken place across the weld boundaries between (a) (c) and (b) after they were welded together, probably during the final forging of the blade. This suggests that the final forging was fairly prolonged which would tend to be confirmed by the large grain size of part (b). This large grain size is the probable result of grain growth within the austenitic temperature range which must have occured at about 875°C or above, at or above the upper criticial point for a 0.1% carbon steel. The very large grain size of the ferrite with parts (a) and (c) probably represents austensite grain growth before the final assembly of the blade, therefore the temperature of the final forging is unlikely to have risen much more than 925°C - approximately the temperature that the ferrite of these areas would recrystallize as austenite. This means that the probable final forging temperature for this blade was between about 875°C and 925°C. EPMA analysis showed all parts of the blade to be low in phosphorus (Fig 14b).

6.2 S27: Sword, from Thames at Little Wittenham; Reading Museum, 106.61/1

The surviving fragment from the central part of a sword blade. It was found in the Thames at Little Wittenham, Berkshire, its condition being fairly typical of river finds. The ends were both corroded right away so that it was impossible to say whether the breaks were the result of corrosion or that the blade was already broken beforehand. The metal survival towards the middle of the fragment was quite good although here, as was especially noticeable towards the ends, heavy differential corrosion etching had produced a very pronounced wavy wood-grain effect. Not much in the way of corrosion products could be seen which may indicate that this fragment has been electrolytically cleaned since its discovery, a process which would have highlighted the corrosion etching effects. The blade had a convex profile but a lack of distinguishing characteristics make even an approximate date difficult to assign; ? later Iron Age.

X-radiographic Examination

X-radiography (Fig 15a) clearly showed the wavy wood-grain effect already visible.

Kilovoltage	125
Milliampage	5
Exposure time	60 seconds
Film	Kodak Industrex CX prescreened roll film

Metallographic Examination

A wedge-shaped transverse section extending approximately half way across the blade was taken from where the metal appeared to survive best. Unetched, a very variable slag content was visible across the section mostly as two-phase flattened ribbons and spots.

When etched it became clear (Fig 15c) that a number of different components were present in the blade. These showed up as different areas of metal with contrasting carbon and slag contents.

The different areas were irregular in size and shape and whilst within each area the slag ribbons were mostly parallel to one another, the direction of these varied from area to area. Each area was either outlined by a discontinuous line of slag spots and ribbons or was clear from the change in orientation.

An interpretative view of this structure is given in Fig 15c. The grey areas represent pearlitic zones of variable carbon content, mostly 0.1-0.3%. These mostly consisted of fine grained ferrite and poorly formed pearlite although some patches in area (a) exhibited a large grained spiky Widmanstätten formation probably a result of localised overheating during forging. The predominantly lamellar form of the pearlite is probably indicative of fairly slow air cooling of the blade after the final forging.

Much of area (b) showed a large grain ferrite structure with an even distribution of a short rod-like formation, probably of iron nitride or carbide.

The hardness readings taken and the results for the main different parts of the section were as follows: (a) ferrite and pearlite, approx. 0.1-0.3% carbon - 191 HV: (b) ferrite and a little pearlite - 168 HV; (c) ferrite and pearlite, approx. 0.2 - 0.3% carbon - 178 HV; (d) ferrite - 120 HV; part (e), ferrite with some pearlite, approx. 0.1-0.2% carbon - 149HV.

It appears that this blade was made by welding together a series of wrought iron and low carbon steel strips, possibly as many as 14 in all, which were interleaved and overlapped and forged out along the length of the blade. A three dimensional reconstruction of this is shown in Fig 15d. The wavy wood grain effect has resulted from differential corrosion along the slag of weld lines between the components, and along the slag ribbons within each of these pieces. It would appear likely that this blade was aircooled after final forging.

This bundle construction is likely to represent a forerunner or prototype of the more formal pattern-welded structures of which many examples are given in the following reports. The same proto-pattern-welded structure has been identified on the Peterborough late Iron Age sword (Figs 71 - 73) and it seems very likely that this Little Wittenham sword blade is of the same proto pattern-welded type.

6.3 S29: Sword from the Thames, Reading Museum, 141.60 (T.C.B).

The lower surviving half of a sword blade found in the river Thames at Little Wittenham, Berkshire. It was bent sharply, at right angles, roughly in the middle and although the surface appeared to be fairly heavily pitted in places the corrosion effects were mostly fairly even and the metallic core of the blade appeared to be quite well preserved. The blade had a convex profile but no other distinguishing characteristics survived to indicate its date. The sharp bend in the blade was probably the result of more recent contact with a heavy object (? dredger) rather than having been bent nearer the time of deposition in the river. Date : - ? Late Iron Age.

X-radiographic and Metallographic examination

Radiography of the sword showed very little detail except faint traces of a straight grain effect within the blade.

A complete transverse section was cut from just inside the broken end of the blade. When viewed unetched, a rather variable slag content could be seen. It was fairly low and evenly spread as spots and flattened ribbons over the centre of the blade whereas towards the cutting edges the proportion of slag increased a little and tended to be aligned in flow patterns suggesting folds within the metal of the cutting edges. Some much larger, partially corroded slag inclusions suggested weld lines between the cutting edge and core zones of the blade section.

When etched with nital a composite structure was revealed. This consisted of two edge pieces and a core piece, itself probably made up from 3 different parts (Fig 16b).

The cutting edge pieces (a) and (b) showed up fairly well outlined partly by slag inclusions and partly by the grey pearlitic areas which in both cases appeared to be folded around a paler central area which consisted mainly of ferrite with a small proportion of pearlite near the centre, with a carbon content of less than 0.1%. The proportion of pearlite to ferrite gradually increased on either side to give a maximum carbon content of 0.3% in the darker grey areas. The ferrite of these edge zones was of varied grain size - with some large grained areas showing a Widmanstatten columnar distribution.

The main core part (c) of the section consisted almost entirely of ferrite although some carbon had diffused inwards from the edge parts (a) and (b). The core area (c) itself consisted of three parts with the smaller areas (d) and (e) being fairly clearly visible. Areas (d) and (e) appeared to have originally consisted of ferrite although there had clearly been extensive carbon diffusion inwards from across the junctions with the edge parts (a) and (b).

The weld junctions between the different parts of the blade were mostly fairly clear. These welds were mainly marked by lines of slag inclusions. The folded nature of the edge pieces (a) and (c) is also shown by white lines running parallel to the slag inclusions.

This may be the result of forging and piling a strip of wrought iron which was finally folded along its length. Both the edge pieces (a) and (b) appeared to have a steel jacket which showed up as a grey pearlitic zone, gradually becoming paler towards the centre, the carbon contents varying from about 0.3% at the outside of about 0.1% at the centre. This seems clear evidence that these cutting edge pieces were carburised after forging, piling and folding.

The weld junction between (a) and (b) was also partly marked by a white line. The white line visible within part (d) and slag lines visible in (d) and (e) may indicate that a piling technique was used in the preparation of these pieces.

The main central core area (c) did not contain readily discernible slag lines - it had a generally low slag content and appears therefore to have been a piece of well prepared wrought iron. A hardness value of 329 HV was obtained for the area of the cutting edge part (a) nearest the tip where the carbon content was higher and a value of 214 HV near the centre where the carbon content was lower. The wrought iron of the central core pieces (c) and (d) gave hardness values of 158 and 141 HV respectively, whereas the higher carbon part of the other cutting edge, part (b) gave a hardness value of 239 HV (Fig 16a).

A hardness value of 329 HV was obtained for the area of the cutting edge part (a) nearest the tip where the carbon content was higher and a value of 214 HV near the centre where the carbon content was lower. The wrought iron of the central core pieces (c) and (d) gave hardness values of 158 and 141 HV respectively, whereas the higher carbon part of the other cutting edge, part (b) gave a hardness value of 239 HV.

6.4 S39: Sword from Funtham's Lane, Whittlesey (T.L. 238968); Peterborough Museum, 28:65.

This sword was found in 1965 in a claypit owned by the Central Brick Company. It lay 8-10 ft below modern ground level, under material containing 2nd-4th century pottery. The sword is complete and is very well preserved, probably as a result of having been buried in waterlogged conditions low down near the clay-land subsoil. It is 0.72 m long with an unusually thin blade with a flat profile and maximum thickness 3.0 cm. A well preserved bone grip survived in place on the tang and traces of a possible fabric scabbard lining were still adhering to the blade which measures 4.7 cm at its widest.

A late 1st or early 2nd century date for the sword may be indicated by the material found above it and it is probably of the *spatha* type, (Howe 1978, 21-23) its length comparing more closely with the two *spathae* from Canterbury(Webster, 1982, 185), rather than the shorter *gladius*. The sword may have belonged to a Roman soldier, possibly attached to the fort at Longthorpe which lay about five miles from the findspot.

Metallographic examination

A radiograph of the sword showed very little except slight hints of a straight wood grain effect visible in some areas. The image of the radiograph was unusually clear because the blade had been only slightly corroded but no weld lines were visible.

A wedge shaped section was cut from the blade approximately two-thirds of the way up from the tip. The sectioning was done at right angles to the cutting edge and extended to just over half way across the blade.

Before etching a little of slag was visible in the form both of small spots and parallel flattened ribbon-like formations. None of these could easily be interpreted as a weld line.

After etching a relatively carbon rich darker zone (b) of pearlite and ferrite could be seen running along the centre of the section (Fig 17b). The carbon content of this zone varied between approximately 0.3% nearer the cutting edge and 0.2% nearer the centre of the blade. The carbon content of the paler zones (a) and (c) on either side varied between almost pure ferrite and about 0.2%.

Discontinuous lines of slag ribbons were visible on either side of the darker central zone. These appear to mark the positions of welds between the outer and central portions of the blade which have otherwise become very blurred by the extensive diffusion of carbon across the welds from the higher to the lower carbon zones. The paler outer zones contained more parallel slag filaments than the darker, carbon rich central area. The outer zones also exhibited some darker banding within them where there was no indication of further weld lines.

The three main zones (a), (b), and (c) gave microhardness values of 149, 185, and 193 HV respectively at three points across the centre of the section (Fig 17a). Part (a) here showed as ferrite with some pearlite and (b) and (c) as ferrite with rather more pearlite.

It appears probable that the blade was constructed of three main parts; a central fairly low carbon steel strip welded between two very low carbon wrought iron strips to form a sandwich. The central steel strip may have begun as a well-forged strip of wrought iron carburised for long enough (several hours) to give a fairly even carbon distribution throughout; or alternatively, it may have been formed from a steel portion of a bloom well forged to give an even carbon and low slag content. It is not clear from the observed section which was the case. The slightly streaky and banded nature of the outer portions are probably the result of the fairly extensive forging of the wrought iron of these strips which may have originally contained localised patches of low carbon pearlite. Without further treatment this blade would have been typical of a type 1 (iron-steel-iron sandwich) blade construction (Fig 66).

In this case however, the subsequent diffusion of carbon from the central to the outer parts of the blade has been so great that the original structure has almost disappeared to give the appearance of a generally more homogeneous low carbon steel which is presumably what the smith was trying to achieve. The carbon of both the central and outer zones of the blade is distributed as fairly even fine-grained pearlite whose structure is mainly irresolvable, although a somewhat spheroidal or granular form is just visible in some areas - mainly those of a lower carbon content. After the sandwich type of assembly and subsequent forging, the blade must have been held for a fairly long time (probably several hours) at about 750°C in the part of a forge where reducing conditions predominated. This is indicated by the lack of surface decarburisation of the blade.

6.5 S17: Sword, from Sarre; Maidstone Museum, K.A.S.830.

A sword more-or-less complete, except for the tip, and still within the encrusted and barely recognisable remains of its scabbard. It measured 82.6 cm in length by 5.3 cm in width. It was in very poor condition and looked to be mostly mineralised although the fact that it held together suggested that at least a network of metal survived in the core of the weapon. It was excavated in 1853 from grave 34 of the Anglo-Saxon cemetery at Sarre in Kent (Brent 1864) but it is not known whether the break occurred in antiquity or whether the missing tip fragment was lost subsequently. It could be seen from the break that the profile of the blade approximated to a flattened convex shape but it was so corroded that only a very rough estimate of the original thickness could be made. This would appear to have been about 0.5 cm. Date: approximately 6th-7th century.

X-radiographic examination

Radiography showed the blade to have a pattern-welded core (Fig 18a). The detail was not very clear, probably due to the present of the encrusted and mineralised remains of the scabbard. The general form of the pattern, however, was visible as a herringbone design running uninterrupted from the hilt down the surviving length of the blade. The design was formed by three adjacent twisted composite rods welded side by side. It was very difficult from the radiograph to say whether or not a separate set of three adjacent composite rods was present on either side of the blade and no sign of any separate central core piece could be seen. The herringbone pattern shows up as being criss-crossed on the radiograph which could either have resulted from composite rods with opposing (right and left hand) twists having been welded behind one another, or by a single layer of rods whose twists would have pointed in the opposite directions on either side of the blade. No structural detail could be seen along the cutting edges of the weapon. Fig 18f shows the pattern as it may have appeared on the surface of the weapon.

Exposure and film details

Kilovoltage	125	Exposure time	60 seconds
Milliampage	5	Film	Kodak pre screened roll film Industrex CX

Metallographic Examination

A wedge-shaped section was cut from a point 8.0 cm from the broken end of the blade (Fig 10). Before etching little slag was visible over most of the section. However, flattened slag inclusions of varying size ran horizontally across the section (parallel to the main axis) suggesting that both the core area and the cutting edge might consist of three horizontal layers.

Etching with nital revealed the structure of the section (Fig 18c). The cutting edge appeared to consist of three main horizontal bands, (a) - (c) in Fig 18b. A fourth piece may have been welded on to a piece (a) to form the outside of the cutting edge but the evidence for this was too inconclusive to be sure.

Part (a) varied a great deal in appearance from end to end. Near the tip of the cutting edge it consisted of mixed pale etched coarse martensite and dark etched irresolvable nodular troostite (radial pearlite) at the tip of the cutting edge (Fig 18e) with increasing amounts of a Widmanstatten-like distribution of ferrite with grey irresolvable pearlite towards the weld with part (e). Some decarburisation from forging was evident along the upper surface of part (a).

Some small slag inclusions indicated the weld line between strips (a) and (b) of the cutting edge. Extensive carbon diffusion appears to have taken place across this weld line into part (b) which otherwise consisted mainly of fairly large grained ferrite with a Widmanstatten-like distribution of ferrite and unresolved pearlite. Part (c) also consisted mainly of fairly large grained ferrite with a little Widmanstatten-like ferrite and unresolved pearlite but was separated from (b) by a weld marked by a clear line of slag inclusions.

The different microstructures observed in part (a) of the cutting edge was clearly the result of the quenching of the blade after final forging. The progressive nature of the quenching effect was very noticeable; the martensite forming near the tip of the cutting edge which cooled first and fastest, and the progressive change in the microstructure, towards the weld junction with the core of the weapon, to a mixture of Widmanstatten-like ferrite and unresolved pearlite. The inner part of (a) would have cooled slowest and this change in the microstructure probably reflects the differences in the cooling rate between the inner and outer ends of strip (a) rather than any appreciable difference in its carbon content. The quenched nature of the microconstituents made a visual estimate of carbon content difficult although at the inner end a rough estimate of about 0.3-0.4% carbon may be made.

Apart from the effects of diffusion from (a) the carbon contents of parts (b) and (c) were less than 0.1% so that the cutting edge appears to have been made by welding together three strips, one of fairly low carbon steel, and the other two of little more than wrought iron. The cutting edge must then have been welded to the already assembled core part of the blade. This weld junction was mostly not very clear, being marked along most of its length only by a faint line of slag spots. A few large slag inclusions did occur within the core part of the blade, at the weld junction between three or four components.

The core part of the blade consisted of six composite twisted pieces welded onto a central core piece, (d) on Fig 18b. Four composite pieces, were represented on the section (e) - (h)although two parts (g) and (h) were not quite complete.

The central core part (d) showed a fairly even Widmanstatten distribution of ferrite and unresolved pearlite of medium grain size and with a low slag content (Fig 18d). The structure appeared very similar to the inner or core side of the cutting edge piece (a) and the two parts may have had similar carbon contents, that is, very approximately 0.3%. The central core strip (d), therefore, appeared to be a similar low carbon steel to piece (a).

The folded appearance of the twisted composite rods (e) - (h) can be seen in section (Fig 18c). They were all composed similarly of alternating bands of very large grained ferrite and medium grain sized ferrite and unresolved pearlite in a spiky-looking Widmanstatten formation. The pearlitic bands looked very similar to the central core part (d) and thus appear to have been a low carbon steel of a similar carbon content. In (d) and the pearlitic parts of (e) - (h) a few small grained patches occurred where the carbon content appeared to be somewhat lower than the rest. The ferrite bands of (e) - (h) contained rather more slag and a solitary pair of Neumann bands were also visible.

A pair of hardness readings was taken each for the low carbon edge parts (b) and (c) and two pairs of reading taken for the steel edge part (a), one pair near the inner weld and one pair near the tip of the cutting edge. The results of these were as follows: (b) 164 and 177HV; (c) 158 and 182 HV; (a) 258 and 179 HV, 564 and 564 HV. One pair of hardness readings were taken for the central steel core piece (d) which gave the values 204 and 236 HV. For the pattern-welded parts (e) and (f) two pairs of hardness readings were taken in each case, firstly for one of the very large grained ferrite bands, and secondly, for one of the grey pearlitic bands. The values obtained were : (e) 246 and 256 HV, 212 and 217 HV; (f) 232 and 256 HV; 205 and 207 HV (Fig 18b).

It would appear that the cutting edge of this sword was made from three pieces, a low-medium carbon steel piece and two pieces of low carbon iron An iron-steel-iron sandwich may have been intended but, if so, the three edge pieces have been welded together in the wrong order with one of the wrought iron pieces in the middle. The central core and pearlitic bands of the pattern-welded parts were of a similar low-medium carbon steel to the edge part (a). The relatively higher hardness values for the paler ferrite or iron bands of the pattern-welded peices probably indicate that a high phosphorous iron was used for these. The blade was quenched and slightly imperfect results obtained, probably indicating that the carbon content of the steel was too low for the particular querich. The blade appears to have been subjected to some final cold hammering.

6.6 S49: Sword, ? from Bifrons; Maidstone Museum, KAS 620. 1954. 20

A very corroded but more-or-less complete sword blade apart from the end of the tang which was missing. It was one of a group of objects which formed the Tomlinson bequest to the Kent Archaeological Society and which, according to the museum index may have come from the Anglo-Saxon cemetery at Bifrons. The length of the blade was 89.0 cm with a maximum surviving blade of 5.3 cm but it was too corroded to gauge the original thickness as most of the surface had flaked away. Date : approximately 5th-7th century.

X-radiographic examination

A radiograph of the blade showed a fairly clear straight grain pattern running down the length of the blade (Fig 19a.) Superimposed on this but not clearly visible were a series of short parallel diagonal lines giving both a herringbone and criss-cross effect in a few places. There was no grain pattern visible along the cutting edges. The double image of the radiograph was difficult to interpret but it would appear that the central part of the blade consisted of two quadruple sets of composite rods welded back-to-back, possibly with a plain central core piece in between. Each quadruple set appeared to consist of alternating straight and twisted composite twisted rods welded side by side. The diagramatic reconstruction of this (Fig 19b) shows the two twisted rods on either side as having opposite directions of spiral (right and left hand threads) although it is equally possible that the two twisted rods on each side may have been of the same spiral - it was not clear which alternative was more likely from the radiograph. The x-ray exposure and film details were the same as for the previous sword, 6.5.; S17.

Metallographic examination

A wedge-shaped section extending approximately half way across the width was cut from one side of the blade about 13.0 cm down from the hilt. Unetched, a fairly low overall slag content was visible across the section.

When etched with nital, the remains of six different parts, (a) - (f) welded together could be seen in the section although they do not show up very well on Fig 19c.

The cutting edge consisted of two halves (a) and (b) both of fairly homogeneous small grained ferrite and pearlite with a carbon content of about 0.2%. Some large grain patches ferrite and lamellar pearlite showed a Widmanstatten type of formation probably the result of localised overheating during forging.

The surviving parts of four composite pieces, (c) - (f) were also visible (Figs 19b and 19c). These would have been of approximately equal size but for the effects of corrosion. There was no separate central core piece, the composite pieces have been welded back-to-back. Piece (c) consisted mainly of large grained ferrite with some carbide visible at the grain boundaries. Piece (f) had nearly all corroded away with just a small corner surviving at the central junction with (c) and (e). It appeared to be ferrite, very similar to piece (c).

Parts (d) and (e) both showed an interleaved,-banded structure with pale bands consisting of very large grained ferrite, and darker bands of small-medium grained ferrite with some pearlite, the carbon content of these darker bands being about 0.1% or less. The very large grained ferrite of part (e) also included short rod-like 'needles' probably of nitride or carbide inclusions.

Hardness values of 158 and 143 HV were obtained for the edge parts (a) and (b) near the tip of the cutting edge. The mainly ferritic pattern-welded part (c), gave a hardness value of 118HV. One of the pale very large grain ferrite bands of the opposite pattern-welded part (d) gave a hardness of 178 HV while one of the adjacent bands, of ferrite with some pearlite, gave a hardness of 159 HV (Fig 19b). The greater hardness of the very large grained ferrite band probably indicates a higher phosphorus content here which probably also explains the very much larger grain size of the ferrite in the pale bands of the pattern-welded parts (d) and (e).

The core of the blade consisted, in all, of eight pieces and the individual pieces appear to have consisted either of a plain wrought iron, or of a mixture of a harder, high phosphorus wrought iron and very low carbon steel. After final welding and forging the blade appears to have been air cooled.

6.7 S51: Sword from Sarre; Maidstone Museum, KAS 820

A sword blade missing the tip end of the blade and with the tang in two pieces. It was excavated from grave 64 of the Anglo-Saxon cemetery at Sarre in Kent in 1863 (Brent 1864, 168). The tip was apparently already broken off when excavated but it is not clear whether it was already missing then. This may therefore have been a sword already broken when buried. It was very corroded and encrusted with flaky rust which included the remains of a scabbard. Its length was 75.0 cm with a maximum width of 5.8 cm and its date c 6th century.

X-radiographic and Metallographic examination

Radiography showed very little structure to the blade except some slight hints of a straight grained effect in places.

A wedge-shaped section extending about half way across the width was cut from one side of the blade, 22.0 cm down from the hilt. Unetched; the section showed a fairly low slag content of mainly small inclusions of two phase, medium and darker grey constituents (? fayalite and a glass).

When etched with nital a horizontal laminated or banded structure became visible across the section (Fig 20b). The paler bands, (a), (c), and (e) , consisted of small-medium equiaxial grains of pearlite and ferrite. The pearlite was mainly lamellar but partially granular in places and the overall carbon content appeared to vary between about 0.1 and 0.2%. The narrower darker bands (b) and (d) consisted of fine equiaxial grained lamellar pearlite and ferrite with a carbon content of about 0.3%. Within the paler bands (a), (c) and (e) additional grey and white streaks of segregated pearlite and ferrite were also visible.

Hardness readings taken across the section gave fairly similar values for the different bands and these mostly varied within the range 156-174 HV. An additional reading for band (a) gave a value of 189 HV Fig 20a.

The banded structure suggests that the blade was made from five separate parts, (a)-(e), welded together and forged out to give the 'triple decker' sandwich effect visible in section when etched. They would appear to have been very skilfully welded together, leaving little trace except the banded structure, before the blade was forged out to its final shape. The subsidiary streaks visible in places may indicate the paler bands were piled or folded and forged out before the final assembly of the blade although segregation caused by a variable phosphorus content, plus forging, may also have caused this effect. No additional heat treatments were used.

6.8 S52: Sword from Sarre; Maidstone Museum, K.A.S. 823

A mostly complete sword blade in five fragments but with parts of the edge missing. It was in very poor condition, corroded right through in places and was covered with a thick flaky incrustation which included the remains of a scabbard. It was excavated in 1864 from grave 113 of the Anglo-Saxon Cemetery at Sarre, Kent (Brent 1865). Its length was 76.6 cm with a maximum width of 6.0 cm and its date c.6th century.

X-radiographic examination

A radiograph of the sword showed it to be pattern-welded. The detail of this was clearer towards the hilt (Fig 21a) and from this it was quite clear that the surface on either side of the central part of the blade consisted of separate sets of four partially twisted composite rods welded side-by-side but it was not as clear whether or not these two quadruple sets of rods were welded back-to-back without any intermediate central plain strip although no evidence of one could be seen. The composite strips showed alternating straight and diagonal graining and the adjacent diagonals were in opposite directions so that a chevron pattern would have showed on the surface. The pattern appeared to alternate in panels down the blade (in a similar way to the Acklam sword - Fig 68) , terminating in a straight grained area at the tip. The only exception being the panel next to the hilt on one side where the rods at this point were alternately straight and twisted whereas on the opposite side this upper panel showed a straight grained pattern only. The cutting edges showed some slight traces of straight graining in places.

Exposure and film details

Kilovoltage	125	Exposure time 55 seconds
Milliampage	5	Film Kodak Industrex CX pre-screened roll film

Metallographic examination

A wedge-shaped section extending to just over half way across the width was cut from one side of the blade (Fig 10). When viewed unetched a mostly fairly low slag content could be seen across the section. Some large ribbon-like inclusions of a two-phase slag consisting of a pale grey blobby constituent, probably wustite, visible against a darker grey background (? a glassy constituent) and these together with some smaller inclusions of a similar slag clearly marked the positions of welds between some of the main parts of the blades. Over the rest of the section the slag inclusions were mostly small ribbon-like inclusions either of two phases - medium grey against a darker background, probably fayalite, and a glassy constituent of one darker grey phase (? fayalite).

When etched with nital, the structure of the section became quite clear (Fig 21c). Eight separate components (a)- (h) on Fig 21b were represented on the section. The part of the blade, selected by radiography for sectioning was one which had shown a criss-cross pattern. The banded structure of these can be seen in section. The pale bands were of very large grained ferrite whereas the darker bands consisted of fairly small grained rather spiky (Widmanstatten) looking ferrite and pearlite which was poorly resolved although partially lamellar . The carbon content of these darker bands appeared low, varying between about 0.1 and 0.2% and less in some areas. Part (g), however consisted mainly of medium-large grained ferrite with only a little carbide visible. The carbon content here was very low and the piece appeared to be of wrought iron only.

A hardness value of 149 HV was obtained for edge part (a) and rather higher figures, 185 and 187 HV obtained for the other edge part (b), although both parts showed as a similar very large grain ferrite. Hardness values of 159 and 162 HV were obtained from within the grey or low carbon pearlite bands of pattern-welded parts (c) and (d) respectively. Hardnesses of 189 and 174 HV were obtained from the pale or very large grained ferrite of pattern-welded parts (d) and (e), probably indicating a rather higher phosphorus content for these bands.

The surviving parts of the cutting edge were of wrought iron only whereas the core pieces varied between wrought iron and a low carbon steel . The blade was probably air cooled after final forging and there was no sign of any further heat treatment. Assuming symmetry across the blade, both cutting edges will have consisted of two similar halves and the core of a pattern-welded arrangement of two quadruple sets of twisted composite rods welded back-to-back.

6.9 S53: Sword, from Sarre; Maidstone Museum, KAS 825

The fragmentary remains of a sword which is now in five pieces with the end of the tang, tip and some parts of the blade missing. It was excavated in 1864 from grave 250 of the Anglo-Saxon cemetery at Sarre in Kent (Brent 1865, 317). It was in a very poor condition, the blade being mainly mineralised and covered with a thick incrustation which included the remains of a scabbard. It could be seen from the breaks that the blade was a flattish convex shape in profile. It was 73.5 cm long by approximately 5.4 cm in width, and c 6th century in date.

X-radiographic examination

X-radiography showed the blade to have a fairly narrow pattern-welded central zone(Fig 22a). This was very similar to that visible on the radiograph of 6.23 except that here the image showed a clear chevron pattern running down the blade whereas in the case of 6.23 a criss-cross pattern showed up in places. No trace of straight graining was visible along either the central area or the cutting edges of the blade. It is fairly clear from the radiograph that two separate but very similar chevron patterns were superimposed to give the image and these have resulted from two pairs of composite twisted rods having been welded together. The direction of twist or spiral of the rods forming each pair ran in opposite directions. There was no indication from the radiograph of any separate central core piece so at this stage it seemed most likely that the two pairs of twisted composite rods were welded together back-to-back. Fig 22d shows how the pattern may have appeared on the surface of the blade. The exposure and film details were the same as for the previous sword 6.6, S52.

Metallographic Examination

A wedge-shaped section extending to about half way across the width was cut from one side of the blade 14.0 cm down from the hilt. Unetched, the most obvious feature was a very large two-phase pale and darker grey slag inclusion (? wustite and a glassy constituent) which ran right across the width of the section marking the position of the weld between the core and the cutting edge on this side of the sword. The slag content across the section was quite low with some small two phase darker grey (? fayalite and a glassy constituent) ribbon-like inclusions scattered patchily across it and also some broken lines of small two phase, pale and darker grey inclusions appearing to mark the positions of welds (horizontally) dividing both the cutting edge and core areas into two halves.

When etched with nital the structure became clearer, showing the extensive corrosion effects even in this part of the blade where the metal survives best(Fig 21c) Two halves of the cutting edge and two composite pieces welded back-to-back can be seen diagrammatically in Fig 22b and these are marked (a), (b), and (c), (d) respectively.

The two edge parts, although little of part (b) survives, both consisted of very large grain ferrite with patches of short rod-like carbide or nitride needles. There were also irregular patches where a little carbide was present and here the grain size of the ferrite was much smaller.

The composite pieces (c) and (d) were very similar to one another, both showing a folded and banded appearance. The folded appearance is indicative of the twisted nature of these pieces. The pale bands consisted of very large grained ferrite whereas the darker bands were of medium grain sized ferrite with some lamellar pearlite indicating a low carbon content - mostly about 0.1% or less.

The edge parts (a) and (b) gave very similar hardness values of 143 and 144 HV respectively. The slighly pearlitic bands of the composite core parts (c) and (d) gave values of 153 and 159 HV whereas the pale very large grain bands of the same parts (c) and (d) gave hardness values of 217 and 210 HV respectively. The slightly higher values for the pearlitic bands over the edge parts is probably indicative of the low carbon content of the latter but the much higher values obtained for the very large grained ferrite band is probably indicative of a high phosphorus content for all the pale bands in the pattern-welded core of the blade.

It would seem from this that the cutting edge was made from two similar pieces of wrought iron and that the composite pieces of the core were of a laminated structure each consisting of alternate parts of high phosphorus wrought iron and very low carbon steel or just lightly carburised iron. After its final assembly and forging the blade was probably air cooled and not subjected to any further heat treatment. Fig 22d shows how the different elements of the blade were assembled.

6.10 S54: Sword from Sarre or Bifrons; Maidstone Museum, KAS 834

A sword in very poor condition in two main fragments, missing most of the tang as well as the tip and much of the cutting edge which was corroded away . The remains were covered in a flaky incrustation which included the remains of a scabbard. It was 78.8 cm long with an approximate maximum width of 6.0 cm. Its provenance is uncertain according to the museum records, but it probably came from the Anglo-Saxon cemetery either at Sarre or Bifrons, and is likely to be approximately of 6th century date.

X-radiographic Examination

A radiograph of the sword revealed a pattern-welded central zone running along the blade (Fig 23a). This was clearest near the hilt where a criss-cross grain effect showed up and this did not vary where it was visible along the radiograph. This appeared to represent a pair of twisted composite rods welded side by side with the twists running in opposite directions which would have given a chevron surface effect upon etching. The criss-cross pattern tended to overlap in places, suggesting that a second pair of twisted composite rods lay behind the first, forming the surface on the other side of the blade. Some traces of straight graining were visible in places, suggesting a separate central core piece. Some faint hints of straight graining were also visible along the cutting edges.

Exposure and film details

Kilovoltage	125	Exposure time	55 seconds
Milliampage	5	Film	Kodak Industrex CX pre-screened roll film

Metallographic Examination

A wedge-shaped section extending half way across the width was cut from the main blade fragment (Fig 10). Unetched, the section showed a variable content of slag inclusions. It was mostly low with patches of rather irregularly shaped, small single dark phase (?fayalite) inclusions, some linear scatters of fairly small mainly ribbon-like inclusions of two phase, pale and darker grey (?wustite and a glassy constituent) slag suggested the position of weld lines between the main parts of the blade.

When etched with nital, it became clear that four main parts were represented in this half of the blade and these are shown as (a) - (d) in Fig 23b. The cutting edge part (a) appeared to be of a single piece consisting of medium - large grained ferrite with a little pearlite visible in places. The carbon content appeared to be well under 0.1% so that this piece appears to be a wrought iron with a little carbon present. Some of the larger single darker grey phase inclusions of slag (?fayalite) in this part congregated along curved lines which indicated that this piece was probably folded and forged out before being welded to the core part of the blade.

The central core piece (c) shows up as being rather darker in its heavily etched state on the macrograph (Fig 23c) and the weld line between it and the cutting edge was marked by a broken line of two phase, pale and dark slag inclusions. It showed a fairly even distribution of ferrite and lamellar pearlite of mostly small - medium grain size, with a carbon content of about 0.1% although this tended to decrease towards the weld boundaries on each side presumably indicating some decarburisation during forging. The surface pieces (b) and (d) must represent two of the twisted pieces which gave the criss-cross pattern visible on the radiograph although not much survives in the section, corrosion having removed the rest. The weld lines between these parts and the central piece (c) were also quite clearly marked by a broken line of quite small two-phase, pale and dark grey slag inclusions. The pieces of (b) and (d) that survived consisted of large grained ferrite with a very little pearlite or grain boundary carbide present in places but no visible sign of any banded structure.

It would appear that the twisted or pattern-welded surface parts of the core of the blade consisted only of wrought iron, possibly piled and then twisted to give the effect visible on the radiograph. Those surface pieces were welded on to what appears to have been a fairly even very low carbon steel central core piece, itself barely more than wrought iron and the cutting edge was of a very similar composition. The blade appears to have been air cooled after its final forging and not subjected to any further heat treatments.

Three hardness readings were taken from the edge part (a) of the blade. These were taken along the central axis of the section at points nearer the tip of the cutting edge, roughly at the centre and nearer the inner weld and values of 164, 181 and 197 hV respectively were obtained for these points. The mostly ferrite core piece (c) gave a hardness value of 172 HV and the two pattern-welded surface parts (b) and (d) gave values of 165 and 162 HV (Fig 23b).

6.11 S55: Sword ? from Sarre or Bifrons, Maidstone Museum, KAS 836

A nearly complete sword blade missing the end of the tang, tip and parts of the cutting edge. It was in very poor condition, mainly mineralised and covered with flaky incrustation which included the remains of the scabbard. Its provenance is uncertain and according to museum records probably came from one of the Anglo-Saxon cemeteries, at either Sarre or Bifrons, in Kent. It is very similar in appearance and condition to other swords from Sarre which may favour Sarre as the findspot. In any case it is likely to have come from one of the Kentish Anglo-Saxon cemeteries and to be of approximately 6th century date. It measured 82.5 cm in length by, at most, 5.6 cm in width.

X-radiographic examination

Radiography showed up a criss-cross pattern running down the central part of the blade (Fig 24a). The criss-cross pattern indicates that the central part of the blade consisted of at least one set of three twisted rods welded side by side with adjacent twists in opposite directions, with the probability of a separate set of three composite rods behind the first. No evidence of straight graining, which might indicate a separate central core piece, could be seen along the central area, although traces of straight graining could be seen along the cutting edges. The criss-cross pattern appeared to be unchanged down the length of the blade.

Exposure and film details

Kilovoltage	125	Exposure time	55 seconds
Milliampage	5	Film	Kodak Industrex CX pre-screened roll film

Metallographic examination

A wedge-shaped section was cut 20 cm from the tip end of the blade. Unetched the slag content appeared to be fairly low. Some linear scatters of small two phase inclusions, pale and darker grey (? wustite and a glassy constituent) suggested the positions of welds between major components of the core part of the blade. A larger inclusion of similar slag marked the weld position between the core and the cutting edge. Across the rest of the section a fairly random distribution of small slag inclusions of either one or two phases, medium-darker grey (?fayalite and a glassy constituent), was visible.

After etching with nital it became clear (Fig 24c) that the core part consisted of twisted composite pieces (c)-(f) in Fig 24b, welded onto either side of a central core piece (b). To this core a cutting edge had been welded and this appeared to consist of a single piece, (a), although much of the cutting edge had been lost to corrosion and, therefore, one or more further parts could have been present. However, the most simple structure has been adopted in the reconstruction diagram (Fig 24d).

The structure of the cutting edge part (a) varied and near the tip it consisted of patches of martensite and the dark nodular constituent troostite (radial pearlite) in a matrix of acicular (Widmanstatten) looking ferrite and poorly formed pearlite. The proportion of martensite decreased away from the cutting edge. The structure represents a steel which has been imperfectly quenched and in this heat treated state the carbon content was difficult to estimate. In a normalised structure the equivalent proportion of pearlite would indicate a carbon content of about 0.5% but here it may be nearer 0.3-0.4%, still a medium carbon steel. The area near the weld line with the core piece (e) has become decarburised, presumably when the cutting edge was welded to the core.

The central core piece (b) consisted of ferrite and pearlite of rather variable grain size. Where the grain size was larger, a Widmanstatten formation was visible. Although this piece (b) shows up in Fig 24c as fairly dark after heavy etching, the carbon content appeared to be very low, probably about 0.1%. Slag content was low, mostly of small inclusions of one medium grey phase (? fayalite), although one inclusion was large and cracked.

The composite pieces (e) - (f) showed a banded appearance (Figs 24c) in which the pale bands were similar, consisting of very large grained ferrite. The darker bands were very similar in appearance and structure to the central core piece (b) although the carbon content was mostly lower - about 0.1% or less.

Three hardness readings were taken for the edge piece (a), the first in the martensitic area near the tip of the cutting edge, the second further in an area of fine pearlite, and the third in part (a), near the inner weld where both pearlite and ferrite occured. The respective values obtained were 581, and 211 HV. The low carbon core part (b) gave a hardness value of 181 HV. One of the pale very large grain ferrite bands in the composite pattern-welded part (c) gave a hardness of 206 HV whereas one of the grey, low carbon bands in the adjacent pattern-welded part (d) gave a hardness value of 164 HV (Fig 24b). The higher value for the pale ferrite band probably indicates a fairly high phosphorus content.

It would seem likely, by comparison with other blades which show a similar structure (for instance 6.5 and 6.19), that the edge piece (a) originally consisted of a sandwich with this steel piece between two iron pieces, now lost to corrosion. The whole of the core part of the weapon was little more than wrought iron consisting of two pairs of twisted composite rods welded to a central core. Each composite rod consisted of strips of low carbon iron and iron with a probable higher phosphorus content.

The blade was quenched, possibly in water, leaving an incompletely quenched structure, probably the result of the carbon content being too low for the speed of quenching. No additional treatment such as tempering appears to have taken place.

6.12 S56: Sword from Bifrons; Maidstone Museum, KAS 837

A sword blade in two fragments minus the tang and tip. It was in very poor condition, mostly mineralised and covered with a thick incrustation which included the remains of a scabbard. It was found c 1860 in grave 39 of the Anglo-Saxon cemetery at Bifrons in Kent (Maidstone Museum records). The two fragments together measured 70.4 cm in length with a maximum width of about 6cm although the true width is likely to have been rather less, allowing for the corroded incrustation. The break revealed the blade to have a flattish convex profile. Date: approximately 6th century.

X-radiographic examination

Radiography showed the blade to have a pattern-welded central area running down the blade (Fig 25a). An alternating herringbone and straight grained pattern was fairly clearly visible in places with no sign of any criss-crossing and no sign of any straight graining superimposed upon the herringbone pattern. From this it would appear that two sets of three adjacent composite partly twisted rods were present although it wasn't possible to say from the radiograph whether the two sets were welded together back-to-back or whether there was an intermediate central core piece between them although no indication of one was visible. Fig 25d shows how the pattern may have appeared on either side of the blade. The radiograph also showed no signs of straight graining along the cutting edge parts of the blade.

Exposure and film details

Kilovoltage	125	Exposure time	55 seconds
Milliampage	5	Film	Kodak Industrex CX pre-screened roll film

Metallographic Examination

A wedge-shaped section was cut from the blade 12.0 cm down from the hilt end of the blade (Fig 10). Unetched the section showed a variable slag content, very high in parts, with distinct types of slag present. Linear concentrations of two phase inclusions, blobby pale grey (wustite) against a darker grey background (?fayalite a glassy constituent) marked the positions of weld lines which divided the section into four main parts, (a)-(d) in Fig 25b. Even before etching it was clear that the composite pieces of the core of the blade had been welded to a separate central core piece before the cutting edges were welded on. The central core piece (b) contained much slag both as large three-phase inclusions, a little pale (wustite) showing against a background of medium to darker grey (?fayalite and a glassy constituent), and smaller inclusions of the two darker phases.

The slag content of the composite parts (c), (d) and of the cutting edge part (a) was mostly much lower and consisted mostly of smaller inclusions of two phase, medium and darker grey inclusions. The slag appeared to be cracked in places.

When etched with nital the structure of the four main parts the section showed more clearly (Fig 25c). The cutting edge part (a) consisted of medium - very large grained ferrite with a little carbide visible where the grain size was smaller. The central core piece (b), part from its high slag content, consisted of fairly even sized large grained ferrite. The composite pieces (c) and (d) showed a banded structure with pale bands of very large grained ferrite which contained patches of short rod-like nitride or carbide needles; and darker bands of medium grain sized ferrite with a small proportion of carbide.

Hardness values of 152 HV and 134 HV respectively were obtained for the cutting edge part (a) and the central core piece (b). One of the low carbon grey bands of pattern-welded part (d) gave a value of 164 HV whereas one of the pale very large grain ferrite bands of pattern-welded parts (c) and (d) respectively gave hardness values of 214 and 207 HV. Again this is probably indicative of a higher phosphorus content for these pale bands in the composite pattern-welded pieces.

It would appear that all the main parts of the blade consisted of wrought iron plus a little carbon mostly as grain boundary carbide. Fig 25d gives an idea of how it was assembled.

6.13 S12: Sword, from Wickhambreux; Maidstone Museum

The very corroded remains of a sword blade consisting of two main fragments plus flakes, some of which were adhering to the main pieces. The sword was found in 1886 at a gravel quarry at Wickhambreux in Kent. It was found with another sword (see 6.18 below) and appears to have come from a small portion of a cemetery which included a bronze bowl and a blue glass vessel (Dowker 1887).

The poorly preserved two main fragments only roughly join together but together indicated a total length of about 90+ cm. No recognisable part of the tang or tip was present. Much of the edges were missing and the mineralised and flaky remains of a scabbard formed the outer incrustation on either side. The blade appeared to have been just under 6.0 cm wide by about 0.5 cm thick. Date ; approximately 6/7th century.

X-radiographic examination

Radiography of the sword fragments showed it to be a composite weapon with a pattern-welded central zone of an unusual type similar to that seen on the radiograph of the sword from Aylesford (6.17). The pattern did not vary and showed up as a central and two outer twisted bands with a distinct criss-cross effect showing up along these. Interleaved between the twisted bands were two clear bands which showed a distinct straight grain pattern. The cutting edges also showed traces of a straight grained effect Fig 26a.

Exposure and film details

Kilovoltage	110	Exposure time	2 minutes
Milliampage	60	Film	Kodak Industrex CX used with lead screening sheets, 0.10 mm front

Metallographic examination

A transverse section extending across the blade was taken from near one of the broken ends. When examined unetched a very varied slag content could be seen. Most noticeable were very large, roughly triangular shaped inclusions which occured at intervals approximately along the main axis of the section (Fig 26d). These slag inclusions most probably became trapped in each case at the central weld junction between three separate parts of the blade. These large slag inclusions were distinctly two phase - mostly a dark (? glassy constituent) surrounding paler areas (?of wustite). The slag content across the section was otherwise mostly low except for localised patches of small spots or ribbon-like inclusions which appeared mostly dark (?fayalite or a glass) but against this background a paler phase showed in some cases.

When etched with nital the structure of the blade became much clearer (Fig 26c). Only one cutting edge part (a) survived in the section as well as eight composite parts of the core of the blade (b) - (i).

The cutting edge part (a), appeared to be a piece of fairly homogeneous low carbon iron or mild steel. This consisted of an equiaxial distribution of fine grained ferrite and pearlite which was either unresolved or partially lamellar or partially spheroidised. The slag content here was low. Some decarburisation appears to have occurred along the weld between the cutting edge (a) and the core pieces (b) and (c). There was little sign of carbon diffusion across this weld.

The rest of the section consisted of three pairs of twisted composite pieces, (b)/(c), (e)/(f) and (h)/(i). welded back to back with each pair divided from the next by a single untwisted piece, (d) and (g) (Fig 26b). The banded nature of the composite pieces was not clear even after etching. There appeared to be approximately eight bands to each composite piece. The twisted parts showed up partly as alternate pale and slightly darker bands which gave a folded appearance particularly in part (e), and a folded appearance was also indicated by the distorted flow patterns of slag inclusions.

The pale bands of the twisted composite pieces consisted of very large grained ferrite with a few Neumann bands visible. The other bands while sometimes noticeably darker were often very little different in shade to the pale bands. Where darker they consisted of medium large grained ferrite with some pearlite, similar in form to that seen in the cutting edge area (a), but the carbon content here was much less, only 0.1% or less and this decreased where the bands became paler where only a little carbide was visible at the grain boundaries. These bands were, therefore, little more than wrought iron even where the carbon content was at its highest.

The only banding visible in the areas (d) and (g), which exhibited straight graining on the radiograph, were occasional and very intermittent vertical lines of small slag inclusions which showed that these piled composite pieces were set at right angles to the surface of the blade. Parts (d) and (g) were little more than piled wrought iron; fairly even medium - large grained ferrite with small amounts of carbide visible at the grain boundaries, sometimes visible as poorly formed pearlite lamellae.

Five hardness readings were taken across the blade section and the results were as follows: parts (a) near the tip of the cutting edge, carbon content 0.3%, hardness value 206 HV; part (b), band of medium grained ferrite and some grain boundary carbide, hardness value 178 HV; part (b), band of very large grain ferrite, hardness value 177 HV; part (d), medium grain ferrite, hardness value 177 HV; part (f), band of very large grained ferrite, hardness value 202 HV (Fig 26b).

6.14 S13: Sword, from Kent; Maidstone Museum, Tomlinson bequest, KAS 620, 1954, 17

The upper, two thirds of a sword blade of which the provenance is uncertain. Other finds from the Tomlinson bequest in a similar condition reputedly came from the Anglo-Saxon cemetery at Bifrons and these include the unidentifiable remains of a sword (KAS 620, 1954.20; Chapter 6.6) and a weaving batten (KAS 620, 1954.19) (D.B. Kelly pers. comm.). The sword surviving blade fragment was 61.8 cm long by 5.8 cm wide and a very approximate thickness of 0.5 cm. It was in a poor state the surface having already corroded and flaked off and what was left was deeply pitted although it did appear to have some metallic core surviving. The lack of provenance is unfortunate as there were no particular aspects to the blade to suggest any particular date range although 5th-7th century is most likely. The blade profile was of a shallow convex form.

X-radiographic examination

Radiography showed up some structural detail to the blade although it was not very clear. In places a wavy grain was visible on either side of a central dividing line running down the centre of the blade. This wavy effect was consistent along the blade but stopped at the tang where it changed to quite clear straight graining.

Metallographic Examination

A wedge-shaped section was cut 16.0 cm from the upper end of the blade. Before etching a very varied slag content could be seen across the section. The slag occured as small spots or well flattened inclusions, both one dark phase (?fayalite) and two phase - light and dark (? wustite and fayalite or a glass).

Etching with nital revealed a structure consisting of a number of horizontal laminations, possibly six altogether with a cutting edge welded on (Fig 27b). The cutting edge (a) in Fig 27a, appeared to have been a strip welded on to one side of the already partly assembled blade and occupied about half the thickness of the blade. It seems probable that a similar cutting edge was welded on to the opposite side of the blade (Fig 27c). A large curved, ribbon-like slag inclusion was trapped in the weld between piece (a) and the rest of the blade. Part (a), itself, varied gradually between medium grain sized ferrite mixed with a little carbide near the inside, and large grained ferrite near the tip of the cutting edge. The ferrite was equiaxed in each case. At most the carbon content was well under 0.1% so that part (a) appears to have been a piece of wrought iron with a little carbon, probably accidentally included.

The remainder of the section consisted of a possible total of six horizontal bands, (b) - (g) in Fig 27a. These are partially discernable as areas of widely differing slag content and were divided by broken lines of slag inclusions which coincided with faint grey lines of pearlite in places highlighted by slight traces of white lines which did not show up well against a pale ferritic background. These lines appear to mark weld positions between the horizontal laminations of which the main part of the blade was composed. The slag content of bands (c) and (g) was low, but was quite high in (b), (d), (e) and (f) and the flattened inclusions were aligned along the main (horizontal) axis of the section. Much Neumann banding was also visible across this main part of the section indicative of some cold hammering after the final hot forging of the blade.

A total of eght hardness readings were taken across the section and these were done in four pairs and covered bands (c) - (g) inclusive. The results obtained were : (c) 171 and 185 HV; (d) 215 and 230 HV; (e) 204 and 215 HV; (f) 181 and 183 HV (Fig 27a). These values are high for iron and probably indicate a fairly high phosphorus content throughout the blade.

The main part of the blade appeared to be a piled structure of wrought iron laminations. The extra piece welded along one edge (and probably the other as well) may have been a largely unsuccessful attempt to provide a harder and tougher cutting edge.

6.15 S14: Sword, from Eastrey; Maidstone Museum, A S 121

Two fragments which together represented a nearly complete sword broken in the middle. A small part of both the tip and tang were missing. The total surviving length was 85.1 cm, thickness about 0.5 cm and with a width of 5.0 cm, it was a noticeably narrow blade with a fairly pronounced, slightly flattened, convex profile. The surface was very corroded with much pitting although it appeared to have a quite good surviving metallic core. No hint of any internal structure was preserved in the surface corrosion products. It was one of three very similar sword blades apparently found in graves at Buttsole, near Eastrey in Kent and donated by Mr. W Cobb but no further details survive concerning the circumstances of the find. Date; approximately 6th-7th century.

X-radiographic examination

Radiography showed a superimposed double chevron-like pattern running down the central part of the blade (Fig 28a). This pattern was not very clear but showed that along this part of the blade, a separate pair of composite twisted rods formed the surface on either side. There was no apparent indication of a separate central core. The chevron effect did, however, appear to alternate with short straight-grained elements in places. The cutting edge hardly showed any structural details although some hints of straight graining were just visible in a few places. A reconstruction of the pattern visible on the radiography is shown in Fig 28f

Exposure and film details:

Kilovoltage	125	Exposure time	55 seconds
Milliampage	5	Film	Kodak pre-screened roll film Industrex CX

Metallographic examination

A transverse section was cut from near the centre of the blade (Fig 10). When viewed unetched the slag content was seen to be quite high in places although it was very variable and tended to be segregated into parallel zones giving a banded appearance to the section. A narrow broken line of slag spots ran vertically across the section marking the weld position between the cutting edge and core of the blade. The slag inclusions across the blade were mostly quite small appearing as spots and well flattened ribbons except over the central part of the core area where an irregular distribution of large partly flattened inclusions occured.

When etched with nital the structure shown in the macrograph of Fig 28b became visible. The cutting edge was divided mainly into two halves (a)/(b) and (c)/(d) (see Fig 28d) and each of the two halves also appeared to consist of two parts although these subdivisions were much less clear. The lowermost part (a) consisted of very large grain ferrite with many slag inclusions. There was no very clear dividing line with (b) although this was rather different in appearance, being a rather banded zone of medium-large grained ferrite with much slag (small spots and ribbons) and streaked with medium grained ferrite with a small amount of pearlite. All the slag seen in the cutting edge formed discontinous lines running horizontally across the section.

Both (a) and (b) appeared quite pale on the macrograph whereas the other main part of the cutting edge, (c), was quite grey consisting of medium grained ferrite and pearlite. The pearlite was partly spheroidised and partly lamellar in form with mostly equiaxial grains and was lowest in density near the inner (or left hand) area where its carbon content was approximately 0.1% or less, whereas at the centre the carbon content was about 0.2%.

Elsewhere across part (c) the carbon content varied between these figures. The pearlite stopped abruptly along a straight horizontal line which marked the boundary with part (b). It was difficult to say whether this marked the exact position of a weld between these two parts because a small but even amount of carbon diffusion masked this and appeared to show a weld position a little to one side.

The small part (d) was very similar to (c) with a similar pearlite distribution giving a carbon content of about 0.1 - 0.2%, but it varied in that it contained much more slag.

The weld junction between the cutting edge and the core of the blade section was very clearly marked, both by a broken line of slag spots and a pale band of ferrite (Fig 28b and d). The pearlitic zones of the cutting edge and core stopped fairly abruptly at this line with little evidence of carbon diffusion across the weld into neighbouring ferrite areas.

The core of the blade was made up of a central strip (e) on to either side of which the composite rods, which gave the blade its patterned effect, were welded. The composite pieces (f) and (g) appeared in the section with a very small part of a third composite piece (h) just appearing in the section (lower left on Fig 28b) divided from (g) by a few slag spots in a vertical line probably marking the position of a weld. The corresponding fourth composite piece on the other side of the blade did not appear within the area of the section.

The central core piece (e) consisted mostly of very large grained ferrite with occasional patches of medium grain size which were mixed with a little pearlite. Neumann banding occured in a central patch near the weld junction with the cutting edge. Many of the large slag inclusions seen in this piece were two-phase with voids where cracking had occured.

The composite pieces (f) and (g) were very similar to one another, each consisting of alternate and roughly horizontal dark (pearlitic) and pale (ferritic) bands (Fig 28f). The inner grey pearlitic band in each case was rather wider than the rest. The pale bands consisted of medium grain size ferrite with some carbide whereas the darker, grey bands consisted of fine grained ferrite and pearlite with a carbon content of approximately 0.1-0.2%. The pearlite was partly lamellar and partly spheroidised in form. The divisions between the bands were diffuse and there had evidently been fairly extensive carbon diffusion between what started out as alternate wrought iron and low carbon iron or mild steel bands welded together to form the composite rods. The slag content of these parts, (f) and (g), was inconsistent but mostly fairly low. The small part of (h) consisted wholly of ferrite and pearlite similar to the adjacent part of (g), with a carbon content approximating to 0.1-0.2%.

A series of hardness readings were taken for the parts (a)-(g) of the section and these were mostly done in pairs as a check on the consistency of the results. Three pairs of readings were taken for edge parts (a)-(c) and a single reading for part (d). The results obtained were: (a) 232 and 234HV; (b) 168 and 174 HV; (c) 153 and 167 HV; (d), 177 HV. Pairs of readings were taken for the core part (e), and for the pattern-welded parts (f) and (g). A pair of readings was taken firstly for one of the paler ferrite bands and secondly for one of the grey pearlitic bands. The results were as follows: (e) 226 and 228 HV; (f) 230 and 243 HV, 152 and 163 HV; (g) 193 and 195 HV, 162 and 170 HV. The consistently higher readings for the ferrite areas indicate a higher phosphorus content in these parts. This was confirmed by EPMA. The phosphorus map (Fig 28c) shows the high phosphorus parts of the blade as white areas whereas the areas lower in phosphorus are dark. EPMA showed one of the harder white bands to contain 0.67% phosphorus whereas the phosphorus content of the darker bands was 0.11% or less (Table 8).

The central core piece (e) consisted mostly of very large grained ferrite with occasional patches of medium grain size which were mixed with a little pearlite. Neumann banding occured in a central patch near the weld junction with the cutting edge. Many of the large slag inclusions seen in this piece were two-phase with voids where cracking had occured.

The composite pieces (f) and (g) were very similar to one another, each consisting of alternate and roughly horizontal dark (pearlitic) and pale (ferritic) bands (Fig 28f). The inner grey pearlitic band in each case was rather wider than the rest. The pale bands consisted of medium grain size ferrite with some carbide whereas the darker, grey bands consisted of fine grained ferrite and pearlite with a carbon content of approximately 0.1-0.2%. The pearlite was partly lamellar and partly spheroidised in form. The divisions between the bands were diffuse and there had evidently been fairly extensive carbon diffusion between what started out as alternate wrought iron and low carbon iron or mild steel bands welded together to form the composite rods. The slag content of these parts, (f) and (g), was inconsistent but mostly fairly low. The small part of (h) consisted wholly of ferrite and pearlite similar to the adjacent part of (g), with a carbon content approximating to 0.1-0.2%.

A series of hardness readings were taken for the parts (a)-(g) of the section and these were mostly done in pairs as a check on the consistency of the results. Three pairs of readings were taken for edge parts (a)-(c) and a single reading for part (d). The results obtained were: (a) 232 and 234HV; (b) 168 and 174 HV; (c) 153 and 167 HV; (d), 177 HV. Pairs of readings were taken for the core part (e), and for the pattern-welded parts (f) and (g). A pair of readings was taken firstly for one of the paler ferrite bands and secondly for one of the grey pearlitic bands. The results were as follows: (e) 226 and 228 HV; (f) 230 and 243 HV, 152 and 163 HV; (g) 193 and 195 HV, 162 and 170 HV. The consistently higher readings for the ferrite areas indicate a higher phosphorus content in these parts. This was confirmed by EPMA. The phosphorus map (Fig 28c) shows the high phosphorus parts of the blade as white areas whereas the areas lower in phosphorus are dark. EPMA showed one of the harder white bands to contain 0.67% phosphorus whereas the phosphorus content of the darker bands was 0.11% or less (Table 8).

6.16 S15: Sword, from Holborough; Maidstone Museum

The main part of a sword blade of which the tip is missing. It was one of two swords found in the Anglo-Saxon cemetery at Holborough in Kent. Associated finds indicate the cemetery to be 7th century in date (Evison, 1956). The surviving blade fragment was 76 cm long by 5.6 cm wide and it was badly corroded with a very uneven flaky and pitted surface although there was at least some metal left underneath the corroded surface. The original thickness of the blade could not be measured but would appear to have been about 0.5 cm and it appears to have had a flattened convex profile. Much of the edges of the weapon had corroded right away.

X-radiographic examination

Radiography produced a clear image showing a pattern-welded core to the blade (Fig 29a). The pattern-welded part consisted of three adjacent twisted rods forming the surface on either side of the blade. The pattern was the same on either side and on the radiograph the images overlapped only slightly and produced an alternating herringbone and straight grained effect in panels each of which measured about 5 cm in length except for the uppermost, panel next to the tang which was longer. Fig 29f shows a diagrammatic reconstruction of how part of the pattern showed. The cutting edge also shows a clear straight grain effect in places.

Exposure and film details:

Kilovoltage	125	Exposure time	55 seconds
Milliampage	5	Film	Kodak pre-screened roll film Industrex CX

Metallographic examination

A wedge-shaped transverse section was cut from the blade approximately 10 cm from the tang (Fig 10) and just within the first and longest of the herringbone panels which showed on the radiograph. When viewed unetched very varied slag concentrations were visible across the section and overall the slag content was quite high. A few slag spots formed a faint intermittent line vertically across the section, marking the weld position between the cutting edge and the core parts of the blade. On the core side of this weld swirling slag patterns mark the folded aspect of the twisted composite rods that shows in section. The slag content of the cutting edge was especially varied, very high in patches with small-medium sized spots, partially flattened ribbons and quite large irregular inclusions and it was mainly two-phase, a pale phase in a generally predominant darker background (? wustite in a glassy matrix). Some areas, however, contained very little slag.

When etched with nital the structure became clearer although it did not show up very well in the macrograph (Fig 29b). The main reason for this was that the structure was entirely one of wrought iron with no steel present at all and so there was not the contrast between pale and darker (ferritic and pearlitic zones) that has been observed so clearly on other sections.

The cutting edge appeared to consist of one piece (a). Two very large dark slag ribbons (probably of fayalite and a glassy constituent) the dark corroded outlines of which can be seen, on Fig 29b ran at roughly 45 degrees across the cutting edge. These large slag inclusions and the generally rather variable orientation and distribution of the slag suggest that the cutting edge part (a) consisted of one piece of poorly prepared bloomery iron forged out to the desired shape before being welded to the core. The grain size of the ferrite of part (a) varied between very large nearer the tip of the cutting edge and medium-large nearer the core area where a very little carbide was visible at the grain boundaries in places. The very large grained area near the tip also contained a patchy distribution of rod-like nitride or carbide needles.

In the core area of the section only two of the twisted strips was represented on the section. These, (b) and (c) (in Fig 29d) had been welded back-to-back without any intermediate central core piece, the weld line showing up as a narrow intermittent line of small slag spots and ribbons. Parts (b) and (c) too, consisted almost entirely (slag excepting) of ferrite, and folded appearance being slightly accentuated by alternating bands of very large grained ferrite, and medium-large grained ferrite with a very little carbide visible at the grain boundaries in places.

A pair of hardness readings was taken for the cutting edge part (a) and for the pattern-welded core parts (b) and (c). Pairs of readings were taken firstly in one of the paler, larger grained ferrite bands and secondly in one of the smaller grained ferrite bands. In this order the results were as follows: (a) 113 and 115 HV; (b) 129 and 134 HV, 116 and 117 HV; (c) 204 and 217 HV, 119 and 127 HV (Fig 29d). The paler band in part (c) gave a markedly higher value, indicative of a higher phosphorous content here.

This was confirmed by EPMA analysis. The phosphorus map clearly shows the high phosphorus bands, within the pattern-welded parts (b) and (c), as white areas contrasting with the darker areas low in phosphorus. EPMA analysis gave phosphorus contents of 0.34, 0.61 and 0.53% for the white bands compared with 0.11% or less for the darker areas (Table 8).

6.17 S18: Sword, from Aylesford, Maidstone Museum

The corroded remains of a sword blade of which the top half of the tang and other smaller fragments were missing. One main core fragment survived to which a number of flakes of totally mineralised surface incrustation adhered in places. These and other surface flakes looked as if they contained the remains of a scabbard although this was barely recognisable as such. According to museum records the sword was reportedly found in a gravel pit at Preston Hall, Aylesford in Kent, in March 1924.

The main fragment was 58.3 cm in length by 5.2 cm in width. The thickness was difficult to estimate but appears to have been about 0.4 cm or slightly more, and its profile looks to have been either of a flattened or shallow but continuously convex form although this is uncertain due to corroded and fragmentary state of what survived. Although badly corroded the main core piece appeared to contain at least some network of metal over most of its length. Date : approximately 6/7th century.

X-radiographic examination

A radiograph was taken of the main blade fragment plus the flakes adhering to it and those whose correct position could be worked out. This produced what seemed at first to be a surprisingly clear image considering the poor state of what survived and gave some good indications as to the internal structure of the blade (Fig 30a). The core part of the blade was pattern-welded with a triple banded design running continuously down this central area of the blade. This consisted of two outer twisted portions which showed up as a criss-crossed double image (of the two surfaces) in places. Between these a straight-grained element ran right down the middle of the blade. Apart from the criss-crossing of the twisted parts there was little obvious sign that two images were superimposed and not enough to determine whether more than one set of composite rods were involved across the thickness of the blade. There was also no indication of any central core strip onto which the patterned surface strip(s) might have been welded. The cutting edges appeared to be separate and exhibited some slight traces of a straight grained effect but not nearly as clear as that of the central portion of the composite core.

It is significant that the parts of the radiographic image to show up most clearly were those devoid of surface incrustation whereas the areas where this survived, particularly on both sides, the radiograph was fuzzy and hence difficult to interpret.

Exposure and film details:

Kilovoltage	125	Exposure time	60 seconds
Milliampage	5	Film	Kodak pre-screened roll film Industrex CX

Metallographic examination

A wedge-shaped section was taken 9.0 cm from the lower broken end of the sword (Fig 10). Unetched the section showed a very varied slag content and distribution. Weld lines between the main component parts of the blade were very clearly marked by lines of two-phase slag inclusions with a pale (? wustite) phase predominating over a darker (? glassy) phase. Inside the main components the slag content was mostly fairly low but was patchily high in places. Where it occured it was noticeably different to that occuring at the main welds and it generally appeared as a dark (? fayalite and a glassy) phase with only occasional paler spots of the oxide (wustite) phase visible within this.

When etched with nital the weld boundaries between the main components of the blade became more heavily outlined than before (Fig 30b). Thick lines of pearlite became superimposed upon the lines of slag inclusions, which divided the section clearly into six pieces, a one piece cutting edge, (a), and the core pieces (b) - (f) (Fig 30d).

The surviving part of the cutting edge (a) consisted of medium grain ferrite mixed with pearlite in irregular patches. The ferrite/pearlite mixture gave a rather spiky appearance typical of the Widmanstatten structure. The pearlite was mostly irresolvable but did show a poorly formed lamellar structure in places. The carbon content at its highest was approximately 0.2%, quickly fading to well below 0.1% over most of the area. The slag content of this area was low and the distribution, orientation and size of the inclusions was fairly irregular. The overall impression of the cutting edge part (a) was a piece essentially of wrought iron, probably a piece of bloomery iron subjected to some hammering after smelting to remove most slag but not subsequently forged to any great extent or piled which would have given a more banded and less irregular and patchy appearance in section. There was no surviving evidence for any harder tip to the cutting edge.

All the parts of the pattern-welded core, were represented in the section. The outer two twisted elements visible on the radiograph each consisted of two composite rods welded back-to-back, (b)/(c) and (e)/(f) (Fig 30d) and between these was a single composite rod (d) which was subdivided into eight vertical (in section) bands corresponding to the straight grained central part of the radiograph. These vertical bands were highlighted as alternate paler and darker etched areas. The folded appearance of the composite parts (b), (c), (e) and (f) was very marked, parts (b) and (c) also consisting of eight alternate paler and darker bands. Parts (e) and (f) looked similar but only half of them appeared in the section so the total number of bands could not be counted.

The microstructure of the paler and darker areas of composite parts (b), (c) and (d) were very similar. The paler bands consisted of very large grained ferrite with a variable content of slag inclusions. The darker bands consisted mainly of medium grained ferrite mixed with some pearlite in the same spiky looking Widmanstätten distribution seen in the cutting edge part (a). The pearlite was either partially unresolved or granular in appearance or exhibited a poorly formed lamellar structure.

The carbon content of these darker bands was very low, no more than about 0.1% and mostly less. The composite pieces (e) and (f) were similar but here the carbon content was even lower. The bands within the composite pieces mostly showed because of the contrast between the paler and darker areas on etching and there were no particular indications of weld lines such as lines of slag inclusions or segregation of pearlite and ferrite.

Three hardness readings were taken for the cutting edge piece (a), two nearer the cutting edge and one near the inner weld and the results were 212, 212 and 187 HV. From the twisted composite piece (b) hardness values were obtained for one of the pale, very large grain ferrite bands and one of the pearlitic bands and these were 204 and 206 HV. For the adjacent twisted composite part (c) two readings were taken for one of the pale, very large grain ferrite bands and one each for two of the grey pearlitic bands and, in this order, the results were: 202 and 202 HV, 210 and 215 HV. Readings from one pale very large ferrite band and from one grey, pearlitic band were taken giving hardness values of 199 and 202. The very large grained part (e) gave a hardness of 197 HV (Fig 30d).

An EPMA phosphorus map also showed up a banded structure to the pattern-welded parts of the blade with the parts high in phosphorus showing up as paler bands. No absolute values were obtained for this sample although the contrast between the paler and darker bands was not as great suggesting that the phosphorus content of these paler bands was less than was found in the previous example (6.16 with phosphorus contents of 0.34 - 0.61%).

At most the darker bands of the composite rods could only be described as a very low carbon steel, little more than wrought iron, although it had clearly been carefully combined with carbon free, high phosphorus iron and piled to produce the alternate strips. The highest carbon content of the blade occured in places along the weld boundaries between the main parts of the blade where the grey pearlitic lines were at their densest although even here it was not much higher than elsewhere.

6.18 S19: Sword, from Wickhambreux; Maidstone Museum

One surviving piece of a sword blade with the barely recognisable and flaky remains of part of a scabbard attached to it . It was found in a gravel pit at Wickhambreux, Kent in 1886 (Dowker 1887). It came from part of an Anglo-Saxon cemetery disturbed by gravel quarrying and associated finds included two (fragmentary) swords, a large bronze bowl and a blue glass vessel. One of these other swords was metallographically examined (6.13).

The sword fragment was 75.2 cm long by approximately 5.0 cm in width and roughly 0.5 cm thick. The tang, the tip end and much of the edges of the blade were missing and what was left was very badly corroded with little metal surviving.

X-radiographic examination

Radiography of the sword showed a rather fuzzy image with very little structural detail visible although traces of a criss-cross pattern, was visible in places. In one place this criss-cross effect was superimposed upon a straight grained element (Fig 31a). This superimposition is probably indicative of a separate central core piece sandwiched between two sets of three twisted rods. Separate edge pieces could be seen in places but these bore no discernible structural traces. The x-ray exposure and film details were the same as for the previous sword (6.17, S18).

Metallographic examination

A complete transverse section was taken from near one broken end of the blade. Much slag was visible across the unetched section especially in the central area but no individual welds were discernable as specific lines of slag inclusions.

Etching with nital confirmed that the cutting edges had been welded to a core made up of two sets of three composite strips welded on to either side of a central piece (Fig 31c). Metal survival was patchy although all the main elements of the blade were represented; part of one cutting edge, (a), parts of four (b) - (e), of the original six outer pieces of the core and about half of the central core piece (f) (Fig 31b).

The edge piece (a) survived as a small island, isolated by corrosion from the core part of the blade at this point, the weld zone having been lost. The slag content of the edge piece (a) was quite high, consisting of small flattened inclusions. This edge piece which otherwise consisted mainly of large grained ferrite and pearlite dispersed in a distinctively spiky Widmanstatten form. Much of the pearlite appears lamellar although somewhat granular in some areas. The Widmanstatten formation must represent fairly fast cooling although probably not quenching.

Allowing for the Widmanstatten structure, the carbon content would appear to be about 0.3 - 0.4%. The pearlite content of this edge piece dropped away sharply towards the sides and more gradually towards the tip where the carbon content is less than 0.1% . This gradient may have been the result of fairly extensive decarburisation although the sharper gradient seems more likely to represent carbon diffusion outwards, across weld boundaries, into adjacent wrought iron pieces. The edge of the blade may originally have been composed of a three part, iron-steel - iron sandwich skillfully welded together and the welds subsequently masked by carbon diffusion outwards. There was not sufficient evidence to resolve this problem. A single edge piece is suggested in the reconstruction diagram of Fig 31d as the simpler, although not necessarily correct alternative.

Surviving small areas of core pieces (b) - (e) were similar and gave a folded appearance typical of twisted and flattened composite rods in section. They consisted mostly of wrought iron, the folded appearance being partly the result of slag segregation and partly by a banded appearance created by alternating slightly darker and paler bands. The darker bands consisted of equiaxed medium grain ferrite with a little carbide at the grain boundaries, the carbon content being low, mostly well under 0.1%. The paler bands consisted of large grain ferrite. The composite pieces contained a fairly even distribution of small slag inclusions, although fewer than the cutting edge. The weld lines between the composite pieces (b) - (c) and the central core piece (b) were marked in each case with a broken line of slag inclusions upon which was superimposed a bright white line, possibly the result of arsenic enrichment by oxidation.

The core area (b) consisted of wrought iron with a high slag content, much higher than the cutting edge (a) or composite pieces (b) - (c). The slag was evenly distributed but varied in size, the larger inclusions being partially flattened and aligned along the main axis of the section. Apart from the slag this area consisted of mainly large grain ferrite with occasional grain boundary carbide present.

Three hardness readings were taken for the edge part (a), giving a value of 241 HV for the most pearlitic part of this and values of 177 and 191 HV in the areas nearby which showed more ferrite. Hardness values of 187 and 192 HV were obtained for the central core piece (f). One of the larger grained paler ferrite bands of the composite pattern-welded part (c) gave a hardness value of 185 HV and one of the darker smaller grain ferrite bands of pattern welded part (d) gave a hardness value of 138 HV (Fig 31b).

The blade was mainly one of wrought iron with the exception of the edge piece (a) which was probably sandwiched between two pieces of wrought iron in a similar way to 6.5 and 6.19.

Apart from the low-medium carbon steel of the central part of the cutting edge, this sword blade consisted predominantly of wrought iron and there had been no apparent attempt at heat treatment after final forging. An enhanced decorative effect would have been produced, after final polishing and etching, by the different grades of iron combined in the composite twisted rods of the pattern-welded core.

6.19 S20: Sword, from Lenham, Kent; Maidstone Museum, 3.1977

The very fragmentary and barely recognisable remains of a sword from an Anglo-Saxon grave found by chance during building work at Lenham, Kent. Parts of two graves were uncovered and recorded (Goodsall 1966) and the sword and a number of associated finds retrieved. These were almost completely mineralised and now only survive in a very fragmentary state. An iron shield boss would appear to indicate a date probably within the 6th century A.D. (D.B. Kelly pers. comm.) and the graves probably belonged to a more extensive cemetery of this date. The main blade fragment to survive intact, although with little or no metal left inside it, was fused (by corrosion) to a knife or small scramasax. The broken sections showed the blade to have had a flattened convex profile. Its original thickness can only be estimated from the corroded section but was probably about 0.5 - 0.6 cm. The outer parts of the sword blade fragments were coated with a thick orange-brown sandy incrustation which probably included the remains of a scabbard.

X-radiographic examination

Several radiographs were taken to determine the internal structure of the sword blade from the fragments that survived. The images were mostly very poor, probably due to the mineralised state of the blade, plus the thick incrustation which formed the surface layer on either side. There were slight indications of a pattern-welded core to the blade which appeared to consist of three adjacent bands.

One of the incrusted surface fragments, fortunately, was found to have attached to it a small piece of blade which still contained some metal. This was removed and radiographed separately with rather better results (Fig 32a). The radiograph showed that the central core part consisted of a double layer of three adjacent bands. The chevron or herringbone pattern created by the twisted elements showed up quite clearly in places. The twisted elements alternated, at least in part, with untwisted or straight grained portions. From such a small fragment it was impossible to say whether or not this formed part of a design which alternated between twisted and straight grained elements along the whole length of the blade. Fig 32d shows a reconstruction of the pattern indicated by the radiograph. The x-ray exposure and film details were the same as for the sword 6.13 (S12).

Metallographic examination

Two transverse sections (20A and B) were taken from the small surviving metallic blade fragment so that the combined results from them would provide some information about both the pattern-welded core and the cutting edge. When viewed unetched the section across the core showed an uneven and varied slag content which appeared to be mostly present as one phase (dark grey - ? fayalite) fairly small flattened spots and ribbons mostly segregated along broken lines giving a somewhat banded appearance in places. Slag was also present near the edge of the section, as two-phase spots, ribbons and also larger irregular inclusions. The section that included part of the cutting edge showed less slag inclusions - mainly fairly small spots and ribbons confined to the central part of the wider end of the section.

Etching with nital (Fig 32c) showed the section of the core area to be composed mostly of a central piece or strip (a) on either side of which the three adjacent composite rods, seen in the radiograph, had been welded and only quite small areas (Fig 32, (b)-(e)) of the rods survived.

The central core piece (a) consisted mostly of very large grained ferrite with some flattened slag and a little pearlite at the grain boundaries. Much of part (a) was covered with short rod-like nitride or carbide needles (similar to those shown in Fig 37d) which tended to be concentrated in the areas of largest ferrite grain size. Much Neumann banding was also present in a patch near the centre of (a).

The surviving pattern-welded pieces, (b)-(e) all showed alternating pale and dark bands with a quite sharply folded appearance indicating the twisted nature of these rods. The pale bands consisted mainly of very large grained ferrite with a variable but mainly low slag content. The slag also followed the lines of the folds which tended to emphasise this appearance. Nitride or carbide needles were again visible mainly in the areas with the largest ferrite grains.

The grey darker bands consisted of fine grained pearlite and ferrite with very little slag. The pearlite was difficult to resolve optically but a lamellar structure was visible in places. With a carbon content of approximately 0.1%, these grey bands were little more than a low carbon iron, not greatly different to the wrought iron of the rest of the section.

The welds between the pattern-welded pieces and the central core piece (a) were good quality with only a few flattened slag inclusions showing along them. These welds showed up mainly because of the presence of thin but fairly clear grey lines of pearlite.

On the second section the central core strip (a) and pattern- welded rod parts, (g) and (h) compared closely with those seen on the section already described. The weld junction between the core and cutting edge was not clearly marked either by slag inclusions or by the thin pearlite lines that marked weld positions in the core zone of the blade sections.

The cutting edge contained little slag and appeared to consist of a sandwich of three horizontal bands although there was no obvious signs (slag, pearlite or ferritic lines) to mark any welds between. The very dark central band (h) consisted mostly of large grained lamellar pearlite indicating a fairly high carbon steel with a carbon content of about 0.6-0.7%. Some of the largest grains exhibited a Widmanstatten structure. The paler grey outer bands (g) and (i) consisted mostly of a fairly even med-fine grained mixture of ferrite and pearlite, partially lamellar and partially unresolved. The change between the outer bands (g) and (i) and the central band (i) was fairly abrupt and even on either side. The skill in welding shown elsewhere on the sections could certainly have produced welds of this quality and the weld between composite rod (b) and the upper edge band (g) was similarly invisible although it must have existed and subsequently become lost between two areas of similar carbon content. The decarburisation of a single high carbon steel edge piece is less likely as the effect appeared to be rather too even for this to have happened accidentally . The cutting edge therefore most likely consisted of a sandwich of two-pieces of low carbon iron (similar to the pearlitic bands of the composite rods) with a piece of high carbon steel welded between.

Five hardness readings were taken from section which included parts of the cutting edge and core of the blade (S20A). The central steel band (h) of the cutting edge gave a value of 298 HV while one of the outer, low carbon iron parts, gave a hardness value of 189 HV. The central wrought iron core piece (a) gave a hardness value of 162 HV. One of the grey low carbon iron bands in the pattern-welded part (b) gave a hardness value 179-HV whereas one of the adjacent very large grain ferrite bands gave a hardness of 232 HV. The apparently inconsistently high value of this final reading probably indicates a high phosphorus content for both this and the pale, very large grain ferrite bands observed in the pattern-welded parts of both sections (Fig 32b).

6.20 S1: Sword, from Loveden Hill; Lincoln City and County Museum, 6:66

A sword blade bent double in two places and broken at the bend nearest the hilt. The metal survival was quite good apart from heavy surface pitting. The break may have been the result of corrosion along a crack or point of stress caused by the bending before burial. The blade was 87.6 cm long by 4.8 cm wide with a mainly flat profile becoming convex towards the cutting edges. The sword was not encased in its scabbard when buried and the practice of bending or 'ritual killing' of a sword blade has been found elsewhere (Chapter 1.3.1). This sword was found in grave 31 of the Anglo-Saxon cemetery at Loveden Hill during excavations of 1956 (Fennell 1957) and the cemetery has been dated to 6th-7th century.

X-radiographic Analysis

It was obvious from X-radiography that the central part of the blade was pattern-welded, although the detail was not clear. It appeared to show up along this central part of the blade partly as a chevron or herringbone effect, partly as criss-crossing and partly as a straight grained effect (Fig 33a). These represented the double image of two sets of five composite rods forming the surface on either side of the blade. These composite rods had been twisted for parts of their lengths and left straight at intervals and then welded together so that, for each set of five, the herringbone pattern would show in panels at intervals down each side of the sword blade as shown in Fig 33d. There was no indication of a separate central core strip and no signs of any 'graining' in the cutting edge areas of the blade.

Exposure and film details:

Kilovoltage	125	Exposure times	60 seconds
Milliampage	5	Film	Kodak Industrex AX using a cassette with 0.025mm thick lead screening sheets.

Metallographic examination

A complete transverse section was taken from one side of the break in the blade. Unetched, the slag content showed up as being mostly fairly low across the blade, although one of the cutting edges gave a rather banded appearance caused by broken lines of small two-phase, pale and darker grey inclusions, probably of wustite with a glassy matrix. Similar inclusions marked the weld boundaries between the pattern-welded parts of the blade in particular one large inclusion trapped inside during the welding together of these components. A scattering of small dark grey slag inclusions, of one phase (?fayalite) or two phases (probably fayalite in a glassy matrix) were visible across the section.

Etching with nital revealed a pattern-welded core consisting of two sets of five composite rods welded back-to-back without a separate central core (Fig 33c). Each of the cutting edges could also be seen to consist of a single piece.

The cutting edge parts (a) and (b) each consisted mostly of medium-large grain ferrite. Part (a) showed one low carbon (up to approximately 0.1%) pearlitic zone along one side whereas part (b) showed a more general but similar low carbon content which in patches was as high as 0.2%.

The pattern-welded part (f) had completely corroded away (in the section) but apart from this the pattern-welded components (c) - (l) showed a very similar structure to one another. The pale bands showed up mostly as very large grained ferrite with some Neumann banding and nitride or carbide needles are also visible in places. The darker, grey bands consisted of small to medium grained ferrite with some carbide with a carbon content of about 0.1%. In some areas the grain size was much larger and the ferrite/pearlite showed a spiky looking Widmanstatten formation, probably indicative of localised accidental over-heating during forging.

Three hardness tests were done near the tip of cutting edge (b) where the carbon content was at its highest (about 0.2%) and values of 164, 165, and 164 HV were obtained. Values of 104 and 85 HV were obtained near the inner weld of part (b) where a ferrite structure showed. A series of hardness values were obtained for some of the pale, very large grain ferrite and the darker, low carbon pearlite bands of the core components and the results of these were as follows: (h) pale bands, 202, 193, and 154 HV; (1) darker bands, 119 and 133 HV; (j) pale band, 193 HV; (k) pale band, 175 and 200 HV; (k) darker band, 143 HV.

The unexpectedly high hardness values of the pale large grain ferrite bands probably indicates a high phosphorus content for these parts. The blade had not been given any additional heat treatments after final forging, although the Neumann banding or stress lines indicate some final cold hammering.

6.21 S40: Sword, from Chesterton; Peterborough Museum, 16/1979/1

A nearly complete sword blade minus end of tang and tip found in 1979 by chance (metal detector) apparently in a ploughed field near Chesterton (TL 124 947) in Cambridgeshire. The exact circumstances of the find were not carefully recorded and no associated finds survive. It measured 82.8 cm long by 5.8 cm at the widest part of the blade which appeared to have had a flattened convex profile, 0.5 cm thick, although this had been obscured by the extensive corrosion of the surface. It was similar in size and shape to many swords found in Anglo-Saxon graves of about the 5-7th centuries and this is probably the most likely attribution for this particular sword. When found it had probably already been disturbed from its original resting place as it was bent sharply in two places along the blade, the most likely result, when already weakened by corrosion, of having been struck by a heavy, sharp object such as a plough. The blade was heavily corroded and the edge was missing in places but the fact that it had withstood being bent sharply without breaking showed that some metal of the core survived. No structural details could be seen on the corroded remains of the surface of the blade and no traces of scabbard, guard or pommel survived. Date: approximately 6-7th century.

X-radiographic examination

A radiograph of the sword (Fig 34a) showed the blade to consist of a pattern-welded core running down the centre of the blade with a plain cutting edge on either side. The core appeared to consist of two-superimposed sets of four adjacent composite strips. These strips exhibited a very pronounced light and dark 'grain' structure which alternated between being straight and twisted so that a herringbone or chevron pattern alternated with straight 'grained' areas. As far as could be seen the surface pattern was probably similar on both sides and a diagrammatic interpretation is given in Fig 34d. The pattern-welding continued along the tang although much distorted in this area. The cutting edges did not exhibit any 'grainy' appearance.

Exposure and film details:

Kilovoltage	125	Exposure times	50 seconds
Milliampage	5	Film	Kodak pre-screened roll film Industrex CX

Metallographic examination

A transverse section was cut from near the centre of the blade from a part which showed up as being straight grained on the radiograph. When viewed unetched a markedly varied slag distribution was seen. The overall slag content was fairly low mostly consisting of small spots and ribbons aligned along various planes of forging. There were, however, several very large triangular shaped two-phase slag inclusions at intervals along the central axis of the section of the core part of the blade.

When etched with nital it became clear that the core was composed of several adjacent composite pieces welded back-to-back without any central core piece (Fig 34c). These are marked (d) - (i) on the sketch (Fig 34b). The cutting edge which appeared plain on the radiograph showed up as being a sandwich composed of three layers, a piece of low carbon steel between two pieces of low carbon iron marked (a) - (c). The microstructure of the central part (a) of this sandwich consisted mainly of a spiky looking Widmanstatten distribution of ferrite and irresolvable pearlite. Towards the tip this became increasingly mixed with quite dark etching nodular troostite (radial pearlite). This dark etching constituent faded out about two thirds of the way from the tip toward the weld junction with the core area. The proportion of pearlite in the ferrite/pearlite mixture also decreased towards this inner weld junction. This structure would appear to be the result of fairly rapid cooling although the cooling rate was too slow to produce any martensite. The fading out of the nodular constituent and the apparent decrease in the proportion of pearlite present nearer the weld junction with the central core is probably just a reflection of the increasing thickness of the blade away from the tip of the cutting edge.

The outer parts (b) and (c) of the cutting edge sandwich, also consisted of an acicular Widmanstatten distribution of ferrite and pearlite. The proportion of pearlite was generally quite low although it increased towards the middle of the section along the zone marking the junction with (a) in each case. This increase would appear to be the result of carbon diffusion outwards from the central piece (a) during the final heating and forging of the blade. The evidence of weld lines between these three parts of the cutting edge was difficult to see. Between (a) and (b) a narrow grey line of pearlite was fairly distinct, outlined by an adjacent line of ferrite whereas between (a) and (c) a faint grey line of pearlite could just be made out although it was not very clear. These lines appeared to mark the position of welds of a high standard to judge from the general absence of accompanying slag lines. The overall structure of the cutting edge was of a fairly even medium grain size.

Allowing for the heat treated nature of the microstructure it would seem that the outer pieces (b) and (c) of the cutting edge were very little more than wrought iron with a carbon content of probably no more than 0.1% and probably much less before diffusion from (a) took place. The central piece (a) was probably a low carbon steel with a carbon content of between about 0.2 and 0.3%. The quenching rate may have been quite rapid but, probably because of the low carbon content, too slow to give a fully quenched or martensitic structure. The cutting edge must have been assembled before being welded to the pattern-welded core of the blade.

Most of the welds between the composite strips, (d) - (h), and between the core and the cutting edge was marked by narrow grey lines of pearlite which in places were highlighted by adjacent white lines of ferrite and a little slag. Fig 34c clearly shows the rectangular shape of each composite rod in section as well as the very large, mainly triangular shaped, slag inclusions that were trapped at the corners of the composite bars when they were welded together.

The seven alternately dark and pale zones gave the rods (d), (f) and (g) a distinctive banded appearance in section. The darker zones consisted of a medium to fine grained mixture of unresolved pearlite and ferrite distributed mostly fairly evenly and in the same spiky looking Widmanstatten formation seen in the cutting edge. These areas contained very little slag. The pale zones consisted of very large grained ferrite with occasional streaks of pearlite and rather more slag than the darker pearlitic zones. Neumann banding was also visible in places in the large ferrite grains. The carbon contents of all the darker pearlitic zones, were low, mostly varying between about 0.1 (or less) and 0.2%.

The dividing lines beween the dark and pale zones of the composite rods, were quite sharp with little evidence for carbon diffusion across these boundaries and instead the pearlite tended to appear rather darker here. This thickening effect gave a darker grey appearance in outline to the pearlitic zones which sharpened the distinction between these and the pale ferrite bands. Little or no slag particles could be seen along these boundaries which would appear to represent near perfect welds.

The composite rod (e) mostly consisted of a thick grey band of Widmanstatten-like ferrite and pearlite with one narrow horizontal pale band of very large grained and the slight remains of a further dark band just showing on the corroded surface of the blade. The thick grey band appeared to be streaked in places with darker grey lines of pearlite suggesting that it might have been composed of several bands, or one piece folded and forged out several times (piled).

Only about half of the rods represented by (h) and (i) were included in the section. The part (d) was wholly composed of Widmanstatten pearlite and ferrite although in a similar way to those seen on (e) there were horizontal traces of darker pearlitic streaks possibly indicating weld lines between subdivisions. The piece (h) probably contained much the same seven alternate dark and light vertical bands as the adjacent pieces (d) and (f).

A hardness test was taken for each of the three parts of the cutting edge, the steel central piece (a) near the tip of the cutting edge and the two outer low carbon iron pieces (b) and (c) further in towards the weld with the core of the blade. The results were as follows: (a) 272 HV; (b) 207 HV; (c) 181 HV. For each of the pattern-welded pieces (d) and (h) a hardness test was taken firstly for one of the pale, very large grained ferrite bands and secondly for one of the darker grey bands where the pearlite content appeared to be at its highest, where the carbon content was about 0.2%. The results for these were as follows: (d) pale band 226 HV; darker band 221 HV; (h) pale band 261 HV, darker band 230 HV Fig 34b. The probable reason for the pale ferrite bands being harder even than the low carbon steel of the darker bands is a high phosphorus content for these bands.

The two main constituents of the composite rods of the core of the blade were low carbon iron or mild steel, of approximately 0.1-0.2% carbon, and high phosphorus wrought iron, and unlike the cutting edge there had been little diffusion between these banded areas. The observed microstructures indicates that the final forging temperature was probably round 850-900°C. from which it was finally quenched and the occurence of Neumann banding suggests that some subsequent cold hammering took place.

6.22 S10: Sword, from Mitcham, Museum of London, 56 : 106/14

The greater part of a badly corroded sword blade missing the tip, pommel, end of the tang, and parts of the cutting edge. It was found in the Anglo-Saxon cemetery at Mitcham in Surrey. Another sword from this cemetery (c.2444, with a surviving pommel) was given a 6th century date by Wheeler (Wheeler 1935, 175-6) and a similar date is likely for this example. A black encrusted (?wax impregnated) corroded surface masked the profile of the blade but, from the general appearance, a flattish, shallowly convex shape would seem most likely. Its length was 79.5 cm and approximate width 5.0cm.

X-radiographic examination

Radiography gave a rather fuzzy image with traces of superimposed criss-cross and straight grained effects along the central part of the blade (Fig 35a). The image appeared to show two triple sets of composite rods welded one behind the other to form this central part. On one side it appeared that a simple chevron or herringbone pattern had been achieved by welding three twisted composite rods side-by-side with adjacent twists running in opposite directions. On the other side, however, the two outer composite rods had been twisted and left straight at intervals resulting in an alternating pattern. The middle rod of this set appeared to have a continuous spiral. Fig 35d shows a diagrammatic reconstruction of how the pattern may have appeared on either side.

Exposure and film details

Kilovoltage	125	Exposure	60 seconds
Milliampage	5	Film	Kodak Industrex CX pre-screened roll film

Metallographic examination

A wedge-shaped section was cut from the blade 28.0 cm down from the shoulder or hilt on one side from a point which, on X-ray showed both criss-crossed and straight grained effects. Unetched, two fairly distinct formations of slag inclusions could be seen, although overall the slag content was fairly low. Lines of small two-phase, pale and darker grey inclusions, probably of wustite and a glassy matrix, marked the positions of weld lines between the main components of the section. These also showed that the two sets of triple composite pieces, recognised on X-ray, had been welded on to a separate core piece. Across the rest of the section an irregular scatter of slag inclusions of one or two darker phases (? fayalite and a glassy constituent) were visible, varying in size and shape between small spots and ribbon-like inclusions to larger more irregularly shaped inclusions.

When etched with nital, the structure shown in Fig 35c became visible. The cutting edge consisted mainly of two halves (a) and (b) with an additional small part (c) forming the tip of the cutting edge (Fig 35b). (a) and (b) consisted almost entirely of large grained ferrite whereas the extra piece (c) showed up a large grained structure of ferrite and lamellar pearlite which tended towards a spiky-looking Widmanstatten formation suggesting some overheating during final forging. A carbon content of about 0.4-0.5% would appear to be indicated for this piece (c) (Fig 35e). The weld position between (a), (b) and (c) has been masked by the extensive carbon diffusion outwards, from the steel piece (c) to the wrought iron of pieces (a) and (b), during the final heating and forging of the blade.

The composite pieces (d - i) had been welded onto a separate central core piece (j). All these pieces were made from wrought iron consisting of medium to large grained ferrite. The slag distribution in parts (e), (g) and (h) gave an overall folded appearance, showing these to be twisted pieces whereas in part (d) a fairly horizontal slag distribution indicated this to be an area of the blade which showed as straight grained on X-ray. Too little of parts (f) and (i) appeared in section to be certain of their structure but (f) is probably similar to (d), and (i) similar to (g).

The central core piece (j) consisted of a single piece of wrought iron which showed up as mostly very large grained ferrite. Some of the very large ferrite grains here and also in the other core parts showed Neumann banding or dislocation lines caused by cold hammering after final forging.

A further feature which showed up on etching and which further accentuated the weld lines between the various components were narrow grey lines of pearlite which upon higher magnification (Fig 35d) could clearly be seen interspersed with the pale and dark phase slag inclusions along these weld positions.

The steel part (c) of the cutting edge gave a hardness value of 203 HV whereas the iron parts (a) and (b) gave hardness values of 128 and 115 HV. The wrought iron central core part (j) gave hardness values of 123 and 96 HV. The iron of the pattern-welded pieces (d) and (g) gave hardness values of 104, 116 HV and 123, 108 and 105 HV respectively (Fig 35b).

This blade appears to have been made almost wholly of wrought iron, the exception being the small strip of steel used for the tip of the cutting edge. The blade was not quenched after final forging and not subjected to any additional heat treatments.

6.23 S45: Sword, from Mitcham; Museum of London, 56.106/13

A sword blade, complete except for part of the tang,from the Anglo-Saxon cemetery at Mitcham, Surrey. An approximate 6th century date has been given to another sword from the cemetery (Wheeler 1935, 175). The blade was in poor condition with a very pitted surface in which no structural detail could be seen, nor any distinguishing characteristics from which its type or date might be estimated. The blade was 84.9 cm long, including the surviving 6.0 cm of the tang and its maximum width 6.0 cm with an approximate maximum thickness of 0.5 cm. Date : c.6th century.

X-radiographic examination

Radiography of the blade showed very faint traces of what appeared to be a herringbone or double chevron pattern running down the central area and in a few places the pattern appeared to overlap to give a rather indistinct criss-cross effect (Fig 36a). No structure was visible along the cutting edges. The pattern would suggest that the central core part of the blade was made up of four twisted rods welded side-by-side with the twists of adjacent rods running in opposite directions (right and left hand spirals) so as to give the double chevron effect. It was not possible to say from the radiograph whether the core part of the blade was any more complex than this.

Exposure and film details

Kilovoltage	125	Exposure time	55 seconds
Milliampage	5	Film	Kodak Industrex CX pre screened roll film

Metallogaphic analysis

A wedge-shaped section was cut from the blade approximately 31 cm down from the tang (Fig 10). Before etching some small and ribbon-like slag inclusions plus a few larger inclusions were visible in the cutting edge. These inclusions were mostly of one, dark (? fayalite) phase. Over the central core area of the blade the slag content was much higher and more irregularly distributed although it was again predominantly of a similar dark phase. Weld divisions between different parts of the blade were difficult to see but appeared to be marked by broken lines of two phase slag inclusions where the predominant phase was a pale grey constituent, probably iron oxide (wustite), in a medium grey glassy matrix. The broken lines of these two-phase inclusions appeared to divide the cutting edge into two halves and the core part into four parts. A very large and irregular two phase slag inclusions of this type occured near the centre of the section where the two halves of the cutting edge, (a) and (b) in Fig 36b, joined the adjacent two parts, (c) and (d), of the core. This must represent slag entrapped at the main junction between these components when they were welded together. A very similar two phase inclusion occured at the central junction between the four parts (c), (d), (e), and (f) of the core area and this, too, must represent slag entrapped in the centre of the blade when the parts were welded together.

When etched with nital it became clearer that six separate parts, welded together, were visible on the section (Fig 36c), the two halves (a) and (b) of the cutting edge and the four composite core parts (c)-(f). The two halves of the cutting edge appeared to mirror each other along the central weld between the two. Along either side of this weld line was a fairly narrow margin of medium grained partially resolvable lamellar pearlite. Away from the weld this faded into very large grained ferrite of which the rest of (a) and (b) consisted. The cutting edge would, therefore, appear to have been made from two pieces of similar wrought iron, lightly carburised then hammer-welded together. The pieces might originally have come from one bar, subsequently cut in two.

The composite core parts (c)-(f) were similar to one another and consisted of large grained ferrite distributed in bands interleaved with areas of smaller grained ferrite with a little carbide at the grain boundaries. These were clearly what survived of four composite pieces welded together, without a separate central core piece, to form the middle part of the blade. They consisted essentially of wrought iron although before each of these composite pieces was itself welded together a partially successful attempt at carburization seems to have been made.

In the largest grained areas of ferrite, of both the cutting edge and core, Neumann banding was visible in places indicating that the blade was subjected to some cold working final forging.

The edge pieces (a) and (b) gave hardness values, near the tip of the cutting edge, of 199 and 221 HV respectively. A larger grain ferrite band in composite part (d) gave a hardness value of 179 HV whereas one of the grey bands of part (c), still predominantly ferrite, gave a value of 215 HV (Fig 36b).

Allowing for symmetry on either side of the blade, it would appear to have consisted of eight central twisted composite core components welded together back-to-back in two sets of four. To this were welded the cutting edges which themselves each consisted of two halves (Fig 36d). Despite the complexity of this construction, the blade was still essentially one of wrought iron although some degree of carburization appears to have been attempted, although this can have had comparatively little effect on the properties of the weapon.

6.24 S16: Sword, from Sarre; Maidstone Museum, K.A.S. 818

A nearly complete sword blade consisting of four fragments. It was excavated from grave (?) 264, of the Anglo-Saxon cemetery at Sarre, Kent (Brent 1864, 157). The end of the tang and several small fragments were missing from the blade which was in a very poor state, very corroded and flaky and appeared to be rusted right through in places. Its length was 85.7 cm; width 6.0 cm and thickness difficult to gauge but , allowing for expansion during corrosion looked, from the breaks to have been about 0.5 cm. The width included the thick uneven crust of rusty corrosion products round the blade part of which were the barely recogniseable remains of a scabbard.
Date : approximately 6/7th century.

X-radiographic examination

Radiography showed some structural but not very clear detail to the sword (Fig 37a). A core with three adjacent composite rods could be seen running down the centre on either side of the blade. These mostly appeared to give the pattern shown in Fig 37f with twisted parts, giving a diagonal pattern, alternating with straight grained lengths. Some very slight indications of a straight grained effect could be seen along the cutting edges. Several cracks were visible on the radiograph between both the cutting edge and the core and between composite rods in the core. These are probably the result of corrosion penetrating and proceeding along the welds between these parts and where this cracking was noticed, between the composite rods, it was probably a fairly good indication that there was no separate central core piece to the blade.

Exposure and film details:

Kilovoltage	125	Exposure	60 seconds
Milliampage	5	Film	Kodak Industrex CX prescreened roll film

Metallographic examination

A wedge-shaped section extending approximately halfway across the blade was cut from an area near the hilt end of the sword where, on the radiograph, metallic survival appeared to be better. When viewed unetched the slag content appeared variable but mostly quite low but there were a few very large inclusions which along with broken lines of much smaller inclusions appeared to mark weld positions between component parts of the blade section.

Etching with nital revealed the structure shown in Fig 37c and drawn diagrammatically in Fig 37b. The cutting edge was made of two halves (a) and (b) which were divided by a horizontal weld line marked by a pale ferrite line which coincided with a line of flattened slag inclusions. This line stood out in contrast to the grey fine grained pearlite on either side and also showed up as a raised ridge under oblique illumination. The proportion of pearlite in (a) and (b) was low and the carbon content approximated to 0.1% at most. The pearlite which was partially lamellar and partially granular or irresolvable in appearance, mostly faded out towards the cutting edge tip and the grain size progressively increased and was quite large in these ferrite areas where the short rod-like nitride or carbide formation showed up in places.

The weld between the cutting edge and the core part of the blade, marked partly by slag inclusions, was mainly shown up by a superimposed white line which contrasted sharply with the grey pearlite areas of the edge parts (a), (b) and the adjoining paler ferrite areas of the core (Fig 37d). There had been little carbon diffusion across this weld and consequently the line remained clear. Parts (c) - (f) of four composite rods were represented on the section although only a small area of each of (e) and (f) were included. These composite pieces were welded back-to-back with no intermediate central core pieces. The weld lines between them were fairly clear, marked by lines of slag inclusions which were highlighted in places by the contrast between grey pearlitic and the paler ferritic parts of adjacent composite pieces. The composite pieces were all similar in composition each consisting of alternate pale and darker grey bands.

The bands in each case bore a distorted or folded appearance which showed in section the twisted nature of the composite rods. The pale areas of the composite core pieces consisted of large grained ferrite which in places also showed up more of the short rod-like nitride or carbide formation (Fig 37d)seen in the ferrite areas of the cutting edge. The grey proportion of pearlite in the fine grained grey bands was low, the carbon content being about 0.1%. The boundaries between these ferritic and pearlitic bands showed up mainly as a result of the contrast between the paler and darker bands. Little carbon diffusion appears to have occurred between these areas and virtually no slag inclusions show up along these lines which must mark the positions of welds between the parts that together formed these composite rods.

Four pairs of hardness readings were taken for the edge of the blade, one pair near the tip or cutting edge end of part (b) and a pair each for parts (a) and (b) further in towards the inner weld and a final pair for part (a) near the inner weld. For these the values obtained were 165 and 170 HV; 132 and 135HV; 122 and 128 HV; 129 and 129 HV. Pairs of hardness readings were taken for one of the large grained ferrite bands of pattern-welded parts (c) and (d) and a pair of readings for one of the grey slightly pearlitic bands in part (d). The values obtained were: 124 and 129 HV; 163 and 172 HV; 108 and 113 HV (Fig 37b)

6.25 S31: Sword from Caversham, Reading; Reading Museum, 51:80

The remaining lower half of a sword blade found at SU7386 7511. No further details were given and the circumstances of its findings are not known. Its condition and the way it had corroded suggested that it was a river find. It had corroded very unevenly with some parts corroded right through while in some places the surface, as well as the metal core, was well preserved as was the wide shallow central fuller that ran down either side of the blade. What remained of this blade fragment survived mostly as metal and deep etching by corrosion had revealed some of the internal structure of the blade. Parts of what appeared to be a triple banded pattern-welded structure were visible in the central fullered part of the blade, and in places, the cutting edge had a coarse straight grained appearance. The broken end of the blade was very irregular and badly corroded and there was no indication as to whether the sword had been already broken or bent when it was lost or buried.

The blade profile, with the wide shallow fuller, is very similar to that of 6.26 below which has been given an approximately 7th-9th century date. This blade is unlikely to be earlier so an approximately 7th-9th century range is probably the safest estimate.

X-radiographic Examination

Radiography of the sword confirmed the observations described above but provided a little more detail. A triple banded pattern-welded element to the blade could clearly be seen (Fig 38a). The chevron or herringbone pattern appeared to overlap in places which is probably indicative that two separate sets of triple twisted composite strips form the surface of the central part of the blade on either side.

On one side the chevron pattern appeared to alternate in places with straight grained variations to the pattern. Some traces of straight graining also appeared to represent a central plain core onto which the three twisted strips were welded. The cutting edge also showed a fairly pronounced straight grain effect. The exposure and film details of the radiograph are given below:

Kilovoltage:	125	Exposure times:	60 secs
Milliampage:	5	Film:	Kodak Industrex CX pre-screened roll pack

Metallographic Examination

A transverse wedge-shaped section was cut (Fig 10) from an area where the surface on one side of the blade, survived quite well.

Unetched, a very variable slag content was visible in different parts of the section although no very clear weld lines were discernible.

When etched with nital the structure of the section became very much clearer. The horizontal weld lines marking the division between central plain core of the blade and the outer twisted composite parts showed up as clearly visible dark lines (Fig 38b). The surviving weld junctions between the composite surface strips, cutting edge and the central core also became clear as dark grey lines. These lines consisted mainly of pearlite which coincided in places with discontinuous lines of small slag spots and ribbons. Although not so clear on the macrograph it was possible to separate the cutting edge area of the section into four different areas from which it appears that the cutting edge was assembled from four separate pieces (a) - (d).

The central part (d) of the cutting edge consisted of a piece of pearlitic steel with a carbon content of approximately 0.3% near the centre which decreased fairly evenly towards the boundaries with (b), (c) and (e) where it varied between about 0.1 and 0.2%. The slag content of (d) was mostly fairly low - mainly fairly evenly distributed small spots and ribbons with a few larger inclusions. There has clearly been much carbon diffusion outwards across the weld boundaries between (d) and (b); and (d) and (c). All the welds on the section, were of very high quality with little slag marking the boundaries. Part of the weld boundary between (d) and (c) was also clearly marked by a grey line of pearlite. By contrast the weld between (b) and (d) had been masked by carbon diffusion from (d). Part (b) however consisted of a very large grained ferrite with much slag mostly as fairly small ribbons but with some larger more amorphous inclusions. The slag was aligned along the section and gave part (b) a rather streaky appearance. Part (e) also consisted mainly of very large grained ferrite but, in contrast to (b), contained little slag.

The tip part (a) of the cutting edge consisted of a separate strip of high carbon steel which showed up as a very dark wedge-shaped area bounded on the inside by two rather faint and fuzzy white lines which are themselves highlighted by further dark fuzzy areas. This strip had been welded between the two outer edges of strips (b) and (c) during the assembly of the cutting edge. It consisted of a mixture of very fine martensite with very dark etching nodular troostite (radial pearlite). The grain structures became much coarser towards the welds and the proportion of nodular troostite increased. The white lines coincided with a rather indistinct line of slag spots and appear to mark the position of welds between (a) and (c), and between (a) and (b). The further dark fuzzy zone round the outside of (a) is indicative of extensive carbon diffusion outwards from (a). The quenched structure of (a) means that only an approximate estimate of 0.5-0.8% for the carbon content is possible.

The grainy appearance on the radiograph of the cutting edge of the blade is most probably a result of the high slag content of strip (b) with the effect magnified by corrosion around and along the slag filaments.

The central part of the blade did consist of two sets of three composite strips welded side by side on to either side of a central plain core. The central core (e) consisted of a fairly even low carbon steel, carbon content approximately 0.1-0.2%. The pearlite here was difficult to resolve but appeared mostly fine grained and rather amorphous but somewhat granular in places. Slag content was fairly low with some ribbons, spots and the occasional larger inclusions. The composite strips (f), (g) and (h) consisted mostly of ferrite. The alternate light and dark folded bands of each strip consisted of interleaved (light) areas of very large grained ferrite with little slag, and (darker) areas medium grain size ferrite with a little carbide distributed around the grain boundaries and much slag which occurred as large and small two-phase inclusions, some fairly well flattened. Although each of these composite strips probably consisted of six interleaved strips welded together (piled) then twisted and forged flat, there is almost no trace left of any welds between the component bands. What slag there was occured within each band and not at the weld boundary which was only marked by the contrasting structural appearance of each band. These welds were clearly of a very high standard.

After assembly and final forging the blade was quenched, probably in water, from about 800° C. The martensitic tip, part (a) of the cutting edge, gave a hardness value of 775 HV. The pearlite and ferrite of the central part (d) of the cutting edge gave a hardness of 193 HV whereas the outer ferrite parts (b) and (c) gave values of 149 and 192 HV. The low carbon central core piece (e) gave a hardness value of 162 HV. Two hardness readings were taken for the pattern welded part (h), from one of the very large grain ferrite bands and from one of the smaller grained ferrite bands with much slag. These gave results of 217 and 167 HV respectively. A large grained ferrite area of pattern welded part (f) gave a hardness value of 178 HV and one of the medium grained ferrite bands with much slag, a value of 195 HV. The rather high value for some of the ferrite areas may indicate a higher phosphorus content for these parts.

EPMA analysis confirmed this and the white high phosphorus bands show clearly in the phosphorus map, contrasting with the darker, low phosphorus bands (Fig 38c).

6.26 S46: Sword, ? from the Thames, Museum of London, 0-2112

The greater part of a sword blade with tang and iron pommel surviving in place. It was found probably in the river Thames at Old England, Brentford. The effects of corrosion were very uneven with a good original lightly patinated surface surviving in some places while other parts particularly near the broken end had completely corroded away. The surviving blade fragment was 79.0cm long by 6.4 cm wide with an approximate maximum thickness of 0.4 cm. The pommel looked like a derivative of the cocked-hat form and was similar to the iron pommel on the sword from Walthamstow illustrated in London and the Vikings (Wheeler 1927, Plate X111). The blade was also similar in that it had a fairly shallow fuller running down the centre on either side, a feature commonly found on blades of the 9th century and later. Wheeler suggested a 7th-8th century date for the Walthamstow sword but the derived form of pommel and the fuller might indicate a somewhat later date, possibly 8th-9th century, for the Brentford sword.

Surface corrosion on the blade had left clear evidence that the blade was made from a number of parts which included composite twisted pieces which had left a chevron pattern visible on the surface on both sides. A double chevron pattern was visible with the ridge on either side of the fuller forming the centre of the chevron in each case, and the chevrons pointed up towards the hilt on one side of the blade and down on the other. A straight grained effect showed up along the central part of the fuller on either side.

X-radiographic examination

Radiography confirmed the structure already seen on the surface of the blade. The chevron pattern showed up as a criss-crossed effect on the radiograph and this appeared to be unchanged down the length of the blade. There was no indication of more than one twisted composite piece occupying the thickness of the blade. On the radiograph the central part of the blade showed a clear straight grained effect suggesting a separate centre core dividing two separate sets of twisted composite pieces. The cutting edges however showed little or no evidence of any structural detail.

Metallographic Examination

A wedge-shaped section was cut from the blade near the broken end (Fig 10). Before etching the section showed a fairly low overall slag content, mostly small spots and ribbon-like inclusions either of a dark grey (?fayalite) phase or of two phases, grey and darker grey (?fayalite and a glassy matrix). Some intermittent lines of small slag inclusions mainly of a pale grey phase (wustite) were probable indications of weld lines between different components.

Etching with nital (Fig 39c) showed the section to consist of seven separate pieces (a)-(g) in Fig 39b. The cutting edge consisted of a sandwich of three parts (a) (b) and (c). Parts (a) and (c) showed up as a fairly even small-medium grained pearlite in ferrite with a carbon content of about 0.1%. The middle part (b) etched much darker and showed up as patches of tempered martensite against a dark background which looked like a poorly resolved lamellar pearlite also exhibiting a spiky looking Widmanstatten appearance.

This imperfectly quenched structure suggests a barely quenchable medium carbon steel of about 0.3-0.4% carbon. Fairly extensive carbon diffusion outwards into parts (a) and (c) had also taken place. The weld lines on either side of part (b) showed up in each case as a white line superimposed on a broken line of pale grey (?wustite) slag inclusions. Other horizontal white lines were visible in parts (a) and (c) which may be indicative of piling. The three parts of the cutting edge appear to have been hammer-welded together before being welded to the main body of the blade.

The twisted composite parts (d) and (e) each occupied the full thickness of the blade. Part (d) consisted of alternate bands of large grained ferrite, and medium grained ferrite and pearlite with a carbon content of about 0.1%. Part (e) appeared to consist of a fairly even distributuion of medium grained pearlite with a carbon content of about 0.1% and the twisted nature of this piece was marked by the curved or folded lines of slag inclusions. Part (e) also contained more slag inclusions, than the rest of the section.

The central strip, which gave a straight grained effect on X-ray, was found to consist of two halves (f) and (g) welded together before welding to the composite twisted parts. Parts (f) and (g) were, however, very similar in appearance, each giving a very darkly etched appearance and appeared to be separated by a weld line marked by a white line superimposed on an intermittent line of a few spots of pale phase slag, probably wustite. These dark areas showed a mainly fairly even martensitic structure. This structure allows only a rough approximation of carbon content, within the region of 0.4-0.8%. The fully quenched structure may indicate a figure nearer the higher end of this range and the darkness of the martensite indicates some light tempering, possibly auto-tempering. Fairly extensive carbon diffusion between parts (f), (g), and (e) appears to have taken place.

The martensitic area of part (b) near the tip of the cutting edge gave a hardness value of 647 HV. The low carbon parts (a) and (c) gave values of 212 and 215 HV. The twisted parts (d) and (e), which gave rise to the chevron pattern, gave hardness values of 236 and 230, 243 HV respectively, possibly indicative of a high phosphorus content in these pieces. The martensitic central blade pieces (f) and (g) were the hardest parts of the section with values of 788 and 737 HV.

The central part of the blade would appear to have consisted of six pieces, two middle strips, welded back to back, of fairly high carbon steel on either side of which were welded, side by side, two twisted composite rods consisting of wrought iron or low carbon steel. The cutting edges (assuming they were both the same) consisted of a sandwich of a medium carbon steel central piece welded between two outer pieces of wrought iron or low carbon steel.

After final forging the blade appears to have been quenched in water and possibly lightly tempered.

6.27 S7: Sword, ? from the Thames; Museum of London, C2260

The upper part of a sword blade with a straight iron guard and a flattish semicircular iron pommel. Its surface was heavily pitted by corrosion but underneath this the metal survived quite well. The total surviving length was 62.5 cm with a maximum blade width of 5.2 cm but it was too corroded to determine the original profile. The find site is uncertain but its condition suggests that it came from a river and the Thames in or near London would seem most likely. It does not readily fall into one of the Wheeler or Petersen types but the short straight guard is typical of Wheeler's Type I (c 9/10th century) although the pommel might indicate a later date, therefore a fairly wide date range, c 9/11th century is suggested here.

There was no indication of it having been broken or bent before submersion and the loss of the lower part may be the result of differential corrosion and water movement.

X-radiographic examination

Radiography showed a fairly clear straight grain effect in places along the length of the blade but no other indications of structure.

Metallographic examination

The projecting part of the broken end of the blade was cut off to give a section representing about half the width of the blade. Examination of the unetched section revealed a sparse but even distribution of slag inclusions with no obvious linear concentrations that might indicate a weld line between different components. The inclusions were mostly small and of one or two darker grey phases (? fayalite and a glassy constituent).

Etching with nital revealed the structure visible in Fig 40b which shows a rather curiously patchy looking appearance in which the white speckles are ferrite forming a matrix around areas of pearlite interspersed with paler patches of martensite and the very dark fast etching nodular constituent, radial pearlite or troostite (Fig 40c). This structure was fairly even across most of the section although it was more predominantly martensitic near the tip of the cutting edge. A rather irregular and faint white (ferritic) line just visible running verticially across the centre of the section (Fig 40b) might suggest a weld position between the cutting edge and core parts of the blade although no corroborative proof such as a (faint) line of slag inclusions could be seen. The structure visible on either side of this line shows that a fairly homogeneous steel was used across the whole section and therefore, probably the whole blade. Weld lines can sometimes leave virtually no trace and so this white line may indicate where a single piece of steel was folded and skillfully welded together during the preparation of the metal for the blade.

It is assumed here that a single homogeneous piece of steel was used to make the blade, however it was prepared beforehand. It was quenched but not tempered, resulting in the structure shown. The carbon content is difficult to estimate in this state but a medium carbon steel of somewhere between about 0.3 and 0.6% carbon can probably be assumed. The incomplete (only partially martensitic) nature of the quenching may be the result of slack quenching, possibly in oil, as opposed to water quenching, or it might be the result of a carbon content towards the lower end of the range suggested above (about 0.3%).

Hardness values averaging 477 HV were obtained for the area near the tip of the cutting edge, a typical hardness for the not fully martensitic structure encountered here. The dark etched area nearer the centre of the blade gave values averaging 268 HV and the palest finer grained areas of ferrite and pearlite, also near the centre of the section, gave an average value of 142 HV. This last value is fairly typical of a low carbon steel which may indicate that the estimate of 0.3% carbon for this piece is approximately correct, the other variations in values indicating the variable effectiveness of the quenching to which the blade was subjected.

6.28 Sword, ? from the Thames; Museum of London, C2258

The upper part of a sword with short straight upper and lower iron guards still in place. The surface was badly but evenly pitted by corrosion although beneath this the metal survived quite well. The total surviving length was 37.9 cm and the maximum blade width was 5.5 cm. The find site is uncertain but the state of preservation again suggests a river bed with the most likely possibility being the Thames in or near London. The short straight upper and lower guards are of the Wheeler type I (Wheeler 1927, 31 - 32) and therefore the sword may be of a 9/-10th century date. The original profile of the blade had been removed by corrosion but a faint hint of a shallow fuller could be made out running down the centre of the blade. There was no evidence that the blade had been broken or bent before submersion and the loss of the lower end may be largely the result of differential corrosion.

X-radiographic examination

Radiography produced a rather fuzzy image with little detail although some traces of a straight grained effect was visible in places.

Metallographic examination

A wedge-shaped section was cut from one side of the blade approximately 10.0 cm down from the lower guard. (Fig 10). Unetched the section exhibited a rather uneven distribution of slag inclusions of one or two darker grey phases (? fayalite and a glassy constituent).

When etched with nital one half (horizontally) of the section became a dark grey while the rest remained pale (Fig 41b) and this suggested that the blade was made from two pieces, one of steel and one of wrought iron welded together and forged out (Fig 41e).

The pale half was of large grained ferrite whereas the darker half consisted of spheroidised pearlite - a distribution of cementite globules in a ferrite matrix (Fig 41d). At its densest this appears to correspond to a carbon content nearing the eutectoid (about 0.8% carbon). There was no discernible line of slag particles indicating the position of a weld between the two halves and there has clearly been much carbon diffusion, from the steel part to the wrought iron part, resulting in a rather diffuse junction between the two halves (Fig 41c). It seems unlikely that this structure could have been achieved any other way than by the welding together of a piece of wrought iron and a piece of steel despite the apparent absence of a visible weld line. The extensive carbon diffusion was probably the result of prolonged heating during or after the final forging and the spheroidised nature of the pearlite indicates that a further fairly prolonged period of heating took place but this time it must have been below the critical temperature of about 700°C at which pearlite re-dissolves.

A series of micro-hardness readings were taken from points running across the section. The results of these varies between 81 HV in the ferrite area to 125 HV in part of the intermediate zone containing approximately 0.4% C and rose to a maximum value of 172 HV in the higher carbon (0.8%) area. The lower value is typical of a fairly pure wrought iron and the higher value consistent with a higher carbon steel that has been subjected to sub-critical annealing. This final heat treatment would have toughened the steel of the blade thereby rendering it less liable to cracking when flexed.

6.29 S43: Sword, from the Thames; Museum of London, A17923

The upper part of a sword blade with tang and grip found in the Thames near London (with no more specific findspot known). The remains of a wooden grip with traces of a fabric covering or binding were quite well preserved. A distinctive downward curving lower gross-guard of iron survived in place as did half of an upper straight cross guard (although there was no sign of any additional pommel).

It was classified by Wheeler as being one of his Type I swords of c. AD900 (Wheeler 1927, 36). the total length of the sword fragment was 32.5 cm, the maximum blade width approximately 5.1 cm. The blade appeared to have a roughly flat backed profile and was about 0.5 cm at its thickest although this was difficult to gauge owing to the poor state of preservation of the surface which was quite heavily pitted by corrosion which had also removed much of the edges. The broken end was heavily corroded and the break was clearly not recent and may have been the result of differential corrosion as there were no signs that the blade had been bent or broken before its deposition in the river. Traces of pattern-welding were visible down the central part on either side of the blade. This appeared to show up as a continuous chevron pattern on either side. In one or two patches, where the corrosion was deeper and the chevron pattern was missing, hints of a straight grain effect survived in the corrosion products suggesting that the blade might have a central core piece.

X-radiographic examination

This confirmed the visual impression that the blade was of a pattern-welded, composite construction (Fig 42c). The double surface image of the chevron pattern showed up as being criss-crossed in some areas. A pronounced straight grained effect also was clearly visible along the central part of the radiograph but this appeared to bear no relation to the chevron effect, although the images overlapped.

It would appear that the central part of the blade consisted of two sets of three parallel twisted composite bars welded side-by-side, one on either side of a plain core piece. The three twisted composite bars on one side of the blade appeared to have been welded side-by-side with the twist of the central bar going in the opposite direction to the other two thereby giving the chevron effect. On the other side, however, two adjacent bars appeared to have twists of the same direction, whilst that of the third was opposite which gave a curiously lopsided effect, possibly a mistake made during welding. A reconstruction of how the pattern may have appeared are shown in Fig 42d. The cutting edges on either side of the blade did not exhibit any visible structural effects.

Exposure and Film details

Kilovoltage:	110	Exposure times:	2 minutes
Milliampage:	60	Film:	Kodak Industrex CX used with lead screening sheets, 0.10mm front and 0.15 mm rear

Metallographic Examination

A wedge-shaped transverse section was cut from the blade (Fig 10). When examined unetched a rather uneven slag content could be seen. This varied most in the central part between areas with much slag, both large irregular inclusions, mainly of a single dark phase - (?fayalite) and smaller ribbon-like inclusions, also of one dark phase, and other areas with almost no slag at all. No clear signs of slag distribution along weld lines could be seen.

When etched with 2% nital the structure shown in Fig 42b became visible. The sketch of Fig 42a shows this more clearly. The cutting edge, which had shown very little structure on X-ray, appeared to consist of two parts, an outer steel part (a), folded around an inner wrought iron part (b). The carbon content of part (a) varied between about 0.8% in places near the tip, where an almost eutectoid structure of fairly coarse but partially spheroidised lamellar pearlite was visible, down to about 0.1% near the weld junction with part (b) where the spheroidised effect was more pronounced. The grain size was mostly even and small. The weld junction between (a) and (b) was quite clearly marked by a thin grey line of pearlite superimposed on a white line of ferrite but not accompanied by any lines of entrapped slag particles. Part (c), by contrast, consisted of medium grain ferrite with more slag than (a), the inclusions varying in shape, size and distribution by contrast with the more even distribution of fairly small inclusions (a). Fairly extensive carbon diffusion had taken place across the weld boundary between (a) and (b) - showing as an even margin of pearlite along, but steadily decreasing away from the weld.

The central part of the blade was made by welding three twisted composite pieces onto either side of a comparatively thick core piece (Fig 42b). The core piece (c) mostly consisted of a medium grain sized ferrite with varying amounts of slag (one dark phase - ? fayalite) mostly small spots and ribbon-like inclusions unevenly distributed across it. Nitride or carbide needles were also visible in places. There was also a horizontal band (f) across the central part of this core piece which was marked on either side by a fairly clear narrow line of pearlite superimposed in places on white lines apparently of ferrite which may mark the position of welds along either side of this band. The band (f) contained very little slag and consisted of a distribution of fairly well spheroidised fine grained pearlite against a ferrite background. The proportion of pearlite was approximately 0.1-0.2% near the centre and this decreased evenly outwards towards and across the boundary with the main central core part (c).

From this it would appear that the main central core part (c) of the blade consisted either of wrought iron folded round a narrow strip of low carbon steel, or two similar pieces of wrought iron with a low carbon steel piece welded between and the resulting sandwich forged out to form the core of the weapon (Fig 42d).

Parts of two composite twisted strips, (d) and (e), were visible on either side of the central core piece (c). The carbon content of these strips was fairly even but low mostly below about 0.1% and the pearlite of these was quite well spheroidised. Slag content was also low and consisted mostly of small well flattened inclusions mainly of one dark phase (? fayalite). These surface composite strips (d) and (e) were quite thin, partly a result of surface corrosion, and the weld lines between each of them and the central core piece (c) was fairly clearly marked by a narrow grey line of pearlite.

It had been expected that (d) and (e) would be resolvable into two surface composite strips on each side although only a small part of the second piece would have occurred on either side. No obvious sign of a vertical weld could be seen on either side although what survived of these surface strips was very narrow and so even quite a clear weld might have been difficult to see. It can only be concluded that poorly marked, good quality, welds may well have been present but that they were not discernable in the section.

Combining the results of radiography and metallography it can be concluded that the blade is likely to have been made from ten separate parts in approximately the following order: A central core part mostly of wrought iron appears to have been folded round a thin strip of fairly low carbon steel. Side by side on either side of this were welded three parallel thin twisted composite strips, of very low carbon steel barely more than wrought iron. The cutting edge with its steel outer part welded around a wrought iron inner piece must have been produced separately then hammer welded on to either side of the central part once this had been assembled. The blade must then have been forged out to produce its final shape. The fairly high degree of carbon diffusion observed in section and the partially spheroidised nature of the pearlite indicates that the complete blade underwent fairly prolonged heating during the final forging; but this heating did not exceed about 700°C. The spheroidised structure of the pearlite also indicates that no further heat treatment took place.

A hardness value of 256 HV was obtained for the higher carbon area of part (a) near the tip of the cutting edge. The hardness of the inner edge part (b) averaged 150 HV. The central core piece (c) gave values of 167 and 177 HV and the pattern-welded surface piece (e) a value of 179 HV. These values are rather high for what is predominantly ferrite and probably indicates the presence of an alloying element such as phosphorus although the smaller grain size of the ferrite and the degree of diffusion of carbon from (a) to (b) may argue against phosphorus itself.

6.30 S48: Sword, from Rochester, Maidstone Museum, 13:1956

A sword blade including part of the tang, with a straight lower iron guard surviving in place. It was found by chance near the junction of Watts Avenue and St Margaret's Street in Rochester, Kent, and evidently came from a grave, although nothing further appears to have been recorded concerning its finding. It was fairly heavily corroded and parts of the edges were missing on one side, although the surface appeared to survive quite well in some places and it appeared otherwise to have a good metallic content remaining. A shallow fuller could also be seen running down the centre of either side of the blade. The straight guard was similar to those of Type I or Type IV in Wheeler's classification (Wheeler 1927) which may suggest a 9th-10th century date and a fullered blade of this kind is fairly typical of swords of the Late Saxon Period. The total surviving length was 78.8 cm, with a maximum width of 5.2 cm. the blade tapered gradually towards the tip.

X-radiographic examination

Radiography of the blade revealed it to have a pattern-welded core running down the centre of the blade (Fig 43c). This appeared to alternate between panels which showed a straight grained effect and panels which either showed a criss-cross effect or one of parallel diagonal lines. The absence of criss-crossing on the sections which show the parallel diagonal lines indicates that more than one composite twisted bar occupied the thickness of the blade because this effect is only possible by the superimposition of the images of at least two components which have been twisted in opposite directions so that the images of the surfaces appear on radiograph as parallel rather than criss-crossing lines. A straight grained effect was also visible in some places along the cutting edges.

It is clear from this that the surface part of the central zone of the blade on either side consisted of a separate pair of composite rods twisted in alternating sections and welded side by side. It appeared that each pair was then welded back-to-back to form the central part of the blade to which the cutting edges were added. No sign of a separate central core piece could be seen on the radiograph.

Exposure and film details

Kilovoltage	130	Exposure time	60 seconds
Milliampage	5	Film	Kodak Industrex CX pre-screened roll film

Metallographic examination

A wedge-shaped section was cut from the blade approximately 13.5 cm from the tip (Fig 10). Unetched this showed a variable but mostly low slag content. There was more slag visible in the middle of the blade and the inclusions were mostly small and ribbon-like, mostly two phase, medium and darker grey (? fayalite and a glassy constituent) although some showed up a different two phases - pale grey on a darker grey background (? wustite and a glassy constituent).

When etched with nital it became clear (Fig 43b) that the section was made from three main parts, the cutting edge (a) and two composite core parts (b) and (c) (Fig 43a). A large triangular two-phase slag inclusion - pale grey on a darker background (? wustite and a glassy matrix) - had become trapped in the weld junction between parts (a) (b) and (c) and a large ribbon like inclusion of a similar two phase slag was visible where it had become trapped further along the weld junction between parts (b) and (c), near the centre of the blade.

The edge piece (a) consisted of three parts, a horizontal darker etched band (a2) between two bands (a1) and (a3), of large grained ferrite. The darker band (a2) consisted of fairly small grained poorly resolved pearlite in ferrite in a spiky looking Widmanstatten formation with a carbon content of about 0.2 - 0.3%. Near the tip of the cutting edge the ferrite and pearlite gave way to a coarse, mainly martensitic structure. The structure appears to represent incomplete quenching, the effects of which were most pronounced at the tip. The lack of visible welds between (a1), (a2), and (a3) makes the presence of a low-medium carbon steel band running through the cutting edge between two outer bands of wrought iron is difficult to explain. It might represent one steel piece that has become excessively decarburised but is possibly more likely to have been made from three pieces very skillfully welded together so as to leave no entrapped slag to reveal the site of the welds.

The composite core pieces (b) and (c) were both very similar with a banded appearance showing the composite nature of the structure. The pale bands consisted of large grained ferrite alternating with grey bands of poorly resolved medium grained pearlite and ferrite with a spiky-looking Widmanstatten structure and carbon content of about 0.1% to 0.2%. The carbon distribution was fairly even across these darker bands with some diffusion across the welds into the pale ferrite bands.

The martensitic area near the tip of the central part (a2) of the cutting edge; gave a hardness value of 564 HV. A little further in from the tip where the proportion of martensite was less, a value of 305 HV was obtained. About three-quarters of the way between the tip of the cutting edge and the inner weld, three hardness readings were taken across the edge parts (a1), (a2) and (a3) giving values of 179, 226 and 195 HV respectively. Two hardness readings were taken in the composite part (c); one of the smaller grained ferrite + pearlite bands giving a value of 200 HV, and one of the larger grain ferrite bands a reading of 163 HV.

The composite pieces of the core of the blade appear to have consisted of alternate wrought iron and low carbon steel strips. The cutting edge may have consisted originally of three separate parts forming a sandwich of a piece of low-medium carbon steel between two pieces of wrought iron. The blade was quenched after final forging.

6.31 S23: Sword, from Thames near Reading; Reading Museum 112.66/1

A complete sword in two parts, broken about a quarter of the way along the blade from the tip. A thick straight iron guard and similar pommel still survived in place. The surface of the sword was badly pitted by corrosion but traces of a wide central fuller could still be seen running along the central part of the blade on both sides. The straight guard and pommel are similar to the Petersen type H and the Wheeler type I (Wheeler 1927, 31-2) which indicates the sword to be a Late-Saxon period weapon probably of the 8th-10th century.

X-radiographic examination

A radiograph of the sword (Fig 44c) revealed that a lettered or similar design had been inlaid into the surface of the blade on both sides near the hilt. The inlaid design appears to have been contained within the fuller of the blade and consisted of a series of uprights (at right angles to the cutting edge) and diagonal pieces of twisted or pattern-welded iron rods forged into the surface. An interpretation of the form of the design is given in Fig 44e. The type of design is quite common and has been found on a number of Viking age sword blades in both Britain and Scandinavia (Thalin - Bergman 1979, 125). The radiograph was difficult to interpret for fine detail because of the many corrosion pits on both sides of the blade but it was just possible to see hints of a straightish 'wood grain' effect in places. It is doubtful, however, if the corrosion had occurred more evenly whether the 'wood grain' would ever have been more than fairly faint on the radiograph.

Metallographic examination

A section was cut from the tip fragment of the sword, along the edge of the break with the main part of the blade (Fig 10). The section was thus an oblique transverse section and was at an angle of about 60° with the cutting edge, and it also extended about two thirds of the way across the blade.

Before etching, the section showed a few slag inclusions of mostly fairly uneven size and distribution. A line of slag particles running diagonally across the centre of the section showed the position of a scarf weld. A diagonal weld like this is indicative of a scarf weld running down the blade between two main components. The cutting edge area appears to be divisible into three-parts separated by discontinuous lines of slag inclusions along which much corrosion had taken place. Corrosion was also visible along the scarf weld and around some of the other larger slag inclusions.

The section etched rapidly and the result was rather patchy and uneven looking - although the central scarf weld and corroded slag lines of the cutting edge zone did show up (Fig 44b). A paler band, (between the two corroded slag lines, was visible with a darker area towards the central scarf weld and a narrow rather blotchy area towards the tip of the cutting edge. The cutting edge thus appeared to consist of a sandwich of three parts.

Examination under higher magnification revealed that the outer part of the sandwich consisted mainly of (paler etching) martensite with some irresolvable (darker etching) pearlite.

The middle paler band appears to consist of a mixture of irresolvable pearlite and ferrite. The inner darker part consisted mainly of dark etching irresolvable pearlite with small patches of dark etched martensite.

The central fullered part of the blade, consisted mostly of dark etching irresolvable pearlite with some ferrite and patches of paler etching martensite. Also visible across much of this part of the section was an outline, in ferrite, of a large grain, former austenitic structure infilled by the generally dark fine grain structure of an irresolvable pearlite mixed with ferrite and martensite.

This middle part of the blade is clearly a fairly homogeneous piece of steel. A good quality steel appeared to form the greater proportion of the cutting edge. The presence of dark etching irresolvable pearlite and martensite with a particular concentration of martensite in the outer part of the cutting edge shows that the blade had been quenched fairly rapidly from a temperature above the lower critical point of 723°C although not fast enough to give a fully quenched martensitic structure.

Six hardness readings were taken across the section. The martensitic area near the tip of the cutting edge part (a) gave a value of 762 HV. The paler band (b) and higher carbon part of (c) gave hardness values of 292 and 383 HV respectively. Two of the higher carbon non-martensitic areas of the central part (d) gave hardness values of 423 and 329 HV respectively whereas a mostly ferrite patch of part (d), near the blunt end of the section, gave a value of 178 HV (Fig 44a).

The survival of a ghost image of a former large austenite grain outline shows that the sword was not heated very far above the lower critical point before quenching. The quenched structure made a more accurate assessment of carbon content, difficult although a carbon content in the region of 0.6 - 0.8% C over much of the blade seems most likely. The surviving ghost image of a former austenite, grain outline would not be possible had the temperature risen above the upper critical point which would have probably been between about 750 and 800°C. In this case the sword blade was probably quenched from a temperature of 725-750°C.

6.32 S47: Sword, from the Thames; Museum of London, A 3670

The remaining upper part of a sword with a straight iron lower guard and upper pommel guard surviving in place. The lower guard also has the remains of a copper alloy cladding on it. Wheeler places this sword fragment with Type I of his classification and reckoned its date to be somewhat after AD 900 (Wheeler 1927, 36). It was 37.7 cm long by a maximum width of 6.0 cm and an approximate maximum thickness of 0.45 cm. The surface was very corroded and pitted although there was clearly a fairly solid metal core remaining and a central fuller could still be seen. There was no indication that the blade had been bent or broken before its submersion and there was no sign of any decoration on its corroded surface.

X-radiographic examination

On x-ray, a series of inlaid iron pieces showed up along the central part of the blade towards the hilt. It seemed to take the form of a kind of lattice design rather than lettering and a similar design looks likely to have shown on either side of the blade. This is suggested by overlapping aspects to the design, almost certainly a result of the superimposition of two surface images which made the design more difficult to work out and seem more complex than it really was (Fig 45c). A suggested interpretation of the design is shown in Fig 45d. The inlaid pieces appeared to consist of short bars which showed a fairly distinctive twisted or spiral grain probably indicating that these were all part of at least one long twisted composite rod which was cut into small pieces and inlaid by being hammer welded into the surface of the blade to give the desired design. The rest of the blade, by contrast, shows hardly any evidence of structure, although some slight hints of a straight grain effect appeared to show up in the radiograph in a few places.

Exposure and film details

Kilovoltage	125	Exposure time	55 seconds
Milliampage	5	Film	Kodak Industrex CX pre-screened roll film

Metallographic examination

A wedge-shaped section was cut from near the broken end of the blade on the shorter side. It was taken from here partly to avoid the inlayed design so as not to prejudice further attempts to determine the design, although it would have been interesting to compare the metal of the composite inlays with that of the rest of the blade.

Unetched, the section appeared to show few slag inclusions although many corrosion pits showed up where corrosion had penetrated from the broken end of the blade. This may to some extent have occurred along the lines of slag inclusions which have subsequently become lost.

When etched with nital the section appeared to consist of two parts, (a) and (b), separated by a diagonal line marking the position of a scarf weld (Fig 45b). this was very difficult to see under low magnification but higher magnification revealed a rather intermittent line of small two or even three phase slag inclusions where the central phase was pale grey, probably wustite.

Part (a) mostly consisted of a dark etched constituent with a fairly fine grained rather feathery, lamellar appearance which also appeared to be partially spheroidized. This would appear to represent pearlite of a fairly high carbon content, possibly as much as 0.6-0.8% which has undergone fairly rapid air cooling but not quenching. Towards the weld line with (b) the proportion of larger grained ferrite increased markedly and much of this showed as a spiky distribution suggestive of a Widmanstätten formation - also indicative of fairly rapid cooling. The increase of ferrite towards the weld probably resulted from decarburization before the welding of (a) to (b) took place.

Part (b) had a rather variable carbon content, as can be seen from the two main darker etched patches of Fig 45b, although no sign of any further welds which might indicate subdivisions could be seen in this area. Even at its greatest, at the cutting edge, the carbon content of this area was similar to that of part (a) but it was generally much less and appeared to decrease to about 0.1% or less over most of the rest of the area. The structures observed were similar to those of part (a) although near the cutting edge the structure appeared fine grained and somewhat lamellar but more granular, and it would appear that the spheroidizing effect was more pronounced here. It is difficult to explain the great variation in carbon content across part (b) but to some extent this might have been caused by successive effects of carburization and decarburization.

Hardness readings obtained from the higher and lower carbon areas of part (a) were 232 and 144 HV respectively; corresponding values for the higher and lower carbon areas of part (b) were 239 and 139 HV.

The spheroidized structure indicates that the blade underwent a period of subcritical annealing or heating for a time at somewhat below the lower critical temperature of about 700°C before final cooling.

The blade appeared to have been made from two pieces of steel with a mainly high carbon content (Fig 45f). The blade was not quenched but given an annealing treatment presumably intentionally to soften or toughen the steel from which it was made.

6.33 S24: Sword, from Thames at Cleeve; Reading Museum 256:63a&b (T.C.B.)

This sword was found in the river Thames at Cleeve, Goring-on-Thames, Oxon and survives in two-parts which represent most of the weapon, the tip and pommel being missing. The breaks were clearly not recent, having been subject to fairly extensive corrosion over a long time but it was not possible to say whether or not the blade was broken before deposition in the river. A slightly curved iron guard survived in place. The effects of corrosion were uneven, some parts of the blade having corroded right through whilst others appeared to survive in relatively good condition with only slight surface corrosion. In these areas the etching effect of the corrosion had highlighted a pattern-welded core to the blade. This appeared to consist of three or four parallel narrow bands but the detail was not very clear. The blade was not fullered but had a fairly pronounced convex profile which was somewhat flattened in the area of the pattern-welded core. This weapon is probably Late Saxon and although most swords of this period appear to have had fullered blades, the slightly curved iron guard appears similar to Wheeler's Type VI or VII (Wheeler 1927, 32). The very narrow strips used in the pattern-welding of the core would tend to confirm this approximate date range as this is a form common to Late-Saxon scramasaxes but not to earlier Saxon weapons. Date: approximately 9th-11th century.

X-radiographic examination

An x-radiograph (Fig 46c) confirmed the presence of a pattern-welded core to the blade, consisting of three very narrow parallel strips. The detail was not very clear and was made more confusing by the double superimposed nature of the image. Three main strips appeared most readily identifiable and of these the outer two appeared to be twisted where it was possible to see them at all, whereas the central one appeared to exhibit a straight grain effect in places. Some straight wood grain effect was also faintly visible in places along the cutting edges of the blade. The pattern-welded core and the cutting edge parts could be clearly seen to continue up through the tang.

Metallographic examination

A transverse wedge-shaped section was cut from the lower surviving blade fragment. The cut was taken so that the section would extend right across the pattern-welded area. Unetched, the section showed up as having a generally fairly low slag content distributed fairly evenly across it, mostly appearing as small spots and flattened ribbons. Various orientations and concentrations were visible which indicated the probable presence of welds and piling.

The structure of the section became much clearer upon etching (Fig 46b). The pattern-welded central core consisted of three main parts each separated from the other and from the cutting edges by a slightly diffuse grey line. Further diffuse grey lines showed the distorted, folded composite nature in transverse view, of each of the three strips forming the core. The grey lines separating the main elements of the section clearly marked the position of welds.

The cutting edge appeared to consist of two outer parts (b) and (c) of piled wrought iron or iron/steel welded to a central, fairly uniform steel strip (a). The outer parts showed up as parallel grey pearlite and white ferrite bands while the central part was a thicker grey pearlitic band. Under higher magnification the grey lines showed up as narrow bands of pearlite with a carbon content of approx 0.1-0.3% C. These were superimposed upon lines of slag spots or ribbons which marked the positions of welds. A vertical line of slag inclusions and superimposed fuzzy grey line of pearlite can be seen marking the weld between the pattern-welded core and the cutting edge. At right angles to this can be seen further similar parallel lines of slag inclusions and superimposed pearlite separated by wider bands of ferrite showing that the outer parts (b) and (c) of the cutting edge consisted mainly of piled wrought iron. The pearlite may have been introduced, not as thin steel strips or partial carburisation of thin wrought iron strips - but as carbon in a fairly finely divided form, possibly as a constituent of a flux used during the welding together of the various parts of the blade. This may also account for the distorted lines of pearlite, visible in the central pattern-welded strips (Fig 46b).

The wider central grey band (a) of the cutting edge cannot be explained in this way. It consists of a piece of steel with a fairly even carbon content of about 0.4-0.5%. Towards the tip of the cutting edge this central strip showed up mainly as martensite mixed with some dark etching irresolvable carbide or poorly resolved pearlite. Going inwards towards the central core the proportion of martensite decresed while that of the darker etching carbide increased. Where the carbon content was lower at the junction with the ferrite areas and in the diffuse grey lines the carbide occurred in a typical Widmanstatten distribution.

Three hardness readings were taken along the steel central part (a) of the cutting edge sandwich, firstly in the mainly martensitic area near the tip, then in the centre in a pearlitic area between martensitic patches and lastly near the inner weld where the structure showed as mixed pearlite and ferrite. The hardness values obtained were 647, 277, and 253 HV respectively. The low carbon iron of the pattern-welded core pieces (d) and (e) gave values of 221 and 217 HV respectively.

It would appear that the blade was quenched from within the critical range, about 750 - 800°C. The quenching was not rapid enough to give a fully martensitic structure even at the tip of the cutting edge.

6.34 S41: Sword, from the Thames at Vauxhall; Museum of London, A13592

Two fragments of a sword blade found in the River Thames in London at Vauxhall. The tang and lower end of the blade were missing although a straight iron lower cross guard survived in place. The total length of the fragments was 50.0 cm and the width of the blade 5.8 cm by approximately 0.45 cm thick. The blade had undergone fairly heavy but mostly even surface corrosion and beneath this the metal survival looked to be quite good. In profile there appeared to be a shallow fuller running down the centre on either side of the blade and in places along this part the corrosion products showed up a chevron pattern indicating this central area to be pattern-welded. The sword is difficult to date from what survived, although it would appear to belong to the late Saxon period. The straight form of lower cross guard appears in the Wheeler Types I and IV and also occurs in various of the Petersen Types, and from these an approximate 8th - 10th century date is suggested here, although it may be later. It may have been broken before deposition in the river, but this is not clear. The breaks were clearly not recent and may have been mainly the result of localised corrosion whilst submerged. At the lower break the core of the blade appeared to have corroded in preference to the cutting edges.

X-radiographic examination

A radiograph confirmed the blade to have a pattern-welded central area (Fig 47d). The pattern on each side consisted of two twisted composite strips which side-by-side gave a chevron pattern which ran uninterrupted down this central part of the surviving blade fragments. This pattern was fairly clear on the radiograph which also showed the double surface image up as a criss-cross effect along the composite area. The images overlapped to a large extent, especially along the central axis of the blade; enough to be fairly sure that there were two pairs of twisted composite rods on either side of the blade. There was no sign of a central core although this could not be ruled out at this stage. The edges of the blade had been welded on separately and bore fairly distinct traces of a straight grained effect in places.

Exposure and film details

Kilovoltage	125	Exposure time	60 seconds
Milliampage	5	Film	Kodak Industrex CX pre-screened roll film

Metallographic examination

A wedge-shaped section was cut approximately 10.0 cm from the lower broken end of the lower blade fragment, about the middle of the original sword. When viewed unetched the overall slag content appeared quite low, although it was much higher in a few patches over the core area where it appeared mostly as small spots. A few quite large ribbon-like formations of slag in the central part of the section were indicative of welds in this area.

When etched with nital the structure shown in Fig 47a became visible. The cutting edge appeared to consist of three parts (Fig 47c); one main part (a) which mostly etched very dark, a smaller pale zone (b) which possibly represented a separate piece welded on to one side, although this was not clear. A further, rather curious circular area (c) of low carbon iron was quite clearly outlined by slag ribbons. This appears to have been a separate small piece welded on to the main part (a) of the cutting edge, before the cutting edge was welded to the core of the blade. Also, the more obvious part of the straight graining visible in the cutting edge on the radiograph occurred along the boundary with the core. The roughly circular area (c) would, therefore, appear to be the view in section of a piece of iron wire welded on to the inner side of the cutting edge before the final assembly of the blade.

The cutting edge, piece (a) consisted mostly of a dark and fast etching constituent. This was partially lamellar and feathery looking, and although the structure was difficult to resolve it appeared to have broken down somewhat and become spheroidised. Near the tip this was mixed with a dark etched acicular constituent, tempered martensite. The mixed lamellar or feathery looking constituent was probably a pearlite or carbide distribution resembling upper bainite.

The way this predominates with a small martensitic area near the tip of the cutting edge means that the blade was inefficiently quenched, quite probably deliberately so. The tempered nature of the martensite and somewhat spheroidised nature of the very dark pearlitic constituent, show that the blade has undergone tempering to some extent. The heat treated nature of the structure meant that the carbon content was difficult to estimate optically but it probably represents a fairly high carbon steel of between about 0.5 and 0.8% carbon.

Near the weld junction with (c), the carbon content of part (a) decreased, probably the result of localised decarburisation while piece (c) was being welded to (a). The paler area (b) visible on to one side of (a) may also be the result of the decarburisation of part of the surface of (a), which would most likely have taken place at the same time. There was no evidence (in the form of slag inclusions etc) that (b) was a separate piece and in this case the partial decarburisation of the cutting edge piece (a) may be the most likely explanation, although the possibility of a separate piece (b) should not be discounted. Some further decarburisation may have taken place after the cutting edge was welded to the composite core, but there was no particular indication of this.

The core of the blade consisted of two pairs of composite rods welded back to back without any separate intermediate core piece. Two of these (d) and (e) and a small part of a third (f) came within the section (Fig 47a and 47c). The weld between (e) and the adjoining piece on the same side must have been only just outside the edge of the section. The weld junction between (d) and (f) was well inside the section which accounts for the overlap effect visible along the central part of the radiograph (Fig 47a). These core pieces did not give a particularly banded appearance when etched. The slag content was low and well scattered, although where visible, as small flattened inclusions, it tended to congregate along lines which outlined the folded appearance of these twisted pieces in section. Parts(d) (f) and most of (e), appeared to consist of a low carbon steel which showed both paler and darker areas, although the differences were slight, diffused and rather patchy. The microstructure of these areas consisted mostly of fairly equiaxial small - medium grain ferrite and unresolved pearlite. A visual estimate of the carbon content varied between about 0.1 and 0.3%.

There was however, a very pale band clearly visible at the inner end of part (e), near the centre of the blade and this consisted of large grain ferrite with little or no pearlite. A small part of a further darker band, similar to most of the rest of (e), was also clearly visible by contrast on the extreme inner edge of part (e). The composite rods forming the core of the blade appear to have been made mostly from a varying low carbon steel although some wrought iron bands were included.

Two hardness readings were taken in the cutting edge part (a), one near the tip where a very dark partly acicular, tempered martensitic structure showed up, and the other in the centre where a very dark, possibly bainitic structure showed up. In both cases a hardness value of 490 HV was obtained. The lower carbon iron area (b) gave a hardness value of 143 HV and the similar area (c) a value of 144 HV. Two of the darker grey ferrite + pearlite areas of the pattern-welded part (d) were given hardness tests as was one of the pale very large grained ferrite bands in part (c). The hardness values obtained were : (d), ferrite + pearlite - 192 HV; (d), ferrite + (less) pearlite - 153HV; (e), very large grain ferrite - 305HV. This very high final hardness value for the ferrite indicates a very high phosphorus content for this band, which was confirmed by EPMA. An EPMA phosphorus map showed up this high phosphorus band very clearly as a white area in contrast to the other dark, low phosphorus parts (Fig 47b).

6.35 S25: Sword from Oxford Road, Reading; Reading Museum, 16.36

This sword consisted of two fragments representing the upper-two-thirds of the weapon, the tip end being missing. It was badly corroded with at best a heavily pitted surface, although a shallowly curved iron guard and pommel survived in place. It was found in 1936 at Reading in the Oxford Road at Tilehurst Street but no further burial circumstances are known. The form of guard and pommel are similar to the Petersen Type Y and Wheeler classified it as one of his Type VI swords of the 10th-11th century (Wheeler 1927, 33 - 35). Although very heavily corroded the remains of a fuller could just be seen running down the centre of each side of the blade. The blade fragmens were bent as well as broken and there is a strong possibility that this damage was inflicted on the blade before burial but unfortunately, because the circumstances of the find were not recorded, it is not possible to be more definite.

X-ray and Metallographic Examination

An x-radiograph (Fig 48c) of the blade showed it to be pattern-welded along the fullered central zone and this showed up fairly clearly in places as a superimposed criss-cross pattern. This represented the surface effects of two twisted and flattened composite rods welded side by side, but it was unclear whether or not there were two similar pairs of composite strips welded back to back and there was no sign of a central plain core. The cutting edges both exhibited a fairly pronounced straight wood grain effect which tended to highlight the pattern-welded central zone. Both the cutting edge and pattern-welded components of the blade were clearly visible running up through the tang.

A transverse section was cut from the lower blade fragment from near the break with the upper blade fragment (Fig 10). The section extended from one cutting edge approximately half way across the blade.

Before etching, a very contrasting, non-uniform slag content could be seen across the section. In the cutting edge various discontinuous lines of flattened slag ribbons and spots could be seen and these ran between the core zone and the tip of the cutting edge and gave the cutting edge a banded appearance suggestive of a piled structure in which the slag content was generally fairly low. The core area, particularly the central part, contained much slag varying from small spots to very large irregularly-shaped inclusions which had only been partially flattened. The slag appeared to be mostly a two-phase wustite and ?fayalite with the pale wustite phase predominating. A great deal of corrosion had taken place around the slag in this central part.

Etching revealed a structure in which the cutting edge appeared to consist of three parts, (a), (b) and (c) in Fig 48a, divided from each other and the core by thin, clear white lines marking the position of welds (Fig 48b). The lower part (c) only survived near the central core of the blade. It consisted of a more or less homogeneous piece of fairly high carbon steel, about 0.5-0.6% carbon, in which pearlite and ferrite were mostly distributed in a coarse-grained Widmanstatten formation. Within this formation the pearlite was partially lamellar and partially spheroidised in structure. The central part (b) gave a banded appearance with a carbon content varying between 0.3 and 0.6%. This central component of the cutting edge seems to have been a piece of steel or a steel and iron laminate of uneven carbon content which has been piled and heated for long enough for extensive, if incomplete, carbon diffusion to have taken place. Part (b) was visible mostly as ferrite and appears to have been a piece of well-forged (low slag) wrought iron that has absorbed some carbon after being welded on to the central piled part (a). A fairly even zone of pearlite can be seen where it has diffused across the white line of the weld. As expected, the proportion of pearlite steadily decreases away from the weld until it fades out altogether.

The core zone of the blade visible in the etched section is also divided into three parts by weld lines marked by narrow white lines (Fig 48b). This clearly shows that the pattern-welding of the blade consisted of twisted composite strips welded onto either side of a single plain central core strip which itself did not show up on the radiograph. Only one pattern-welded strip was represented on each side of the section and these are both badly corroded. In both cases the strips had a fairly high slag content which ran and outlined the folded nature of these components of the blade. The upper strip on Fig 48b has partially corroded along the folds highlighting the non-corroded folded metal. The folds point in opposite directions on either side of the blade which illustrates that the twist or spiral of the strip ran in opposite directions on either side of the blade. The uncorroded metal of these pattern-welded strips consisted mostly of ferrite bands interleaved with bands of low carbon iron with 0.1% carbon or less.

The central, plain core strip was made of a very coarse wrought iron that contained so much slag as to be hardly more than a piece of poorly prepared iron bloom.

Three hardness readings were taken along the middle, piled steel part (a) of the cutting edge, firstly near the tip where the carbon content was about 0.6% and then in two places nearer the inner weld where the carbon content was less, about 0.3-0.4%. The values obtained were respectively 272, 202, and 204HV. The mainly wrought iron part (b) of the cutting edge gave a hardness value of 175 HV. The mainly wrought iron central core part (d) and pattern-welded surface parts (e) and (f) gave very similar hardness values - 179, 172, and 171 HV.

The coarse grained Widmanstatten form of much of the pearlite in the cutting edge may have resulted from overheating above the upper critical point during forging, causing excessive grain growth in these areas. The partially spheroidised lamellar nature of the pearlite shows that after forging the blade must have cooled fairly slowly, probably in air, and then been reheated for a time below the lower critical point, 723°C, allowing some of the pearlite lamellae to spheroidise, a process known as subcritical annealing.

The reconstruction diagram of Fig 48d shows how the blade appears to have been assembled.

6.36 S44: Sword from the Thames; Museum of London, A.24419

The upper part of a sword found in the Thames at Brentford. A downcurving iron cross guard and curved three-lobed pommel survived in place. Both of these had been overlain with a thin covering of copper alloy incised with fine lines and some of this covering survived in place. Wheeler classified this weapon as one of his Type VI swords of probable 11th-century date (Wheeler 1927, 37). The surface was heavily pitted by corrosion although the blade bore no sign of having been bent and its fragmentary state may have been caused by differential corrosion during immersion. The sword fragment was 48.7 cm long, with a maximum blade width of 5.1 cm and a thickness of about 0.5 cm, and it had a central fuller, approximately 2.2 cm in width, running down the centre of the blade. No other signs of decorative or structural details were visible.

X-radiographic examination

A pronounced straight-grained effect showed up along the central fullered part of the blade (Fig 49d). Superimposed on this were traces of what looked like inlaid lettering which appeared to overlap so as to suggest that this inlay work might appear on both sides of the blade. It was too indistinct to make out any design or specific letters. Traces of a straight grained effect was visible in some places along the cutting edge but this was not nearly so pronounced as in the central part of the blade.

Exposure and film details

Kilovoltage	125	Exposure time	55 seconds
Milliampage	5	Film	Kodak Industrex CX pre-screened roll film

Metallographic examination

A wedge-shaped section extending to about halfway across the blade was taken about 4.0 cm from the broken end, on the shorter side. Before etching little of significance could be seen across the section. A fairly even but low slag distribution was visible consisting of small spots and ribbon-like inclusions of one dark grey (?fayalite) phase.

When etched with nital three different elements to the section could be seen (Fig 49a). These are marked (a)-(c) on Fig 49c and appeared to represent three different parts to the section, a cutting edge and two halves of the central zone of the blade, separated by weld lines. The weld position between (a) and (b) was clearly marked by a narrow white line. The weld position between (b) and (c) was marked by a broader and much fainter white line superimposed upon a narrow broken line of pearlite.

The cutting edge part (a) etched darkly and appeared to consist of a nearly eutectoid structure of large grained lamellar pearlite. The pearlite gave a somewhat feathery appearance in places and a Widmanstätten-like form was also visible. The carbon content over most of (a) appeared to be about 0.7-0.8% which shows the cutting edge to consist of a piece of high carbon steel. The diagonal position of the weld line between (a) and (b) shows the cutting edge to have been scarf welded onto the central core part of the blade.

Part (b) of the core area consisted of a quite even distribution of fairly fine grain lamellar pearlite in a background of ferrite with a carbon content of about 0.2%. The slag content of (b) was very low, showing this to be a piece of good, low carbon steel. Some carbon had diffused across the weld between (a) and (b) which showed up as an even localised area of somewhat lower carbon content along the weld zone in (a), and an area of correspondingly higher carbon content in part (b) near the weld line.

The other half, part (c) of the core area of the blade, consisted almost entirely of fairly coarse grained ferrite with just a little pearlite visible at the grain boundaries except for a margin along the weld boundary with (b) across which fairly extensive carbon diffusion had taken place. Slag content of (c) was similar but slightly greater than for (b).

Hardness values obtained for the three parts of the blade section were as follows: the high carbon cutting edge, part (a), 325 HV; the lower carbon steel part (b), 181 HV; the mainly ferrite part (c), 157 HV. These values are fairly consistent with the structures observed although possibly rather higher than might be expected.

It would appear that the core of the blade was made by welding a rod of low carbon steel to one of wrought iron and, assuming symmetry, to this core were welded cutting edges of high carbon steel (Fig 49e). The carbon diffusion across the weld boundaries may have been the result of fairly prolonged heating during the final forging of the blade. The structure observed in the cutting edge would tend to indicate a fairly rapid air cooling for the blade after its final forging.

Each of the composite rods (c) and (d) were made up of six individual strips and it is probable that the other composite rods were similar - certainly the small areas of (e) and (f) appeared similar in section and the overall appearance of the composite rods is much the same as on the radiograph. The metal of both halves of the cutting edge and the core parts of the blade appears to vary between wrough iron and very low carbon steel itself little more than wrought iron.

6.37 S26: Sword from the Thames; Reading Museum, 1608.64

The bent remaining blade fragment of a sword found in the river Thames at Wallingford Bridge. The condition of this fragment varies between heavily corroded at the irregular, broken end where little metal survived, and fairly good at the other end where corrosion appeared to have been restricted to fairly light surface pitting. This end had been cut at right angles across the blade fairly recently but no record of this having been done could be found. The blade had a very pronounced convex profile which was ridge-like along the centre of each side. This ridge-like form of the blade suggests a date range of 12th - 14th century.

Metallographic Examination

X-radiography of this blade was mostly not very informative although a straight wood grain effect was fairly clearly visible in some places.

A section was taken extending across the blade parallel to the existing cut. Unetched, several lines of flattened slag ribbons and spots were visible suggesting possible weld lines running diagonally across the blade. Corrosion had also taken place along some of these lines, as well as around some larger slag inclusions. Etching showed the blade to consist of alternate iron and steel bands divided by slag spots and ribbons running diagonally across the section (Fig 50c).

On either side of the blade, steel strips (a)-(h) both of approximately 0.6% carbon (Fig 50a) formed the tip parts of the cutting edges. The approximate carbon contents on the other parts were as follows: (b) nil, (c) 0.8%, (d) nil, (e) 0.2-0.3%, (f) 0.4-0.5%, (g) nil. These estimates do not allow for the fact that a certain amount of carbon diffusion had occurred in places across steel/iron welds, especially in the area of (f)/(g). Also considerable decarburisation was evident in places along the sides of the steel strips, most noticeably between the steel strips (e) and (f) and along the high carbon steel strip.

The slag content of the ferritic strips varied between (b) which appeared only to have the occasional spot or ribbon and (g) which contained many slag inclusions of one or two dark phases (?fayalite and a glassy constituent). The pearlite of the steel strips was in a mainly spheroidised form which indicates that after forging and air cooling the blade was subjected to subcritical annealing - fairly prolonged reheating to below the lower critical point (723°C) which has allowed the pearlite lamellar to spheroidise.

A series of eight hardness readings were taken, one from each of the parts of the blade (a) - (h), running roughly along the central axis of the section. The results were as follows: (a) 195 HV; (b) 140 HV; (c) 272 HV; (d) 133 HV; (e) 164 HV; (f) 183 HV; (g) 134 HV; (h) 197 HV.

6.38 S28: Sword, no provenance; Reading Museum, 50.80 (H.L).

The upper half of a sword blade with a long narrow iron guard which widened to a knob at each end. The pommel was missing and the surface of the blade was fairly heavily but evenly corroded and the metallic core appeared to have survived quite well. A narrow fuller ran down the centre of the blade on either side. The provenance of this sword fragment is not known but the distinctive long, narrow form of the guard is typical of sword guards (or quillons) of later medieval weapons of the 13th or 14th centuries. The narrow form of fuller is also common amongst sword blades of this period.

Metallographic Examination

A radiograph of the blade fragment showed very little except some faint traces of a straight wood-grain effect.

A transverse section was taken from the broken end extending across the full width of the blade. Unetched, the section showed a fairly low content of slag as spot and ribbons running horizontally across the section which suggested a piled or sandwich structure to the blade. This was confirmed on etching (Fig 51b) from which it appeared that the blade had consisted of a sandwich of five inter-leaved steel or steel and iron strips (Fig 51c) of alternating higher and lower carbon content, the latter possibly the result of carbon diffusion from the former. The outer, darker-etching strips only survived on the less heavily corroded part of the section (right side on Fig 51b). These consisted of a mixture of troostite (or radial pearlite) and paler martensite patches. The thick central dark band consisted of a similar structure in addition to which could be seen a number of parallel fine white lines which appeared to occur at the probable weld boundaries with the paler zones on either side and also within the strip. Towards one end most of these inner white lines converged, which suggested the possible presence of a fold here. This area was fairly slag free but some slag spots did also appear to form a convergent pattern which would also tend to suggest the presence of a fold. These indications suggest that the central strip has been piled - in this case folded and forged out, possibly two or three times, before the final assembly of the blade. The clear narrow white lines may be the result of localised arsenic enrichment caused by the migration of arsenic towards surfaces being welded.

Hardness values of 496 and 503 HV were obtained for areas of tempered martensite in part (a), firstly near the tip on one side and secondly near the centre of the blade on the other half of the section. The small grain ferrite and pearlite of the intermediate parts (b) and (d) gave hardness values of 204 and 246 HV respectively while the tempered martensite of the other part (c) gave a hardness value of 393 HV (Fig 51a).

The carbon contents of parts (a), (c) and (e) appeared to be approximately 0.4-0.6%, and that of parts (b) and (d) approximately 0.2-.03%.

6.39 S30: Sword, from Sunbury Weir Stream, Reading Museum

A fragment of sword blade broken approximately half way along towards the tip and also at the shoulder of the blade where it narrows to become the tang. It was found near the Thames in the Sunbury Weir stream. It was in quite good condition, the corrosion effects having mostly been limited to fairly even and shallow etching of the surface, although some deeper pitting had occurred. In profile the blade thickened to a central rib on either side. The fragment was 46cm long with a maximum width of 4.6cm and thickness of 6mm at the central rib. An old label attached to the blade said '?17th century', but apart from its fairly distinctive profile with its central rib it bore no particular distinguishing characteristics from which its date or type might be deduced. Date : Late Medieval/post Medieval.

X-ray and Metallographic Examination

A radiograph of the blade did not show up much detail - just some faint traces of a straight wood grain effect. A wedge-shaped section extending a little over halfway across the width was cut from the blade 3cm from the wider broken end. When viewed unetched the section showed a small amount of slag fairly evenly distributed as fairly small spots and ribbons. There were no lines of slag suggesting a weld position.

When etched the section (Fig 52b) showed the blade to consist predominantly of steel. It was mainly of a sandwich construction with two similarly high 0.6-0.8% carbon steel outer parts (a) and (c), with a low-med 0.3-0.4% carbon steel band (b) running across the section from the centre of the core between the two outer parts, meeting the surface a little before the tip of the cutting edge (Fig 52a). Following the central band in the opposite direction (leftwards in Fig 52b) from the core of the blade, it can be seen to curve fairly sharply towards the surface of the blade near where the rib would have been had it not been corroded away here. It curved over another high carbon steel portion similar to the other outer two parts. A schematic diagram to shows in a simplified form the structure visible on the macrograph Fig 52e. Part of a higher carbon steel piece (d) was also visible next to (a) on the blunt end of the section. The structure was similar to that of (a) being one of mainly coarse lamellar pearlite.

There are no clear weld lines between these zones but a certain amount of slag segregation gives a definite hint of a weld line between (b), (c) and (a) with similar but less definite hints of welds between (b) and (c); and (c) and (d).

The higher carbon zones (a), (b) and (d) were predominantly pearlitic with only small areas of ferrite visible (Fig 52d). Much of the pearlite showed a fairly large grain structure and was mainly in a fairly coarse lamellar form.

The blade was not of a true sandwich construction but mainly consisted of two halves; one a fairly homogeneous piece of high carbon steel (a), and the other consisting of pieces of alternately high and lower carbon steel (b), (c) and (d) in Fig 52a. These parts appear to have been welded together leaving little traces of entrapped slag along the welds. The divisions between the different parts have become very blurred as a result of extensive carbon diffusion across the likely weld junctions. This is probably the result of prolonged heating of the blade above the upper critical point - in this case (for the higher carbon zones) about 750°C and the likely cause of the extensive occurrence of large grained pearlite.

The lower carbon zone is subdivided in places by some localised small bands or lenses of lower carbon content, about 0.2%, showing a much smaller grain size. A photomicrograph (Fig 52c) shows the contrasting pearlite grain sizes within zone (c). This may indicate that the upper critical temperature for these localised lower carbon areas, approximately 800°C, was not exceeded during this prolonged re-heating or annealing of the blade. The fairly coarse lamellar nature of the pearlite is indicative that the blade was finally cooled slowly.

A hardness reading was taken for each of the four parts of the blade visible on the section and the results were as follows: -
(a) 226 HV; (b) 171 HV; (c) 236 HV; (d) 221 HV (Fig 52a).

6.40 S50: Scramasax, from Barham Down; Maidstone Museum, no acc. number

A heavily corroded scramasax, missing the tip of the blade and the end of the tang, apparently found in a grave at Barham Down in Kent in 1842 although there is no further record of this . It was covered in a heavy crust of iron corrosion products which had split into several large flakes. The approximate shape could just be made out and this, with its gently curving back and cutting edge, was similar to other examples of Wheelers Type I or Frankish type of 6th-8th century date (Wheeler 1927, 178). It seems most likely that this blade came from an Early Saxon burial and it is approximately of 6th-7th century date.

X-radiographic and Metallographic examination

Radiography showed no structural features although much of the metal core of the blade appeared to survive.

Two wedge-shaped sections were cut from the blade, one from the back and one from the cutting edge. The sections were cut from fairly near the middle of the blade but were staggered a few centimetres apart so as not to weaken the metallic core too much but so as still to achieve an overall complete transverse section.

Much slag was visible in the unetched sections. This included some very large irregular three-phase inclusions with a central phase of pale grey (?wustite) in a dendritic formation in a medium and darker grey matrix probably of a glassy constituent and fayalite. Some two-phase pale grey and darker grey inclusions were also visible. The slag content was much lower along a narrow margin on one side of the back section and also nearer the tip of the cutting edge section.

When etched with nital, the areas of much lower slag content, the margin of the back section and the area towards the tip of the cutting edge section, both rapidly darkened (Fig53b) and tended to stain blue. These dark etched areas, (b) and (d) in Fig 53a, consisted of fine grain pearlite with some ferrite. The pearlite was fairly well spheroidised but still partially lamellar and the overall carbon content appeared to vary between 0.5 and 0.8%. The pale areas (a) and (c), on the back and cutting edge sections respectively (Fig 53a), etched slowly. These consisted mainly of very large grained ferrite with a few patches of short rod-like nitride or carbide needles also visible. The large quantity of slag visible in both sections was confined to these large grained ferrite parts.

No easily distinguishable weld lines between areas (a) and (b), or between (c) and (d) were visible although in both cases it is quite clear that a piece of fairly high carbon steel, (b) and (d), has been welded to a piece of wrought iron, (a) and (b). The wrought iron is of fairly low grade to judge from the high slag content. Fairly extensive carbon diffusion was also visible across the approximate weld positions.

The steel part of both sections gave, in each case, a hardness value of 248 HV. The very large grain ferrite core gave a hardness of 171 HV in both sections (Fig 53a). The latter value is rather high for plain wrought iron; this and the very large grain size probably indicating the presence of phosphorus in this core piece.

It seems most probable, despite corrosion having removed so much, that areas (b) and (d) were parts of one piece of steel that formed a jacket, a single piece folded and welded around a wrought iron core of which both (a) and (c) are representative areas. The high quality of the steel outer jacket contrasted markedly with the wrought iron of the core. The finished blade appears to have been air cooled then subjected to a period of sub-critical annealing, fairly prolonged heating at below the lower critical point of about 700°C, which was presumably done specifically to toughen the steel. The blade with its steel jacket and iron core is a clear example of Type 4 form of blade (Fig 66).

6.41 S22: Scramasax, from Thames at Reading, Reading Museum, 52.80

The surviving main part of the blade of a narrow scramasax approximating to the Wheeler Type III or Hurbuck scramasax type of the 8th-10th century. (Wheeler 1927, 178). Although the tang end is missing, the remainder of the blade is in comparatively good condition. The surface corrosion products appear to have been stripped off by electrolytic reduction, one result of which has been to reveal the differential effects of corrosion etching on the surface of the blade, in particular the clear outlining of a narrow pattern-welded strip running along through the centre of the blade on either side. Also still clearly visible were two parallel grooves running along the blade on both sides near the back, a form of decoration very common on Late-Saxon scramasaxes.

X-ray and metallographic examination

A radiograph of the blade (Fig 54c) showed the superimposed images of the parallel grooves, the partially overlapping images of the pattern-weld strip, visible on either side of the blade, and also showed up a somewhat wavy but generally straight wood-grain effect across the rest of the blade.

A narrow section was taken right across the blade at the existing tang end which had clearly been cut before, but not in antiquity, although no record of this survives. Examination of the unetched section revealed a very variable distribution of both large and small two-phase slag inclusions across the blade. These were mostly irregular in shape and only some showed a tendency to be flattish or ribbon-like.

The only distinctly linear distribution of slag inclusions was congregated along the weld lines along either side of the central pattern-welded zone. Much corrosion had clearly taken place particularly along the larger slag inclusions which also showed signs of cracking during forging.

Etching with nital further accentuated the variable composition within the different parts of the blade which could now clearly be seen to consist of three parts, a wide back and a cutting edge between which had been welded a single twisted pattern-welded strip (Fig 54a). In the pattern-welded strip the main elements showed as alternate light and dark wavy, folded bands. Although much variable sized slag was generally visible a greater proportion of the slag was concentrated in the darker areas, giving a very coarse appearance. Apart from slag, the pale areas comprised fairly pure very large-grained ferrite with occasional Neumann bands visible as straight lines in the ferrite grains. These contrasted with the darker areas which were mostly of fine-grained ferrite with some grain boundary pearlite. The carbon content of these areas was very low, mostly less than 0.1%, which classes it as a low carbon wrought-iron rather than a steel. The central pattern-welded part (b) of the blade, therefore, consisted of one twisted composite rod containing alternate bands of iron of differing composition.

The composition of the back part (c) and of cutting edge part (a) was very variable, but in both cases it is predominantly a patchy looking coarse wrought iron. The carbon content is mostly low, below about 0.1%, although in some uneven (darker) patches the carbon content was as much as 0.2-0.3%.

Two hardness readings were taken along the central axis of the low carbon iron cutting edge part (a), the first nearer the tip of the cutting edge and the second nearer the inner weld. These gave hardness values of 152 and 143 HV respectively. One of the pale very large grained ferrite bands of the pattern-welded central part (b) gave a hardness value of 220 HV. The back piece (c) of the blade gave two hardness values, 181 and 184 HV (Fig 54b). The relatively much higher value for the pale ferrite band of part (b) probably indicates a higher phosphorus content for these pale bands.

The etching of the section also further accentuated the weld lines between the main components (a), (b) and (c), now also marked by a narrow linear distribution of pearlite amongst the slag along both weld lines. This grey line distribution of pearlite would appear to be the result of the absorption of an even but small amount of carbon during the forge-welding possibly of the main elements of the blade; possibly the result of the use of a fluxing agent with carbon in a fairly finely dispersed form. The central pattern-welded strip did not exhibit any sign of a grey line phenomenon between the light and dark areas, the junctions between which were rather diffuse. The alternate banding of these zones may have been the result of welding, forging out, folding, and forging out again of a piece of phosphoric iron and a piece of low carbon iron.

Two or three repeats of this forging process (piling) would probably, after a final twisting, been sufficient to given the final banded effect visible in this case. The very variable content and distribution of slag and pearlite in the back and cutting edge of the blade suggests that these parts consist of a piece of only roughly consolidated bloom of variable carbon content. Fig 54e shows how this blade may have been assembled.

6.42 S34: Scramasax, from the old ford at Kempsford, Gloucestershire (Swindon Museum, 790308).

A small scramasax found near the river Thames at Kempsford, Gloucestershire. The fairly straight cutting edge and the sharply angled back suggest this blade to be one of the Wheeler Scramasax Type IV or Honey Lane type of approximately 10th-11th century date. The blade surface had been fairly heavily etched by corrosion although the metallic core survived well. Different parts of the surface had etched or corroded preferentially so as to reveal a continuous chevron pattern formed by two twisted composite rods welded side by side. The direction in which the chevron pattern pointed reversed on each side so that it was impossible to deduce whether or not two similar pairs or twisted composite strips had been welded back to back across the thickness of the blade.

X radiographic Examination

A radiograph (Fig 55e) of the blade highlighted the details already visible on the corrosion etched surface. The superimposed images of the two surfaces of the blade showed some overlapping of the pattern-welded bands, the adjoining plain back and cutting edge parts, but it was still not clear whether or not two pairs of composite rods were welded back to back because this overlapping effect may have been caused by the weld planes across the blade having been at an oblique angle to the path of the X rays.

Exposure and film details:

Kilovoltage	125	Exposure time	1.5 min
Milliampage	5	Film	Kodak Industrex CX pre-screened -roll film

Metallographic Examination

Two offset wedge-shaped sections were cut from the central area of the blade. When viewed unetched both sections showed distinct although fairly fine broken lines of small slag spots and ribbons which ran across the section marking the positions of welds between the four different parts of the blade. The central part of the blade consisted of two twisted composite rods welded side-by-side. The back of the blade showed only a few small inclusions while the composite rods contained varying amounts of slag inclusions, uneven in both size and distribution. The cutting edge contained much two and three-phase slag inclusions, varying from small spots to large irregular inclusions. These were grouped mainly towards the centre of this area with less slag occurring along the margins towards the surface and the tip of the cutting edge.

Etching with nital revealed the blade to consist of four clearly visible parts, a cutting edge piece (a), two composite pieces (b) and (c), and the back of the blade (d). The weld lines between parts (b) and (c), (c) and (d) were marked by dark grey lines of pearlite, with a very acicular appearance, superimposed upon the broken lines of slag spots seen before etching. Faint traces of a similar line of pearlite were visible amongst the slag spots along the weld junction between parts (a) and (b).

The cutting edge part (a) mostly showed up as a pale area of ferrite of a variable medium to large grain size with much slag in the central area. A narrow diffuse pale grey margin of pearlite lay along and just inside the weld line but the carbon content of this margin was clearly very low-probably less than 0.1%. A grey area of very acicular pearlite occupied the area of the tip of the cutting edge. It exhibited an almost martensitic appearance and would appear to represent a quenched structure in an area whose carbon content was too low to give a martensitic structure. The carbon content is difficult to estimate but is probably unlikely to be more than about 0.1 - 0.2%. The margin of pearlite near the weld as well as that of the tip may be good indications that this part of the blade was partially carburised before the final assembly of the blade. At the weld some decarburisation appears to have taken place, hence the pale zone between the grey margin and the weld. If surface carburisation did take place then the corresponding pearlitic areas that might have been expected on the upper and lower surface areas of the cutting edge must have to be removed either by decarburisation - less likely since the pearlitic area at the tip survived - or by surface grinding after the final forging of the blade. There was no evidence that the tip might have been welded as a separate piece onto the cutting edge. The acicular appearance indicates a Widmanstätten distribution of pearlite in ferrite.

The composite parts (b) and (c) both showed up as a distorted laminated structure, in each case made up of three white and three grey bands (Fig 55a and d).

The medium grain pearlite of the grey bands was of an acicular appearance, similar to that of the thick grey lines of pearlite marking the weld junctions between (b), (c) and (d), and contained only a little slag. Allowing for the acicular Widmanstatten distribution of the pearlite, the carbon content of these bands was probably no more than 0.1 - 0.2%.

The white zones consisted mainly of very large grained ferrite (Fig 55d)with much slag - mostly as small blob-like and partially flattened ribbons with a few larger inclusions. Neumann banding was also visible indicating some cold working.

The junctions between pearlitic and ferritic areas showed up very sharply and although there were almost no tell-tale lines of slag spots these must indicate weld lines. The sharp distinctions show no sign of decarburisation or carbon diffusion across the weld junctions, but by contrast the pearlite appears denser along most parts of these boundaries. These denser margins of pearlite appeared similar to the grey lines of pearlite observed along the welds between areas (b), (c) and (d) but were here less obvious because of the masking effect of the adjoining grey pearlite bands.

The back part (d) of the blade consisted of acicular grey pearlite and ferrite and the carbon content was about 0.2%, slightly higher than in the grey bands of (b) and (c). Near the surface of the back part the pearlite and ferrite had partially segegrated into narrow bands, giving a kind of wood grain effect to the section. This may have been the result of a small area locally rich in phosphorus causing the segregation, the banding being created by the forging out of this strip or bar of metal before the final assembly of the blade.

The tip part of the cutting edge (a) gave a hardness value of 204 HV and the inner, iron part a hardness of 125 HV. One each of the pale very large grain ferrite and grey ferrite + pearlite bands in the pattern-welded piece (b), and two each of these bands in pattern-welded piece (c) were given hardness tests with the following results:
(b) very large grain ferrite 261 HV (b), ferrite and pearlite 144 HV; (c), very large grain ferrite 230 and 234 HV;
(c), ferrite and pearlite 128 and 139 HV. The much higher values for the very large grain ferrite bands indicates a high phosphorus content for these pale bands. The back part (d) of the blade gave a hardness of 165 HV.

There would appear to have been four parts to the blade, a back piece (d) of fairly homogeneous low carbon steel, two twisted composite or pattern-welded rods consisting of alternate bands of high phosphorus (pale) and low carbon (grey) iron, and a cutting edge made of a piece of partially carburised wrought iron (Fig 55f) . The cutting edge must have been partly ground down at the sides, removing further evidence of carburisation which might have been expected.

EPMA analysis confirmed the pale bands of the pattern-welded pieces to be high in phosphorus and the darker bands to be low in phosphorus. The EPMA phosphorus map (Fig 55b) also shows the phosphorus rich white areas as the same large grained ferrite bands visible in the photomacrograph (Fig 55a). EPMA results gave phosphorus contents of 0.46 - 0.78% for the pale large grained bands compared with 0.03 - 0.08% phosphorus for the fine grained darker bands (Table 8).

6.43 S37: Scramasax, from the Thames at Kempsford; Swindon Museum

A long scramasax found in the river Thames near the old ford at Kempsford in Gloucestershire. The surface had been fairly evenly and lightly corroded but under this the metal of the blade appeared to have survived well. Its dimensions were: Length 77.5cms, maximum width 42cms, and maximum thickness 0.8cms. On either side of the blade near the back was a wide groove or fuller. It is similar in form to the Wheeler Type III or Hurbuck type of scramasax which would place it within the Late-Saxon period, probably the 9th or 10th century.

X-radiographic and Metallographic examination

Radiography showed little except for a faint hint of a line running along the blade near the centre, possibly indicating a weld. The back of the blade bore traces of a straight grain effect which was not visible along the cutting edge.

Two wedge-shaped sections were cut from positions staggered along the blade so as to enable a composite transverse section to be examined (Fig 11).

When viewed unetched the section across the back part of the blade showed a varying slag content with two broad bands containing many partially flattened slag ribbons and spots running unevenly along the main axis of the section. These two bands were separated by a generally wider, fairly slag-free area, with a further slag free area to one side of the blade. Towards the cutting edge end of the back section the slag band faded out and only the occasional flattened inclusion was seen here. The cutting edge section also showed a varying amount of slag with very little in the areas along the sides whereas the central zone along the main axis contained a slightly higher proportion of slag ribbons and spots.

Etching with nital showed the blade to consist of two main parts, the back (a) and the cutting edge which itself consisted of a very clearly marked sandwich of three parts, (b), (c), and (d) (Fig 56a and b). The weld position between the back (a) and the cutting edge components was difficult to see as it was not marked by any discernible line of slag spots although along part of its length it was marked by a narrow faint line of pearlite.

The back and the cutting edge were, however, of a markedly different composition. The back part (a) appeared to consist of one piece although its structure and hence its appearance varied greatly. The two broad banded areas of high slag content noted above consisted otherwise mostly of large grained ferrite. The adjacent low slag bands also consisted mostly of large grain ferrite. The two dense dark patches of part (a) which represent two areas of quite high carbon steel in an otherwise mainly ferrite matrix. (Fig 56a). These showed a heat treated microstructure of very dark etched irresolvable pearlite with some tendency towards an acicular, martensitic appearance. The carbon content of these areas was difficult to gauge optically but was approximately between about 0.5 and 0.8%.

There appears to have been considerable carbon diffusion outwards from the two steel patches which shows that this part of the blade was subjected to fairly prolonged heating. The banded nature of part (a) suggests that this back piece was first of all formed by the forging out, folding, and forging out again (piling) of one piece of wrought iron of greatly varying slag content or, more likely, a similar forging procedure involving two different pieces of wrought iron, one containing much slag, the other very little. The two steel areas are difficult to interpret for certain but they are unlikely to represent steel wires welded into this back part of the blade during any forging or piling procedure, as this would almost certainly have left some traces in the weld junction, probably in the form of entrapped slag, but none were observed.

One possible explanation is that these patches, which both lay within bands of ferrite with a high slag content, are the product of uneven conditions within the bloomery furnace which produced this piece of wrought iron. Localized, highly reducing conditions could have produced this effect. The coarse nature and quantity of the slag in these bands suggests that the iron from this particular bloom was not subjected to careful or prolonged forging after smelting in order to remove slag. Accidentally produced particles of steel might survive as distinct areas within a piece of iron not subjected to much forging as seems to have been the case here.

The cutting edge of the blade was of very distinctive sandwich construction (Figs 56c and d). The outer parts (b) and (c) were similar to each other, consisting mainly of fairly large grained ferrite with small amounts of pearlite visible at the grain boundaries in places and with a quite low slag content. However, in each case, the boundary with the central area (d) was marked by a wide diffuse zone of pearlite which faded out away from the central area (d). This clearly represented diffusion outwards across welds from part (d) to parts (b) and (c). The actual weld lines themselves were probably marked by patchy and faint grey lines of pearlite or the faint and fuzzy white ferritic lines also visible in places across the section.

The central part (d) consisted mostly of dark etched irresolvable pearlite and nodular troostite (radial pearlite) which, towards the weld junctions with the other parts was mixed with increasing amounts of ferrite with an acicular Widmanstätten appearance. A distinctive spine of paler etched martensite was visible along the centre of part (d) and this widened out towards the tip of the cutting edge which consisted mostly of martensite. The zone where carbon had diffused into areas (b) and (c) also showed a predominantly martensitic appearance near the cutting edge tip.

The weld junction between the cutting edge and the back part (a) of the blade was also not very clearly marked. No line of slag was visible across the section although a patchy grey line of pearlite could be seen separating areas (c) and (d) of the cutting edge from the back area (a) but the junction between (b) and (a) had become lost in generally rather fuzzy area of low carbon pearlite.

The martensitic area of the cutting edge steel part (a) near the tip gave a hardness value of 737 HV but near the centre, where mainly pearlite with some ferrite showed, a hardness value of 236 HV was obtained. The very low carbon iron of the outer edge parts (b) and (c) gave hardness values as follows: part (b), 178 and 175 HV; part (c), 174 and 214 HV. The higher value for part (c) came from an area near the inner weld where there had been considerable carbon diffusion across the weld boundary from one of the high carbon patches in the back part (d) of the blade. The centre of this particular high carbon patch in part (d) gave a hardness value of 369 HV whereas the low carbon iron which formed the great majority of this back part (d) gave a hardness of 167 HV (Fig 56 a and b).

The structures observed in the sections show that the blade underwent prolonged heating during forging which caused fairly extensive carbon diffusion across the weld junctions between the different parts. The blade was also quenched after its final forging although there is no indication of any subsequent tempering. The heat treatment has rendered the carbon content of the central steel part (d) of the cutting edge sandwich difficult to estimate although, at the centre, it was probably within the region of 0.5 - 0.8%c. Before the assembly of this part of the blade, part (d) appears to have been a well prepared quite homogeneous piece of steel.

6.44 S42: Scramasax, ? from the River Lea at Leyton ; Museum of London, Leyton Collection, 0.2275

The lower or tip part of a scramasax found in the River Lea near Leyton, Essex. There was no indication that it had been bent or broken in antiquity but the break was not recent and the tang end may just have corroded away as a result of differential corrosion under water. The surviving piece of blade was much pitted by corrosion although the metallic survival of the core appeared to be quite good. It measured 46.2 cm in length by 3.7 cm width and 0.85 cm at its thickest. Near the back of the blade on either side were two narrow grooves separated by a wide groove or fuller. The two narrow grooves ran parallel to the straighter part of the back and came together to form a point where the back of the blade curved towards the tip. The cutting edge was fairly straight, curving up a little towards the tip. In form this blade was closest to the Wheeler Type III or Hurbuck Type of scramasax, attributed to the 8th - 10th centuries (Wheeler 1927, 179).

X-radiographic and Metallographic examination

Radiography revealed little detail although traces of a straight grained effect could be seen in places, particularly at the tip.

Two wedge-shaped sections were cut from either side of the blade so as to obtain a composite transverse section. The sections were taken 1.5 cm and 9.5 cm respectively away from the broken end of the blade (Fig 11).

Unetched a varied slag content was visible mostly as small spots and well flattened inclusions. These inclusions were grouped in fairly broad bands which were aligned along the main axis of both sections.

When etched with nital the banded appearance of the sections became more pronounced and a distinctive flow pattern showed up. (Fig 57a and b). A possible total of seven bands (a) - (g) were differentiated (Fig 57c and d). Bands (a), (c) and (e)-(g) may effectively have been two pieces of piled or laminated wrought iron, between which a small strip of fairly homogeneous steel, (d), had been welded. This central steel strip showed up as a dark etched central band. Towards the back of the blade this dark band narrowed almost to a point, although it appeared to continue as a narrow but distinct very dark grey line along the weld between the two piled wrought iron outer components of the blade. Near the back of the blade the bands of the outer piled pieces curve sharply outwards which reflects some final hot forging at right angles to the main axis of the section, that is against the back of the blade.

The central steel strip (d) was of a fairly homogeneous carbon content of about 0.5 - 0.6% although it gave a varying etched appearance from pale, at the cutting edge tip to very dark at the inner end. The tip end consisted mostly of martensite which away from the tip end progressively became more mixed with a darker etched constituent which showed up, under higher magnification, as a feathery structure, probably of upper bainite. Towards the back of the blade where it tapered down to a narrow grey line, the central band (d) consisted of an increasing proportion of ferrite in an acicular form with partially spheroidised pearlite.

The remaining parts of the blade all appear to have been wrought iron with little carbon although after the final welding together fairly extensive carbon diffusion occured outwards from the central steel piece (d) into the adjacent iron pieces (c) and (e). On either side of the central piece (d) the iron parts appeared to consist of three bands: (a) (b) and (c) which each consisted of large grained ferrite with widely differing slag contents.

The bands (e) (f) and (g) varied in roughly the same way, (e) with a generally low slag content while the slag content of (f) was similarly high to (a), and that of (g) fell approximately between the two. The band (f) differed from the others in that it contained a little carbon towards the back of the blade, but probably no more than about 0.1%, therefore little more than wrought iron.

Two hardness values, 831 and 748 HV, were obtained for the martensitic area near the tip of the central steel piece (d) and a third value of 397 HV, further in where a dark nodular constituent, probably troostite (radial pearlite), showed up. A hardness value of 264HV was obtained for part (d) near the inner end, and a further value of 204 HV nearby where it had been decarburised. From the iron parts that made up the rest of the blade the following hardness values were obtained: (a) large grain ferrite - 157 HV; (b) medium grain ferrite - 177HV; (e) ferrite and pearlite, probably diffused from (d) - 217 HV; (f), large grain ferrite - 199HV.

Before the final welding together of the blade components the mainly wrought iron parts (a) (b) (c) and (e) (f) (g) most probably already formed two single pieces between which the steel piece (d) was welded. They appeared to consist of individual pieces of iron of differing slag contents which were welded or piled together (Fig 57e).

After final forging, the blade was quenched although a fully quenched or martensitic structure only occured near the tip of the cutting edge, which means that the quenching was inefficient, possibly deliberately so. The acicular nature of the ferrite in the pearlitic areas also indicated fairly fast cooling, but the partially spheroidised nature of the carbide in places and the more nearly equiaxial form of the ferrite near the centre may indicate that some self-annealing took place in the middle of the blade.

6.45 S4: Scramasax, from Dorset County Museum

A scramasax with a slightly angled back and a gently curved cutting edge. It appeared to be fairly lightly and evenly corroded with a good metallic core. The condition was fairly typical of finds from riverbeds or other waterlogged environments although the findsite for this object is not known. Its length is 31.6 cm with a maximum width of 3.3 cm and in shape it is similar to the Wheeler Type III/IV scramasax found at Walthamstow, dated 9th-10th century (Wheeler 1927), and so a similar date may be likely here.

X-radiographic examination

Radiography showed the blade to be of a fairly complex pattern-welded construction (Fig 58h). A double band on each side showed a clear diagonal grain pattern running down the blade from the tang, parallel to the upper part of the back until it met the surface of the lower part of the back near the angle. The absence of any criss-crossing on this pattern showed that two pairs of similar twisted composite rods had been welded behind one another. On the radiograph two straight grained strips outlined the double diagonal pattern. The remaining areas, the narrow margin by the upper part of the back and the wider area by the cutting edge showed little or no sign of graining. At least eight separate parts to the blade were indicated by the radiograph.

Exposure and film details

Kilovoltage	110	Exposure time	2 minutes
Milliampage	60	Film	Industrex C with lead screening plates. 0.10mm front and 0.15 mm rear

Metallographic examination

Two wedge-shaped sections were cut from the blade, one from the back and one from the cutting edge. Unetched, a very low slag content showed, although many corrosion pits were visible.

After etching with nital a very clear structure showed up (Fig 58c and e) and the blade could be seen to have been made from eight main components, (a) - (h) in Fig 58b. The edge part (a) gave a rather banded appearance with darker bands consisting mainly of a dense mostly irresolvable pearlite with some ferrite interleaved with paler bands predominantly of martensite with some pearlite. There were no obvious signs of welds between the bands but a skilfully welded piled structure would seem most probable for this piece, probably originally of high carbon steel and wrought iron parts welded together, forged out , and subjected to fairly prolonged heating although not long enough to give a completely homogeneous medium carbon steel. The carbon content was difficult to estimate but probably varies between about 0.4 - 0.6%.

The pale etched plain pieces (b) and (g) had been welded to either side of the pattern-welded parts and they each consisted of very large grained ferrite.

The pattern-welded core consisted of four twisted composite rods (c) - (f), welded side by side and back to back as show in Fig 58i. The very large, roughly diamond shaped corrosion pit visible in Fig 58c occupies the position of a very large three-phase slag inclusion (of wustite, and fayalite in a glassy matrix) some of which still survived and is just visible in Fig 58g. This very large inclusion was trapped in the centre of the pattern-welded part of the blade when the four composite components were welded together. The composite pieces (c) - (f) consisted of alternate pale bands of very large grain ferrite and darker, grey bands of small grain ferrite plus a little pearlite, at most giving a carbon content of about 0.1% - 0.2%, therefore the whole of the pattern-welded part of the blade, as well as the adjacent strips appeared to consist mainly of wrought iron with some fairly low carbon iron in the grey bands of the pattern-welded pieces.

The back part (h) consisted of a piece of fairly high carbon steel probably in the region of 0.5 - 0.7% carbon. Fig 58c and f shows its rather patchy appearance varying between paler areas of martensite, darker nodular troostite (radial pearlite) and darker areas of grey fine grain virtually irresolvable pearlite with some ferrite.

The edge part (a) was given four hardness tests, three from the martensitic areas and the other from one of the dense pearlitic areas. The first three gave values of 775, 555, and 647 HV, and the fourth a hardness of 318 HV. The two plain pale etched, very large grain parts (b) and (g) gave hardness values as follows: (b), 192 and 261 HV; (g), 234 HV. The pale, very large grain ferrite bands in pattern-welded parts (d) and (e) gave hardness values of 230 and 210 HV respectively. The darker, grey lower carbon iron of pattern-welded parts (d), (e) and (f) gave hardness values of 184, 185, and 152 HV respectively. One of the martensitic areas of the back part (h) gave a hardness value of 311 HV (Fig 58b and d). The comparatively high values for all the very large grain ferrite areas in parts (b) - (g) suggested a high phosphorus content for these parts. This was confirmed by EPMA and is shown on the phosphorus map (Fig 58a) in which the white areas are high in phosphorus. EPMA values of 0.58-0.78% phosphorus were obtained for the high phosphorus (white) parts compared with 0.01-0.06% phosphorus for the low phosphorus (dark) parts (Table 8).

After final assembly, welding together and forging out, the blade was quenched although not effectively enough to give a fully martensitic microstructure to the steel parts (a) and (h). The structure does however appear to be quite even, which may be indicative of a deliberately slower or slack quench.

6.46 S9: Scramasax, from the Thames; Museum of London, A 27086

A fairly short wide, decorated scramsax or knife with a sharply angled back and missing all but a small part of the tang. It was found in the Thames at Hampton and has been classified as a Wheeler Type IV or Honey Lane type of scramasax and, therfore, probably of 10th - 11th century date (Wheeler 1927, 179). The visible decoration consisted of three parallel bands of twisted copper and bronze or brass wires inlaid into the surface near, and parallel to, the back. Near the angle of the back further similar twisted portions of wire have been inlaid so as to join the three parallel bands together. Parallel and next to the three bands of inlaid twisted wire towards the cutting edge, traces of a pattern-welded design were visible in the iron corrosion products on the surface of the blade. Its length was 19.0 cm, width 4.5 cm and the maximum thickness at the back 0.55 cm.

X-radiographic analysis

Apart from the non-ferrous wires, radiography showed up the wavy weld pattern which was visible in the corroded surface. This pattern was in the form of a sine wave which represented a weld running through the full thickness of the blade. It would appear that this weld was achieved by taking two pieces, each initially forged to give a ribbed or corrugated profile along its length and then welding these together. The back of the blade showed a straight grain effect but otherwise appeared to be of one piece, to which the composite piece was welded. The side of the blade towards the cutting edge also showed straight graining although this was restricted to the half of this area alongside the wavy weld. This suggests that the cutting edge half of the blade may have been made from two pieces, although, without further work, this must remain just a possibility indicated by the radiograph.

Kilovoltage	110	Exposure time	1.5 minutes
Milliampage	60	Film	Industrex C with lead screening plates. 0.10mm from and 0.15 mm rear

Metallographic analysis

Sectioning was attempted across the back half of the blade by an existing break and it was hoped that an examination of most parts of the blade would be possible by so doing. Unfortunately excessive corrosion in this area, probably promoted by the presence of the non-ferrous metal inlay work, meant that only a small part of metal was found surviving right at the back of the blade. This piece proved to consist of a very coarse wrought iron with much slag in it. Fig 59b shows the section after etching with nital. The very large grain structure of the ferrite shows up and the dark patches are a combination of slag inclusions and corrosion surrounding them. The slag inclusions were of varying size and irregular shape and consisted of two medium-darker grey phases, probably fayalite and a glassy matrix. Also visible are stress lines or Neumann bands which indicate some final cold hammering although not enough to distort the ferrite grains. A series of hardness values ranging between 75HV and 98HV were obtained, which are fairly typical of a soft fairly pure wrought iron. The metal used here for the back of the blade appears to be a poor quality (slaggy) piece of wrought iron, little more than a roughly consolidated piece of bloom. Without further metallographic work the structure of the rest of the blade remains unknown.

6.47 S57: Dagger (Kris), Malaya; I Glover, Institute of Archaeology

This was a fairly typical example of a Malayan Kris or double edged dagger and although it is thought not to be very old - 19th or 20th century (I. Glover pers. comm) - it is a good example of a pattern-welded south-east Asian blade (Fig 12). The lower part of the blade was rather pitted by corrosion but the upper part was in quite good condition and a relief map form of pattern could be seen.

Metallographic Analysis

A narrow wedge-shaped section was cut from near the wider flared shoulder and unetched, little slag was visible. Etching with nital revealed the structure shown in Fig 60b. This section represented approximately half the width of the blade and consisted of four parts welded together, (a) - (d) in Fig 60a.

Part (a) which formed both the cutting edge and core of the blade consisted of a piece of fairly homogeneous high carbon steel. A structure predominantly of fairly well spheroidised pearlite with some ferrite showed up, the carbon content of this piece being about 0.6 - 0.7%. This steel core piece gave a hardness value of 189 HV.

The remaining core piece (b) showed a clear pale and dark banded structure which appeared to consist of alternate pale bands of medium to large grain ferrite interleaved by darker bands of fairly fine grain ferrite and partially spheroidised pearlite. The carbon content of these darker bands was quite low, varying between about 0.1 and 0.2%. The laminated appearance of this piece suggested a piled structure made by welding together and forging out a piece of carbon-free iron and a piece of low carbon iron or mild steel, and repeating the process several times.

The surface showed a similar banded structure and it is likely that this banded structure consisted of alternate laminations of high and low nickel iron formed either by oxidation encirchment during the welding together of similar pieces of iron with a low to medium nickel content, or by the welding together of iron or steel alternately high and low in nickel (see Chapter 5.7). Surface x-ray fluorescence (XRF) analysis suggested a nickel content of about 2.3% for alternate bands in the blade.

The cutting edge was formed by grinding away one side of the assembled pieces after they were forge-welded together. The result of this oblique grinding on either side was that the core part (b) was exposed to form the cutting edge and whatever final polishing and etching that was done to the blade caused the characteristic contour map pattern to be exposed.

During and after the final forging and before this final grinding and finishing treatment the blade must have been subjected to fairly prolonged heating followed by slow cooling which left the steel core of the blade in a relatively soft spheroidised state. This may have been part of a deliberate toughening process.

6.48 S38: Spearhead, from Kempsford, Swindon Museum, 790311

A socketed spearhead found in the river Thames at the old ford at Kempsford, Gloucestershire. It measured 15.7cm in length by 3.9cm in width at the widest part of the wings of the blade. The holes to locate an iron securing peg lay on opposite sides of the socket near the mouth and the corroded remains of the peg survived in place. The spearhead was very similar in shape and size to Late Bronze Age socketed spearheads and therefore may be an early Iron Age copy of a Late Bronze Age type of spearhead, a transitional Bronze Age/Iron Age type, possibly of about 600 BC. The full extent of corrosion was difficult to gauge but it appeared to be mainly confined to fairly heavy surface pitting. Radiography showed little structural detail to the spearhead.

Metallographic examination

A wedge-shaped transverse section was cut from near the widest winged part of the spearhead. When the section was viewed unetched, both sides of the socket showed a fairly low slag content with the shorter surviving part containing proportionally more than the other. In each case the slag was present as small spots and ribbons which tended to be segregated into lines which gave a flow pattern to the metal of the socket, on either side, which was aligned along each arm of the section and joined along a line which coincided with the main axis of the section from the centre of the weapon to the tip of the wing or flange at the edge.

When etched with nital this flow pattern effect was emphasised (Fig 61a). It could now also be seen that the section consisted of two halves, (a) and (b) (Fig 61b) which joined at a weld line along the main axis of the section. This weld line was marked by a white line that coincided in places with a broken line of flattened slag ribbons.

Part (a) proved to be mainly a low carbon iron or mild steel of about 0.1 - 0.2% carbon which consisted of a fairly even distribution of fairly small grained lamellar pearlite over most of the socketed part, while over the wing or edge part the pearlite became rather banded, interspersed with narrow bands of larger grained ferrite. The carbon content of (a) was less, approximately 0.1% in this wing part. Part (b) consisted of alternate narrow bands of large grained ferrite and small grained lamellar pearlite resulting in an overall carbon content of (b) of about 0.1%. Short rod-like carbide or nitride needles were also visible in places in the ferrite bands particularly along the innermost band of part (b), next to the socket void.

Hardness values of 141 and 149 HV were produced from either end (in section) of the fairly low carbon iron part (a). Corresponding tests from either end of the very low carbon iron part (b) gave hardness values of 112 and 113 HV. The ferrite line marking the weld between (a) and (b) gave a hardness value of 164 HV (Fig 61b). The white line may represent a band of localized arsenic enrichment at the weld junction.

The low slag content of the two halves of the blade showed that the initial forging work on the bloom metal after smelting was done well and the banded nature of the slag present may also reflect that the metal was forged out, folded, and forged out again (piled) several times before the final assembly and forging of the spearhead. If this is correct then the alternate ferrite and pearlite bands observed in parts (a) and (b) may indicate that surface carburisation was carried out before each folding operation. Some surface decarburisation may also have taken place at each stage and the rather higher carbon (0.2%), more homogeneous part of area (a) might have been the result of variable reducing/oxidising conditions in different parts of the smith's hearth.

6.49 S35: Spearhead from Kempsford; Swindon Museum, 790309

A small spearhead found near the river Thames at the old ford at Kempsford in Gloucestershire. The surface had corroded away although the corrosion was mostly not deep and the majority of the weapon survived with a good metallic core and the light corrosion meant that the shape survived quite well. Its type and date are uncertain. In outline it resembled the Swanton series K (Swanton 1974, 23) although the profile was quite different, being convex in section. Date: ? Anglo-Saxon 6/11th century.

Metallographic examination

Radiography showed a plain structure to the blade with some slightly hints of straight graining mainly near the point. There were no obvious indications of welds.

A narrow wedge-shaped section was cut from near the widest part of the blade. Unetched the section showed the slag content to be fairly low, mostly present as a few small flattened ribbons and spots with a few larger and one particularly massive irregularly shaped inclusion . The slag inclusions mostly congregated along the main axis of the section, giving a streaky or layered appearance.

When etched with nital a central line of slag spots became more prominent, highlighted by a narrow but distinct line of pearlite which appeared superimposed upon it. This most probably marked the position of a weld dividing the blade into two halves along the main axis of the section (Fig.62a and b). The two halves of the blade (a) and (b), showed up mainly as fairly even, grey zones of pearlite and ferrite representing a carbon content of about 0.2-0.3%. In the darker areas in the upper right and lower left parts of the macrograph the carbon content was rather higher, probably about 0.3-0.4%. Conversely in the upper left and lower right hand parts of the macrograph the pearlitic zones faded out altogether to leave localized areas of large grained ferrite. The pearlite occured as fairly well spheroidized lamellae in a small-medium grain size matrix of ferrite.

The streaky effect created by the parallel broken lines of slag across the section suggested that the metal of both parts (a) and (b) may have been subjected to or a process of forging out, folding and forging out again piling until this kind of layered effect was produced.

The overall fairly even carbon distribution across the section may have been achieved by the carburisation of the two pieces (a) and (b) before these two pieces were welded together as part of the final forging of the spearhead. The two ferritic areas where the carbon content fades out altogether might then be explained as localised areas where carbon absorption did not take place during the carburising process or possibly just as areas which were decarburised during the final forging of the spearhead. The latter is probably less likely because a more general surface decarburisation might have been expected in this case. The third possibility is that (a) and (b) were at one time both parts of the same bar of bloomery steel which did include smaller areas of ferrite. This possibility too is less likely in this case because of a process of folding and forging out several times would have distributed the ferrite areas more evenly or at least tended to flatten them out more.

Four hardness readings were taken, one in part (a) where the carbon content was at its highest, approximately 0.3-0.4% carbon, and three from part (b) ranging from where the carbon content was at its highest, again approximately 0.3-0.4%, to a decarburised area where only ferrite was visible. The results were as follows: part (a) near the centre, 172 HV; (b), near the centre, 172 HV; (b), nearer the outside of the blade where the carbon content was somewhat lower, 172 HV; (b), near the tip of the cutting edge where only large grain ferrite was visible, 116 HV (Fig 62a).

The great similarity between parts (a) and (b) does suggest strongly that they were at one stage part of the same bar of metal that was either cut or folded then forged out to produce the spearhead. The reconstruction diagram (Fig 62c) illustrates this. The overall quality was quite good, the weapon mostly consisting of a low carbon steel of a fairly low slag content. The spheroidised nature of the pearlite of the steel suggests that the spearhead was subjected to fairly prolonged heating at a little below the lower critical point, possibly about 650-700°C; long enough for the pearlite lamellae to partially spheroidize. This procedure of subcritical annealing may have been done deliberately to toughen the metal after final forging of the spearhead.

6.50 S36: Spearhead from Kempsford; Swindon Museum

A fairly small spearhead found in the river Thames near the old ford at Kempsford in Gloucestershire. The surface had been extensively but quite evenly pitted by corrosion although the metallic core survived quite well. The surface corrosion meant that the original profile was difficult to gauge but it appeared to be roughly convex with some tendency towards a central rib. Its dimensions were 20 cm long by 3.2cm wide (max). Its outline, size and profile were similar to the Peterson Type G spearheads (Petersen 1919) although the socket was proportionately longer in this case. It would appear to belong to the Late-Saxon period, possibly the 10th or 11th centuries.

X-radiographic examination

Radiography revealed several probable weld positions from which it appeared that the blade was divisible into three main parts; the cutting edges which also form the tip, a central V-shaped zone pointing towards the tip, and lastly the socketed end of the blade (Fig 63a). The central V-shaped portion showed traces of further welds suggesting a pattern-welded construction to this piece. This was difficult to interpret but appeared to consist of one mostly twisted and one untwisted rod welded side-by-side (Fig 63d).

Exposure and film details:

Kilovoltage	110	Exposure time	2 minutes
Milliampage	60	Film	Industrex C with lead screening plates. 0.10mm from and 0.15 mm rear

Metallographic examination

A transverse wedge-shaped section was cut from the wide part of the spearhead in such a way that the edge to be examined was cut obliquely to the edge of the weapon, at right angles to what appared to be the main weld lines visible on the radiograph.

When viewed unetched the slag content was low. Several broken lines of mostly small slag ribbons and spots ran across the section from side to side suggesting welds running in this direction dividing the section possibly into several parts. An irregular patch of partially flattened slag ribbons and spots, aligned this time along the main axis of the section, occurred centrally near the tip of the cutting edge.

When etched with nital the structure became much clearer (Fig 63c). The section was made up of four main parts (a)-(d) in Fig 63b. A possible fifth part is also shown which divides what would be a much larger part (d), otherwise containing very little slag, into three parts - (d), (e) and (f) as shown on the diagram and macrograph. Part (e) occupies the more or less exact centre of the spearhead and two rather discontinuous and irregular lines of slag inclusions, indicated as broken lines on Fig 63b mark the probable position of welds between these central pieces. Traces of these welds could be seen on the radiograph (Fig 63a).

The cutting edge part (a) gave an uneven etched appearance. The area at the surviving tip of the cutting edge was fairly pale etched and had a distinctly acicular martensitic appearance. Away from the tip this soon gave way to darker etching Widmanstatten-looking ferrite and pearlite, the pearlite fraction not being optically resolvable. This would appear to represent a quenched low carbon steel probably not more than 0.2-0.3% carbon. The very dark-etched zone which can be seen on the macrograph to occupy most of the inner area of (a) consisted of a central very dark acicular looking area of tempered martensite. This was mixed with unresolved pearlite and away from this central patch the structure gradually changed to a paler etching zone of pearlite with an increasing proportion of ferrite.

The carbon content of the dark etched area of (a) is difficult to estimate but appears to be approximately 0.4% - 0.5%. In some places part (a) was almost entirely ferritic. The very uneven carbon distribution across part (a) is not to be expected from a piece of carburised wrought iron so this piece may have been a piece of specifically produced bloomery steel.

The weld line between cutting edge piece (a) and the inner piece (b) was very clearly marked by an almost continous line of slag ribbons highlighted by a diffuse white line along its length. Piece (b) appears to have been a twisted and possibly composite strip - the folded appearance being outlined in places by a few slag spots. The main area consisted of a fairly even fine grain low carbon distribution of pearlite in ferrite, the carbon content being probably mostly less than 0.1%. The weld boundary between (b) and (c) although less easy to see was marked by a few slag ribbons and spots and one deep corrosion pit.

Part (c) consisted of several parallel bands running vertically acros the section from side to side (Fig 63a and b). There were four main bands with parts of two further bands on either side. In a few places the boundaries between the bands are marked by a few small slag spots and ribbons but mostly it was only the change in structural appearance which enabled the bands to be separated.

The bands consisted alternately of a fairly fine-grained distribution of pearlite in ferrite very similar to the main area of part (b) and with a similar carbon content of about 0.1% or less; and of large grain ferrite with very little carbon at all.

The boundary between the composite strip (c) and core piece (d) was fairly clearly marked by a few slag spots and ribbons and also by two very deep corrosion pits which have clearly followed the weld line between (c) and (d).

It would appear that the three separate central parts were forged together before the final assembly of the spearhead. Part (e) showed a fairly even distribution of fine grain pearlite and ferrite. The pearlite was mostly unresolved although appeared somewhat granular with a few acicular patches possibly of martensite. The carbon content of this central part appeared to be about 0.3-0.4%. Parts (d) and (f) were similar although their carbon content was lower.

Four hardness readings were taken in the edge part (a), firstly at the martensitic tip, (360HV); tip secondly a little further in where the martensite gave way to ferrite and pearlite (272 HV), thirdly in the centre of the very dark etched area of tempered martensite (496 HV); and finally near the inner weld where a dense area of unresolved pearlite showed up (333 HV). The low carbon large grain ferrite of piece (b) gave a hardness value of 210 HV. One of the paler, very low carbon bands of piece (c) gave a hardness of 163 HV while an adjacent ferrite band with slightly more pearlite gave a hardness value of 159 HV. Of the central parts of the spearhead, the ferrite of the iron piece (d), away from the zone of carbon diffusion, gave a hardness of 108 HV although in the area heavily affected by carbon diffusion a hardness value of 217 HV was obtained. The small grain pearlite of central steel piece (e) gave a hardness value of 277 HV.

There has been a great deal of carbon diffusion outwards into parts (d) and (f). The pearlite proportion gradually decreases away from (e) and the pearlite fades out altogether by about half way across part (f) to give way to large grained ferrite.

It would appear that the core of the spearhead was originally made up of a sandwich of two pieces of wrought iron between which was forged a piece of medium carbon steel which may have contained about 0.4-0.5% carbon. This composite piece must then have been heated above the upper critical point - approximately 800°C for a fairly long time, possibly several hours, in what may have been a deliberate attempt to produce a composite piece of fairly homogeneous steel.

6.51 S33: Spearhead, from Kempsford; Swindon Museum

A spearhead found near the river Thames at Kempsford in Gloucestershire. Its distinctive wide-bladed form (Fig 13) closely resembled those of Petersen's type H Viking spearheads (Petersen 1919) which would appear to date it to around AD 900. Its condition was fairly typical of river finds with fairly heavy surface corrosion pitting but with fairly good metal survival underneath. It was 33.1 cm in length by 5.6 cm at its widest point.

Date : approximately 9th-10th century

X-radiographic examination

Radiography revealed a fairly complex structure to the spearhead (Fig 64d). The thick central ridge forming the lower part of the socketed central part of the spearhead did not show any structural detail towards the tip although a V-shaped pattern-welded central band showed up further back. The pattern-welded zone showed up as several parts, an outer sine wave pattern separate from an inner twisted or spiral pattern by a narrow straight band. An even narrower straight band appeared to mark the inner edge of the pattern-welded area. It was difficult to deduce anything further about the structure of the pattern-welded zone from the radiograph. The edge parts of the weapon did not show any signs of structural detail apart from some slight traces of a straight graining effect which was visible in a few places.

Exposure and film details:

Kilovoltage	110	Exposure time	2 minutes
Milliampage	60	Film	Industrex CX film used with lead screening sheets - 0.10mm front and 0.15 mm

Metallographic examination

A narrow wedge-shaped section was cut from the blade 4 cm down from one of the shoulders of the weapon with the aim of getting a transverse view of all the main elements of the blade. A second section was cut from a point about 8 cm down from the shoulder on the other side of the spearhead. This was cut as a wider but less deeply penetrating section and was mounted so as to get a surface view of the cutting edge and part of the pattern-welded design . The transverse view, unetched, showed a generally fairly low slag content across the section except for a band in the centre which contained much slag, mostly small spots and ribbon-like inclusions of one or two darker phase constituents (probably fayalite and a glassy matrix) but with some larger irregular inclusions showing a third phase (of wustite) as a pale dendritic pattern.

When etched with nital the structure showed up clearly (Fig 64a). The section can be divided into ten main parts, these being the different components of the spearhead. The weld lines between these parts were fairly clearly marked by white lines which consisted of ferrite, probably locally enriched by arsenic. These were superimposed by a few small two-phase slag inclusions probably of wustite plus fayalite or a glassy matrix. Also superimposed were some narrow linear segregations of pearlite.

The small tip part (a) appeared to be a strip of steel welded between the edge of the inner parts (bi) and (bii) which were of wrought iron. It mostly consisted of a fairly fine grain, unresolved or granular-looking distribution of pearlite with ferrite indicating a carbon content of about 0.5% . The carbon content decreased towards the welds where fairly extensive carbon diffusion had taken place into the adjacent ferritic parts of (b). The mainly large grain ferrite parts (b) each showed a slightly pearlitic area next to the inner weld with part (c), possibly indicating a slight degree of accidental carburisation while the individual pieces were being forged. The two halves of (b) were virtually identical even to the extent of partial carburisation, suggesting that they were two halves of the same piece of wrought iron folded in half, welded together, and forged out again during which time the steel edge piece (a) was welded in.

The weld line between the two halves of part (b) and between these and part (c) gave rise to the sine wave pattern, visible on x-ray, which forms the outer part of the pattern-welded zone. The line is fairly clearly marked by small slag inclusions and particularly by one large inclusion, showing a pale dendritic pattern of wustite against a darker matrix probably of fayalite or a glassy constituent, which was trapped between the parts (b) and (c) during welding. The part (c) itself had a high slag content of varying sized inclusions mostly of a dark phase, possibly fayalite, but otherwise consisted of mainly large grained ferrite.

The central plain core piece (g) was unsuspected from X-ray and consisted of ferrite with a rather variable pearlite distribution which was very similar to the narrow band (d); both parts with a carbon content varying between 0.1 and 0.3%. It would appear that parts (d) and (g) are both little more than low carbon iron although in patches the carbon content is one of a low carbon steel. They are so similar that they probably came from the same piece of low carbon iron.

The surface parts (e) and (f) gave rise to the spiral or corkscrew-like inner pattern in the pattern-welded zone visible on X-ray. They are very similar to each other and consisted of alternating bands of pale very large grained ferrite and darker grey small-medium grained ferrite plus pearlite with a carbon content of approximately 0.1%. These bands gave a gently folded appearance showing how a transverse view of the spiral structure looks. The spiral structure of parts (e) and (f) has been achieved by welding together then twisting the paler and darker elements which show in the section...

The narrow band (i) appeared to be a low carbon iron consisting of medium grain ferrite plus a little pearlite with a carbon content of no more than 0.1%.

The inner piece (h) showed a fairly even ferrite and pearlite distribution with a carbon content of about 0.2%. Towards the edges this faded out suggesting that the piece may have been at one stage a fairly even piece of low carbon steel which became extensively decarburised during the initial forging of the socket of the spearhead. This is uncertain and part (h) can probably be regarded as a piece of low carbon iron of a patchy composition.

The steel edge part (a) gave a hardness value of 269 HV and the iron part (b) to which it had been welded gave a hardness of 115 HV. The pale large grained, slaggy iron part (c) gave a hardness value of 171 HV. The low carbon iron of parts (d) and (g) gave hardness values of 122 and 136 HV respectively. Hardness values of 220 and 234 HV were obtained for the pale bands in each of the pattern-welded parts (c) and (f) and the low carbon iron of part (e) produced a hardness of 143 HV. A hardness value of 133 HV was obtained for the low carbon strip (i) and a hardness of 141 HV for the central piece (h) with its similar or slightly higher carbon content. The relatively high hardness values for the ferrite parts (c) and especially (e) and (f) suggest a high phosphorus content for these parts.

This was confirmed by EPMA which gave values of 0.59 - 0.86% phosphorus for the suspected high phosphorus bands compared with values of 0.03-0.07% phosphorus for the other parts (Table 8). An EPMA phosphorus map very clearly shows the high phosphorus parts as white in contrast to the dark areas low in phosphorus (Fig 64b).

The second section when etched gave the structure shown in Fig 64g. This shows how the surface of the weapon may have looked when polished and etched in a similar way. Parts (a) - (d) and a very small part of (e) or (f) are represented here. Most of the darker etched steel tip part (a) has corroded away although a small part survives. The wider edge part (b) shows an interesting 'watered' effect, a result of a variable but low carbon content with areas of paler, larger grain ferrite which, on forging, out has given this wavy streaky appearance, very similar to that observable on some medieval and later Japanese sword blades. The mainly small grained clean grey metal of part (b) contrasts sharply with the high phosphorus pale large grain ferrite of (c) with its slag streaks and the way weld line giving the sine wave pattern shows up clearly. This pattern appears to have been achieved by the initial preparation of the edges of the pieces (b) and (c) that were destined to be welded together. These edges must each have been given a corrugated profile during initial forging so that the two profiles would interlock and could then be forge welded together to give a single piece with parallel sides but which would then give this sine wave pattern on later surface preparation. The grey fairly small grained low carbon iron piece (d) occupies most of the rest of Fig 64g and the dark band of corrosion runs roughly through the middle of it. A very small part of the inner pattern-welded parts, either (e) or (f), appears but it is too small an area to really show any detail.

CHAPTER 7

Discussions and Conclusions on Anglo-Saxon edged-weapon technology

This chapter has been divided into four sections which cover the three classes of weapon studied, the sword, scramasax and spearhead; the fourth section covering the development of pattern-welding in north-western Europe and comparing this to relevant techniques in use elsewhere.

7.1 Swords

A total of thirty nine swords were examined dating from the pre-Roman Iron Age to late Medieval times. Thirty two of these date from the Anglo-Saxon period (5th-11th centuries). The swords from this large group fall fairly well into three main sub-divisions with twenty swords from the Early Saxon period, (5th-7th centuries); two from the Middle Saxon period (7th - 9th centuries) and ten from the Late Saxon period (9th-11th centuries). Of the remaining seven swords, three appear to belong to the pre-Roman Iron Age, one is Roman-British while the other three are late medieval or later in date.

Of the three blades which can probably be attributed to the pre-Roman Iron Age the most unusual was the one (6.1.S32) which would appear to be an Early Iron Age copy of a Late Bronze Age leaf-shaped sword. The other two were surviving parts of blades of long swords and could not be reliably categorised although it was felt that they most resembled other examples of Late Iron Age swords, rather than later weapons. These attributions were strengthened by the similarity of the appearance and results of radiography of these two swords compared with the examination of other late Iron Age swords. All three of these blades were predominantly of wrought iron or very low carbon steel with no attempt at heat treatment.

The Early Iron Age blade (6.1 S32) was the simplest in construction. The section examined suggested that it may have been made from up to three different pieces of iron although it seems equally possible that a single piece of iron with a variable slag distribution and a low, uneven carbon content was used. Variable smelting furnace conditions and incompletely effective bloom consolidation would account for this. Of the two later Iron Age blades, one (6.3.S29) showed signs of a simple composite construction with low carbon cutting edges scarf welded to a wrought iron core. The other (6.2.S27) was structurally more interesting and consisted of an interleaved bundle of wrought iron and low carbon strips. This sword was difficult to date closely and the curious form of construction can best be interpreted as a prototype form of pattern-welding that would have given a coarse grained effect after a final polishing and etching treatment. This is confirmed by the more recent finding of the Peterborough sword which showed a very similar coarse-grained structure on x-ray and had an exceptionally well preserved and unmistak¢able, patterned surface etched in relief on the surface on either side of the blade (See Chapter 7.4.2. and Figs 71-73).

Only one sword of the Romano-British period was examined in the present study although this can be compared with the few others examined in this country and a few continental examples. The *spatha* from Whittlesey was surprisingly uniform in structure although it still showed a trace of having been made as a simple sandwich with slightly higher carbon central horizontal band lying between two lower carbon pieces which formed the surface of the blade on either side. The metal contained little slag and extensive carbon diffusion had blurred the divisions between what may originally have been a piece of medium carbon steel sandwiched between two pieces of low phosphorus wrought iron. The intention was clearly to produce as uniform a structure as possible. This had resulted in a blade varying in hardness between 159 and 193 HV. There appeared to have been no attempt to heat treat the blade although quenching would not have had a noticeable effect given that the overall final carbon content varied between about 0.2 and 0.3%.

The results of metallographic analyses from six Roman short swords or *gladii* from this country show clearly that similar looking sword blades can be very different in structure (Lang 1988, 199-216). These swords are perhaps not directly comparable to the Whittlesey *spatha* as not only are they examples of the shorter sword but also they are rather earlier, mostly, if not all, belonging to the 1st century AD. None of these was pattern-welded although some of them showed a laminated or layered construction.

Eighteen of the twenty Early Saxon sword blades examined were pattern-welded. Pattern-welding is discussed in more detail below (7.4) but in general it can be said that the blades which exhibit this technique consist predominantly of low carbon wrought iron and vary greatly in quality. They are complex in construction (Fig. 65), consisting on each side of between two and five composite rods welded side by side. The rods have been variously twisted or left straight to give rise to the patterns which would have been visible on the surface of the blades after a suitable etching treatment. Each group of rods was normally either (Type VI) welded to a single central 'core piece' or (Type V) welded back to back to the similar group of rods forming the surface on the other side of the blade. Another arrangement seen in three of the Kentish blades was (Type IV) where pairs of composite rods had been welded together back to back but were separated by an untwisted composite rod which ran through the thickness of the blade (Fig 67).

The composite rods used for these pattern-welded parts varied in composition between low carbon, low phosphorus wrought iron (6.22.S10) and a laminate consisting of interleaved bands of high phosphorus iron and low carbon iron with a carbon content mostly between about 0.1 and 0.2% at most approximating to modern mild steel (6.15.S14). High phosphorus contents were initially deduced from a combination of higher than expected hardness values often coupled with a very large observed ferrite grain size. This was confirmed by electron probe micro-anlaysis (EPMA) for several of these blades. Microprobe analysis showed the carbon free parts of these laminated pieces to contain between about 0.4 and 0.8% phosphorus (Table 8). Where the carbon content of the low phosphorus bands in the composite rods was so low that they had the appearance of wrought iron there was little difference in appearance, apart from grain size, between the bands of the laminate when viewed in section. The composite rods of the Holborough sword (6.16.S15) appeared to be ferrite in section but a microprobe phosphorus map revealed their true high and low phosphorus, laminated composition (Fig 29). In other cases an appreciably higher hardness value for some of the ferritic bands together with a much larger grain size enabled a higher phosphorus content for these bands to be deduced.

One of the least expected results was the discovery that the cutting edges, which had all been butt-welded on separately, had usually been made of more than one strip. Six of these eighteen blades had edges made of a single piece of low carbon wrought iron. The edges could all be grouped into one of the knife categories shown in Fig 66.

In six other cases the edges were of a similar low carbon iron but had been made in two halves with a central weld seam. At first this seems a curious technique where a single strip or rod would have been sufficient. However, in one of these cases (6.22.S10) a narrow low or medium carbon steel rod had been welded between the two halves at the outside so as to form the actual tip of the cutting edge. It is possible that some if not all of these cutting edges, which consisted of two halves of iron, originally also had a narrow steel strip or rod welded between the two halves along the outside of the edge. These blades are all sufficiently heavily corroded for the loss of any steel tips to the cutting edges to have been very likely.

In the remaining six Early Saxon swords a sandwich construction had been used, where a low or medium carbon steel strip had been welded between pieces of iron, fairly clear examples of the Type 1 knife construction. The edges of two of these blades (6.5.S17 and 6.11.S55) had been hardened by quenching in water, hardnesses of between 550 and 600 HV having been achieved. The carbon contents were probably slightly too low to achieve fully heat-treated hardness of 700HV or over, and there was no indication of any subsequent tempering.

The carbon contents of these Early Saxon pattern-welded sword blades were usually much too low for quenching to have been any use and for the most part this does not even appear to have been attempted. This probably means that the sword smiths knew that most of their blades would not benefit from this form of heat treatment. Attempts to produce a harder edge for some of these weapons were clearly being made although from the blades examined so far it is not possible to say how common this was.

(6.7.S51 and 6.14.S13)

The two other Early Saxon sword blades were not pattern-welded and consisted of piled low carbon iron. Phosphorus also seem to have been low although slight variations in carbon and phosphorus content appear to be responsible for the banded structure visible in sections with between six and eight bands visible in each case.

The swords of the Early-Saxon period are noticeable for the very limited use-parts only of some cutting edges - to which (hardenable) steel is used. This is in marked contrast to the much greater use of high phosphorus iron in the composite-pattern-welded parts of these weapons.

The two Middle Saxon sword blades show certain changes in style and techniques of manufacture from the earlier blades. They are the earliest examples seen in this study of blades with a central groove or fuller down each side and the fullers here were rather wide and shallow. Both these blades were pattern-welded, the pattern-welded parts occupying the full width of the fuller. The Reading blade (6.25.S31) shows a Type V form of pattern-welding, very similar to that seen on earlier blades whereas the Brentford blade (6.26.S46) shows a variant of Type IV pattern-welded construction where the pattern-welded parts occupy much of the width of the blade. Instead of being just a combination of wrought iron pieces the central untwisted part was a rod of high carbon steel which had been fully hardened by quenching. The edges of both blades showed a more advanced technique of construction than seen on nearly all the earlier blades. In both cases a sandwich construction had been used, the Reading blade showing in section as a knife Type 1/2 and the Brentford blade a Type 1. The edge of the Reading blade was rather curious in that it had a piece of low carbon steel sandwiched between pieces of iron with an additional narrow rod of high carbon steel also welded in between two of these pieces to form the very tip of the cutting edge. The Brentford blade had been given an edge which was a straightforward sandwich of a medium-carbon steel piece between two iron pieces. The pattern-welded parts of these swords were again made up of composite rods consisting of a laminate of high phosphorus iron and low carbon iron.

Both sword blades had been quenched, probably in water to judge from the more or less fully martensitic state of the steel parts, and the Brentford blade had also been lightly tempered, the earliest example of this technique found amongst the blades in this study. Although only two sword blades of this period were examined, already we are seeing a much higher standard of manufacture for (what seem now) outwardly similar blades than we have seen for the sword blades of the Early Saxon period. We now see the economical use of steel to give fully hardened edges, in the range 647-775 HV.

The hardened steel spine and edges of the Brentford blade combined with the ductility of the other, mainly wrought iron, components have produced a very strong blade combining much of the normally mutually exclusive qualities of hardness and flexibility. The ideal aim of the sword smith, at least where a functional weapon was concerned, must have been to produce a blade which would not bend or break easily but one with hard, sharp edges. The Reading blade is better than previous examples and the Brentford sword a much better weapon again, going a good way toward achieving this aim.

We can see from the analysis of the swords of the Middle and Late Saxon periods that a much greater use of steel was made in these weapons than had been the case earlier. The use of high phosphorus iron declines with the decrease in the use of pattern-welding in these weapons.

There now seems little doubt that in this country most swords of the Anglo Saxon period up to the 9th century were pattern-welded. During the Late Saxon period however, this technique of manufacture becomes less common for sword blades and ceases to be used for these from about the mid 11th century, although it continued to be employed for scramasaxes or knives for longer. Five examples of pattern-welded knives have recently been found excavated in the City of London from contexts ranging in date from the late 12th to the late 14th century (Cowgill 1987, 16).

A new type of sword blade emerged during the Late Saxon period, one with a non pattern-welded blade, into which an inscription or design made of small pattern-welded or plain pieces of iron had been forged into the surface of the blade, either on one or both sides, near the hilt of the weapon. In these plain blades the inlayed designs do not form an integral part of the construction.

Although these blades, apart from the inlaid design, appear plain on X-ray, they do not necessarily consist of a homogeneous piece of metal and the results here confirm this.

Ten sword blades of the 9th-11th centuries were examined in this study and five of these found to be pattern-welded. Although less common the pattern-welded element showed a variety of form similar to that seen in earlier blades and the pattern-welded parts of these blades were made very largely of low carbon iron sometimes laminated with high phosphorus iron. Steel forms an important element of the welded on cutting edges of these five weapons with the three examples of a steel-cored Type 1 knife, sandwich; one example of the opposite, Type 4, iron-cored construction with a steel outer casing, not seen earlier; and the final example (6.34.S41 from the Thames at Vauxhall) where the edge was mostly a fairly high carbon steel with a narrow iron strip welded down one side. All five blades had been subjected to some form of heat treatment after final forging. Slack quenching (possibly in oil) may have been used for the Vauxhall blade whereas of the other blades, two (6.33.S24, 6.30.S48) appeared to have been quenched in water, and two had been subjected to the almost opposite technique of prolonged heating or sub-critical annealing to toughen rather than harden the steel of the edges. These last two have maximum hardness values in the range 256-272 HV which compare with 490 HV for the Vauxhall blade and 564-647 HV for the water quenched blades. Only the Vauxhall blade gave evidence for auto-tempering.

Three of the remaining six swords of this period appeared on X-ray to have designs formed from short lengths of twisted rods forged into the surface of both sides of the blades near the hilts. These inlaid designs were difficult to make out but in each case appeared to consist of a series of crosses interleaved and flanked by vertical lines (Figs. 91, 95, 99). The parts of the blades with designs were not sampled so the structure of this residual form of pattern-welding cannot be given here. It would however, seem most likely to have consisted of a low carbon or wrought iron possibly rich in phosphorus, similar to that found in the twisted elements of the pattern-welded swords examined.

Two of these three inlaid swords had blades of a fairly homogeneous medium-high carbon steel although they had been given quite different final heat treatments. 6.31.S23 had been quenched, from about 725-750°C, in water to give an edge hardness of 762 HV whereas the blade 6.32.S47 had been given a final prolonged period of sub-critical annealing giving an edge hardness of only 239 HV. The two blades would have possessed very different properties, the first being very hard but inclined to be brittle which may explain how it came to be broken, whereas the other blade would have been much more ductile, although its edges would have been inclined to blunt more easily. The sword from Brentford probably possessed the best overall qualities of these inscribed blades. The fullered part of one side consisted of wrought iron which had been welded to a piece of low carbon steel which formed the fullered part of the other side of the blade. High carbon steel edges had been scarf welded to this duplex core. Hardnesses ranged between 325 HV for the high carbon edge to 157 HV for the ferritic half of the core. The blade appears to have been air cooled without further heat treatment.

The remaining two 'plain' sword blades examined were also quite different to each another in construction. 6.27.S7 consisted of a fairly homogeneous low to medium carbon steel which showed an incompletely quenched structure, possibly the result of slack quenching, and gave an edge hardness of 477 HV. The sword 6.28.S8 had a duplex structure, one face of the blade consisting of a high carbon steel and the other of wrought iron. The blade here had been given a prolonged final sub-critical anneal - probably more than was desirable - to toughen the steel. The hardness range here was between 172 HV in the steel half and 81 HV in the ferritic half, a very soft wrought iron.

The observations made on the ten swords of the Late Saxon period have been discussed in some detail in this section because of the great variety of their fabrication methods which has come to light in this study.

In summarising the overall changes and developments in sword smithing from the Early to Late Saxon periods, two main points are clear. Firstly, all of the later pattern-welded sword blades, (8th-11th centuries) show a much higher standard of overall manufacture with the more extensive and efficient use of steel which would have made these swords more serviceable weapons that those of the 5th-7th centuries, which as we have seen, were mostly of low carbon iron although this was usually combined with high phosphorus iron for the pattern-welded parts. The actual pattern-welded components, however, did not themselves change much throughout the Anglo Saxon period. Secondly, the same change in the standard of construction and use of steel is true of non pattern-welded swords, the earlier swords being predominantly of low carbon iron, while later on either a more or less homogeneous steel or quite elaborate combinations of iron and steel were being used and various heat treatments employed as well.

The major change and improvement in the standard of sword smithing, as seen in the examples studied from this country, appears to have taken place during the 7th-8th centuries. It is perhaps surprising that Early Saxon sword smiths did not strive harder to produce better blades as they must surely have been capable of doing so. The only Early Saxon scramasax examined was by contrast a good example of a steel cased, iron cored blade - seemingly a much more functional weapon than the contemporary swords. It is possible that the sword was more of a ceremonial weapon at this time and there may simply not have been a demand for the part or wholly steel weapons which would have been both more expensive and difficult to make. The sword may have become a more functional weapon during the 7th-9th centuries creating a demand for the better quality blades. The earlier swords, were, presumably, regarded as adequate for their purpose, although to what extent they were functional or ceremonial is unknown. The hardness values obtained for the earlier blades tend to suggest that these were rather better and more serviceable weapons than their predominantly wrought iron structures would otherwise indicate although still much inferior, as fighting weapons, to the later blades.

Three other sword blades were examined to gain some idea of how the manufacturing techniques might compare in the later medieval period. One of the blades was possibly even later but whatever its date these later blades do show at least that methods of construction did vary later on. The late medieval sword from Wallingford Bridge (6.37.S26) was made in a way quite different to the earlier examples, its three pieces of wrought iron interleaved and scarf welded between pieces of medium-high carbon steel. The second late medieval blade (6.38.S28) was probably made from two pieces of wrought iron sandwiched between three pieces of high carbon steel. The piled structure may earlier have been one of a higher carbon steel interleaved with pieces of low carbon iron into which carbon had diffused during forging or by being kept for a time in a non-oxidising part of the smith's hearth. The blade appears to have been finally slack quenched to give hardness values of about 500 HV for the higher carbon areas - similar to the hardness of other blades quenched in this way. The third blade (6.39.S30) was a more or less homogeneous medium high carbon steel. Neither the Wallingford Bridge sword nor this third blade from Sunbury Weir Stream had been quenched but both had been given a sub-critical anneal to toughen the steel of the blades. These results can be compared with the more recent analysis of an early 14th century sword blade from the Thames (Gilmour forthcoming) where a medium carbon steel casing had been welded around an iron core and narrow high-carbon steel strips had been inserted along the edges and blade had been finally quenched to harden the steel parts. The construction was again different to those seen earlier.

7.2 Scramasaxes

The single-edged weapon known both as *seax* and scramasax was popular during the later Anglo Saxon period (Chapter 1.6). These weapons vary greatly in size ranging from single-edged swords down to small daggers. Size and burial circumstances can be used as very general criteria to divide smaller examples into weapons, and knives used for other purposes. The two classes merge into one another, the weapons being mostly larger and the knives smaller. The term scramasax is used here to cover the whole range of these single-edge weapons.

It is not known to what extent knife smithing was practised separately from sword smithing. As scramasaxes are single edged weapons not unlike large knives, it is possible that they were made by knife smiths rather than, the possibly more specialised; sword smiths. Although only seven scramasaxes were examined in this study, the comparisons with the main structures found in the large numbers of both swords and knives are interesting.

A total of seven scramasaxes were examined, one coming from a probable 7th century grave at Barham Down in Kent while the rest were later (9th-11th century) and all came from waterlogged contexts, mostly in or near the River Thames. The Barham Down scramasax (6.40.S50) was a clear example of a Type 4 knife blade with a slaggy iron core around which a piece of high carbon steel had been welded. The finished blade was not quenched but given an alternative final heat treatment in which the steel jacket was toughened by fairly prolonged heating at about 700°C after initial air cooling from forging temperature. This would have been very much a functional rather than decorative blade, and would have remained very effective so long as the steel jacket remained intact. The abrading through of the steel jacket by repeated sharpening may have been much less of a problem with scramasaxes which being weapons, probably needed sharpening much less often.

This construction contrasts markedly with the Early Saxon sword blades examined here which nearly all were pattern-welded and consisted mostly of iron, and only in their cutting edges can they be compared with one of the five knife construction types. In those sword edges, where steel had been incorporated, a Type 1 or 2 construction had been used (Fig 66). No example of the Type 4 construction was found among any of the Early Saxon sword blade edges.

The remaining six scramasaxes all belonged to the Late Saxon period and differed from the Barham Down scramasax. One example was of Type 1/2 while another was of Type 1, a popular knife construction, and the edge hardnesses are not unlike the best quality knives of the period (Tylecote and Gilmour 1986, Table A3). The other four blades were pattern-welded, the pattern-welded areas having been inserted as decoration between the back and the cutting edge.

The combination of the twisted copper alloy wire inlay with the simple sine wave pattern created along the wavy weld between cutting edge and back in the scramasax (6.46.S9) from the Thames at Hampton may be seen as an example of a simpler and cheaper non-ferrous alternative to a more elaborate form of pattern-welding. Here the back of the blade into which non-ferrous wires have been inlaid was a coarse slaggy iron. The metal of the cutting edge could not be examined so it is uncertain whether or not it is of a similar, poor, quality.

Two of the other pattern-welded scramasaxes (6.41.S22; 6.42.S34) were similar to one another, both with pattern-welded pieces inserted between cutting edge and back, both consisting of low carbon iron. The structure of each of these two is rather more like the majority of earlier Anglo-Saxon swords examined here than the contemporary pattern-welded swords.

The remaining scramasax (6.45.S4, from Dorset) is more elaborately made and has both back and edge made of medium-high carbon steel which has been fully heat-treated showing that the whole blade was heated to 800°C and quenched in water. The ferritic bands in the pattern-welded composite part would have lent some ductility to the blade, but the average hardness was high. If the way in which steel has been incorporated into these blades, as well as their overall complexity and standard of construction, is used to judge their quality, then we do seem to have some variation in quality here. The Dorset blade can, thus, be seen as a much better quality weapon than the two previous examples which themselves, on the evidence available, appear to be of a better standard than the Hampton blade.

We can begin to draw some general conclusions concerning the technological development of the scramasax by comparing these seven scramasax analyses with the results from the examination of seven similar weapons, from Frankish cemeteries in eastern France, by Salin (1957, 47-51). Salin also reported that scramasaxes of the fifth century did occur in Frankish cemeteries but he says that they only became popular in the later sixth and seventh centuries.

Since all seven scramasaxes examined by Salin belong to the late sixth or seventh century, and all but one of the seven scramasaxes in the present work belong to the 9th-11th century we can use both sets of results to begin to draw some more general conclusions on the technological development of the scramasax in north-western Europe.

Of these fourteen scramasaxes, the eight belonging to the 5th-7th century period were not pattern-welded. This contrasts with the four pattern-welded weapons among the six Late Saxon (9th-11th century) scramasaxes examined. It can also be seen from the radiographic catalogue (Appendix 1) that of 69 scramasaxes examined belonging to the Late Saxon period 29 were pattern-welded, therefore approximately 42% of the total were pattern-welded.

The earliest pattern-welded scramasaxes so far reported are two eighth century weapons from the cemetery at Lembek in Wesphalia (Westphal 1986, 217-224). Antiens (1968, 563-57) describes another (similar in pattern to 6.42.S34) dated to the eighth-ninth century. It would seem that the available evidence allows us, at least, to conclude that pattern-welding for scramasaxes may have been first used in the eighth century and that it is widespread and popular for these weapons by the ninth or tenth century. Pattern-welding continued to be used for some smaller scramasaxes or knives after the eleventh century when it goes out of fashion for swords in western Europe. Recently excavated finds from the City of London (Cowgill 1987, 16) suggest that pattern-welding continued in use for knives although it became progressively less popular during the twelfth and thirteenth and fourteenth centuries.

7.3 Spearheads

Four spearheads were included in the present study with the intention of drawing some general comparisons with the results obtained for both swords and scramasaxes. One spearhead (6.48.S38, from Kempsford, Glos) would appear to be an Early Iron Age copy of a Late Bronze Age form of socketed spearhead. This weapon had been made from rather inhomogeneous, low carbon and low phosphorus wrought iron. There had been no attempt at any form of piled or composite construction and the metal was rather similar to that used for the other probable transitional Bronze Age/Iron Age weapon examined, the sword (6.1.S32) from Reading Museum.

The remaining three spearheads were attributed, on stylistic grounds, to the Anglo-Saxon period. One (6.49.S35, from Kempsford) was not datable closely although its shape possibly favoured an earlier Anglo-Saxon date (5th-7th century). This had been made from a well forged low carbon steel (of approximately 0.3% carbon) which had been partially decarburised while being forged into shape. This spearhead appears to have been given a final low temperature (approximately 650-700°C) anneal which has left the metal comparatively soft (172 HV). The structure of this spearhead would suggest that a plain and functional weapon, without any decorative appearance, was the intended end product. As a plain functional weapon this spearhead is similar to the sixth to seventh century scramasaxes in the previous section.

The two other spearheads (6.51.S33 and 6.50.S36, from Kempsford) were both dated approximately to the 10th century and were both pattern-welded. These two spearheads were of a complex construction having been made of several different parts. The pattern-welded parts were mostly a combination of low carbon and high phosphorus iron - especially clear in the case of 6.51.S33 . The core part of 6.50.S36 appeared to have been made from a sandwich consisting of a piece of medium carbon steel welded between two pieces of wrought iron. Very extensive carbon diffusion into the iron pieces suggests that this piece may have been heated (at approximately 800°C) for several hours in an attempt to homogenise it. This resulted in a carbon content just low enough (0.2-0.3%) to be relatively unaffected by quenching to which this spearhead was later subjected. The 'cutting edge' of this spearhead consisted of a medium carbon steel of a rather variable carbon content - possibly the same as originally used in the central sandwiched piece. The other spearhead had a fairly homogeneous low carbon steel central part but in this case the weapon had only been given a medium carbon (0.4-0.5%) steel tipped 'cutting edge' although this time the weapon had not been quenched.

The radiographic survey (Appendix 1) shows that many spearheads of the Late Saxon period were pattern-welded and it would seem likely from the evidence available that pattern-welding for these weapons became popular (in north-western Europe), in about the eighth to ninth centuries, at approximately the same time as for the scramasax.

Antiens (1968, 81-109) reports having seen 301 pattern-welded spearheads mostly (19-59.5cm) much larger than those examined in the present study. He claims that these were dated 11th-14th century which is rather later than we might expect especially as most of them came from cremation sites. Some of these were analysed and two were found to have quench hardened steel edges (260-478 HV). Many of these spearheads had a 'serrated' join between the edge and the central part of the weapon - the same or similar to that found in the Kempsford spearhead, 6.51.S33, - as well as a pattern-welded core. Unlike the Anglo Saxon spearheads so far examined some of these weapons also had parts with an appreciable nickel content which (like in some more recent south east Asian daggers) may have been included to enhance the decorative appearance of the pattern-welded parts. An enhanced decorative appearance was achieved in Anglo Saxon pattern-welding by the use of high phosphorus iron in combination with low carbon iron for the composite patterned pieces and this is particularly noticeable in the Kempsford spearhead, 6.51.S33 (see Fig 64).

In common with scramasaxes of the same period, spearheads do not appear to be pattern-welded before about the eighth or ninth century before which time they appear to have been plain functional weapons. Pattern-welding for these weapons appears to have been very popular between the ninth and eleventh centuries and may have continued for slightly longer although, in this country, only pattern-welded knives have so far been shown to be later. It would appear that after this period, when decorative welding and differential etching effects are particularly popular for both scramasaxes and spearheads, that both these classes of weapon returned to their former plain functional appearance although a great deal of work clearly remains to be done to find out how the structures and metallurgy of these later weapons varies.

7.4 Pattern-welding

7.4.1 Background and reconstruction experiments

Much has been written on the construction and smithing techniques used for pattern-welded swords (Maryon 1960; France-Lanord 1948, Salin 1957; Ypey 1983) and the technique was reproduced in 1958 by Anstee (see Fig 70), using 19th century wrought iron and described and discussed by Anstee and Biek (1961). Until now the conclusions on the manufacture of pattern-welded weapons have not been based on a sizeable x-ray and metallographic study of the weapons themselves. More recently some pattern-welded weapons have been reproduced in Germany where a mixed construction using modern iron and steel has been used (Denig 1990). These reproductions are remarkable looking objects although they re not intended to be exact replicas in terms of the iron alloys used or the patterns followed. Instead they represent a series of experiments to reconstruct the general methods which a sword smith is likely to have followed in preparing and welding together the components of a pattern-welded blade, as well as to get an idea of what these blades have looked like after final polishing and etching.

So far, the closest imitation of an Anglo Saxon pattern-welded sword blade is a replica of the sword from the Sutton-Hoo ship burial of the first half of the sixth century (Bruce Mitford 1978, 273-309). This replica is now on display in the British Museum for whom it was made recently by Lankton (Engstrom, Lankton and Engstrom 1989). The original Sutton-Hoo sword was not metallographically examined and so its metallurgical make up is not known but the iron alloys on which this replica was based were chosen using the metallographic results obtained, in the present study, for similar swords of the sixth-seventh century (Tylecote and Gilmour 1986, 251). The bulk of each composite rod in the pattern-welded central part of this replica was made using a more modern phosphorus containing wrought iron and a standard (American wrought iron and steel Institute) grade of mild steel. The results of the present work show that these alloys bear a fairly good resemblance to those used for many of the pattern-welded parts of Anglo Saxon sword blades of this date although the early wrought iron used in these composite pieces usually contained much less iron silicate (than the 1-3% by volume) and more phosphorus (usually in the range 0.4-0.8% - see Table 8) than the more recent wrought iron which is presumed to have been made by the puddling process. Similarly, the modern mild steel contained 0.6-0.9% manganese which would not have been present in the equivalent early low carbon iron.

The composite rods which formed the pattern-welded part of this replica sword also included thinner bands of a modern high carbon steel which has no known parallel in the pattern-welded parts of Anglo-Saxon weapons. This was included to enhance the pattern-welded effect in the blade after final polishing and etching, an enhancement which was probably achieved instead by Anglo-Saxon smiths by the use of higher phosphoric wrought iron, the use of which is further discussed in this section.

The thinly laminated, piled medium carbon steel cutting edges of the replica sword bear little relation to the alloys or construction types (Fig 66) of Early Anglo-Saxon sword blades which typically contain very little steel with a carbon content comparable to this.

The procedure developed by both Denig and Langton for their replica pattern-welded swords is likely to be very similar to that followed earlier by Anglo-Saxon sword smiths and which will only be outlined very briefly here. The pattern-welded central parts of the replica weapons were prepared, to begin with, by making each of the composite rods that would make up one component of the pattern-welding. Each composite piece was made up as a block or billet consisting of iron and steel interleaved and hammer-welded together. Denig uses a fine sand (silica) as a flux and, although Langton's procedure does not mention the use of a flux it is likely that he, too, would have needed to use a fluxing agent to counter the effect of surface oxidation at welding heat. Slag trapped between the pattern-welded components of Anglo-Saxon swords and other weapons examined in this study generally consisted of a two phase mixture of iron oxide (wustite) in a glassy or silicate matrix indicating that a fine sand flux was used during hammer or forge welding by the earlier weaponsmiths to overcome the effects of surface oxidation during heating and welding.

In Langton's reconstruction each of the composite billets, that was to form one of the rods in the pattern-welding, was heated to 1090°C and forged out to produce a composite rod. Short (4.5 cm) sections of each rod were successively heated up to this temperature and twisted. Between each twisted part 2.5 cm of the composite rod was left untwisted. To imitate the pattern on the Sutton Hoo sword four such composite rods were placed side by side so that the untwisted parts were next to each other. The rods were also placed so that the adjacent twisted parts twisted in opposite directions (right and left handed spirals). A similar second set of four rods was placed behind the first to give a double layer with a total of eight composite, partially twisted rods. The untwisted parts of each rod were placed so that the laminated edge lay uppermost, that is at right angles to the eventual surface of the finished sword blade. This double layer of eight composite rods was held with clamps before being heated and hammer-welded together to provide the pattern-welded central part of the replica sword blade.

A billet of thinly laminated medium carbon steel was then made by interleaving two thinner pieces of modern mild steel (0.15 - 0.20% carbon) between three pieces of modern medium (0.43-0.5%) carbon steel and hammer welding these pieces together. The billet was forged out to three times it original length, notched twice and then folded where notched, and welded together to leave a fresh billet of approximately the same length and thickness as before forging out. This process of piling (also known as fagotting) was repeated twice resulting in a thinly laminated billet which was then forged out to produce a rectangular rod which was welded onto the outside of the core to give the pattern-welded edge of the blade.

A fuller or channel was then forged along the centre of either side of the blade by using a specially made up fuller tool which progressively forged the channels simultaneously on either side along short heated lengths of the blade. The final shape of the cutting edges was also forged, a slow process which took seven hours. After final grinding and filing, which had been kept to a minimum, the blade was heat-treated by slack quenching in a tube of oil from 850°C. This gave a hardness to the edge of 350-400 HV (55-60 Rockwell) - fairly typical for a slack quenched medium carbon steel.

After final polishing the blade was etched with 3.5% nitric acid in water at 10°C. After the desired patterned effect had been achieved the acid etching medium was neutralised using a solution of baking soda (sodium bicarbonate) in water.

7.4.2 Origins and development of pattern-welding in Europe

As far as we know, weld patterns were first exploited in the Late Iron Age although the origins must lie in the Early Iron Age with the consolidation of the spongy and often fragmentary lumps of iron produced by a bloomery smelting furnace. These spongy lumps had to be heated up to white heat (approx 1200°C-1300°C) and gently hammered to remove slag and fuse together or consolidate the lumps to produce a usable piece of iron. Hammer welding started like this and, at some stage, welding imperfections must have been noticed, probably on sword blades when they rusted.

The prototype form of pattern-welding appears sometime during the Late pre-Roman Iron Age in Britain and is best represented by a sword (now on display in Peterborough Museum and known as the Peterborough Sword) found in a former bed of the River Nene near Peterborough. The anaerobic waterlogged burial conditions had preserved this sword and its decorated bronze scabbard almost perfectly although the surface of the blade had been stained black or dark grey. Apart from the dark discolouration caused during burial the original surface pattern on the blade was clearly visible (Fig 71, 72).

There was an undecorated margin all the way around the cutting edge inside which was a heavily etched decorated central area running down the blade. The pattern is not a formal one, like those found later, in that it doesn't follow a specific design but it resembles a coarse wood grain or fibrous pattern.

A radiograph of this blade showed up pattern resembling that of a coarse wood grain which was uninterrupted across the full width of blade including the cutting edges (Fig 73). It was clear, therefore, that a resist method of etching had been used on the blade. The edges of the blade must have been masked with a wax or grease (a resist agent) which prevented the etching solution from affecting these margins of the blade. This etching treatment must have been quite prolonged as the pattern was etched very deeply.

The sword fragment (6.2:S27) from Little Wittenham was less well preserved but showed up a very similar coarse grain effect to the Peterborough sword on x-ray (Fig 15). In section it appeared that the Little Wittenham sword had been made up of a bundle of irregular rods of fairly pure or low carbon iron. Slow corrosion during waterlogged burial had resulted in very heavy surface etching across this whole blade so that it is now impossible to say whether a resist etching method was used to reveal the pattern inherent in the structure of this blade. From x-ray and the visible fibrous appearance, these blades seem to have been made in the same way which seems to lack any other likely purpose than to give a patterned appearance when etched.

This prototype form of pattern-welding would appear to have been unrecognised as such until now and other examples may come to light as swords recovered earlier are re-examined and further discoveries are made. It will usually only be possible to identify this early form of pattern-welding from radiography, where possible, supported by metallographic analysis. Another sword, which may prove to belong to this type of early pattern-welded blades, was found in 1982 in waterlogged deposits near a Late Iron Age causeway by the River Witham near Fiskerton in Lincolnshire (Field 1982). A radiograph of this sword showed the same coarse grained appearance as the Peterborough and Little Wittenham swords suggesting it to be another prototype example of pattern-welding. This method of construction and pattern production may be interpreted as the first stage in the development of pattern-welding where, perhaps for the first time, smiths were exploiting the potential of weld lines and (alloy) compositional differences to produce a coarse fibrous decorative effect (Fig 76)

A more direct forerunner of the pattern-welded sword can be seen in a blade from Llyn Cerrig Bach in Anglesey, one of five swords found in a hoard of 2nd century B.C. to first century A.D. date (McGrath 1968, 78-80; 1973, 264 and Plates LX1X-LXX1). In this blade several rods of low carbon iron or steel had been welded together side by side with the welds running from surface to surface, at right angles through the thickness of the blade. Without any separate cutting edges this may be seen as the second stage in the development of pattern-welding in which the banded patterns were more regular or formal than before (Fig 76). When polished and etched this would have resulted in a series of parallel lines or alternating bands, a simple form of pattern which can be seen on some 18th and 19th sword blades from south east Asia now in European collections. The technique had developed by the late second century A.D. into the more familiar form in which twisted rods were welded side by side to form the core part of a sword blade and then a separate cutting edge welded on (Stage 3, Fig 76). A blade like this from South Shields was found in 1953 beneath contexts dated to c A.D. 200 (see Chapter 1.2) and the twisted form of pattern-welding occured in one (see Fig 75 ii) of two swords found more recently in a third-century grave in Canterbury (Webster 1982, 185-7).

The second sword from Canterbury was also pattern-welded although it is a more obvious direct development of the Llyn Cerrig Bach type of sword. The pattern-welded part of this sword consists of two straight laminated rods welded onto either side of a 'plain' rod thus forming the central part of the blade. The laminated rods had been placed so that the laminations were at right angles to the surface of the blade and showed up their laminated appearance upon etching (Fig 75 i). On one side of the blade two narrow grooves ran along the two laminated bars. Separate cutting edges had been welded on to either side of the decorated pattern-welded central part of the blade.

Several parallels for this untwisted form of pattern-welding came from the third-fourth century votive peat bog deposits of Illerup and Nydam in Jutland (Thomsen forthcoming, Group 2). These deposits also contained many examples of twisted forms of pattern-welded designs. The increasing popularity of pattern-welding at this time can be judged from the Jutland bog finds. The mainly third century deposit at Vimosé included 14 (recognised) pattern-welded blades amongst 67 swords whereas at Nydam the mainly fourth century deposit included 93 pattern-welded blades amongst 106 swords (Davidson 1962, 32; Todd 1975, 192-4).

Most pattern-welded swords from the second or third century onwards were made by welding and sometimes twisting multiple rods together and forming composite pieces which were laid and welded together in various ways to form the core of the blade to which the edges were added. There appears to have still been much more variation and experimentation in pattern types during the third and fourth centuries as can be seen in the Illerup example (Thomsen forthcoming) where pattern-welded edges had been welded onto a plain core; and at Nydam where a fragmentary sword with a rare lattice pattern was found (Maryon 1960, Fig 7). One of these fragments may have found its way (via the Arthur Evans collection) into the Ashmolean Museum, Oxford, where it is currently on display in the Late Anglo-Saxon Gallery although the only known parallel is from Nydam. This fragment was examined in the course of the present study and is reproduced here (Fig 77 iii). The diagram shows it to be a complex combination of narrow laminated bars welded, edge on, into a lattice arrangement with the diamond shaped gaps filled in with small specially cut pieces from a bar of the more familiar double twist or herringbone pattern-welding. This bar would have been made by welding together, side-by-side, two rods with opposite twists, that is right and left hand hand spirals.

A series of pattern-welded types was built up in the course of this study to show the different ways in which these were usually constructed (Fig 67). The Types V and VI were found to be the most common amongst the swords examined although examples of most of the others were encountered and the remainder can be inferred. Further types will probably come to light in the course of subsequent work.

Nearly all the pattern-welded swords found in this country belong to the Anglo-Saxon period. Several hundred swords of this period exist in museum collections in this country, many found a century or more ago, but it is really only in the last twenty-five years or so with the increasing use of X-radiography that the extent to which these blades were pattern-welded is becoming known. The twisted rod pattern occurs repeatedly on X-ray as was earlier shown by Anstee and Biek's survey in their 1961 article which also described a series of experiments in which replicas of pattern-welded blades were made with twisted core elements to which cutting edges were welded on separately. (Anstee and Biek 1961, 71-93). A recent radiographic survey by Janet Lang and Barry Ager of 127 swords of the Anglo-Saxon period in the British Museum collections has recently been published (Lang and Ager 1989). Appendix 1 of the present study includes a full interpretation of these swords together with a schematic reconstruction of any pattern found on each sword as well as including the main details (gained from radiography) from the majority of other Anglo-Saxon sword and scramasax finds.

In the British Museum (Lang and Ager 1989) radiographic survey, pattern-welding was seen in more than half the swords of the 5th-6th centuries, compared with about two thirds of the swords of the 6th-7th centuries. Nearly two thirds of the 9th-10th century swords also showed pattern-welding. During the present study a similar number of sword and scramasax blades from other collections were also examined by radiography in addition to those metallographically examined and discussed. Most of the Early Saxon blades probably belong to the 6th-7th centuries and a comparison with the earlier blades showed that a twisted form of pattern-welding was most common. About two thirds of the blades of a broadly similar 9th-10th century period were also pattern-welded (Appendix 1).

The characteristic patterns of blades incorporating twisted components were first noticed on swords from waterlogged sites such as those from Nydam, where slow corrosion had deeply and differentially etched the surface of the weapons to reveal patterns brought about by the way in which they had been forged and welded together. The patterns seen on x-ray also show up because of the effects of differential corrosion in the ground. Uncorroded pattern-welded structures, such as Anstee's modern replica, will show up much less well on x-ray. The opposite situation may also be true, and buried pattern-welded blades which are totally corroded may show little or none of their pattern-welded structure on a radiograph, especially where a dense surface incrustation is present. The greater density of the surviving metal and the penetration of corrosion along the welds, between the various parts, causes the pattern-welding to show up more clearly on x-ray.

7.4.3 Selection of iron alloys for pattern-welding

We can now see that pattern-welding was very popular in this country for swords during the Anglo Saxon period, but why was this the case? Was pattern-welding used for structural or decorative reasons? Pattern-welded elements within at least one of the Nydam blades have been shown to have combined low and high carbon iron (Schurmann and Schroer 1959,127-30) suggesting that it might have been intended as a way of combining iron and steel to produce a strong blade. Other parts of the blades also had a varying carbon content so this does not necessarily follow. The pattern-welded elements of the Anglo-Saxon blades examined in the present study were consistent in composition right through the period, and show that the technique served a mainly decorative purpose and that the complexity of the patterns bore little relation to the overall functional qualities of the blade.

The pattern-welded composite parts were found to consist almost invariably of iron low in carbon. However, these composite parts were mostly made from alternate pieces of low carbon and high phosphorus iron. The low phosphorus iron of these composites appears to have been often lightly carburised giving these low phosphorus parts a carbon content of up to about 0.1%, the high phosphorus parts remaining virtually carbon free even after the laminated pieces were welded together as carbon diffusion into these parts would have been severely inhibited by the phosphorus. These parts usually contained about 0.4-0.8% phosphorus (Table 8). This interleaving of the two different iron alloys may have been done intentionally not so much to strengthen the metal which it would not have done to any appreciable extent, but to reduce the grain size of the low phosphorus parts thereby improving the effect that would have been obtained on etching the finished blade. Phosphorus, on the other hand, promotes grain growth and, although the sword-smiths would not have realised this, they were clearly producing composite structures which would have been most impressive when etched.

The phosphorus-containing ferrite stays bright when etched (in nital) whereas the non-phosphorus iron etches darker partly due to the much smaller grain size (where the carbon content is low), so it would appear that the sword smith by combining high and low phosphorus components, especially where the low phosphorus iron contained a small proportion of carbon (approx 0.1%), was exploiting these grain size and compositional characteristics by empirical means to achieve the best visual qualities he could. The decorative aspect of the patterns must have been the most important factor.

This conclusion is further underlined by the fact that pattern-welding continued to be popular in the Late Saxon period at the same time that plain blades with or without inlaid inscriptions (of pattern-welded pieces) were being made. As we have already seen, the changeover to blades which contained an appreciable steel content and in which further heat treatments were used, occurred in this country between the 7th-9th centuries and bore no relation to the use of pattern-welding.

Pattern-welding for swords appears to have simply gone out of fashion (in Europe) in c A.D. 1000 although for scramasaxes or knives it continued until c A.D. 1300 and later knives incorporating this technique may yet be found.

The Early Anglo-Saxon sword was contemporary with the Merovingian blades which were pattern-welded in the same way. Salin (1957) has given overall analyses of some of the Frankish blades including mechanical properties. The results show the usual low manganese and sulphur expected of early bloomery irons and the low carbon and higher phosphorus expected from the British metallographic results.

The pattern-welded swords found in Latvia and described by Anteins are believed to have been imported from the Rhineland and are typical of those used by the Rus during the 8th-12th centuries. The structures encountered are in all respects the same as those found in this work. Many have inscriptions such as Ulfbehrt, and there are 115 examples of this type in the Latvian collection. The metal of the inscriptions was itself usually pattern-welded. Some of the blades had a Type 1 sandwich, the centre pieces of which are reported to have been heat treated to give sorbite and troostite with a hardness of 250-330 HV. One blade contained an inlaid 'stick' figure of a man and was possibly local. The Viking type swords from Novgorod depicted by Kolchin, of the 9th-13th centuries seem to be of this type, and are not pattern-welded. Carbon contents reached 1.1% in places.

The observations of Al-Biruni (A.D. 973-1050), that watered swords made of wootz were more brittle in cold weather than the pattern-welded swords of the Rus (Vikings) seems to be a reference to brittle fracture. It is well-known today that certain elements and treatments can embrittle ferrite to such an extent that it looses its ductility on impact at temperatures as high as -10°C, Becker and Dick (1971, 223-227) carried out brittle-ductile transition temperature tests on wrought iron from Roman pile-shoes and compared the results with modern steel and wrought iron. The results gave poor values for the Roman iron by comparison with the modern steel and wrought iron (Tylecote and Gilmour 1986, 253).

The Roman iron contained 0.2% phosphorus and 0.12-0.16% nickel as principal impurities but these are not thought to be responsible for the poor values. This is more likely due to coarse grain size and slag inclusions, although the coarse grain size may have been directly related to the phosphorus content.

Tavadze and others (1975, 409-412) have also examined the brittle fracture properties of early iron with 0.1-0.4% C and came to the conclusion that the notch impact strength was considerably below that of modern material of the same ultimate tensile strength. They also blamed the slag inclusions.

It would seem, then, that the phosphorus content by itself is not the most important factor. The high carbon content of wootz (1.6%) would be a factor militating against it in cold climates. It is possible that the banded structure of pattern-welded swords, in spite of the large number of slag inclusions in some blades, may have a beneficial effect.

It would be expected that the high phosphorus iron would have a large grain size while that of the low phosphorus low carbon iron would be finer. Mixing the two structures in alternate bands would produce the high corrosion resistance of the high phosphorus bands and the crack-arresting characteristics of the fine grained ferrite + carbide structure in the neighbouring bands. It would seem that the pattern-welded swords of the Rus were superior to the oriental swords in the climate in which they had to operate.

The clear indication from the results so far is that weaponsmiths during the Anglo-Saxon period were using carefully selected iron alloys for the production of the pattern-welded and non-patterned parts of the weapons they were producing. In the majority of cases the composite rods which were used in the pattern-welded parts of these weapons consisted of 6-8 laminations alternately consisting of low carbon iron, usually about 0.1-0.2% carbon, and high phosphorus iron. The microprobe analytical results (Table 8) for the blades analysed for phosphorus suggested phosphorus levels of approximately 0.4-0.8% for the alternate laminations of these composite rods. These results confirmed the likelihood that the higher hardness values obtained for the large grain carbon free ferritic bands corresponded to a high phosphorus content for these bands (Table 5).

We do not yet know where the different alloys used for the production of the pattern-welded components were produced, or on what scale or how these alloys were distributed and sold. There seem to be fairly good stylistic arguments for thinking that many of these weapons were made in this country and therefore are indigenous Anglo-Saxon products rather than having been imported although very similar weapons were clearly being produced across the channel on mainland Europe.

High phosphorus iron would have been produced from high phosphorus ores and the results of the present work show that it was known for its optical properties, when polished, and probably for its higher hardness as well, and that it was traded as a specialised product for the pattern-welded weapon industry. The high phosphorus metal could have been made wherever high phosphorus ores occured. These are mainly bog ores and were widespread although specialised centres of manufacture may be more likely.

It seems to have been assumed although not generally stated that, the other main raw material for pattern-welding, low carbon iron was made at or near the place of weapon manufacture by carburising pieces of low phosphorus bloomery iron in the form of bars or strips. If this is eventually shown to be the case, and there seems to be very little evidence either way, the production of these low carbon iron pieces may have been a non-specialised operation carried out by many weaponsmiths. Recent research in Norway (Svan forthcoming) suggests that this may not (always) have been the case. Quantities of varying sized 'currency bars' were being made and transported during the fourth-eighth centuries A.D to a central market from where they were distributed although the destinations are not known. Some of these 'currency bars' have been metallographically examined and shown to consist of a fairly uniform low carbon iron (carbon content approximately by 0.1-0.2%). One of the most likely customers for prepared pieces of low carbon iron (an early form of mild steel) would have been the makers of pattern-welded weapons. It is possible that iron in this form was being imported into Anglo-Saxon England; and it is also likely that a similar, more specialised system for making this 'raw material', both for pattern-welded and for non pattern-welded weapons, existed here although, so far, no evidence for it has been recognised. Possibly its existence, or lack of it, will come to light when we look for it. In any case it is clear that we need to look more carefully at the material remains of this whole industry before we can really answer any problem such as this.

7.4.4 Pattern-welded blade types

The main cross-sectioned pattern-welded types encountered in the present study are summarised in Fig 65. It should perhaps be stressed that some types only occur on specific types of weapons (see Appendix 1). For instance the narrow bands occupying the full width of the blade are common on scramasaxes but are not found on swords or spearheads.

Certain forms of pattern-welding are not readily represented in cross-sectional form and these are not included in Fig 65. One main example of this is the wavy weld or saw-toothed form of pattern. In one method this was achieved by hot forging a corrugated profile along the edge of a piece to be welded and then forging the reverse of this profile (which was sometimes the same) along the side of a second piece (Fig 64). We can see from the spearhead (6.51.S33) that the wavy weld, achieved by joining these two pieces, was enhanced when the metal on one side of the weld consisted of low carbon iron and the other was high phosphorus iron. This, on etching, would have resulted in the same light-dark contrast which seems to have been usual for the laminated central components of Anglo-Saxon pattern-welded weapons. The contrast across the wavy weld can be seen in Fig 64. where part of this spearhead has been mounted and polished to show an enlarged view of the effect that would have been visible.

Another method which also gave a toothed appearance is one which seems to have been only used for scramasaxes or knives. In this method a bar, which was to become the cutting edge part of the blade, was firstly notched at intervals along one side to take the individual teeth. These were probably too difficult to insert separately so that it would seem most likely that a rod of approximately the correct cross-sectional profile, would have been prepared. The end of this was probably welded into the first slot, the end then cut off, and the process repeated until all the 'teeth' were in place (Fig 79). None of these individual toothed pieces has so far been analysed but, by anqlogy with the spearhead 6.51.S33, it seems very likely that a high phosphorus iron may have been used for these 'teeth' which would have contrasted well if a low carbon iron was used for the main bulk of the cutting edge. The Dorset scramasax (6.45.S4)shows that the narrow bands along either side of the pattern-welded parts of these weapons are likely in many cases to have consisted of high phosphorus iron. It appears that these strips were sometimes used in combination with the individual toothed pieces (see Appendix 1). This combination may have simply been a variation of the continuous wavy line or saw tooth weld pattern.

7.4.5 Methods for varying the patterns and for producing the final surface appearance

It is clear from the results of radiography (Appendix 1) that the herringbone pattern, formed by welding together rods of opposite twist, was the most popular form of pattern during the Anglo-Saxon period. The herringbone pattern was sometimes continuous but very often was interrupted at intervals either to give straight grain panels, as in the Acklam sword (Fig 68), or individual rods were given straight grain parts at staggered intervals. Another way that the pattern could be varied was to grind down the twisted rods through part of their thickness before the final polishing and etching. Grinding away progressively greater amounts from the thickness of a twisted rod gave different visual effects (Fig 69).

This technique for varying the appearance of welded twisted rods was not fully exploited until about the ninth century and even then its use was largely restricted to scramasaxes. Before the eighth century, pattern-welding had been restricted to swords whose final shape was mostly achieved by forging, with grinding and polishing being restricted to the final work, the result being that virtually unaltered herringbone patterns predominated. This was still largely true for swords in the late Saxon period (ninth-eleventh centuries although it would appear that for some of these the final grinding did result in fairly distorted herringbone patterns. This is well illustrated by the tenth century sword from Gilling West (Fig 80). In which a distorted herringbone pattern was visible along the central fuller in places where the original surface was perfectly preserved, although stained black (Gilmour 1986). This distorted herringbone pattern must have involved the removal of about one quarter of the original thickness of the twisted rods (Fig 69).

The looped form of pattern was the result achieved by grinding away half the thickness of a twisted laminated rod. This form of pattern (Fig 78) seems to have been only used for scramasaxes (see Appendix 1). In order to achieve a matching looped pattern the individual twisted rods must have been ground down to half their thickness, polished, etched then cut and clamped into the correct position before the welding together of the pattern-welded components. The varying distorted herringbone pattern seen on some swords, scramasaxes and spearheads was the result of differential forging and final grinding after the welding together of the blade components. In some of these blades it may have been the accidental results of over grinding as much as a deliberate effect.

The pattern-welded parts of all these weapons must have been very striking after the blades had been ground, polished and etched. We know from an illustration in the Utrecht psalter that grinding was carried out on a wheel in the 9th century (Fig 1). Polishing would have been carried out, probably as a slurry, using a fine abrasive powder such as the 'shining dust' (? kieselguhur or diotomaceous silice) mentioned by Cassiodorus in the 6th century. There seems to be no clue as to what etchants were being used although what would seem likely is a naturally occuring substance such as the zag (impure ferric sulphate) used by the patterned or watered sword makers of the Middle East from the eleventh century and probably earlier (see Appendix 2).

One clue as to the appearance of pattern-welded spears of the 9th to 11th centuries can be found in an illustration in an early 11th century Anglo-Saxon manuscript (Fig 81) and repeated on the Bayeux Tapestry (Stenton 1957, Fig 30 and Plate 41). We can see how the spears are represented apparently as barbed weapons. Large barbed spearheads like this are not found in this period and although possibly an error it seems more likely that this is a simple representative drawing based on the most obvious visual aspects of the spearheads. A comparison between an enlarged view of one of these and a reconstruction of the final appearance of a common form of large pattern-welded spearhead shows a striking similarity between the two (Fig 82). It would seem that the barbed appearance may well be a representation of the pattern part of the spearhead as the aspect of the weapon most noticeable to the manuscript illustrator of the mid eleventh century. This appearance would have been enhanced by the use of low carbon iron in combination with high phosphorus iron for the pattern-welded parts.

7.4.6 Eastern pattern-welding

There is, so far, no indication that pattern-welded types differed to any great extent across Europe when this technique was popular there before about the mid eleventh century. It seems clear, from the accounts of the early Arab writers, that pattern-welding was well known in the Middle-East from the sixth century A.D. if not earlier (see Chapter 2.1). We do not yet know if pattern-welding developed separately in this region or whether the stimulus for its development came from elsewhere, possibly from north-western Europe where we can now be fairly sure that it developed independently by the first century B.C.

Pattern-welding is likely to have continued in use for edged weapon manufacture in the Middle East after the eleventh century as it was from this area that the technique was re-established in Western Europe by Western arms makers when they began to produce the so-called 'damascus' gun barrels in the eighteenth century.

The surviving material in Middle Eastern collections has yet to be examined and catalogued in detail so that we can assess how fashions and techniques affecting pattern-welding changed before it was re-introduced to the West. Known surviving examples of pattern-welded Middle Eastern weapons in Western collections appear to date from about the sixteenth century or later. The technique of producing patterned barrels, by making twisted composite rods then winding these round a mandril to produce a hollow spiral which was then hammer welded together (Greener 1910, 235), may have been developed in the Middle East during the fifteenth and sixteenth centuries. Contemporary pattern-welded sword blades are likely to have provided the idea for this new form of pattern-welded weapon.

We cannot conclude very much more about the forms and development of pattern-welding in the Middle East or of its relationship to the production of watered crucible steel blades in the region (see Appendix 2) until a great deal more gathering and examining of available material has been done. Apart from the important contribution of the early Arab writer, very little appears to be known at all about the early technological developments of weapons manufacture in the Middle East. The evidence of weapons surviving in modern collections would suggest, however, that variations on the twisted rod patterns, similar to those seen much earlier on edged weapons of the Anglo-Saxon period, were the most popular form of pattern-welding used for Middle Eastern weapons.

The origin and early development of pattern-welding in South-East Asia is not yet known. At the moment we can only speculate as to whether this technique of producing decorated weapons developed independently in this region or whether the idea came from further west. Many pattern-welded edged weapons, particularly the kris and other stabbing or slashing weapons, survive and the earliest of these have been attributed to the thirteenth century (for instance, Solyom and Solyom 1978, 17-21 & 26-27). These include examples of the more familiar (in the West) twisted rod form of pattern and also the earliest known examples of the contour map form of pattern. It has been suggested that the first textured (pattern-welded) blades in Indonesia occur under Hindu influence, during the Majapahit Empire of the 13th-15th centuries (Smith 1960, 35).

Pattern-welded weapons particularly of the kris type have continued to be made, using traditional methods, right up into the late 20th century (Solyom and Solyom 1978, 7-11). It seems clear, from the many surviving examples, that the contour map form of pattern became the predominant form of pattern-welding to be used for these weapons. Many blades are striking for the way in which they have been very heavily etched which has accentuated the surface patterns both of the twisted and contour map varieties (illustrated in Solyom and Solyom 1978, 21 and Smith 1960, 37).

The contour map form of pattern is a result of the laminated construction used for the surface part of either side of these blades. This laminated structure has usually been distorted at varying intervals and directions to produce a variety of patterned effects in which the 'contour lines' or laminations appear either closer together or further apart depending on whether a punch was used to locally compress the laminations, or whether grooves were cut or shallow holes drilled which had the effect of spacing the 'contour lines' or making the laminations seem further apart on the finished blades (Panseri 1965, 63). After the use of a punch to compress parts of the laminated surface the remaining surface had to be partially ground away, before the final finishing of the blade, so that the effect of the differential compression would show up. Conversely, where parts of the lamination were ground away the pattern would not show up until the blade had been forged flat before being finally ground to shape and finished. Final grinding away of the edges at different angles also had the effect of leaving the layered structure exposed to differing extents. This left the laminations appearing when viewed from above to be spaced closer together or further apart depending on the angle of the grinding, again a close analogy with a contour map.

Two similar Malasian kris, one (S60 (T1) - see Tylecote and Gilmour 1986, 144-8) possibly 17th century while the other (6.48.S57) a more likely 19th century weapon, were sectioned at the Institute of Archaeology, London, to examine the manufacture of these relief map pattern-welded blades (Tylecote and Gilmour 1986, 144-149). Both blades were found to have a thicker central piece of medium to high carbon steel (0.5-0.7% carbon) which also formed the cutting edges of the weapons. The steel was comparatively soft (189-197 HV) with a structure mostly consisting of spheroidised pearlite, possibly the result of a final low temperature (below 700°C) annealing treatment.

Thinner laminated pieces, which gave rise to the patterned appearance, had been welded onto either side of the thicker steel core pieces resulting in a sandwich construction. The laminated outer (surface) parts consisted of alternate thin bands of pearlite and nickel rich ferrite.

EPMA analysis of one of these banded pieces showed the ferrite to contain approximately 3% nickel (Tylecote and Gilmour 1986, 147). Surface XRF analysis on the other blade (see 6.48.S57) indicated that alternate bands contained about 2.3% nickel. The nickel rich iron was undoubtedly used because of the brighter (white) optical properties that resulted after polishing and etching. A micrograph of the kris section S60 (T1) showed the contrast between the larger grain nickel rich iron and the smaller grain pearlitic or low carbon iron of the alternate laminations (Tylecote and Gilmour 1986, 146). On the final etched surface of the blade this would have shown up as alternate white and grey bands. This provides an interesting comparison with the technique of smiths, in the Anglo-Saxon period, who used laminated high phosphorus iron with low carbon iron to produce the composite rods for the central pattern-welded parts of their weapons to achieve the same visual contrast upon etching.

It is often said that nickel rich iron of meteoric origin was traditionally used for the *pamor*, the decorative laminated parts, of the South-East Asian contour map pattern - welded weapons although it is far more likely that nickel rich iron was smelted from nickel rich laterite ores which are known to occur on the island of Sulawesi in north-east Indonesia (Bronson 1987, 13). The only meteorite known to have fallen in Indonesia, or the surrounding region, fell near Prambanan in Java probably between 1749 and 1784 and both main fragments were in the hands of the local king by 1797. Parts of the smaller fragment seem to have been used by local smiths but the larger piece was apparently kept safe. Java does not seem to be noted for its kris production and, in any case, there does not seem to have been enough metal in the Prambanan meteorite, even if it had all been used, for all the many thousands of kris blades that were made (Bronson 1987, 12). In any case, the Prambanan meteorite cannot have been used as a source of nickel rich iron before the mid eighteenth century.

There seems no doubt that before the mid nineteenth century the nickel rich iron used for the laminated parts of the kris blades came from Sulawesi, which had been known for its iron production since the 16th century and an account of 1839 describes the metal from Sulawesi being mixed (presumably as a laminate) with 'the iron of old hoops, nails or a sort of iron brough from Billiton' (Bronson 1987, 12). A combination of scrap iron and other metal would most likely have resulted in a low carbon iron which would have contrasted well, after etching, when laminated with nickel rich iron. It seems likely that nickel rich iron was also used in the making of the twisted form of South-East Asian pattern-welding although this does not seem to have been tested yet.

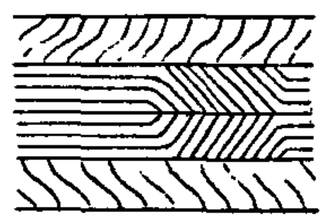
In 1433 the Chinese traveller Ma Huan described the knives carried by all Javanese men as being made of steel and decorated with intricate 'rabbits-hair snowflake' patterns. (Mills 1970, 88) although it seems, at the moment, impossible to say which form of pattern-welding this might refer to. There is clearly a great deal more research to be done before we can trace the development of the two main types of pattern-welding, the twisted and the contour map forms, which are found in South-East Asia. If the suggestion (Smith 1960, 35) that the pattern-welded technique came to this region from India then there seems to be a possibility that the technique originated in Western Europe although we would then need to determine how the technique originated in India. Much more work needs to be done before a greater appreciation of the artistic styles can be made as well as determining how pattern-welding developed as a technique in different parts of the world.

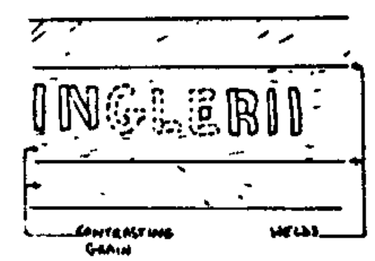
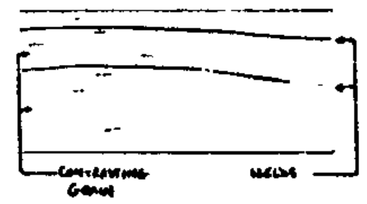
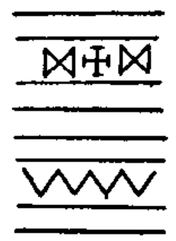
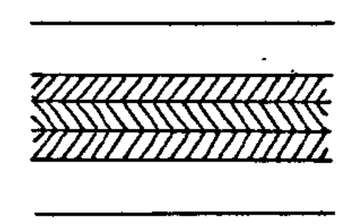
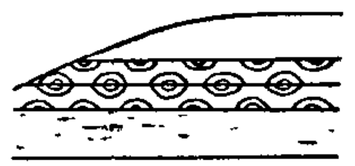
Appendix 1 : Catalogue of edged weapons examined by X-radiography

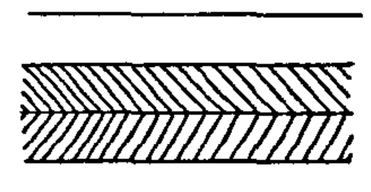
This catalogue is a brief analysis, in tabular form, of the results of the radiography of edged weapons done during course of this study on the development of Anglo-Saxon edged weapons. The purpose of the radiography was to provide structural information to add to the observations made on the initial visual examination of various edged weapons before deciding which weapons should undergo metallographic analysis and where the sectioning should take place.

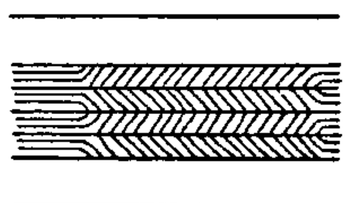
Sketches have been included to provide a diagrammatic view of the surface appearance mainly of the pattern-welded weapons or those inalid with iron pieces. A few sketches have been included to show other features such as the positions of especially obvious welds or the clear 'wood grain' pattern attributable to slag inclusions or, possibly, a specific welded construction. The sketches have not been drawn exactly to scale but are intended to give a proportionally correct impression of the surface appearance of each of the weapons illustrated. As a rough guideline the great majority of the swords were 5-6 cm in width whereas most scramasaxes were about 2.5 - 4.0 cm wide. Most of the spearheads included were approximately 3-5 cm at their widest point.

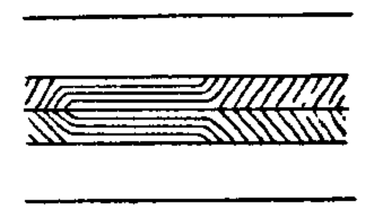
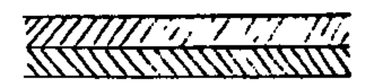
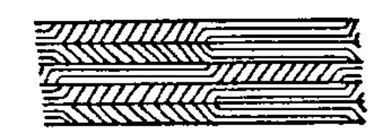
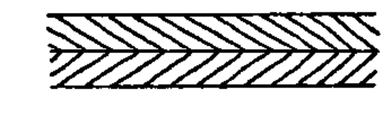
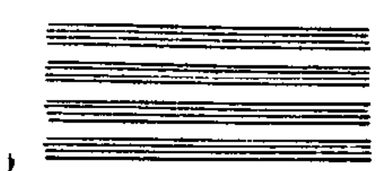
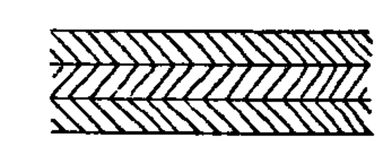
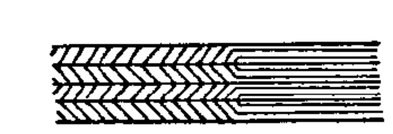
These results do not cover all the weapons of the Anglo-Saxon period that survive in Britain although an initial survey of existing weapons done during the earlier part of this study, suggests that about 75-80% of this material has been included. A number of examples both earlier and later than the Anglo-Saxon period have also been included by way of comparison especially to help illustrate the development of pattern-welding. New weapon finds continue to be made and it is intended that this catalogue will be added to, in the future, to provide further information.

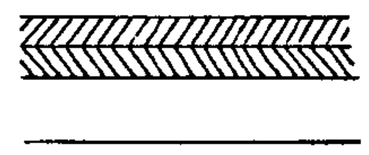
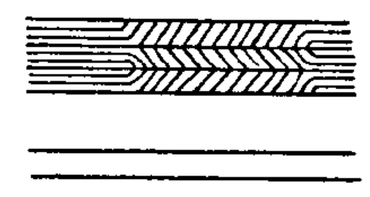
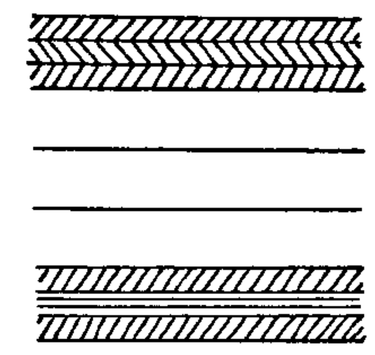
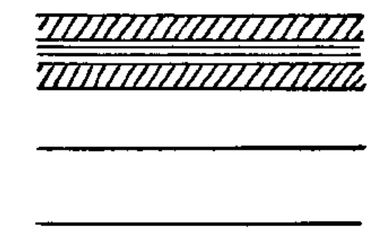
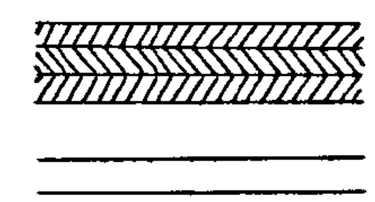
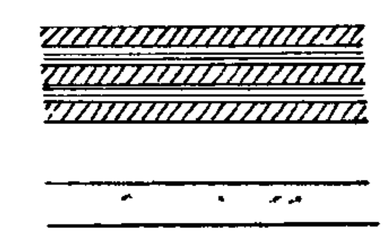
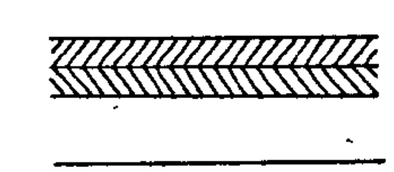
Cat. no.	X-ray no.	Acc. No (or temp no)	Museum: Findsite	Approx. Date	Weapon type and Comments	Sketch of Pattern or Inlay
001	AML B3561	244.71	Reading Mus: Stratfield Saye;	9-10c	Sword: pattern fairly clear - mostly straight grain with 2 short herringbone panels; prob 2 layers & central core between; grain suggests poss. single layer of distorted (by forging) twisted pieces to edges	
002	AML B3568	510.77	Reading Mus: site uncertain	9-11c	Long Scramasax with 1 wider groove between 2 narrow grooves next to back. X-ray shows v. little	
003	AML B3574	232.61	Reading Mus: Keen Edge Ferry	9-10c	Scramasax with intricate non-ferrous inlay pattern & single p-w strip-looped pattern (1/2 ground) 2 layers thick	

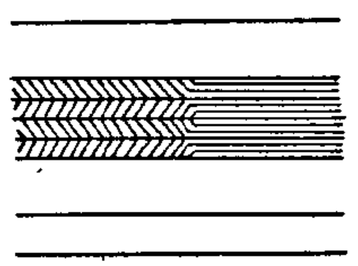
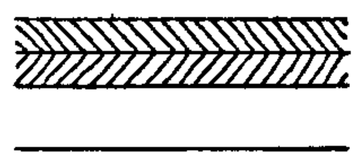
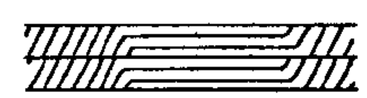
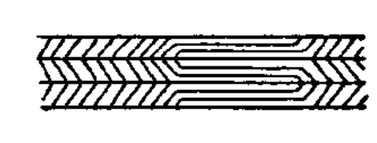
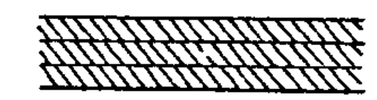
Cat. no.	X-ray no.	Acc. No (or temp no)	Museum: Findsite	Approx. Date	Weapon type and Comments	Sketch of Pattern or Inlay
004	AML B3580	194.62	Reading Mus: prob. river-find; site uncertain	?9-11c	Short Scramasax: with one groove near back; no welds or p-w, but some straight grain visible across blade no p-w	
005	AML B3567	285.47 (T.C.B)	Reading Mus: ? from Thames	9-10c	Sword: blade with ? shallow fuller & inlaid lettering & non ferrous inlay - silver and copper alloy - on hilt and pommel	
006	AML B3575	160.60	Reading Mus: prob. river find; site uncertain	?9-11c	Sword: fullered blade with inlaid lettering on both sides near hilt - v. diff. to interpret on X-ray.	
008	AML B3576	112.63	Reading Mus: site uncertain	9-11c	Long scramasax with 2 narrow grooves along blade near back: signs of 2 welds - on X-ray - dividing blade into 3 parts; straight grain also visible across blade	
009	AML B3578	247:65/1	Reading Mus: prob. river find; site uncertain	? L1A	Sword: flattish convex blade with slight signs of straight grain on X-ray	
010	AML B3586	170.65	Reading Mus: probe. river find; site uncertain	10-11c	Sword: fullered blade with inlaid design on either side near hilt	
011	AML B3587	90.61	Reading Mus: R. Kennet at Reading	?9-10	Sword: fullered blade with clear continuous p-w showing; and slight signs of separate core on X-ray. Pronounced grain visible along edges	
012	AML B3560	1083.64	Reading Mus: R. Lock, above Bow Bridge, Cholsey	?9-11c	Scramasax: double p-w band-prob. 2 layers, thick - near centre of blade	

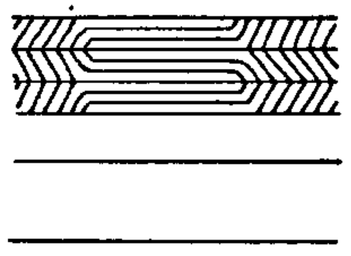
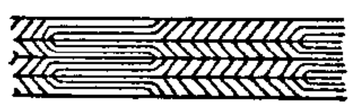
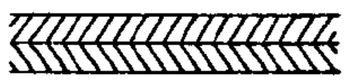
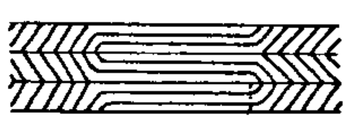
Cat. no.	X-ray no.	Acc. No (or temp no)	Museum: Findsite	Approx. Date	Weapon type and Comments	Sketch of Pattern or Inlay
013	AML B3562	no acc. number [S.30]	Reading Mus: Sunbury Weir Stream	?L Med	Sword: blade fragment with lozenge shaped section but little structural detail; see S30 and and BAR, 155, 240	
014	AML B3563	50.80 (HL) [S.26]	Reading Mus: site unknown	L Med	Sword: blade with narrow fullers; no detail visible on X-ray; see S28 and BAR, 155, 238	
015	AML B3564	1608.64 [S.28]	Reading Mus: Wallingford Bridge	L Med	Sword: blade of convex profile with little detail visible on X-ray. See S28 and BAR, 155, 238	
016	AML B3566	106.61/1 [S27]	Reading Mus: R. Thames at Little Wittenham	L.1A	Sword: blade fragment with convex profile and with grain - prototype p-w showing on X-ray See S27 and BAR, 155, 163	
017	AML B3566	370.78	Reading Mus: prob. river find; site not known	?10-11c	Sword: fullered blade with wide continuous herringbone p-w	
018	AML B3569	52.80 (TCB 491) [S22]	Reading Mus: R. Thames, ? near Reading	9-11c	Scramasax: with narrow single continuous twist p-w running down centre of blade; see S22 and BAR, 155, 134	
019	AML B3570	51.80 [S31]	Reading Mus: Caversham, Berks	?7-9c	Sword: lower half of sword blade with wide, shallow fuller and continuous triple band p-w. See S31 and BAR,155, 209	
020	AML B3571	16.36 [S.25]	Reading Mus: Reading, Oxford Road; Tilehurst St	10-11c	Sword: blade fragment with shallow fuller and continuous herringbone p-w; see S25 and BAR, 155, 232.	

Cat. no.	X-ray no.	Acc. No (or temp no)	Museum: Findsite	Approx. Date	Weapon type and Comments	Sketch of Pattern or Inlay
021	AML B3572 +B3581	258.63a 258.63b (TCB 262) [S24]	Reading Mus: Cleeve, by R Lock at Benson Reach	9-11c	Sword: two halves of convex section with 3 narrow p-w bands of continuous twist along the centre occupying the full thickness. See S24 and BAR, 155, 227	
022	AML B3573	1809.64	Reading Mus: R. Thames above Chalmore Ferry	9-11c	Scramasax: v. little detail shows on X-ray	
023	AML B3577	284.47 (TCB)	Reading Mus: R. Thames above Newbridge	9-11c	Scramasax: grooves along blade near back but little shows on X-ray	
024	AML B3579	141.60 (TCB) [S29]	Reading Mus: R. Thames, ? from Little Wittenham	LIA	Sword: lower half of blade with very little visible on X-ray. See S29 and BAR, 155, 161	
025	AML B3583	112/66/1 112/66/2 [S23]	Reading Mus: ? from R. Thames	8-10c	Sword: two halves which show v. little on X-ray except twisted inlaid pieces on either side near hilt - prob. lattice design - diff. to see. See S23 and BAR, 155, 218.	
026	AML B3584	227.62 (TCB 253)	Reading Mus: R. Thames, below Benson Lock	9-11c	Long scramasax: double groove along blade near back; no other detail visible on X-ray	
027	AML B3585	131.61 [S32]	Reading Mus: prob. river find,	EIA	Sword: leaf shaped blade with v. little detail visible on X-ray. See S32 and BAR, 155, 150.	
028	AML B3551	HOL 2 [EAS 3]	Maidstone Mus: Holborough, Kent	7c	Sword: clear quadruple rod p-w with alternating herringbone and straight grained panels; 2 layers, no core	

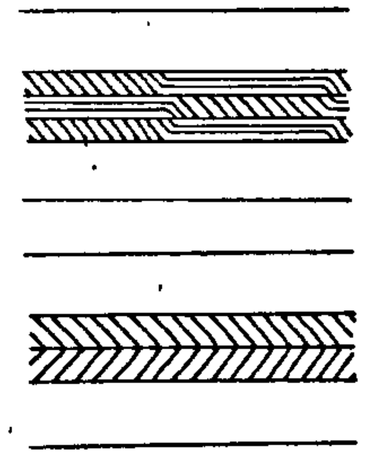
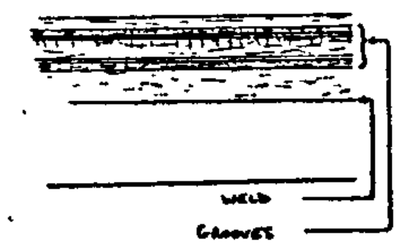
Cat. no.	X-ray no.	Acc. No (or temp no)	Museum: Findsite	Approx. Date	Weapon type and Comments	Sketch of Pattern or Inlay
029	AML B3556	A-S119 [EAS 3]	Maidstone Mus: Buttsole, Eastrey, Kent; from grave	6-7c	Sword: pattern not v. clear, prob separate central core between 2 p-w layers. Alternates as shown	
030	AML B3536	KAS 620 1954.20	Maidstone Mus: ? Bifrons, Kent	? 6-7c	Sword or ? long scramasax: v. little detail on X-ray	
031	AML B3532	KAS 821	Maidstone Mus: Sarre, Kent	6-7	Sword: continuous fairly clear double rod herringbone pattern. 2 layers of p-w with signs of a separate core between	
032	AML B3534	KAS 824	Maidstone Mus: Sarre, Kent, grave 71	6-7	Sword: Pattern fairly clear - alternating as shown. Prob 2 layers of outer part twisted rods but central straight grain rod prob. forms only one layer	
033	AML B3529	KAS 831	Maidstone Mus: Sarre, Kent; grave 156	6-7c	Sword: pattern not v. clear but seems as shown with little 2 layers of p-w prob. without any core between	
034	AML B2545	?775709(b) R-B Grave	Canterbury Mus: Canterbury, Kent	4c	Sword: quite clear coarse herringbone pattern with 2 layers but no sign of a separate core in between	
035	AML B2467	775709	Canterbury Mus: Canterbury, Kent R-B grave	4c	Sword: quite clear continuous straight pattern; only one layer visible	
036	AML B3546	KAS 833	Maidstone Mus: ? Sarre or Bifrons; Kent	6-7c	Sword: triple rod, continuous herringbone pattern; 2 layers with prob. core in between	
037	AML B3548	KAS 835	Maidstone Mus: ? Sarre or Bifrons, Kent	6-7c	Sword: quadruple rod pattern with alternating straightgrain and herringbone panels; 2 layers with probable core in between	

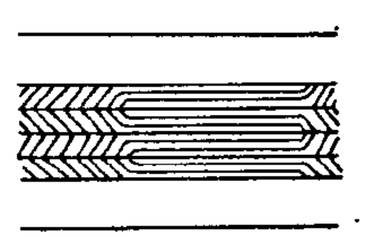
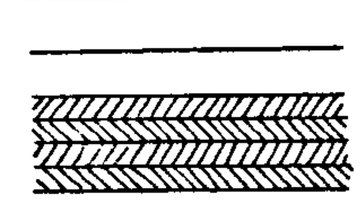
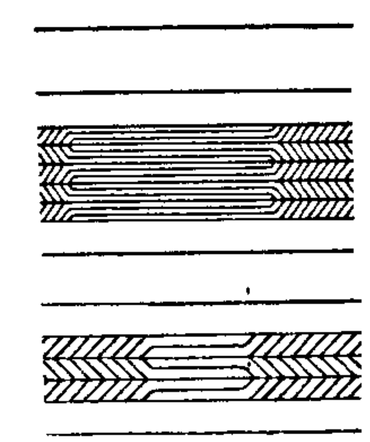
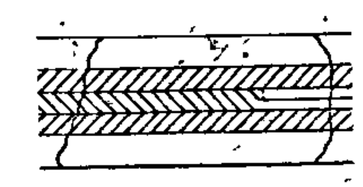
Cat. no.	X-ray no.	Acc. No (or temp no)	Museum: Findsite	Approx. Date	Weapon type and Comments	Sketch of Pattern or Inlay
038	AML B3556	A-S 120 (EAS 2)	Maidstone Mus: Buttsole, Eastrey Kent; from grave	6-7c	Sword: continuous herringbone pattern 2 layers with a probable core in between	
039	AML B3558 + B3545		Maidstone Mus: Kent, site not known	9-10c	Scramasax - large blade (Petersen Type H): v. little structure shows on X-ray	
040	AML B3547	KAS 819	Maidstone Mus: Sarre, Kent; grave 15	6-7c	Sword: fairly clear triple rod pattern with equal length alternating panels of straightgrained and twisted parts; 2 layers prob. without a separate core	
041	AML B3549	KAS 830 [S17]	Maidstone Mus:	6-7c	Sword: continuous triple rod herringbone pattern; 2 layers prob. without a separate core. See S17 and BAR 155, 202-206	
042	AML B3552	? [AYL1] [S18]	Maidstone Mus: Preston Hall, Aylesford, Kent; probable grave	5-6 c	Sword: quite clear continuous pattern; 2 layers to twisted part and no sign of a separate core. See S18 and BAR 155, 195-197	
043	AML 3554	? [WX1] [S19]	Maidstone Mus: Wickhambreux, Kent; from grave	6-7c	Sword: pattern appears continuous; 2 layers & central core. See S19 & BAR, 155, 197-201	
044	IA 22	? [WX2] [S12]	Maidstone Mus: Wickhambreux; Kent; from grave	6-7c	Sword: pattern appears continuous; 2 layers to twisted parts but no separate core	
045	IA18	KAS 825 [S53]	Maidstone Mus: Sarre, Kent; grave 250	6-7c	Sword: pattern appears continuous; 2 layers but no separate central core	

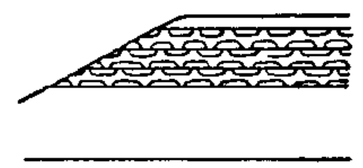
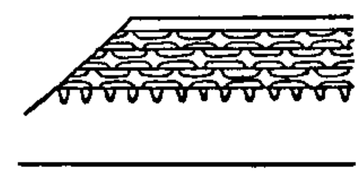
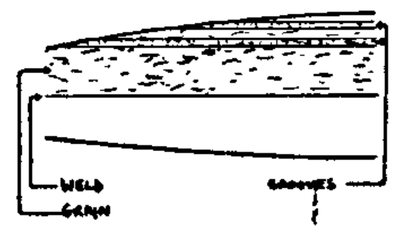
Cat. no.	X-ray no.	Acc. No (or temp no)	Museum: Findsite	Approx. Date	Weapon type and Comments	Sketch of Pattern or Inlay
046	IA10 & IA11	KAS 939	Maidstone Mus: Sarre or Bifrons, Kent	6-7c	Sword: pattern prob. alternates as shown; 2 layers but no sign of separate core	
047	IA14 & IA15	KAS 822	Maidstone Mus: Sarre, Kent; grave 103	6-7c	Sword; continuous pattern; 2 layers and no sign of separate core	
048	AML B3553	13.1956 [RCH1] [S48]	Maidstone Mus: Watts Ave, Rochester,Kent prob. grave.	9-10c	Sword: pattern alternates in long panels; 2 layers with no core	
049	AML B3540	KAS 837 [S56]	Maidstone Mus: Bifrons, Kent; grave 39	6-7c	Sword: alternating pattern; 2 layers with separate core between (hardly visible on on(X)ay) See S56 & BAR 155, 204+206	
050	AML B3527	KAS 836 [S55]	Maidstone Mus: Sarre or Bifrons, Kent	6-7c	Sword: pattern difficult to see but seems continuous as shown; 2 layers and separate core between (can't see on X-ray). See S55 & BAR 155, 177-178	
051	AML B3535	? [TOM1] [S13]	Maidstone Mus: Tomlinson bequest Kent - poss Bifrons	6-7c	Sword: non p-w (6) layered structure - shows curious appearance on X-ray. See S14 & BAR 155, 167 + 169	
052	AML B3533	A-S 121 [EAS1] [S14]	Maidstone Mus; Buttsole, Eastrey Kent; from grave	6-7c	Sword: some short straight panels in herringbone pattern; 2 layers + separate core between. See S14 & BAR 155, 191-194	

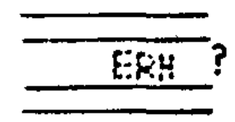
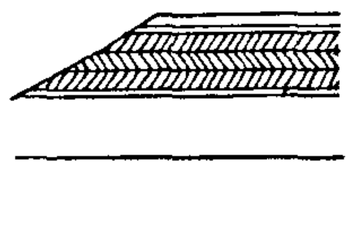
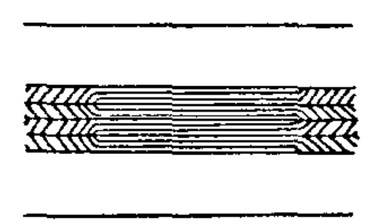
Cat. no.	X-ray no.	Acc. No (or temp no)	Museum: Findsite	Approx. Date	Weapon type and Comments	Sketch of Pattern or Inlay
053	AML B3539	? [HOL1] [S15]	Maidstone Mus: Holborough, Kent	7c	Sword: alternating pattern; 2 layers with no core between. See S15 & BAR 155, 207-209	
054	AML B3550	KAS 818 [S16]	Maidstone Mus: Sarre, Kent; grave 264	6-7c	Sword: alternating non-herringbone pattern, 2 layers with core. See S16 & BAR 155, 199-202	
055	AML B3530	KAS 823 [S52]	Maidstone Mus: Sarre, Kent; grave 113	6-7c	Sword: alternating herringbone pattern; 2 layers but no core between. See S52 & BAR 155,	
056	AML B3531	KAS 820 [S51]	Maidstone Mus: Sarre, Kent; grave 64	6-7c	Sword: no structure visible on X-ray See S51 & BAR 155, 180-183	
057	AML B3555	KAS 620.1954 20 [TOM2] [S49]	Maidstone Mus: ?Bifrons, Kent; Tomlinson Bequest 17	?6-7c	Sword: pattern continuous but not very clear 2 layers with no separate core. NB twists could all be on one side. See S49 & BAR 155, 185 - 186	
058	AML B3528	KAS 834 [S54]	Maidstone Mus: ? Sarre or Bifrons, Kent	6-7c	Sword: continuous herringbone pattern, 2 layers but no separate core. See S54 & BAR 155, 177-178	
059	IA 55	3.1977 [LEN1] [S20]	Maidstone Mus: Lenham, Kent; from grave	6c	Sword: continuous herringbone pattern on one side & alternating on the other, 2 layers with a core between. See S20 & BAR 155, 168-172.	

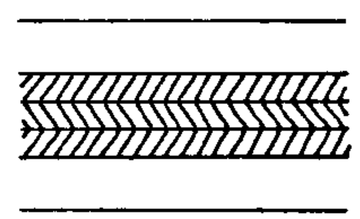
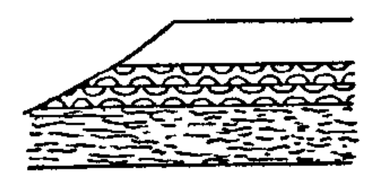
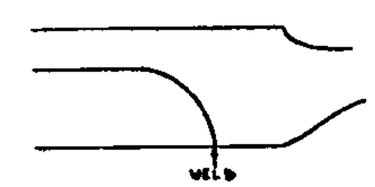
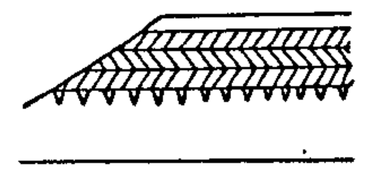
Cat. no.	X-ray no.	Acc. No (or temp no)	Museum: Findsite	Approx. Date	Weapon type and Comments	Sketch of Pattern or Inlay
060	IA 61	KAS 620.1954. 19	Maidstone Mus: ?Sarre or Bifrons, Kent	6-7c	Weaving batten: no structure shows on X-ray	
061	IA 62	KAS 941	Maidstone Mus: Sarre, Kent; grave 4	6-7c	Weaving batten: no structure shows on X-ray	
062	IA 21	? [BAR1] [S50]	Maidstone Mus: Barham Down, Kent; from grave	7c	Scramasax: no structure shows on X-ray	
063	370-373	KAS 832 [OXFIA: 850149-152]	Maidstone Mus: Sarre, Kent; grave 57	6-7c	Sword: pattern seems as shown, 2 layers but prob. no separate core between	
064	374-375	KAS 827 [OXFIA: 850153-154]	Maidstone Mus: Sarre, Kent	6-7c	Sword: alternating pattern seems as shown, 2 layers but prob. no separate core between	
065	376-277	KAS 826 [OXFIA: 850158]	Maidstone Mus: Sarre, Kent	6-7c	Sword: alternating pattern seems as shown, 2 layers but prob. no separate core between	
066	378-380	KAS 828 [OXFIA: 850155-157]	Maidstone Mus: Sarre, Kent; grave 88	6-7c	Sword: alternating pattern seems as shown, 2 layers but prob. no separate core between	
067	381-383	KAS 829 [OXFIA: 850163-166]	Maidstone Mus: Sarre, Kent: grave 256	6-7c	Sword: pattern uncertain - seems continuous but may be 3 or 6 bands? 2 layers - ? central core	

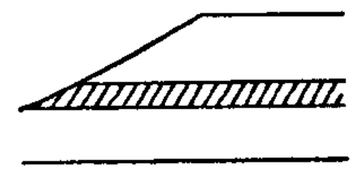
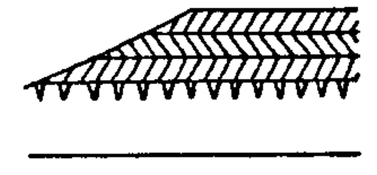
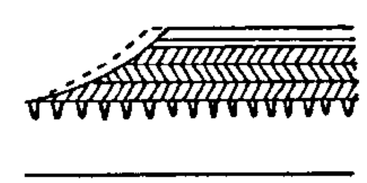
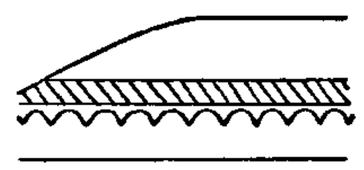
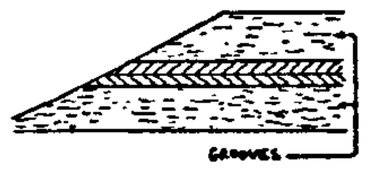
Cat. no.	X-ray no.	Acc. No (or temp no)	Museum: Findsite	Approx. Date	Weapon type and Comments	Sketch of Pattern or Inlay
068	384-385	KAS 940 [OXFIA: 850162]	Maidstone Mus: Bifrons, Kent	6-7c	Sword: pattern seems to alternate as shown, 2 layers but prob. no separate core between	
069	387-388	KAS 988	Maidstone Mus: Bifrons, Kent; grave 62	6-7c	Sword-fragment only: pattern seems continuous as shown, 2 layers but no sign of separate core between	
070	IA 50	? [S33]	Swindon Mus: Kempsford (Old Ford), Glos	9-10c	Spearhead: pattern as shown, 2 layers to twisted part & core; See S33 & BAR 155, 199-123	
071	IA 52	790309 [S35]	Swindon Mus: Kempsford (Old Ford), Glos	?6-11c	Spearhead: shows no structure on X-ray See S35 & BAR 155, 113-115	
072	IA 51	? [S36]	Swindon Mus: Kempsford, (Old Ford), Glos	?10-11c	Spearhead: simple pattern as shown, 1 layer only. See S36 & BAR 155, 117-121	
073	IA 63	790080	Swindon Mus: Kempsford, (Old Ford), Glos	?9-11	Scramasax/knife: no structural details showing	
074	AML 3590	? [GL1] [S37]	Swindon Mus: Kempsford (Old Ford), Glos	9-10c	Long Scramasax: grooves near back - no p-w; grain shows along back half of blade See S37 & BAR 155, 131-134	
075	IA 54	790308 [S34]	Swindon Mus: Kempsford (Old Ford), Glos	10-11c	Small Scramasax: A single twisted rod down centre with central untwisted part See S34 & BAR 155, 131-140	

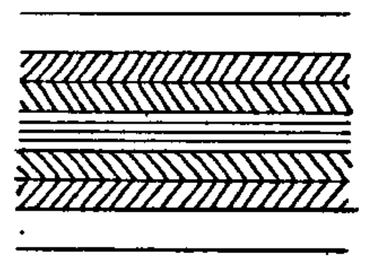
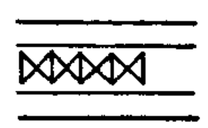
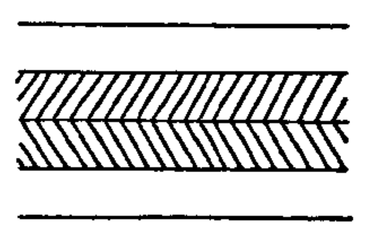
Cat. no.	X-ray no.	Acc. No (or temp no)	Museum: Findsite	Approx. Date	Weapon type and Comments	Sketch of Pattern or Inlay
076	AML B3586	28.65 [S39]	Peterborough Mus: Funtham's Lane, Whittlesey, Cambs	R-B 2c	Sword: v. little shows on X-ray See S39 & BAR 155, 164-161	
077	AML B3588	16/1979/1 [S40]	Peterborough Mus: Chesterton Cambs	5-7c	Sword: pattern of alternating herringbone and straight grain parts in long panels; 2 layers with no core between See S40 & BAR 155, 188-191	
078	AML B3644		Lincs. City and County Mus: Colsterworth, Lincs	?6-7c	Sword: continuous herringbone pattern; 2 layers prob. with a central core in between	
079	AM 258	6.66 [S1]	Lincs, City and County Mus: Loveden Hill, Lincs	e7c	Sword: alternating herringbone pattern, 2 layers with no core between. See S1 & BAR 155, 185-188	
080	OX217	SBP83 F2 10	Inst. of Arch.Oxford Watchfield, Oxon	6c	Sword: alternating pattern with some short straight grain parts, 2 layers with separate core between.	
081	OAV 86	SBP 83 140	Inst. of Arch. Oxford: Watchfield, Oxon	6c	Sword: small blade fragment only; herringbone pattern with short straight grain part in centre on one side; 2 layers with core in between.	
082	AM 259	?	Peterborough Mus: R. Nene near Peterborough, Cambs	L1A	Sword: coarse, slightly wavy straight grain pattern - continuous & extends from edge to edge across full blade width	

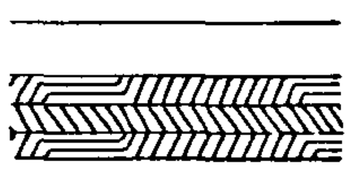
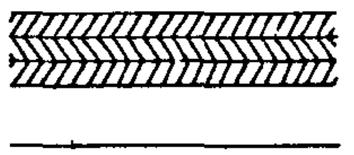
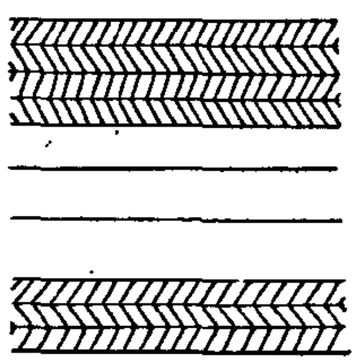
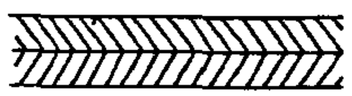
Cat. no.	X-ray no.	Acc. No (or temp no)	Museum: Findsite	Approx. Date	Weapon type and Comments	Sketch of Pattern or Inlay
083	AML 3734B	A24419 [S44]	Mus. of London: Thames, Brentford Essex	10-11c	Sword: pronounced straight grain across blade - ? slag; inlaid near hilt-twisted pieces making? geometric design - v. diff. to interpret; 2 possibilities as shown. See S44 & BAR 155, 234 - 236	 ?
084	AML	C2258 [S8]	Mus. of London: ? poss river find near London - ? Thames - or ? grave	?8-10c	Sword - upper part only: little decorative or structural detail shows on X-ray. See S8 & BAR 155, 221-224	
085	AML 3747B	A13501	Mus. of London: Thames at Hammersmith	?10-11c	Scramasax: continuous pattern as shown, prob. 2 layers without any core between	
086	AML 3747B	C2260 [S7]	Mus of London: ? poss river find near London, or ? grave	?9-10c	Sword: plain blade apart from some v. slight hints of inlaid twisted pieces near hilt; v. diff to see. See S7 & BAR 155, 219-221	
087	AML 3711B	A13935	Mus of London: Thames at Brentford, Essex	10-11c	Scramasax: continuous looped patterns (1/2 ground) as shown on either side of blade: prob. 2 layers without central core, plus 'teeth' occupying thickness of blade	
088	AML 3714B	A19735	Mus of London? Thames at Brentford, Essex	? Late Med	Sword: no structural detail vis. on X-ray	
089	AML 3738B	A13920	Mus of London: Thames, Mortlake	9-10c	Scramasax: plain blade with poss. weld between back & cutting edge	

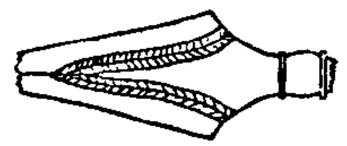
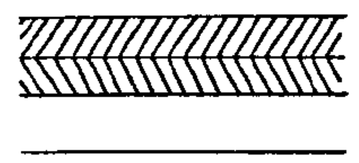
Cat. no.	X-ray no.	Acc. No (or temp no)	Museum: Findsite	Approx. Date	Weapon type and Comments	Sketch of Pattern or Inlay
090	AML 3717B	02108	Mus of London Thames at Hammersmith	? Late Med	Sword: no structural detail vis. on X-ray	
091	AML 3741B & 3740B	C2259	Mus of London: ? poss. river find	?9-10c	Sword: plain fullered blade with slight traces of (part of) inlaid design - ? ULFBERHT type - v. diff to see	
092	AML 3712B	A4978	Mus of London: ? poss river find near London	?8-10	Scramasax: no structural detail shows on X-ray	
093	AML 3709B	A11812 + 10989	Mus of London: ? from Thames in London	?9-10c	Scramasax: triple grooves near back but no structural detail shows on X-ray	
094	AML 3744B	29.94/17	Mus of London: Princes Street, London	10-11c	Scramasax: no structural detail shows on X-ray	
095	AML 3744B	0.2105c	Mus of London: Thames at Brentford	?9-11c	Scramasax/knife: no structural detail shows on X-ray	
096	AML 3744B	80.355/4	Mus of London: ? London	9-11c	Scramasax: no sign of welds or any pattern on X-ray	
097	AML 3744B	?A24909 or ?A24349	Mus of London: Thames at Fulham or Putney	9-10c	Scramasax: Continuous chevron p-w on both sides, 2 layers with no core between + narrow strips across thickness of blade	
098	AML 3748B & 3749B	0.2110	Mus of London: ? A-S cem, Brentford	5-7c	Sword: alternating pattern, 2 layers prob. without central core	

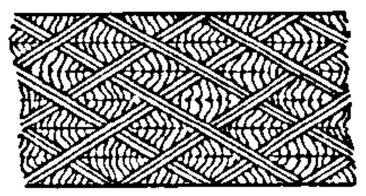
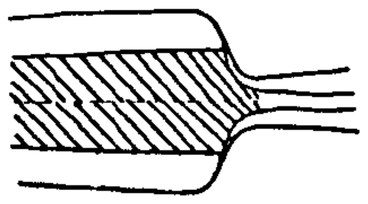
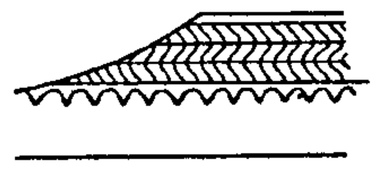
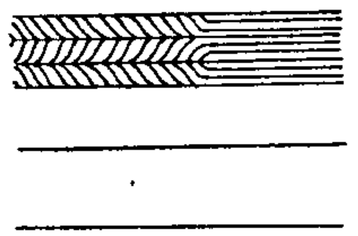
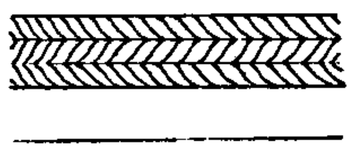
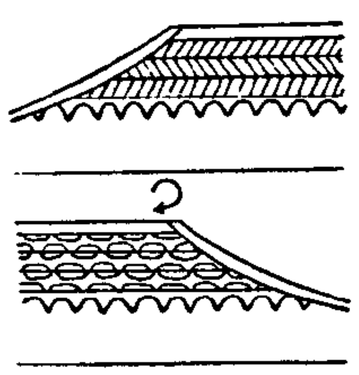
Cat. no.	X-ray no.	Acc. No (or temp no)	Museum: Findsite	Approx. Date	Weapon type and Comments	Sketch of Pattern or Inlay
099	AML 3748B & 3749B	0.2114	Mus of London: ? A-S cem,	5-7c	Sword: continuous pattern, 2 layers prob. without central core	
100	AML 3745B	0.2136	Mus of London: ? Brentford	?9-11	Scramasax/knife: some poss. welds down centre of blade	
101	AML 3745B	80.355/1	Mus of London: ? London	?9-11	Scramasax/knife: poss. weld down centre of blade, 3 narrow grooves near back & a wider groove inside	
102	AML 3745B	10.283 + MA2296	Mus of London: ? London	10-11	Scramasax: looped (half ground) continuous pattern on one side, herringbone on other; 2 layers but no core	
103	AML 3745B	80.355/2	Mus of London: ? London	?9-11	Scramasax/knife: weld visible down centre of blade	
104	AML 3743B	80.355/3	Mus of London: ? London	?9-11	Scramasax: no pattern or welds visible	
105	AML 3743B	A1655a	Mus of London: Thames at Wandsworth	9-10c	Scramasax: continuous pattern, 2 layers without a core between, plus 'teeth' occupying thickness of blade	
106	AML 3743B	A19313	Mus of London: Thames at Blackfriars	9-11c	Scramasax: no pattern or welds visible	
107	AML 3736B	A13920	Mus of London: Thames at Mortlake	9-10c	Scramasax: 2 grooves near back but no pattern or welds showing	

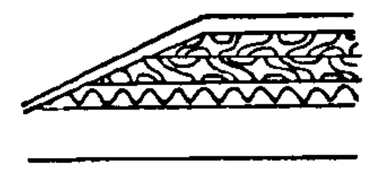
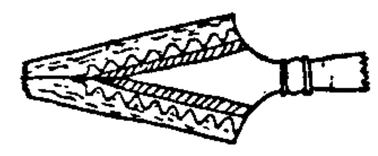
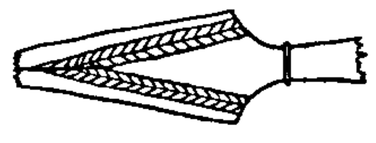
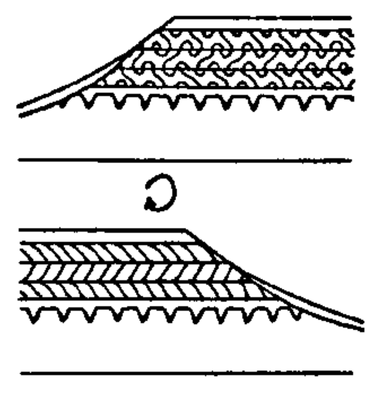
Cat. no.	X-ray no.	Acc. No (or temp no)	Museum: Findsite	Approx. Date	Weapon type and Comments	Sketch of Pattern or Inlay
108	AML 3737B	C727	Mus of London: Thames at Wandsworth	9-10c	Scramasax: 2 grooves near back & weld running down centre of blade, no p-w	
109	AML 3727B & 3730B	A13921	Mus of London: Thames at Battersea	9-11c	Long scramasax: single continuous twisted rod down centre, prob. 2 layers thick, no core	
110	AML 3727B & 3720B	A10485	Mus of London: Thames, London	9-11c	Long Scramasax: 2 grooves + shallow fuller near back but no welds or p-w visible	
111	AML 3726B	A1781	Mus of London: Thames, London	?9-10c	Scramasax: continuous herringbone pattern occupies back part of blade, prob 2 layers without core + 'teeth' occupying the thickness of blade	
112	AML 3710B & 3711B	0.2101	Mus of London: ? Thames at Leyton	?9-10c	Scramasax: continuous herringbone pattern on one side, poss diff on otherside - 2 layers + narrow strip & 'teeth' occupying full thickness of blade	
113	AML 3710B & 3711B	0.2100	Mus of London: ? Thames at Leyton	?9-10c	Scramasax: 3 narrow + 1 wider groove across back half of blade, pattern-continuous single twist, 2 layers + continuous wavy weld line along join between a toothed strip and cutting edge	
114	AML 3708B	0.2100b	Mus of London: ? Thames at Leyton	?9-10	Scramasax: triple narrow grooves near back + pattern continuous & prob. only one layer	

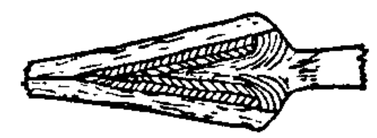
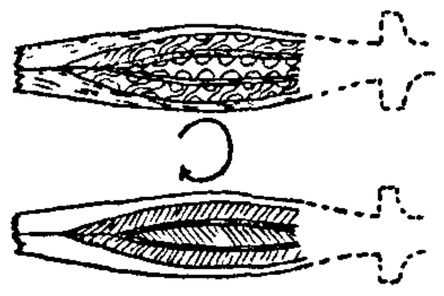
Cat. no.	X-ray no.	Acc. No (or temp no)	Museum: Findsite	Approx. Date	Weapon type and Comments	Sketch of Pattern or Inlay
115	AML 3708B	0.2105	Mus of London: ? Thames at Leyton	?9-10c	Scramasax: 2 narrow grooves near back but no welds or pattern visible	
116	AML 3739B & 3737B	C2444	Mus of London: Mitcham, Surrey; A-S cemetery	?6-7c	Sword: no sign of p-w or other structural detail	
117	AML 3705B	56.106/5	Mus of London: Mitcham, Surrey; A-S cemetery	?6-7c	Sword: no sign of p-w or other structural detail	
118	AML 3717B & 3718B	0.2100a	Mus of London: ? Thames at Leyton	9-10c	Long scramasax: 2 narrow grooves near back + one wider groove between; no signs of welds or p-w	
119	AML 3720B	0.2108	Mus of London: Thames at Hammersmith	LIA	Sword: no sign of p-w or other structural detail	
120	AML 3731B	0.2112 [S46]	Mus of London: ? from Thames at Brentford	7-9c	Sword: 2 continuous herringbone patterns 1 layer - with continuous straight grain pattern in between, no separate central core. See S46 & BAR 155, 212-214	
121	AML 3725B	A3670 [S47]	Mus of London: Thames at Waterloo Bridge	9-10c	Sword: v. little visible except for inlaid twisted pieces - ? lattice design - not v. clear. See S47 & BAR 224-226	
122	AML 3706B	A13592 [S41]	Mus of London: Thames at Vauxhall	9-10c	Sword: continuous pattern, 2 layers with no core between. See S41 & BAR 155, 213-217	

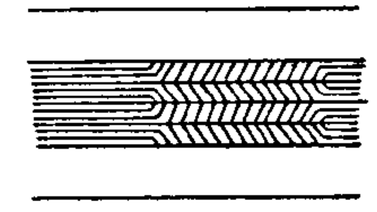
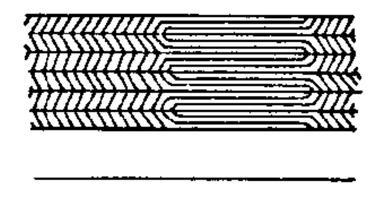
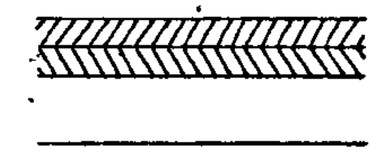
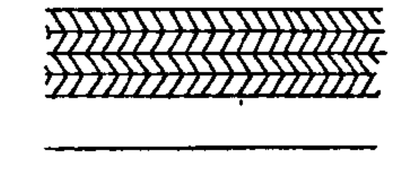
Cat. no.	X-ray no.	Acc. No (or temp no)	Museum: Findsite	Approx. Date	Weapon type and Comments	Sketch of Pattern or Inlay
123	AML 3716B & 3719B	56.106/14 [S10]	Mus of London: Mitcham, Surrey; A-S cemetery	6-7c	Sword: continuous herringbone (3 rods) on one side but part alternating - as shown - on other, 2 layers with a separate core between. See S10 & BAR 155, 174-176	
124	AML 3724B	A17923 [S43]	Mus of London: Thames - ? at London	9-10c	Sword: continuous herringbone pattern, 2 layers + separate core between See S43 & BAR 155, 229-232	
125	AML 3742B	A10486	Mus of London: Thames at Brentford	?9-10c	Scramasax: no welds or pattern showing	
126	AML 3729B & 3732B	56.106/13 [S45] A-S cemetery	Mus of London: Mitcham, Surrey	6-7c	Sword: continuous herringbone pattern, 2 layers without a separate core; See S45 and BAR 155, 172-174	
127	ASH 4	1890.14	Ashmolean Mus: Thames at Abingdon, Oxon	9-10c	Sword: continuous pattern, 2 layers with no sign of a separate core	
128	ASH 5	1966.1148	Ashmolean Mus: Drayton Berks; ? from a grave	?9-11c	Sword: continuous pattern 2 layers + slight poss signs of a separate core between	
129	ASH112 & 113	1972-164	Ashmolean Mus: ? Thames at Water Eaton, Oxon	?9-11c	Spearhead:prob. double pattern - not v. clear	
130	ASH114 & 112	1887-2551	Ashmolean Mus: prob. river find, Oxon	9-11c	Spearhead: no welds or p-w showing but clear straight grain effect visible - ? slag	

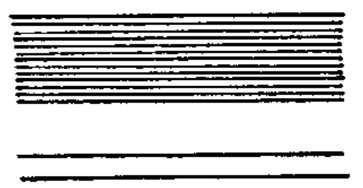
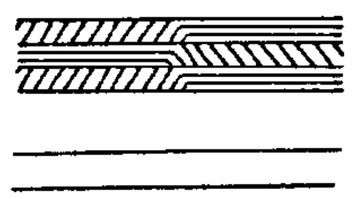
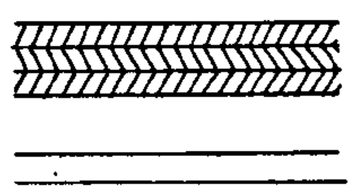
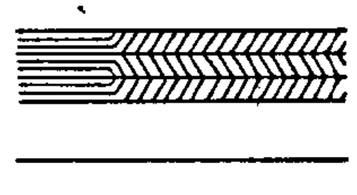
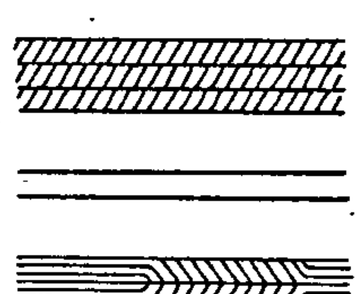
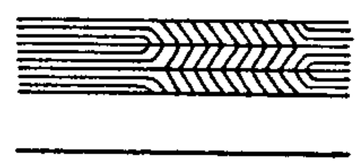
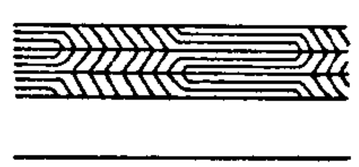
Cat. no.	X-ray no.	Acc. No (or temp no)	Museum: Findsite	Approx. Date	Weapon type and Comments	Sketch of Pattern or Inlay
131	ASH114 & 112	1884-514	Ashmolean Mus: River Cherwell, Magdalen Bridge Oxford	9-11c	Spearhead: no welds or p-w showing; but clear straight grain effect visible - ? slag	
132	ASH114 & 112	SF Loan 82	Ashmolean Mus: prob. river find ? Oxon	9-11c	Spearhead: no welds or p-w showing; but clear straight grain effect visible - ? slag	
133	ASH115 & 116 & 255	1934-159	Ashmolean Mus: Thames at Iffley	9-11c	Spearhead: no welds or p-w showing; but clear straight grain effect visible - ? slag	
134	ASH115 & 116	1976-60 1884-515a	Ashmolean Mus: ? from River	9-11c	Spearhead: clear pattern - may be 2 layers with a thick central core between	
135	ASH115 & 116	1884-515a	Cherwell, Islip Oxon	9-11c	Spearhead: clear pattern	
136	ASH115	1914-65	Ashmolean Mus: River Thames, Oxon	9-11	Spearhead: pattern not v. clear - poss 2 layers with a core between	
137	ASH167	? - Mockler - Private loan	Ashmolean Mus: ? from R. Thames at Reading, Berks	?10-11	Sword: Clear pattern - 2 layers, prob with with a separate core between	
138	ASH167	1954.19	Ashmolean Mus: Cornmarket St, Oxford	10-11c	Scramasax/knife: no sign of welds or p-w straight grain effect - ? slag	
139	ASH 167	SH9982 3	Ashmolean Mus: prob river find, site uncertain	?9-11c	Spearhead: no sign of welds or p-w; straight grain effect - ? slag	

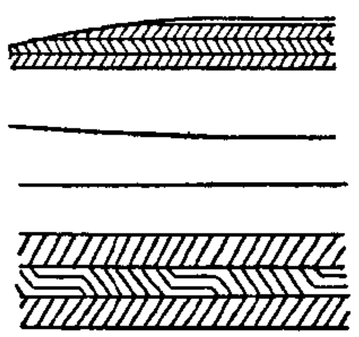
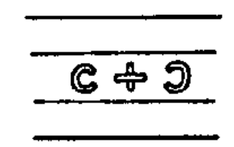
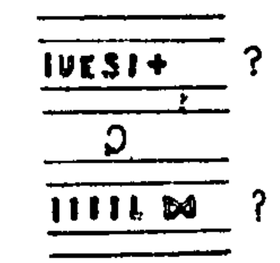
Cat. no.	X-ray no.	Acc. No (or temp no)	Museum: Findsite	Approx. Date	Weapon type and Comments	Sketch of Pattern or Inlay
140	ASH168	1928.516	Ashmolean Mus: Evans Coll'n, [?Nydam bog votive deposit]	?2-3c	Sword: pattern - single layer lattice design as shown [small fragment of blade only] (See also Maryon 1960 for Nydam comparison)	
141	ASH168	1949.960	Ashmolean Mus: R Thames at Newbridge Standlake, Oxon	?9-10c	Spearhead (reforged sword fragment) pattern continuous on one side and long alternating panels on reverse, 2 layers with separate core between	
142	ASH 168	1914.454	Ashmolean Mus: R. Thames, Nr Shifford, Oxon	9-10c	Scramasax: continuous herringbone pattern as shown - prob 2 layers without a separate core between	
143	ASH 169 & 170	1928.518	Ashmolean Mus: Evans Colln, site unknown	?9-11c	Scramasax/knife: no sign of welds or p-w straight grain effect visible - ? slag	
144	ASH 169 & 170	1928.514	Ashmolean Mus: Evans Colln, ? European - prob. waterlogged site	?8-9c	Sword: alternate herringbone straight pattern; 2 layers prob. without a separate central core	
145	ASH 169	1928.513	Ashmolean Mus: Evans Colln, ? European - prob. waterlogged site	?8-9c	Sword: continuous herringbone pattern; 2 layers prob. without a separate central core	
146	ASH171	1967.851	Ashmolean Mus: prob. river find, site unknown	9-10c	Scramasax: continuous herringbone pattern on one side and looped (half-ground) pattern on on the reverse; 2 layers with a separate core between; also continuous toothed rod giving wavy weld to cutting edge side of p-w part	

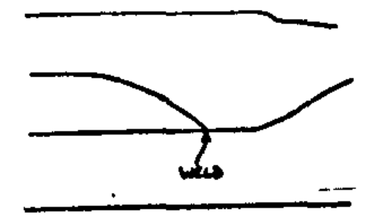
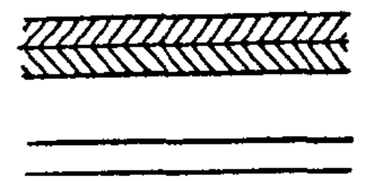
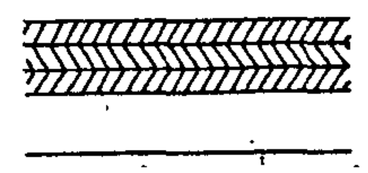
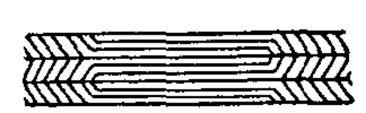
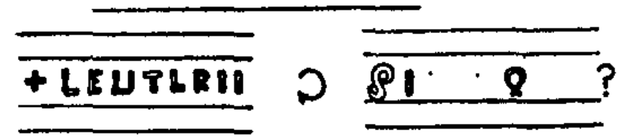
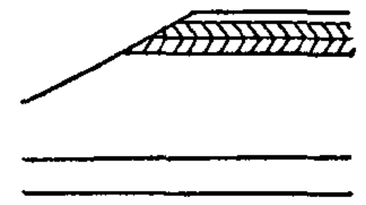
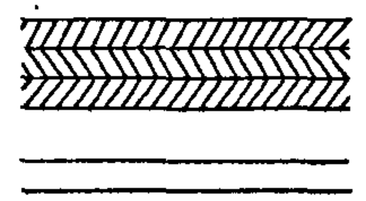
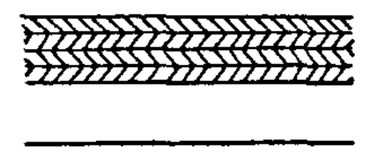
Cat. no.	X-ray no.	Acc. No (or temp no)	Museum: Findsite	Approx. Date	Weapon type and Comments	Sketch of Pattern or Inlay
147	ASH172 & 171	1941.82	Ashmolean Mus: Brackley Northants	9-10c	Scramasax: continuous distorted - 1/4 ground herringbone pattern, prob 2 layers without a core between; wavy weld pattern	
148	ASH 172	1914.456	Ashmolean Mus: R. Thames near Old Shifford, Oxon	?9-10c	Long scramasax: 2 narrow grooves with a wider channel between - (near back) poss weld down centre but no p-w	
149	ASH193 & 194 & 199	1985.48	Ashmolean Mus: prob. river find site uncertain	?9-10c	Sword: no welds or p-w showing faint poss traces of inlaid design near hilt - v. diff. to see - may not exist	
150	ASH 246	1949.961	Ashmolean Mus: prob. river find, site uncertain	9-11c	Sword: no sight of welds or p-w or in lays but a fairly pronounced straight grain effect shows a long blade - ? slag	
151	ASH 247	1920.86	Ashmolean Mus: R. Thames, Oxford	?9-11c	Spearhead: no sign of welds or p-w	
152	ASH 247 & 253 & 254	1967.836	Ashmolean Mus: prob river find, site uncertain	9-11c	Spearhead: continuous twisted pattern, prob 2 layers with a core between; also a continuous wavy weld between cutting edge pieces	
153	ASH 247 & 253	1942.243 (1884)	Ashmolean Mus: ? R Thames, at ? Buiscod Ferry,Oxon	9-11c	Spearhead: continuous herringbone pattern; prob 2 layers with a separate core between	
154	ASH 253	1928.43	Ashmolean Mus: prob. river find; site not known	9-11c	Scramasax: continuous herringbone pattern on one side and a distorted herringbone pattern on reverse, prob 2 layers without a separate core; also a continuous saw tooth piece giving a wavy weld next to edge piece	

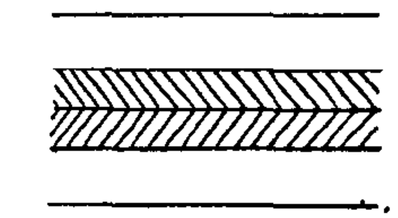
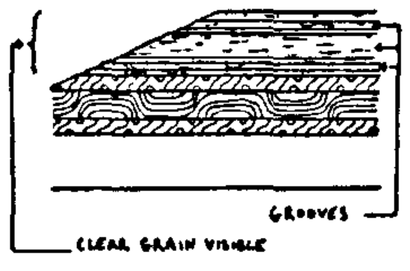
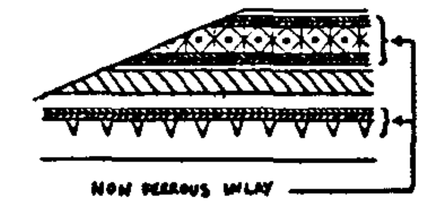
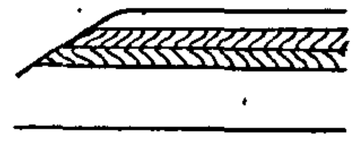
Cat. no.	X-ray no.	Acc. No (or temp no)	Museum: Findsite	Approx. Date	Weapon type and Comments	Sketch of Pattern or Inlay
155	ASH 254	1949.928	Ashmolean Mus: ? from R. Cherwell at Kidlington, Oxon	9-11c	Spearhead: continuous distorted herringbone pattern - (1/4 ground); 2 layers with a separate core between central weld & straight grain showing to edge - ? slag	
156	ASH 256	1975.345	Ashmolean Mus: France, site not known	9-11c	Winged spearhead: no sign of welds or p-w	
157	ASH 257	-	Ashmolean Mus: no acc number; site not known	?10-11c	Sword: fullered blade no welds or p-w but fairly clear straight grain effect - ? slag ; also cracks show at right angles to edge; inlaid letters near hilt - blundered INGELRII form on one side and simple lattice on reverse (see object)	
158	ASH 252	1963.1401	Ashmolean Mus: site not known	9-11c	Spearhead: pattern as shown; prob 2 layers but no sign of separate core; straight grain effect along edges - ? slag	
159	ASH 251 & 264	1975-346	Ashmolean Mus: France; site not known	9-11c	Spearhead: pattern - distorted (1/4 ground) herringbone on one side & ? continuous herringbone on reverse & separating strips - poss 2 layers to twisted pieces	
160	ASH 262 & 263	1955.412	Ashmolean Mus: no provenance	Late Med or Post Med	Sword: no structural detail showing	
161	?	OA 6609	BM: Great Chesterford, Essex	?	? Sword : no sign of p-w or other structural detail	

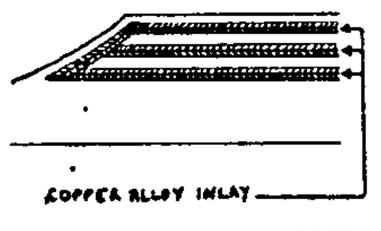
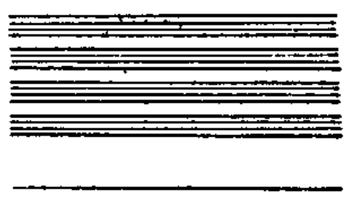
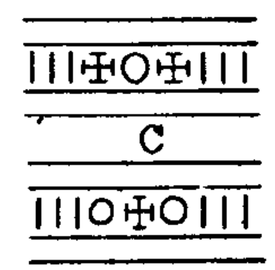
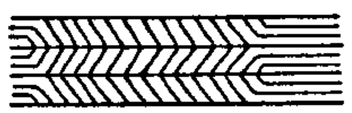
Cat. no.	X-ray no.	Acc. No (or temp no)	Museum: Findsite	Approx. Date	Weapon type and Comments	Sketch of Pattern or Inlay
162	28821V	OA 6610	BM: Barnet, Herts	5-7c	Sword: pattern of alternating panels; 2 layers prob without a separate core between	
163	? 21774	982-1,2	BM: Mucking (600), Essex	5-6c	Sword: prob. totally corroded - shows no obvious structural detail but can see v. slight hints of poss p-w ?	
164	?	9181.421	Yorks Mus: Acklam	c A D 600	Sword: clear alternating pattern in panels; 2 layers without a core between. See fig 68 and Ager & Gilmour, 1988, 18-20	
165	21775S	952.215, 216	BM: Mucking (557) Essex	5-6	Sword: looks totally corroded - some v. faint traces of p-w visible - as shown - continuous with slight signs of central core	
166	21776Q	952 -226& 217	BM: Mucking (618) Essex	5-6c	Sword: poss. totally corroded, clear welds between edges & middle; slight hints of p-w; poss 2 layers with core	
167	21777Z	952	BM: Mucking (682) Essex	5-6c	Sword: poss. totally corroded, v slight poss hints of p-w along centre too uncertain to reconstruct	
168	21778X	952-219	BM: Mucking (769) Essex	5-6c	Sword: poss totally corroded; no sign of welds or p-w	
169	28814V	4913 108-1 (?)	BM: Mucking (766) Essex	5-6c	Sword: poss. totally corroded; some slight sign of p-w near lower end - poss as shown with 2 layers with a core between (not certain)	

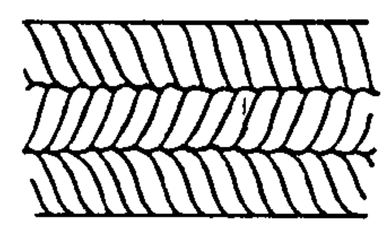
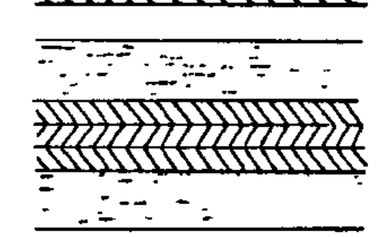
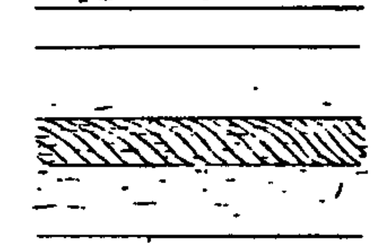
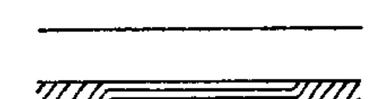
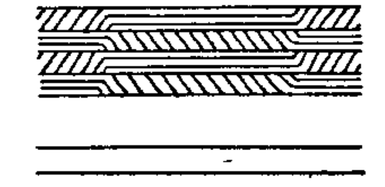
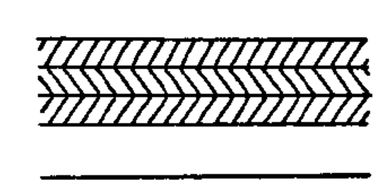
Cat. no.	X-ray no.	Acc. No (or temp no)	Museum: Findsite	Approx. Date	Weapon type and Comments	Sketch of Pattern or Inlay
170	22478P	951-70	BM: Faversham, Kent	6-7c	Sword: continuous non-twisted pattern	
171	22489V	952-70	BM: Faversham, Kent	6-7c	Sword: badly corroded, pattern appears to alternate as shown; prob 2 layers with separate core between	
172	20887W	953-70	BM: Faversham Kent	6-7c	Sword: continuous pattern, prob. 2 layers without a separate core between	
173	22487Y	954-70	BM: Faversham, Kent	6-7c	Sword: alternating pattern; prob 2 layers with a separate core between	
174	28816R	955-70	BM: Faversham, Kent	6-7c	Sword: pattern not clear but seems continuous as shown; 2 layers poss. with a separate core between	
175	28815T	956-70	BM: Faversham, Kent	6-7c	Sword: prob. alternating herringbone pattern; 2 layers poss. with a separate core between	
176	20840V	957-70	BM: Faversham, Kent	6-7c	Sword: alternating herringbone pattern; 2 layers poss. with a separate core between	
177	984.1,2	GRA 867	BM: R. Rhine, Mainz, Germany	1st c	Sword - gladius type: no structural detail showing	
178	?959 [BM]	1981 12-2	Peterborough Mus: Nene Valley, near Peterborough	L1A	Sword: v. little sign of any structural detail	
179	19975s [BM]	962-3 [?BM no]	Peterborough Mus: Nene Valley, near Peterborough, Cambs	L1A	Sword: v pronounced slightly wavy straight grain across width of blade; prototype pattern-welding ; See Figs 71-73.	

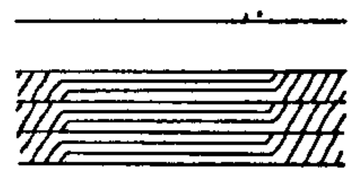
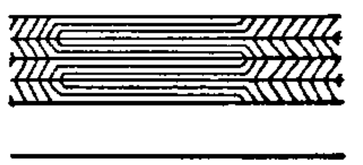
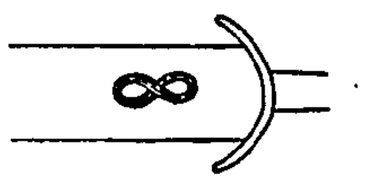
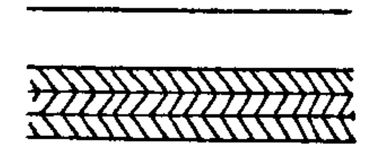
Cat. no.	X-ray no.	Acc. No (or temp no)	Museum: Findsite	Approx. Date	Weapon type and Comments	Sketch of Pattern or Inlay
180	?	962-1,2	Peterborough Mus: Nene Valley, near Peterborough, Cambs	L1A	Sword: Traces of straight slightly wavy grain - poss. not deliberate for patterned effect; + ? makers mark	
181	?	?	BM: Grimthorpe	L1A	Sword: fairly pronounced grain showing down blade - ? poss prototype pattern-welding	
182	23477W	1883 4-7 1	BM: Fulham, London	1st c AD	Sword - gladius type: no structural detail showing	
183	20809T	943 118	BM: Oliver's Battery, Hants	9-10c	Scramasax: continuous pattern; prob. 2 layers without any core between	
184	999-3,5	AL116/775	BM: R. Thames at Windsor, Berks	9-10c	Sword: Partially alternating pattern; 2 layers but no sign of a separate core between	
185	999-2,4,6	A456 [Wallace Coll]	BM: site not recorded	9-10c	Sword: fairly narrow fuller; fairly pronounced grain shows down blade - ? slag + inlaid design near hilt on one side	
186	20767Y	TR169	BM: ? Nottingham	9-11c	Sword: no structurual detail shows, inlaid design or letters near hilt - not clear, poss as shown.	 ? ?
187	22484T	TR173	BM: no provenance	11-12+c	Sword with narrow fuller: no structural detail showing	
188	20789X	TR174	BM: ? Nottingham	?9-11c	Sword: no structural detail shows; some straight grain - ? slag	

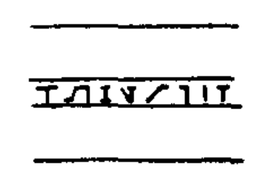
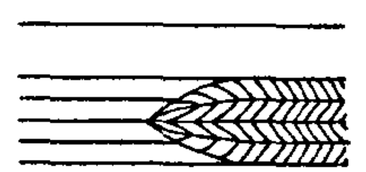
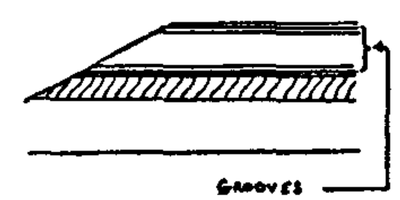
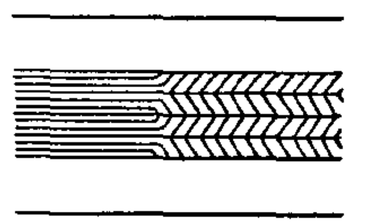
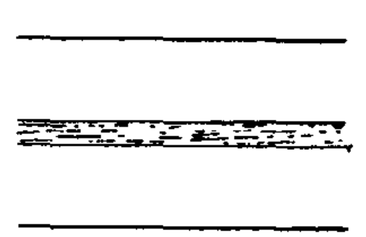
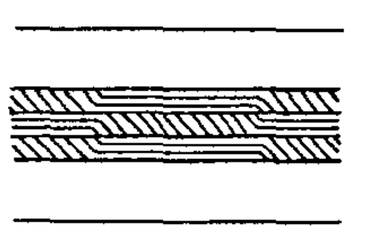
Cat. no.	X-ray no.	Acc. No (or temp no)	Museum: Findsite	Approx. Date	Weapon type and Comments	Sketch of Pattern or Inlay
189	20763V	OA324	BM: no provenance	9-10c	Scramasax: 3 grooves near back & weld between cutting edge & back; pronounced grain - ? slag - in back part	
190	20836Y	39 10-29 144a	BM: Chatham Down, Kent	5-6c	Sword: continuous pattern, 2 layers with a separate core between	
191	21779V	39 10-29 144b	BM: Chatham Down, Kent	5-6c	Sword: continuous pattern; 2 layers prob. with a separate core between	
192	217675	1848 7-271	BM: Burford; Oxon	5-6c	Sword: alternating pattern; 2 layers and no sign of a separate core between	
193	21780Y	48 10-21	BM: R Witham, Lincoln	10-11c	Sword - wide fuller: no structural detail visible; inlaid letters on one side near hilt with unclear design on reverse	
194	21638V	50 2-7 1	BM: R Thames, ? London	9-10c	Scramasax: continuous pattern; 2 layers prob. without a core between	
195	20819P & 20820P	53 4-12 89 53 4-12 90	BM: Barham Down, Kent Barrow cemetery	6-7c	Sword - 2 frags: continuous pattern; 2 layers with no sign of a separate core between	
196	20761Z	54 11-7 12	BM: Norwich	9-10c	Sword - fullered: continuous pattern; 2 layers with no sign of a separate core between	
197	20788Z	55 10-18 1	BM: Ashdown, Berks	5-6c	Sword: no sign of p-w or other welds	
198	21781 W	56 7-1 1404	BM: R. Thames, opposite Temple, London	10-11c	Sword-deeply fullered; no structural details showing; inlaid twisted pieces - INGELRII type - difficult to see	

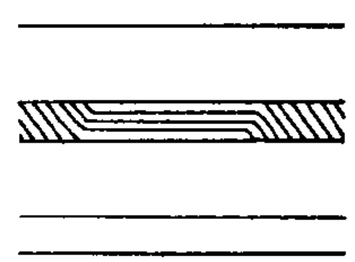
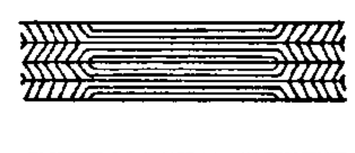
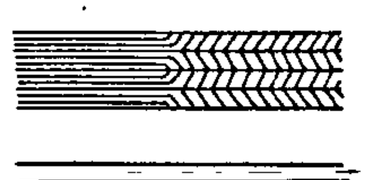
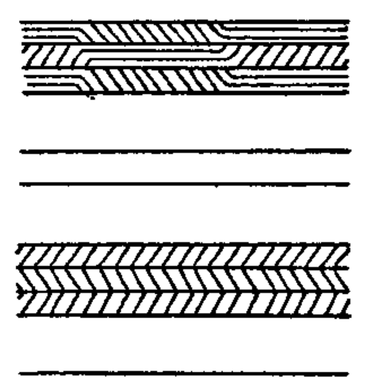
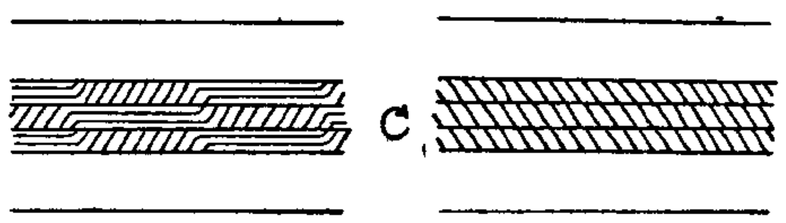
Cat. no.	X-ray no.	Acc. No (or temp no)	Museum: Findsite	Approx. Date	Weapon type and Comments	Sketch of Pattern or Inlay
199	21763P	56 7-1 1405	BM: (? Thames) London	9-10c	Sword: continuous pattern; 2 layers with a separate core between	
200	20765R	56 7-1 1408	BM: ? London	9-10c	Long Scramasax: 2 parallel grooves near back & pronounced straight grain in same part; p-w down centre - continuous as shown, prob. 2 layers, no core	
201	20766	56 7-1 1409	BM: London	9-10c	Long Scramasax: 2 narrow grooves and a wider channel between near back; a single weld running down centre of blade	
202	21642R	56 7-1 1410	BM: London	9-10c	Long scramasax: 2 grooves & wider channel between - near back of blade; no structural detail showing.	
203	20764T	56 7-1 1411	BM: London	9-10c	Long scramasax: 2 grooves & wider channel between near back of blade	
204	21641T	56 7-1 1412	BM: Finch Lane, London	9-10c	Scramasax: no structural detail showing	
205	21772Y	57 6-23 1	BM: ? R. Thames at Battersea, London	9-10c	Long Scramasax: Intricate non-ferrous inlay decoration along blade near back; groove along centre coinciding with a single continuous twisted piece; more copper alloy inlay nearer edge - cable pattern strip & 'teeth' - ? pseudo pattern-welding	
206	21639S	57 6-23 2	BM: ? R Thames at Battersea, London	9-10c	Scramasax: continuous pattern; prob. just a single layer	

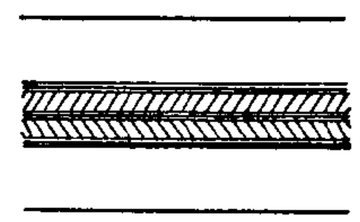
Cat. no.	X-ray no.	Acc. No (or temp no)	Museum: Findsite	Approx. Date	Weapon type and Comments	Sketch of Pattern or Inlay
207	21636Y	OA 6568	BM: Sarre, Kent	6-7c	Sword: v. corroded (? totally) - no structural detail showing	
208	21637 W	59 1-22 12	BM: R. Thames London	9-11c	Scramasax: triple band, cable (? pseudo p-w) pattern in copper alloy parallel to back of blade; cutting edge prob. welded on.	
209	?	61 3-15 9	BM: ?	?L1A or R-B	Sword - lower part only; continuous non-twisted pattern	
210	20786S	62 7-18 5	BM: Milton Field, Berks	6-7c	Scramasax: no structural detail showing	
211	20785U	62 7-19 6	BM: Long Wittenham, Berks	6-7c	Scramasax: poss double groove along near back; no welds or p-w	
212	23335	64 1-27 3	BM: Lough Gur, Ireland	?10-11	Sword: no structural detail visible; clear inlaid design on each side near hilt - as shown	
213	20818R	67 7-29 150	BM: Chessell Down, 1.0.W.	6c	Sword: alternating pattern; 2 layers with no sign of a separate central core	
214	21768Q	67 7-29 151	BM: ? Chessell Down, 1.O.W.	5-6c	Sword - poss. converted to weaving batten: v. corroded; some v. slight hints of p-w - unsure - poss. triple band p-w	
215	20817T	67 7-29 152	BM: Chessell Down, 1.O.W. Grave 84	5-6c	Sword: v. corroded tip end of blade; no sign of structural detail	

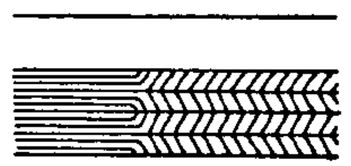
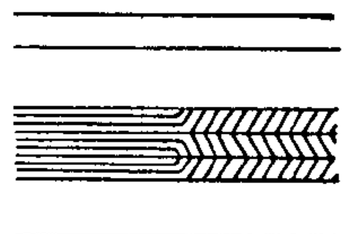
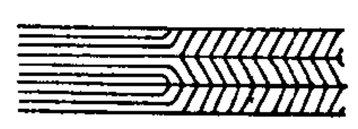
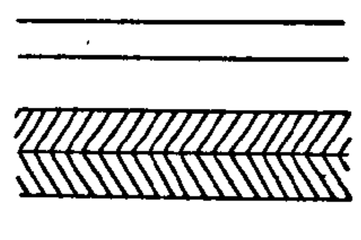
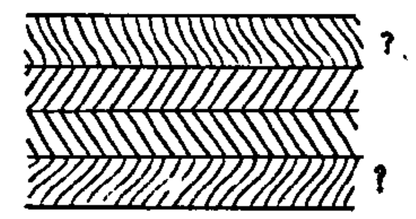
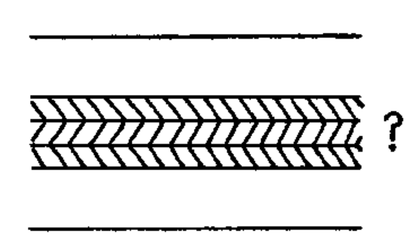
Cat. no.	X-ray no.	Acc. No (or temp no)	Museum: Findsite	Approx. Date	Weapon type and Comments	Sketch of Pattern or Inlay
216	20853W	68 9-4 24	BM: R. Thames London	9-10c	Long Scramasax: one groove near back; + prob weld along near centre; also much grain visible along blade - ? slag	
217	20797X	69 3-13	BM: Waterbeach; Cambs	5-6c	Sword: continuous unusual pattern across whole width of blade; one layer only	
218	20808V	69 10-11 13	BM: Chessell Down, 1.O.W	5-6c	Sword: continuous pattern, 2 layers prob. with a separate core between; also much straight grain showing along edges - ? slag	
219	20811U	69 10-11 14	BM: Chessell Down, 1.O.W	5-6c	Sword: v. corroded, inner welds of edges just visible + slight hints of a simple continuous pattern - ? 2 layers + a separate core between. NB. v. unclear - diff. to interpret	
220	20812S	69 10-11 15	BM: Chessell Down, 1.O.W	5-6c	Sword: v. corroded; straight grain visible across blade, but no sign of welds or p-w	
221	20813 Q	69 10-11 16	BM: Chessell Down, 1.O.W	5-6c	Sword: alternating pattern; 2 layers with no sign of a separate core between	
222	20814Z	69 10-11 17	BM: Chessell Down, 1.O.W	5-6c	Sword: continuous pattern; 2 layers with no sign of a separate central core	
223	20815X	69 10-11 18	BM: Chessell Down, 1.O.W	5-6c	Sword: v. corroded; v. slight signs of p-w (as shown); prob 2 layers with a separate central core between	
224	20816V	69 10-11 55	BM: Chessell Down, 1.O.W	? 6c	Scramasax: no welds or p-w, but straight grain across blade - ? slag	

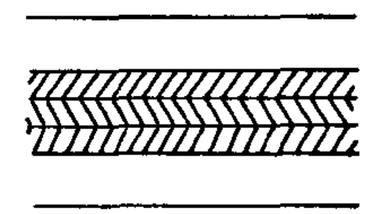
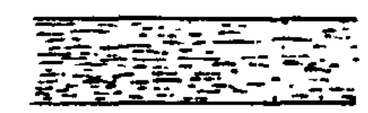
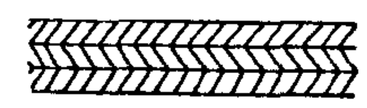
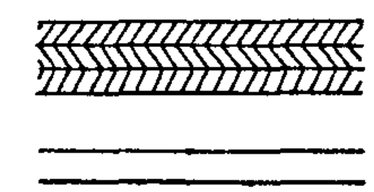
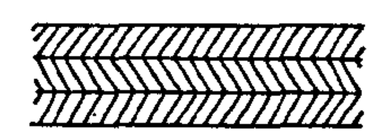
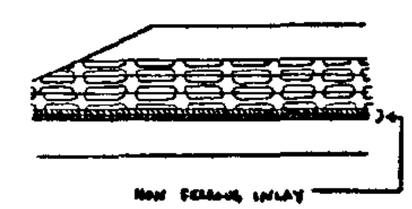
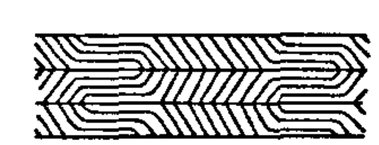
Cat. no.	X-ray no.	Acc. No (or temp no)	Museum: Findsite	Approx. Date	Weapon type and Comments	Sketch of Pattern or Inlay
225	23337T	73 6-2 104	BM: Tissington, Derbys	6-7c	Sword: alternating pattern; 2 layers but no sign of a separate core piece between	
226	20147R	73 12-19 232	BM: ?	9c	Sword (Petersen Type C): fullered blade, no sign of structural detail; inlaid twisted pieces in lattice design on both sides near hilt - diff to interpret	
227	?	75 3-10 40	BM: Long Wittenham, Berks	6c	Sword: alternating pattern; 2 layers with no sign of separate central core between	
228	21769Z	75 4-3 169	BM: Burneston, Yorks	9c	Sword: no welds or p-w visible; a simple inlay, with pronounced grain (? slag) on either side near hilt	
229	?	76 2-12 30	BM: Lakenheath, Suffolk	5-6c	Sword: no sign of welds or p-w, some straight grain visible right across blade - ? slag : non p-w	
230	20795Q	76 2-12 46	BM: Barrington, Cambs	5-6c	Sword: v corroded - no sign of welds or p-w, but some straight grain across blade - ? slag . . prob. not p-w	
231	21766V	79 12-9 2078	BM: Lowick, Northumberland	?7-9c	Scramasax: no welds or p-w, but some straight grain across blade - ? slag	
232	21774U	80 5-21	BM: Longbridge Warwicks	5-6c	Sword: continuous pattern; 2 layers prob. with a separate core between	
233	20796Z	80 8-9 1	BM: Barrington Cambs	5-6c	Sword: v. corroded; no sign of welds or p-w; some straight grain across blade - ? slag .. prob. not p-w	

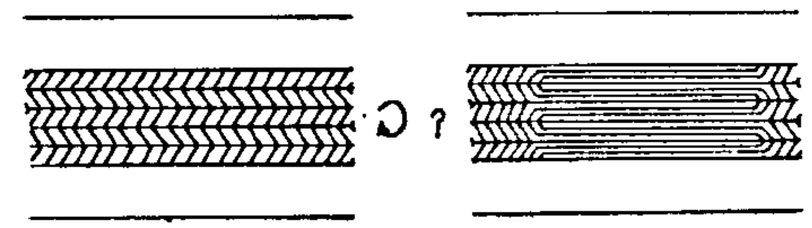
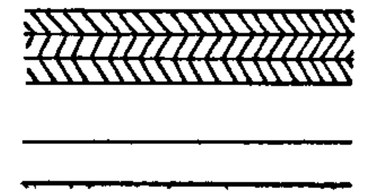
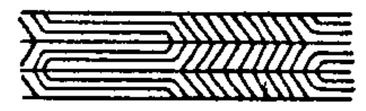
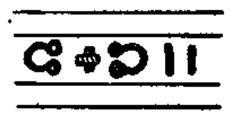
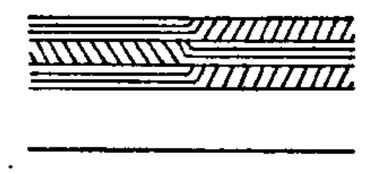
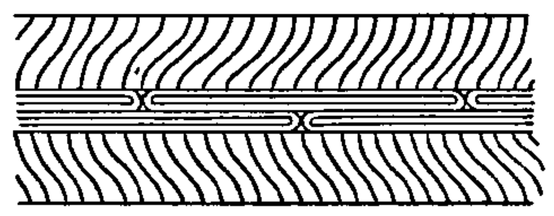
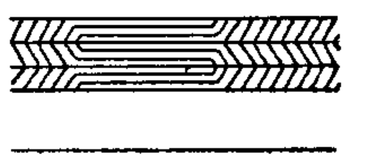
Cat. no.	X-ray no.	Acc. No (or temp no)	Museum: Findsite	Approx. Date	Weapon type and Comments	Sketch of Pattern or Inlay
234	21761T	81 5-9 18	BM: Canwick Common, Lincoln	?11c	Sword, with narrow fullers: no welds or p-w visible but many cracks at right angles to edge - prob v. hard/quenched, silver inlay - ? nonsense inscription	
235	21636Y	81 6-23 1	BM: Sittingbourne, Kent	?9-10c	Scramasax: no welds or p-w visible but decorated with non-ferrous inlays in the style of p-w	
236	22481Z	83 7-26 1	BM: Santon; Norfolk	?6-7c	Sword (lower half of blade): unclear pattern - seems to alternate (straight lower down); prob. 2 layers with a central core between	
237	21773W	83 12-12 1	BM: Little Bealings, Suffolk	9-10c	Scramasax: poss two narrow grooves then one wide groove inwards from back; single twisted band down centre of blade - one layer only	
238	20847S	83 12-13 612	BM: Sittingbourne, Kent	6-7c	Sword: pattern seems to alternate as shown; 2 layers with no sign of a separate core between	
239	20848 Q	83 12-13 613	BM: Sittingbourne, Kent	6-7c	Sword: v. corroded; some straight grain showing, particularly one band down centre - ? untwisted p-w	
240	20849Z	83 12-13 614	BM: Sittingbourne, Kent	6-7c	Sword: v. corroded; no structural detail visible; some poss. straight grain, but . . poss. no p-w	
241	20850R	83 12-13 621	BM: Sittingbourne, Kent	5-6c	Sword: alternating pattern, 2 layers with no core in between	

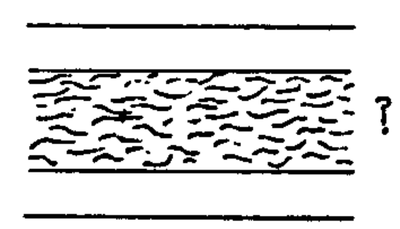
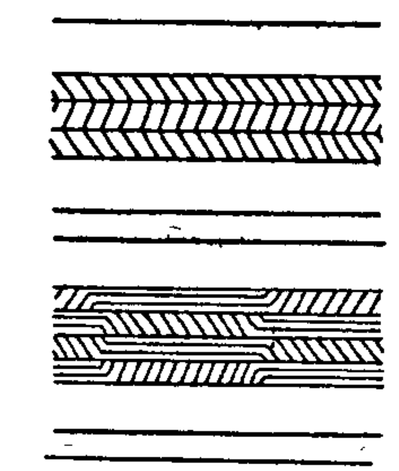
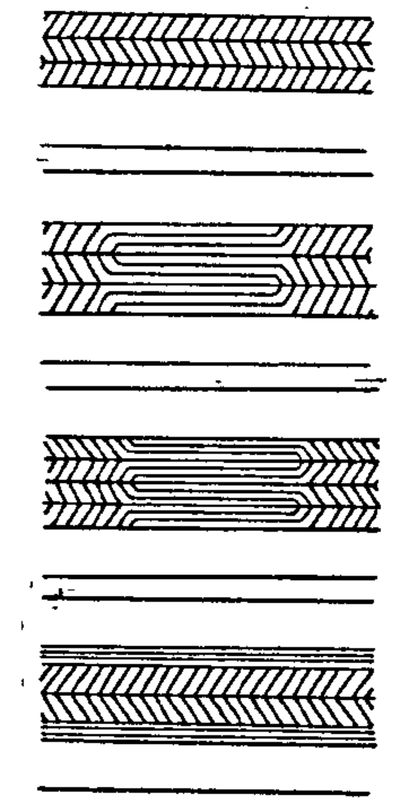
Cat. no.	X-ray no.	Acc. No (or temp no)	Museum: Findsite	Approx. Date	Weapon type and Comments	Sketch of Pattern or Inlay
242	20851R	83 12-13 622	BM: Sittingbourne; Kent	6-7c	Scramasax: no sign of welds or p-w; some straight grain showing - ? slag	
243	20838U	83 12-113 645	BM: Faversham, Kent	?6c	Sword: v. badly corroded and only central part of blade visible; alternating design - diff. to see - prob. 2 layers ? with no central core between	
244	20839S	83 12-13 646	BM: Faversham, Kent	6c	Sword: alternating pattern; 2 layers with no separate core between	
245	20851R	83 12-13 647	BM: Faversham, Kent	6c	Sword: no welds or p-w; some straight grain visible .. prob no p-w	
246	22482Y	83 12-14	BM: Taplow, Bucks	6c	Sword: alternating pattern, 2 layers with prob. no separate core between	
247	21782M	87 2-9 1	BM: ? London	10-11c [?5-7c]	Sword: alternating pattern; 2 layers with a separate core in between	
248	28793Q	88 7-19 57	BM: no provenance	?5-7c	Sword: alternating pattern; 2 layers with a prob. separate central core between. NB. untwisted parts show no grain	
249	20846U	90 9-2 1	BM: Lyminge, Kent	5-6c	Sword: alternating pattern on one side and continuous pattern on reverse; 2 layers with a prob. separate central core in between	
250	20784W	91 3-23 1	BM: East Shefford, Berks	?5-6c	Sword: v. corroded; virtually no structural detail of any kind visible or any grain .. can't tell whether p-w or not	

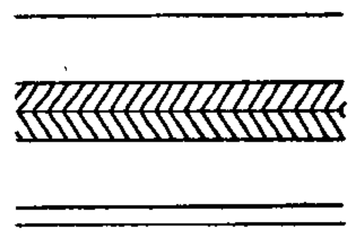
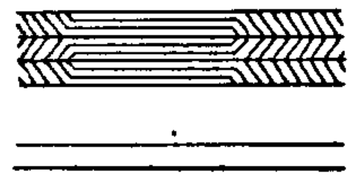
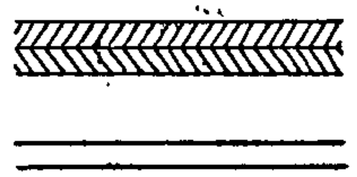
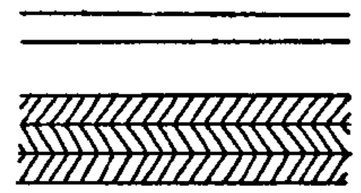
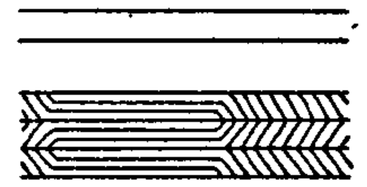
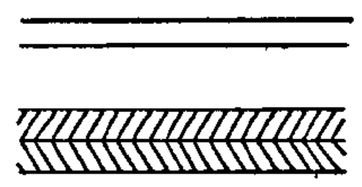
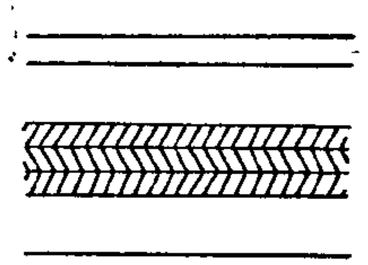
Cat. no.	X-ray no.	Acc. No (or temp no)	Museum: Findsite	Approx. Date	Weapon type and Comments	Sketch of Pattern or Inlay
251	20782 P	91 6-24 75	BM: Kempston, Beds	6c	Sword: v. corroded; no welds or p-w visible, but quite clear straight grain - ? slag - visible across blade . . not p-w	
252	20790P	91 6-24 78	BM: Kempston, Beds? grave 152	5-6c	Sword: continuous pattern; 2 layers with no sign of any separate central core between	
253	20791Y	91 6-24	BM: Kempston, Beds	5c	Sword: continuous pattern - maybe as shown or twists may reverse; 2 layers (of twists) prob. with no separate core pieces in between	
254	28818Y	91 6-24 80	BM: Kempston, Beds	5-7c	Sword - corroded tip end only: pattern v. diff to see but could be same form as for previous blade.	
255	28817P	91 6-24 103	BM: Kempston, Beds	6-7c	Scramasax: no welds or p-w; even straight grain showing - ? slag	
256	28819W	91 6-24 131	BM: Kempston, Beds	6-7c	Scramasax: no welds or p-w; even straight grain showing - ? slag	
257	20145V	91 10-21 27	BM: ?	?9c	Long Scramasax: no welds, p-w or straight grain showing	
258	20759Y	91 9-5 3	BM: R. Thames, Kew, London	?10-11c	Sword: no welds or p-w but much straight grain across blade + inlaid twisted pieces visible near hilt on either side - v. confused . . no interpretation attempted	
259	?	92 9-1 452	BM: ?	?5-7c	Sword: corroded blade; no sign of welds, p-w or any grain	

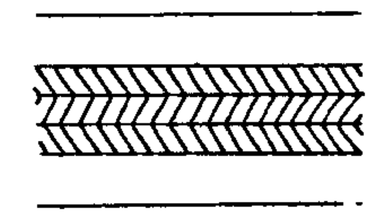
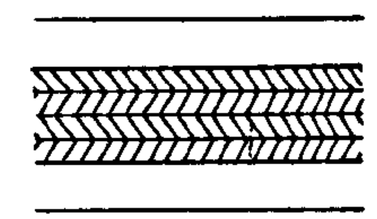
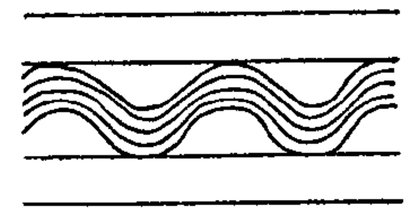
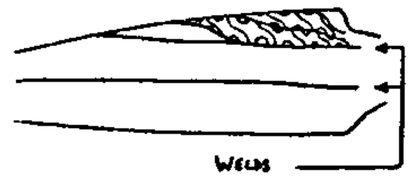
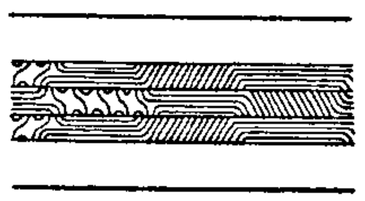
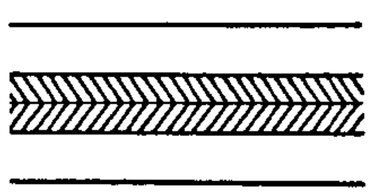
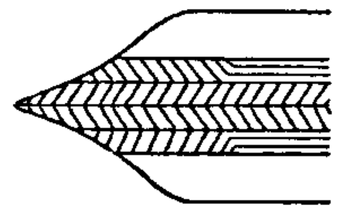
Cat. no.	X-ray no.	Acc. No (or temp no)	Museum: Findsite	Approx. Date	Weapon type and Comments	Sketch of Pattern or Inlay
260	20852Y	94 8-3 87	BM: Strood, Kent Kent	5-6c	Sword: alternating pattern; 2 layers with no sign of a separate central core	
261	22479Y	94 11-3 1	BM: Crundale Down, Kent	7c	Sword: alternating pattern - not v. clear but pattern appears to be distorted on one side (1/4 ground); 2 layers but no sign of a separate core in between	
262	22486P	94 12-16 4	BM: Broomfield, Essex	e7 c	Sword: alternating pattern; 2 layers with no sign of a separate core in between	
263	28820Z	95 6-13 22	BM: Ardvonrig, Barra, Hebrides, Viking grave	9c	Sword: continuous pattern; 2 layers with a separate central core in between	
264	?	95 3-13 10	BM: Croydon, Surrey	?6c	Sword: no welds or p-w, but faint traces of straight grain visible across blade . . prob. non p-w	
265	?	96 5-22 52	BM: ? Thames	?6-7c	Sword: no welds or p-w, but fairly clear slightly wavy straight grain visible across blade . . prob not p-w	
266	20799T	1902 7-22 171	BM: Droxford, Hants	5-6c	Sword: continuous pattern down centre; 2 layers with no sign of a separate core between; plus edges also appear to show twisted pattern - poss distorted during forging of edges	
267	20800P	1902 7-22 172	BM: Droxford, Hants	5-6c	Sword: v. unclear but poss. continuous pattern as shown; prob 2 layers - poss with a central core between	

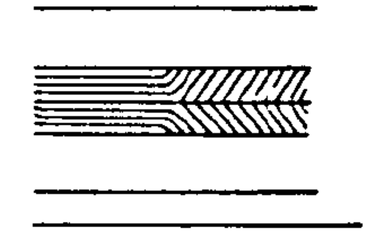
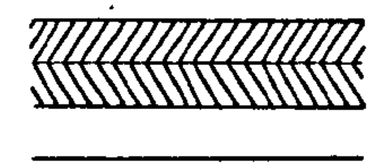
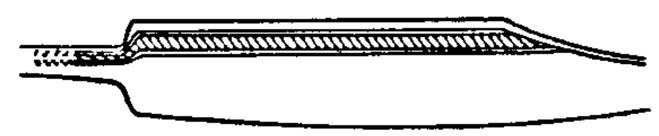
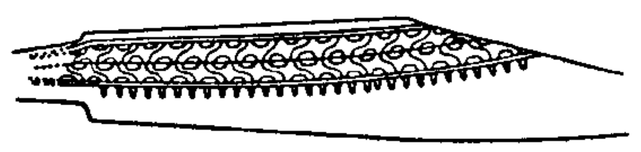
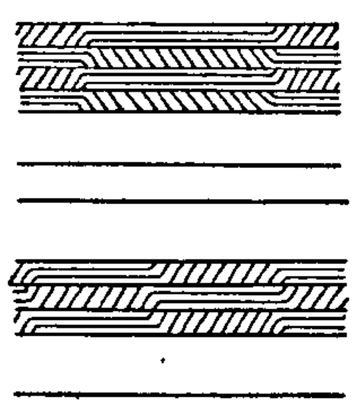
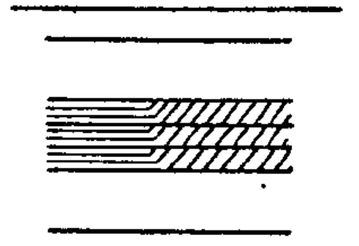
Cat. no.	X-ray no.	Acc. No (or temp no)	Museum: Findsite	Approx. Date	Weapon type and Comments	Sketch of Pattern or Inlay
268	20801Y	1902 7-22 173	BM: Droxford, Hants	5-6c	Sword: pattern poss. continuous as shown but not v. clear; prob. 2 layers but no sign of a separate core in between	
269	20805Q	1902 7-22 174	BM: Droxford, Hants	5-6c	Sword: prob. welds inside cutting edges; seems to be a continuous straight across central area, not much visible along edges	 ?
270	20806Z	1902 7-22 175	BM: Droxford, Hants	5-6c	Sword: v. corroded - slight traces poss. of a continuous pattern as shown; 2 layers prob. with a separate central core in between	 ?
271	20807X	1902 7-22	BM: Droxford, Hants	5-6c	Sword: no welds or p-w,but slight wavy grain visible over much of blade - ? slag - . . no p-w	
272	20783Y	1902 12-16 2	BM: Windmill Hill, Bucks	5-6c	Sword: continuous pattern; 2 layers prob. with a separate core in between	
273	?996-11B	1905 5-20 1047	BM: ?	5-7c	Sword: continuous pattern; poss. 2 layers with a separate central core in between	
274	21765W	1906 6-12	BM: Farnden, Notts	9-10c	Sword: continuous pattern; 2 layers with a thick separate central core in between	
275	20798V	1912 7-23 2	BM: Hurbuck, Durham	10-11c	Scramasax: continuous looped pattern ($^1/_2$ ground) + a non-ferrous cable pattern inlay (? pseudo p-w) below this	
276	22480Q	1912 7-21 1	BM: Hurbuck, Durham	L9c	Sword: alternating pattern; 2 layers prob. without any central core in between	

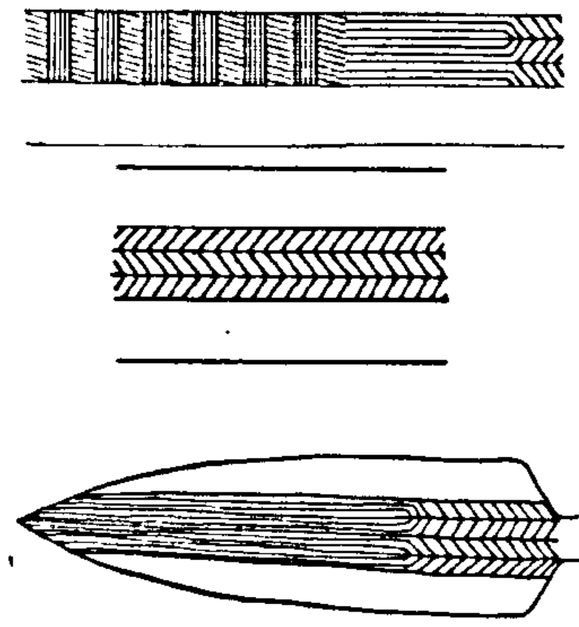
Cat. no.	X-ray no.	Acc. No (or temp no)	Museum: Findsite	Approx. Date	Weapon type and Comments	Sketch of Pattern or Inlay
277	28794Z	1913 7-17 1	BM: Barlaston, Staffs	6-7c	Sword: prob. continuous pattern on one side & alternating pattern on reverse; 2 layers prob. without a separate core piece in between	
278	20787Q	1912 12-20 2	BM: Twickenham Middx	7c	Sword: v corroded; continuous pattern; prob. 2 layers with a separate core between	
279	21771P	1915 5-3 2	BM: Herringswell, Suffolk	5-6c	Sword: alternating pattern; 2 layers with no sign of a separate core in between	
280	21760V	1915 5-4 1	BM: Edmonton, Middx	10c	Sword: no sign of welds or p-w inlaid pieces, some twisted, forming design near hilt on one side	
281	22488W	1915 12-8 353	BM: Astwick, Beds	5-6c	Sword: alternating pattern; 2 layers with no sign of separate core piece in between	
282	20842R	19 15 7-8 13	BM: Howletts, Kent	5-6c	Sword: no sign of structural detail, seems not to be p-w	
283	21762R	1929 2-6 1	BM: Windsor, Berks	10c	Sword: continuous pattern - central part is one laminated rod (one layer) laid edge on with a series of long flattened loops; wide edge parts - poss. single twisted rods (one layer) distorted by final forging.	
284	20844V	12936 5-11 54	BM: Howletts Kent	15/e6c	Sword: v. corroded; alternating pattern, no sign of a separate central core between	

Cat. no.	X-ray no.	Acc. No (or temp no)	Museum: Findsite	Approx. Date	Weapon type and Comments	Sketch of Pattern or Inlay
285	20845W	1936 5-11 76	BM: Howletts, Kent	e6c	Sword: poss. welds between edges & centre pronounced 'wavy' grain pattern along centre as shown - ? one layer, poss. distorted laminated structure	
286	21764Y	1936 5-11 132	BM: Howletts, Kent	5-6c	Sword: no welds or p-w visible, but some straight grain visible .. no p-w present	
287	28743Z	1939 10-10 27	BM: Sutton Hoo, Suffolk	7c	Sword: alternating pattern; 2 layers with no sign of a separate core in between	
288	22502T	1963 11-8 124	BM: Dover, Kent	? 5/e6c	Sword: continuous pattern - poss non herringbone (as shown), 2 layers with a separate central core in between	
289	23040Q	1963 11-8 128	BM: Dover, Kent	6-7c	Sword: alternating pattern; 2 layers prob. with a separate central core in between	
290	23047Y	1963 11-8 174	BM: Dover, Kent	6c	Sword: v. corroded; prob. continuous pattern with a separate central core in between	
291	22499Q	1963 11-8 281	BM: Dover, Kent	6-7c	Sword: v. corroded, prob. alternating pattern prob. with a separate central core in between	
292	22505Y	1963 11-8 340	BM: Dover, Kent	7c	Sword: alternating pattern; 2 layers prob. without a separate central core in between	
293	22500X	1963 11-8 416	BM: Dover, Kent	6-7c	Sword: continuous pattern; 2 layers prob. without a separate central core in between	
294	22501V	1963 11-8 469	BM: Dover,	6-7c	Sword: alternating pattern; 2 layers prob. with a separate core between	

Cat. no.	X-ray no.	Acc. No (or temp no)	Museum: Findsite	Approx. Date	Weapon type and Comments	Sketch of Pattern or Inlay
295	22504P	1963 11-8 483	BM: Dover, Kent	6-7c	Sword: continuous pattern; 2 layers with traces of a separate central core in between	
296	23043V	1963 11-8 493	BM: Dover, Kent	6-7c	Sword: alternating pattern; 2 layers with slight signs of a poss. separate central core in between	
297	23042X	1963 11-8 502	BM: Dover, Kent	6-7c	Sword: continuous pattern; 2 layers with traces of a separate central core in between	
298	23041Z	1963 11-8 509	BM: Dover, Kent	6-7c	Sword: continuous pattern; 2 layers but without any sign of a separate central core in between	
299	22506V	1963 11-8 511	BM: Dover, Kent	6c	Sword: alternating pattern; 2 layers without any sign of a separate central core in between	
300	23044T	1963 11-8 603	BM: Dover, Kent	6c	Sword: continuous pattern; 2 layers with traces of a separate central core in between	
301	23039	1963 11-8 751	BM: Dover, Kent	6c	Sword: alternating pattern; 2 layers no sign of a separate central core in between	
302	23045R	1963 11-s8 782	BM: Dover, Kent	6-7c	Sword: continuous pattern; 2 layers with slight signs of a separate central core in between	
303	23046P	1963 11-8 783	BM: Dover, Kent	6-7c	Sword: continuous pattern (not v. clear), 2 layers with signs of a separate central core in between	

Cat. no.	X-ray no.	Acc. No (or temp no)	Museum: Findsite	Approx. Date	Weapon type and Comments	Sketch of Pattern or Inlay
304	23048W	1964 7-2 381	BM: Great Chesterford, Essex	6c	Sword: v. corroded; poss. continuous pattern (as shown); 2 layers with slight signs of a separate central core piece in between	
305	23220S	1965 7-3 1	BM: Wemsley, N. Yorks	9/e10c	Sword: v. corroded, a possibly continuous pattern as shown; 2 layers with poss. slight signs of a separate central core in between	
306	AML ?	?	West Heslerton	?6-7c	Sword: continuous 'snake' pattern; 2 layers	
307	LAT 80-1		Lincs Mus: Normanby-le-Wold, Lincs	?7-9c	Scramasax: short length of distorted (1/4 ground) herringbone pattern, 2 layers prob. without any separate core in between; also a central weld runs down blade	
308	[YCH]		Yorks Mus: Gilling West N. Yorks	9/e10c	Sword: continuous herringbone pattern distorted (up to 1/4 ground) near hilt; 2 layers with no signs of a separate core in between	
309	- ?	?	Norfolk Mus: Morningthorpe, Norfolk	6c	Sword: continuous pattern; 2 layers without a separate central core in between	
310	AML 3423B	24/3	Norfolk Mus: Spong Hill, North Elmham, Norfolk	6c	Weaving batten - made from cut down sword frag: alternating pattern; 2 layers with a separate central core between	

Cat. no.	X-ray no.	Acc. No (or temp no)	Museum: Findsite	Approx. Date	Weapon type and Comments	Sketch of Pattern or Inlay
311	AML 3423B	40/5	Norfolk Mus: Spong Hill, North Elmham, Norfolk	6c	Sword: alternating pattern; 2 layers with a separate central core in between	
312	LAT 80-2	158.953	Norfolk Mus: Thetford, Norfolk/ from burial	?19c	Sword: continuous pattern; 2 layers with a separate central core in between	
313	- ?	PDN 81 570 (134)	Mus of London: Pudding Lane, City of London	11/e12c	Scramasax/knife: continuous pattern; 2 layers to twisted part but no separate central core in between	
314	- ?	ALG 84 588 (381)	Mus of London: Aldersgate, City of London	11-12c	Scramasax/knife: continuous distorted ($^1/_4$ ground) herringbone pattern - 2 layers with no core between; also teeth	
315	29237T	1936.5-11 75	BM ; Howletts Kent; grave 19	6 c	Sword: Alternating pattern as shown. 2 layers with no sign of a separate core between	
316	29238R	1936.5-11 99	BM: Howletts Kent; grave 25	6 c	Sword: A few fragments only with indistinct p-w, seems to alternate as shown. Probably 2 layers	
317	23221 Q	1936.5-11 164	BM: Howletts Kent	5-6 c	Sword: P-w but v. indistinct; seems to alternate as shown. 2 layers with no sign of a separate core between	

Cat. no.	X-ray no.	Acc. No (or temp no)	Museum: Findsite	Approx. Date	Weapon type and Comments	Sketch of Pattern or Inlay
318	29241 Q	1936.5-11 166	BM: Howletts Kent	5-6c	Sword: Continuous herringbone pattern (3 twisted rods) on one side; on reverse - unusual pattern as shown. 2 layers with no sign of a separate central core between	
319	?8	?	BM. Broadstairs Kent	6-7c	Spearhead - made from cut down sword blade: 4 twisted rods on each side - alternating pattern but no sign of a separate central core	

APPENDIX 2

South Asian watered crucible steel

A2.1 Introduction

The main part of the present study is concerned with the early development of edged weapon manufacture in North-Western Europe. The results already discussed make it clear that pattern-welding played an important part in the development of these weapons during the first millenium A.D. The results also strongly suggest that the welded patterns developed originally either as an accidental by product of bloom consolidation or from the welding together of small pieces of metal during the manufacture of early iron blades and that the technique was being exploited for its decorative effects by the 1st century AD (Chapter 7.4.2).

Pattern-welding was only introduced as a descriptive term by Maryon in 1948, Before this all sword and dagger blades with decorative patterns on their surface were usually known in Western Europe as damascened or by the similar term damasked or Damascus (for instance Baldwin Brown, 1915). Maryon introduced the term pattern-welding to differentiate between blades showing weld patterns and those whose patterns derived from the use of Eastern crucible steel, in particular that from India known in Europe from the late 18th century as Wootz. When examining the development of pattern-welding it is also important to consider the nature, origin and development of the Eastern so-called damascene steel blades so as to compare the two techniques and to assess the influence they may have had upon one another as well as to explore the reasons that they might have originally developed.

The results of the present work have shown that in pattern-welded weapons (of the 5th-11th centuries) the patterns derive from different combinations of iron, iron containing phosphorus and low carbon steel alloys, whereas the patterns of watered blades made from Wootz derive from a dispersion of cementite particles in a high carbon (eutectoid) steel.

The European association of Damascus with swords can be traced back to 1432 when the French traveller Bertrand de la Broquiere wrote that he had secretly purchased a sword and said that 'Damascus blades are the handsomest and best of all Syria'. He describes their method of burnishing sword blades, a piece of iron in a block is rubbed up and down the blade to remove all inequalities. Then they 'temper and polish it'. He reports that the blades have a mirror finish with perfect 'temper' and cut excellently (Alexander 1984, 132). Its fairly clear from this description that the swords being described are ones with polished rather than watered blades. The surviving swords of Syrian type which may have been made in Damascus are identifiable by the inlaid patterns and inscriptions on their blades (Alexander 1984, 133). It therefore seems quite clear that what sword blades did come from the Damascus region are likely to have been notable for their inlaid and highly polished blades and not for any watered patterns despite some claims to the contrary (for instance Maryon 1960, 53).

It would appear that some swords probably were made in Damascus in the fifteenth and sixteenth centuries (Alexander 1984, 135). There appears, however, to be little evidence for sword production in Damascus at most other times nor is it likely to have been on anything but a small scale as the nearest sources of iron ore were small deposits, now largely exhausted, in the Lebanon (Stone 1961, 661).

A2.2 Origin and Use of the Term Damascening for Watered Crucible Steel Sword or dagger blades

The term 'damascene' has been applied to a variety of techniques used given a decorative effect to the surface of sword or dagger blades. Unfortunately the term has been widely misused over the past two hundred years or more which has resulted in a number of misconceptions about the origin and manufacture of many of these blades.

The decorative effects in question include weld patterns and patterns which have resulted from the solidification and subsequent working of crucible steel ingots as well as the elaborate inlaying of non-ferrous metals into the surface of blades. The latter technique of inlaying non ferrous metal into iron or steel sword blades may be partly responsible for the misuse of the term 'damascene'.

In 1952, L.A Meyer suggested that the reputation of Damascus swords was the result of a linguistic error. He pointed out that the word damascene had long been used in Europe in very different ways. It is recorded in 1400 to describe a kind of plum, in 1540 it refers to a rose and from the fifteenth century as a type of (silk) cloth woven with elaborate figures and designs in such a way as to give variegated (damask) patterns when exposed to light (Alexander 1984, 131). This effect must have been compared with the 'light and dark' patterns found on watered crucible steel blades and it would seem most likely that this led to the misuse of the word damask or damascene. The word.is also used from the 16th century to describe metal ornamented or inland with gold and silver, or a watered steel (O.E.D). The Encyclopedia Britannica (11th Edition, 1908) states that the word damask is incorrectly applied to steels.

Watered steel sword blades are not referred to by the word damascene in Islamic texts. Instead watered steel was known in Persia as *poulad jauhar* or *bulat* and the watering was also known as *ferend*; and *bulat* or *poulad* are also the terms by which this special watered steel was known further north in Russia (Belaiev 1918, 417).

The misuse of the term damascene as applied to non-welded watered steel in Europe may date from the late seventeenth or early eighteenth centuries. In 1679 JB Tavernier reports from his travels in Persia that the steel susceptible of being 'damasked' comes from the kingdom of Golconda in central south India, east of Hyderabad.

> 'For when the workman puts it in the fire, he needs no more than to give it the redness of a cherry, and instead of quenching it in water as we do, to wrap it up in a moist linen cloth; for should he give it the same heat as ours, it would grow so hard that when it came to be wrought it would break like glass.
>
> This steel is sold in pieces as large as our one sou (halfpenny) loaves and in order to know that there is no fraud involved, they cut it in two, each fragment being enough to make one saber ... I speak thus to undeceive those people who think our scimitars and cut-lasses are made of steel of Damascus, which is a vulgar error; there being no steel in the world but that of Golconda which can be damask'd' (Bronson 1986, 23).

Chevalier Chardin, the French traveller reports in 1711 that the Persians called both Indian steel and their own by the name

> *poulad jauherder* - wash'd (or wavy) steel, which is that we call Damask'd steel to distinguish it from the steel of Europe. It is from this steel that they make their beautiful blades. They melt it down in a round loaf like the hollow of one's hand, and in small square rods' (Bronson 1986, 24).

Chardin mentions no manufacturing details and therefore is likely to be referring to watered blades traded in Damascus although not necessarily made there. It seems most probable that many of the fine watered steel blades referred to in Europe as damascened came not from Damascus as a manufacturing centre but as a market place for goods produced further East. The city was a trading centre where caravans from East and West met and exchanged products (Stone 1961, 202; Zaky 1961, 23) and the so-called damascene swords found in Europe are usually of Persian or Indian origin.

In the ninth century Al Kindi reports that Serendib (Sri Lanka) was the source of 'modern' (crucible) steel used by sword makers there as well as at Khurasan and Fars (in NE & SW Iran) and Mansura (in Sind, Southern Pakistan). He also reports that (crucible) steel of an ancient type - most likely made according to an ancient method - was used to make swords in India, Persia and the Yemen (Allan 1979, 82, 86 and 138). He also mentions sword polishers of Iraq (Allan 1979, 85) suggesting that swords may have been made here as well in the mid ninth century. The enthusiasm of Al Biruni in the eleventh century and Fakhr-i Mudabbir in the thirteenth century suggests that Indian swords were thought to be the finest (Allan 1979, 69 - 71). Al Idrisi, in the twelfth century, actually says that the Indians' make 'the most famous sabres in the world' (Bronson 1986, 20).

It would seem that Mayer was largely correct in his suggestion that the reputation of Damascus swords was mostly due to a linguistic error, especially where the 'so called' damascene or watered steel swords are concerned. This error was undoubtedly made worse by the adoption and subsequent manufacture by Western gunmakers in the eighteenth centuries of the type of spiral-wound, pattern-welded gun barrels which became known in Europe as 'Damascus' barrels although it would appear that they were never made in Damascus (Puraye, 1968).

The term damascene or any of its variants is not used by early Arab writers. Watering and related terms are used by several of these writers to describe swords with visible surface patterns made from crucible steel. The eleventh century writer, Al Biruni when describing a method for making crucible steel, says that a mixture of *narmahan* and its water (probably cast iron) is called *fuladh* (Allan 1979, 75). Early sources describe three types of metal when referring to iron and steel: *sharburqan* (hard or cast iron), *narmaham* (soft or wrought iron), *fuladh* or *pulad* (steel) (Allan 1979, 71, 136). One sixth century writer describes blades as having a water whose 'wavy streaks are glistening ... It is like a pond over whose surface the wind is gliding' (Smith 1960, 14)..

It would seem that between the fifteenth and eighteenth centuries the term damascening in one of its various forms became gradually more often used as a term to describe particular types of decorated weapons, particularly swords, in which the pattern formed part of the iron or steel structure of the weapon. As far as we can see at the moment decorated weapons of this kind went out of fashion in Europe between the eleventh and thirteenth centuries. It was not until the eighteenth century that pattern-welded weapons, mainly gun barrels, and to a very limited extent swords, were re-introduced to Western Europe. These were modelled on earlier or contemporary examples from the Arab world or further east.

The often indiscriminant use of the term damascene, not only for iron and steel, has led to much confusion, misinterpretation and poor descriptions in written works relating to decorated weapons. Maryon's introduction of the term pattern-welding in 1948 helped by isolating the decorated composite welded iron and steel weapons but this still left the non-welded patterned swords made from high carbon crucible steel. As Zaki said in 1961 'the term Damascus is also applied to swords or steel which have a unique technique of watering ... This has nothing to do with damascening which is the technique of decorating one metal by inlaying another'.

If we return to the older term watering and link it with the term crucible steel then we can abandon the use of damascene (and the rest) for non-welded decorated steel and replace it with the more specific and accurate 'watered crucible steel'. *Jauhar, hadid, makhus* and *firind* are all terms used by early writers to describe types of pattern which Allan calls damask (Allan 1979, 136) but which presumably refer to similar kinds of patterned effect described as watering from the sixth century onwards and recently referred to by Chardin as *poulad jauherder* which, as he explains, closely corresponds to watered steel.

A2.3 Wootz and the manufacture of watered crucible steel in India, Sri Lanka and Persia

The term *wootz* seems to be a corruption of an Indian word *ukku* meaning steel (OED). Wootz appears to have been first used to describe ingots of eastern, and more particularly Indian, crucible steel in 1795 when Pearson describes some specimens of *wootz* which were sent for examination to England from Bombay (Pearson, 1795). Although it appears to be derived from a more general Indian term for steel it has taken on the quite specific meaning of the very high carbon steel made in small clay crucibles, either in India or the surrounding regions, the manufacture of which died out during the nineteenth century with the imposition of British rule and the introduction of more modern steels. The traditional centre for the production of Wootz in the 17th and 18th centuries seems to have been in southern India and possibly Sri Lanka.

Indian iron is mentioned, by contemporary sources, in Roman Europe from about the 1st or 2nd centuries A.D (Bronson 1986, 18). There seems to be no convincing evidence, however, for the production of wootz and associated steel before about the sixth century A.D. Written evidence suggests that wootz may have been imported into China from the Indian sub-continent in pre-Tang times - sixth century or earlier - and is said to be the steel which comes from 'the mountain islands in the midst of the south-western sea' (Needham 1958, 46). This might suggest that the metal came from Sri Lanka rather than the Indian mainland. A recent report of the finding and analysis of a 6th century file made from wootz (Liversedge 1989) also suggests that Sri Lanka may have had a fully developed wootz industry by this time. Sri Lanka would appear to be a major centre for wootz production by the mid ninth century when Al Kindi reports that crucible steel (*poulad jauhar*) is made there for local sword production and exported to the sword making centres at Khurasan and Fars in Iran and Mansura in southern Pakistan (Allan 1979, 86). Al Kindi's report however described Sri Lankan crucible steel as being of modern type and he also says of Indian crucible steel swords that they are of an ancient type (of production) although he does not mention the export of Indian crucible steel. It seems possible, from these reports, that both India and Sri Lanka were well known manufacturers of crucible steel during the sixth to ninth centuries but that Sri Lanka was the more established export centre at this time.

After this time India was more famous as the centre for crucible steel and associated sword production and Sri Lanka is not mentioned by most later writers suggesting at least that Sri Lanka became less important as an international export centre for wootz production. The enthusiasm of Al Biruni in the eleventh century and Fakhr-i Mudabbir in the thirteenth century suggests that Indian swords were thought to be the finest (Allen 1979, 69 - 71). Al Idrisi, in the twelfth century, says

> 'the Hindus excel in the manufacture of iron, and the preparation of those ingredients along with which it is fused to obtain that kind of soft iron which is usually styled Indian steel. They also have workshops wherein are forged the most famous sabres in the world. It is impossible to find anything to surpass the edge you get from Indian steel' (Bronson 1986, 20).

The specimens of wootz received by Pearson were in the form of disc shaped ingots approximately 5 inches (12.5cm) in diameter by one inch (2.5 cm) thick (Pearson 1795, 323). Nineteenth century reports also describe similar flattish plano-convex ingots which seem to vary in size approximately between 3-5 inches (8-12 cm) in diameter, and by 1/2 - 1 inch (1-2 cm) in thickness (Fig 84). Although Tavernier does not use the word wootz in his description he seems to be referring to the same kind of disc shaped ingots of crucible steel. He also noted that these ingots had to be worked in a different way to the normal European method for forging as it was so brittle. Known cast wootz ingots from the mid nineteenth century are, however, not disc shaped but ovoidal or egg shaped with a flat top or roughly hemispherical, approximately 1.5-2.5 inches (4-6 cm) in diameter by 1.2-2 inches (3-5 cm) deep. Examples of these are now in the possession of Imperial College London and the Science Museum (Fig 84) and have also been illustrated (Smith 1960, 23).

The early arab writers are mostly not very specific about the shape and size of the crucible steel ingots although Al Biruni records that the area of Herat is especially noted for it and that these ingots are called *baidat* (eggs) because of their shape (Allan 1979, 75). This description goes on to say that the eggs are long and round bottomed, following the shape of the crucibles and that from them Indian swords and others are fashioned. About a hundred years later Al Tarsusi, in one of his crucible steel recipes, also desribes the ingots as *baidat* (Allan 1979, 75). The egg shaped ingots of these early descriptions must be the same type as the nineteenth century examples of flat-topped ovoidal wootz ingots already mentioned.

Two hemispherical wootz ingots (see Fig 84) from the Percy collection of the Science Museum have dimensions and weights as follows:

1) 3491(a):- diameter - 5.5 cm (2.2 inches) (mean) by 3.5 cm (1.4 inches) deep; weight - 383 gm (13.5 oz)
2) 3491(b):- diameter - 4.0 cm (1.6 inches) (mean) by 3.0 cm (1.2 inches) deep; weight - 1.86 gm (6.6 oz)

The origin of these two ingots has not been recorded.

A consolidated bar of wootz also from the Percy collection (apparently bought from Loomkoor in 1864) was found to weight 307 gm (10.8 oz). It is 20.5 cm (9 inches) long with a square, 1.4 cm (0.5 in) section.

G. Juleff, of the Institute of Archaeology, London, has recently recovered several examples of wootz clay crucibles from the same site in Sri Lanka as that described by Coomaraswamy (1908, 192-193) as having last produced wootz in 1900. The crucible dimensions given by a Coomaraswamy were about 8 inches (20 cm) long by 2 inches (5 cm) in diameter with a wall thickness of half an inch (1-2 cm). This compares closely with the crucibles found recently which have an internal diameter of about 1 1/4 inches (3cm) and the vitrification inside the crucibles indicates that the wootz ingots were about 2 inches (5 cm) long. These wootz ingots are narrower than the known probable Indian ovoidal ingots of the nineteenth century but could still be described as egg shaped.

Where crucible dimensions are given by nineteenth century observers these correspond closely with the dimensions already quoted for the egg shaped or flat topped ovoidal wootz ingots. The weights for these later wootz ingots mostly vary approximately within the range 250-500gm (0.5 - 1.0lb) which correspond quite well with the known crucible dimensions.

The disc shaped plano-convex wootz ingots are only known from certain European descriptions. This type of ingot may be implied by Tavernier when he says in the late seventeenth century that this crucible steel was sold in pieces 'as large as our one sou loaves' and that they were cut in two, 'each fragment being enough to make one saber'. Chardin also says of this crucible steel that 'They melt it down in a round loaf like the hollow of one's hand, and in small square rods' (See A2.2 and Fig 84). Disc shaped cakes were also amongst the 83 kg (1.65 cwt) wootz samples sent to England from Bombay (by Dr Scott) in the mid 1790's for examination by the Royal Society (Pearson 1795, 322; Mushet 1805, 163).

Bronson implies that these disc shaped cakes might not be crucible made steel (Bronson 1986, 24). James Abbot, however, saw watered blades being made in Gujerat (NW coast of India) from imported plano-convex, disc-like cakes of steel which he also illustrates. He reports that the these were small cakes of cast steel weighting about 2lb (0.9kg) and were used to make the simple (as opposed to pattern-welded) Gujerat blades. He also says that these cakes bear obvious signs of having been cast - 'concentric wrinkles and radiations on the upper surface and the impression of the coarse gravelly mould or crucible into which it was poured' (Abbot 1847, 417, and figs 1-8).

The reports of the disc shaped wootz ingots suggest that the metal was commonly traded in this form although the available details on the manufacture of wootz only describe the egg shaped or flat-topped ovoidal ingots. One possible explanation might be that several of the smaller flat topped ovoidal wootz ingots were sometimes melted down to form a single disc-like plano-convex ingot and then traded in this or a bar form. Abbot describes the forging of one complete sword blade from a single disc shaped ingot. A sword weighing about 1kg or (2-3 lb) would, on average, require the metal from 2 or 3 of the ovoidal wootz ingots which fall into the weight range of 250-500 gm. The disc-shaped, plano-convex cast steel ingots might therefore represent a secondary or remelted type of wootz ingot traded and used in the manufacture of full sized swords. The disc shaped ingots obtained by Dr Scott in Bombay would seem most likely to have come from Southern India but whether they were made in this form or remelted is uncertain.

A2.4 Early Arab Accounts of Watered Crucible Steel

Before the seventeenth century there are very few written descriptions which refer to cast steel or the watered blades made from it. In the earlier 6th century the Persian royal poet Imru'ulquais (died c AD540) describes sword blades as having 'wavy patterns like the tracks of ants' (Smith 1960. 14). This could refer to fine welded patterns as well as those resulting from the use of very high carbon crucible steel ingots. Early Chinese writings suggest that this special steel was being imported into China, by the sixth century AD (Needham 1958, 44-46).

The arab historian Al Kindi (AD801-870) describes various patterned sword blades. He was aware that European pattern-welded swords were made by 'the mixing of metals' and describes patterns resembling a stream of water or rings of chain mail (Davidson 1962, 115). Al Kindi says that you can tell the origin of a sword by its pattern or *ferend* , a term which appears to refer to all types of pattern regardless of the metal used, and mentions complex twisting or curled *ferend* on the finest blades as well as small 'knots like peppers' or oblong and zig-zag patterns on certain Yemani blades and similar but more complex patterns on qaliya swords. Most of these patterns, with the possible exception of the knots like pepper appear to be fairly clear descriptions of welded patterns. Al Kindi describes many swords of Frankish and Suleymanish (or Slimanish - probably referring to a different group of foreigners - the Rus or Turks) origin and it is fairly clear that he must have had first hand knowledge of the wide variety of pattern-welded types which are found on swords, scramasaxes and spearheads of this period found in Britain and which are discussed earlier in the present study.

Al Biruni (AD 1073 - 1148) provides the earliest account so far which is specific in mentioning two entirely differed types of patterned sword blades. (Davidson 1962, 116-117) He believed that the Rus manufactured pattern-welded swords in imitation of the Eastern patterned blades produced by different methods. There is no evidence to support Al Biruni's view that western smiths were copying Eastern patterned blades, in fact the results of the present work strongly suggest that Western pattern-welding, at this time, was already a well established tradition that had developed in Northern Europe over the previous millennium. Al Biruni however provides very valuable information about the manufacture of swords by different methods. He praises the wonderful blades made by Indian smiths with their rich patterns and he also says that the Rus make swords and that they find that the oriental steel cannot withstand the cold of their winters. He describes the central panels of these Viking swords as being made by the welding together of different combinations of iron and steely iron in contrast to the Eastern blades thus strongly suggesting that the latter were made from non-welded iron or steel.

It would appear that the oriental blades became brittle in the extreme cold of the Russian winter. Brittle stress fracture, is much more likely to have been a problem with the ultra high carbon steels (of approximately 1.5 - 2.0% carbon) which are now known to be the basis for watered blades made from wootz ingots. Al Biruni's account strongly suggests that watered blades of this type were already well known at this time and the recipe he gives suggests that the manufacture of the crucible steel may have been known in Iran by the early eleventh century. The manufacture of cast crucible steel and non-welded, watered swords may have spread to Persia before the eleventh century and appears to have been well established in Egypt by sometime in the thirteenth century-when Al Tarsusi gives four recipes used locally for making this steel (Allan 1979, 75). Further research may confirm this and may also provide a date for the apparent origins of cast crucible steel and non-welded watered blade manufacture in India.

A2.5 The Production of Wootz ingots

A2.5.1 Early European accounts of the methods used

Between 1795 and 1908 several first hand accounts were written by European observers on the production of wootz or crucible steel ingots as well as analyses made of several wootz ingots. Bronson (1986 13-51) has recently pointed out that some accounts written during this period are not first hand and appear to be an unreliable mixture of other peoples (unacknowledged) accounts with further details which cannot be traced to source and therefore may not be based on fact. Subsequent writers (for instance, Maryon 1960, 52-59) have sometimes overlooked various earlier errors which consequently have become established as part of the literature of wootz and watered crucible steel production. The contribution of our knowledge of wootz production by (mainly) 19th century and earlier observers as well as the reliability of later writers has been presented and discussed by Bronson (1986, 13-51). The known methods are summarised here so that we might follow the stages of manufacture of wootz and watered crucible steel through to the finished sword or dagger blade and assess the effects that the different stages had on the production of one or other of the watered patterns visible on surviving watered steel surfaces.

According to the various eye witness accounts there seem to have been two main methods by which wootz ingots were produced and these were:-

a) The carburisation, in sealed crucibles, of one or more small pieces of bloomery iron with dried wood, and the mixture usually covered with leaves (A2.5.1.1).

b) The carburisation, in sealed crucibles, of pieces of bloomery iron with pieces of cast iron (A2.5.1.12).

A2.5.1.1 Wootz produced by the carburisation of bloomery iron with dried wood

Two of the earliest and most informative accounts, those by Heyne (1814, 358-61) and Buchanan (1807, I, 174-5; II 19-23) who each saw two separate examples of wootz manufacture in the Mysore region of south-west India. Both describe a version of the method in which a single piece of bloomery iron is placed in a clay crucible with pieces of dried wood. In both of the processes described by Heyne (seen in 1795) and one of the processes seen by Buchanan (that of 1802) leaves were also placed on top of the mixture of the crucible. These three descriptions also mention that the crucible mouth was than sealed with clay . Buchanan's description of 1800 does not, however, mention any leaves, or sealing the capping or lid to the crucibles although other accounts would suggest this might be an error of omission.

The crucibles, numbering between 14 and 59 in these processes, were packed together in the furnace with charcoal and fired using (according to Buchanan) two bullockskin bellows. In three of these methods the firing time varied between 4 and 9 hours while Heyne's second process says firing continued until the crucible contents became liquid. It would appear that in both of Buchanan's processes the wootz ingots were fairly rapidly cooled by taking the crucibles from the furnace, breaking them open and removing the steel cake. In Heyne's first method the wootz ingots were cooled with water although his second description gives no details of cooling.

In the two processes seen by Buchanan the wootz ingots varied in weight between approximately 270 and 400 grams (9.5 - 14 ounces) whereas Heyne's first description gives the weight of the wootz as approximately 230 grams (8.0 ounces) and the second, approximately 330 grams (11.5 ounces). Buchanan reports that in some cases the fusion was not complete resulting in poor quality wootz ingots with some of the original wrought iron lumps remaining.

Most later accounts of the making of wootz across Southern India and Sri Lanka are much briefer although in general these describe the same method and, although usually less detailed than Heyne's or Buchanan's accounts, they are useful in providing additional information as well as confirming some of the main details. The crucible charge usually contained one or two pieces of bloomery iron mixed with dried wood - nearly always *cassia auriculata* , a tannin containing plant used in South India by dyers (Bronson 1986, 37) - often covered with leaves. Heath (1839, 392) describes several pieces of bloomery iron being mixed with one tenth by weight of the same chopped dried wood.

Another account (CVB 1820, 442) adds that the crucibles and charcoal charge were fired to a 'white heat' (approximately 1200 - 1400 °C - see Table 6). In this description the firing took nine hours after which the furnace was sprinkled with a little water and the crucibles removed. These were laid on the ground, covered with sand and cooled with water, then broken open and the wootz ingots recovered. Out of 54 crucibles in this process, about 20-30 were reckoned to contain usable steel while the other half-prepared (semi-fused) pieces were returned to the furnace in the 'same manner' (presumably in sealed crucibles). In this process a bar of consolidated bloomery iron 10 cm (4 inches) long by 3cm in diameter is used in the crucible charge which would have yielded a wootz ingot weighing approximately 570 gm (1lb 4oz).

Coomaraswamy (1908, 192) describes the crucible charge as being one piece of iron with some chips of *cassia auriculata* in the proportion of 350 gm (12.5 oz) iron to 140 gm (5 oz) of wood. In this process the crucibles were covered with clay lids perforated for the escape of gas. Coomaraswamy only witnessed demonstration firings with just six crucibles in the furnace. The crucibles were shaken to check liquidity and returned to the furnace until this was reckoned to be complete after which they were laid down (on the ground) to cool. A bar of steel weighing 280-420 gm (10-15oz) was then removed. One of these bars is now on display in the Science Museum. Heath (1839, 392) says that with perfectly completed fusion the top of the cake is covered in striations radiating out from the centre but with no holes or rough projections and says that when fusion has been less than perfect the surface of the cake has a honeycombed appearance and often contains projecting lumps of iron still in the malleable state. He estimates the iron in the crucible charge as weighing between 230 gm (0.5 lb) and 920 gm (2 lb) the latter being rather higher than in the other versions of this process. The resulting wootz ingots would have been a similar weight.

Heath's most interesting addition (1839, 393) to the descriptions of this process is that after smelting, the cakes of steel were then annealed for several hours in a charcoal fire blown with bellows. There are, however, grounds for doubting this statement which comes near the end of his descripton. Firstly, without any protective coating, this procedure would probably result in uneven decarburisation the effects of which would be most severe at the surface which would give a wootz cake of uneven composition. He, himself, earlier says that during the crucible process imperfect cakes had to be returned (in crucibles) and the process repeated to correct the problem of incomplete fusion. Bronson (1986, 41) points out that some of Heath's description derived from Buchanan's and Heyne's accounts and it seems that this final detail may have been borrowed from Voysey's 1832 account (see A2.5.1.2 below) in which it is better described and, in context, makes more sense. It is probably safest to dismiss this part of Heath's description as unreliable as it is not mentioned by any other observers of the iron and wood method of making wootz.

A2.5.1.2 Wootz produced by the carburisation of bloomery iron with cast iron

This method for producing wootz seems to have been much less widely used than the method involving bloomery iron and wood although it is also a crucible process very similar to that already described. According to Voysey (1832, 245-247), who made repeated visits to see the process, the crucible charge here consisted of a mixture of bloomery iron and cast iron. Voysey describes a process which was carried out at Konasamundram in the Nirmal district of Hyderabad in central Southern India. He says that pine (-cone) shaped crucibles of different sizes were used depending on the object to be made - swords, knives etc - and that the crucibles were sealed with a clay lid with one hole in it, presumably for venting.

The crucible charge consisted of a few small pieces of fused glassy furnace waste as a flux together with pieces of white cast iron from Mirtpalli and bloomery iron from Kondapur. These were mixed in a raio of 2 to 3, cast to bloomery iron. In this process the firing of the furnace lasted 24 hours, much longer than any described for the wood/iron method of producing wootz. After firing the furnace contents were cooled slowly and one crucible is described as producing a steel cake weighing approximately 680 gm (1.5 lb), and another a cake weighing approximately 1260 gm (2.75 lb). The cakes were then covered in clay and annealed in the furnace for 12-16 hours then taken out, cooled and the annealing treatment repeated, sometimes three or four times until the metal was left soft enough to be worked.

On his 1820 visit to the wootz making site he met a dealer, Haji Hosyn, of Isphahan who was there buying wootz ingots and who told him that this wootz making process was familiar to the Persians who were unsuccessful at it. He may have meant that the Persians did not produce such a successful product not that they were unable to make wootz. Massalski (1841, 297-300) reporting on the same sort of crucible steel making process in Iran says that the crucible charge was wrought iron, white cast iron, with a little silver, in the ratio of one part cast iron to three parts wrought iron. The silver was added to the molten mixture (possibly to remove impurities such as sulphur) after the two kinds of iron had fused, then the furnace was sealed and allowed to cool slowly over two or three days.

Two of the early arab writers mention aspects of crucible steel manufacture which correspond closely with this method of making wootz. Al Biruni when describing the process used in Persia at Khorasan in the early eleventh century says that *fuladh* (watered crucible steel) is made by mixing *narmahan* (wrought iron) and its water (probably cast iron) in the crucible (Allen 1979, 75). Al Tarsusi, in thirteenth century Egypt, is much more specific when describing four different recipes for making cast crucible steel. In one he says that 3 *ratl* of *narmahan* (wrought iron) and 1.5 *ratl* of hard *shaburqan* (cast iron) were mixed in a crucible with magnesia (flux) and a handful of acid pomegranate bark; these are fired until fusion occurs and the metal becomes egg (crucible) shaped, then the metal is taken out to make the sword (Cahen 1947-48, 127). In another of Al Tarsusi's method's which also involves using cast iron, the crucible is provided with a lid with an inspection hole in it for determining when the crucible contents have become molten at which point the crucible is removed from the furnace and left to cool before removing the steel ingot (Allen 1979, 85).

When describing wootz making in Tamilnadu, in South India, Wood (1893, 179) says that only iron was used in the crucible charge suggesting that, here too, a mixture of bloomery iron and cast iron was used. Wood also adds that the wootz ingots weighed between approximately 910 and 1350 gm (2-3lbs), similar to but slightly heavier than those described by Voysey. These ingots seem significantly heavier than those described for the bloomery iron and wood methods which (where weights are given) vary between 230 and 460 gm (0.5-1.0 lbs).

It would seem from these accounts that the method of wootz manufacture using a crucible charge of mixed bloomery iron and cast iron was used, at one time or another, between the eleventh and nineteenth centuries, as far afield as Egypt, Persia and South-eastern India.

More recently several writers (for instance Belaiev, 1918, and Richardson 1934) have suggested that wootz was also produced in closed crucibles charged with powdered iron ore and charcoal. These accounts, however, seem to be based on a description by Schwarz (1899, 96-99). Schwarz's description is, however, unreliable because his is not an eye witness account and, as Bronson (1986, 45) points out, much of his information is likely to have derived from Voysey's 1832 account although Voysey wasn't credited with the information. Although some of Voysey's information is recognisable Schwarz seems to have substituted some detail such as the use of iron ore and charcoal instead of (Voysey's) cast iron and bloomery in the crucible. Schwartz's (rather too detailed) account is unreliable as a source of information unless other source material should come to light to back up his description and this, so far, seems unlikely to happen.

Hunter (1875, 45-48) briefly mentions that iron ore was used with leaves as the crucible charge for making steel. This report is not substantiated by any other seemingly reliable account so it is possible that Hunter was not accurate in his description of the actual crucible charge. There seems therefore to be, as yet, no convincing evidence that wootz was regularly produced by the direct smelting of iron ore in a crucible.

In 1711 Chardin discusses the manufacture of watered steel blades in Persia (Bronson 1986, 23-24). He doesn't describe the actual crucible process but he does add that Persian steel cannot be joined (welded) to iron and that the Persians mix this steel with Indian steel which they consider softer than their own but both of which are called watered steel. He adds that they melted this down into round (? plano-convex or disc shaped) loaves and in small square rods. A high temperature (c. 1400°C) would have been required for this and a dendritic structure to the steel would have resulted.

A2.5.2 Discussion of the methods described for making wootz

The methods describing the production of wootz and watered blades can be summarised into two stages (Fig 83). The first stage covers the reduction of iron ore to wrought iron using the bloomery process followed by the reduction of the bloomery iron with charcoal in closed crucibles. The second stage covers the prodcution of watered steel blades (or sheet steel for armour) from the ultra high carbon steel (wootz) ingots that result from these crucible methods.

(blank page)

A2.5.2.1 The bloomery iron - wood method for making wootz

On the basis of the 19th century eye witness accounts, the most common method in southern India and Sri Lanka for producing wootz was by using the process, in which one or more pieces of iron made by the bloomery process were heated in a charcoal furnace with pieces of dried wood in a closed crucible. As the temperature rose, the small volume of oxygen in the air in these closed crucibles together with the charred wood would have created a reducing carbon monoxide atmosphere. The carbon monoxide would also have dissociated to form highly reactive atoms of nascent carbon which, as the temperature rose above 930°C, would have begun to be absorbed at the surface of the iron. Above 930°C the (face centred) crystalline form of iron (austenite) becomes more stable and up to about 2.0% carbon can exist in solid solution in (face centred) iron (austenite) whereas the maximum for (body centred) iron (ferrite) is approximately 0.05% (Fig 3). The rate of absorption will be greater the higher the temperature.

As the percentage of carbon increased the melting point of the resultant steel decreased; the melting point of a steel containing 1.6% carbon being approximately 1400°C. When the carbon content of a surface skin like this reaches 1.6% and the temperature inside the crucible is about 1400°C then this outer skin will melt. The inside portion will remain as a white hot 'pasty' lump but provided the temperature is maintained then more carbon will be absorbed until, finally all the metal has become molten. The reactions which take place can be summed up as follows:

$2C + 0_2 = 2\,Co \quad 2Co = C + CO_2$.

If there was no more carbon left in contact with the metal and the crucible was cooled, then a cast steel ingot with a carbon content of approximately 1.6% would have resulted. But if, however, there was an excess of carbon still in contact with the molten metal in the ingot then more carbon would have passed into the liquid steel solution and this would have continued until an approximately eutectic solution (carbon content about 4.3% and melting point of 1130°C) resulted. This, on cooling, would have given a very brittle cast iron ingot, useless for edged weapons or armour unless it was refined (the carbon content reduced).

To produce a usable cast steel ingot by this method it is necessary to control the ratio, dried wood : iron, in the crucible charge and to maintain the charge at a high enough temperature and for long enough for the carburised iron to become completely molten. The nineteenth century descriptions of this process would suggest that the blast was usually maintained for between 2.5 and 9 hours. The eye witness accounts, where they mention them at all, describe the use of 2 or 4 large bullock or goatskin bellows, powered by hand, to provide the blast. Crucible temperatures of 1450 down to 1300°C would have been necessary to fully melt the range of high carbon steels (1.2 - 1.8% carbon) found in the watered blades analysed for Belaiev (1918, 428). Its hard to see how these very high temperatures could have been maintained for prolonged periods using the types of furnace and simple animal hide bellows described by Buchanan. Much of the earlier part of the firing process might have been carried out at rather lower temperatures such as 1200°C, which would have been easier to maintain while still being high enough for carburisation inside the crucibles to proceed fairly rapidly. The blast might then have been increased towards the end of the firing when a higher temperature was required to fully melt the steel inside the crucible.

Where the dried wood: iron ratio in the crucible was too high, an ingot of cast iron would have been the most likely result if the blast in the furnace was maintained for long enough. The iron would continue to absorb carbon until either the carbon was all absorbed or until an approximately eutectic solution (carbon content about 4.3% and melting point about 1130°C) was reached. On slow cooling this would have produced a grey cast iron ingot.

None of the existing eye witness reports suggest that cast iron was produced accidentally, although it would appear that in some cases up to 50% of the crucibles were found to contain a mixture of steel with pieces of unfused iron protruding from it. It would appear that these were returned to the furnace, in crucibles, to complete the process of producing a more homogeneous steel ingot. Each individual process seems to have had its own recipe for producing wootz ingots with an iron : wood ratio which was found to give the desired form of steel ingot. Both Buchanan's and Heath's accounts mention iron to dried wood ratios of about 10 to 1 and this may have been approximately the usual ratio where a fully sealed crucible was used. The Sri Lankan process described by Coomaraswamy used an iron to wood ratio of approximately 3 to 1 but this process used crucibles with perforated lids which may have allowed a critical quantity of carbon monoxide gas to escape. It would appear that this method was controlled by using the correct iron to wood ratio and that relatively short firing times (of less than 10 hours) were sufficient and that the steel ingots were sold without any further treatment.

A2.5.2.2 The bloomery iron - cast iron method

According to Voysey's (1832) description this method was carried out on a larger scale with a bigger (1.5 m or 5 feet in diameter) furnace fired with 4 bullockskin bellows over a much longer firing time (24 hours) to produce rather larger ingots (up to 680 gm or 1.5 lb). Wood's (1893, 179) brief description adds that the ingots from this method weighed 910 - 1350 gm (2-3 lbs).

The ratio of cast iron to bloomery iron in the crucible charge varies according to three different descriptions. Voysey (1832, 246) gives this ratio as 2 to 3 for the Hyderabad method whereas the thirteenth century writer, Al Tarsusi (Cahen 1947, 127) gives one local (Egyptian) process as using 1 to 3. Massalski (1841, 297-300) reports that the cast iron to bloomery iron ratio in the nineteenth century Persian method was also 1 to 3.

If we take these ratios to be fairly accurate and if cast iron with a carbon content of approx 3% was used in all three processes then the carbon contents of the resultant steel ingots would be 1.0%, 1.5% and 2.0%, if we assume that there was no decarburisation during the process. Belaiev (1918, 417) reports that analysis of surviving watered crucible steel blades showed that the carbon contents of these mostly varied between 1.2 and 1.8%. Bronson (1986, 33) gives the results of eight analyses (done by Zschokke and Panseri) of surviving watered blades of this kind. Leaving aside one result (0.596% carbon) which seems much too low, the average carbon content for these watered crucible steel blades was about 1.6%. This may be the carbon-steel alloy which was found, by experiment, to give the best all round properties for a watered crucible steel blade. Its easy to see how small variations in this method, either accidental or deliberate, would still give alloys of about the right composition for a watered blade. The variations in the crucible charges may, of course reflect varying grades of cast iron used in the processes being carried out in the three different places.

A crucible charge of 1 part cast iron (with a carbon content of 4.2%) to 2 parts bloomery iron would eventually have resulted in a wootz ingot of approximately 1.4% carbon. A temperature of approximately 1250°C would have been necessary to melt the cast iron. Carbon would then gradually have diffused into the bloomery iron where it was in contact with the liquid cast iron. At 1250°C this would have continued until a soft pasty lump of fairly homogeneous steel resulted. It would not have been necessary to raise the temperature (by increasing the air blast) in order to melt this lump until towards the end of the 24 hour firing time quoted by Voysey. A long firing time may have been necessary to achieve full carburisation by this method of producing wootz if larger ingots were being made as seems to have been the case. A final firing temperature of approximately 1350°C would have been necessary to fully melt the resultant cast steel and hence give a dendritic structure to the wootz ingot when it cooled. Wootz may sometimes not have been heated much above 1250°C, a temperature more easily achievable using primitive bellows, and when this happened a fairly homogeneous pasty lump would have cooled to give a wootz ingot without a dendritic structure. It is, of course, possible that wootz made by the wood - iron method was also sometimes not heated much above about 1200-1250°C in which case a similar non-dendritic wootz ingot would have resulted.

Voysey also reports that, in the cast iron-bloomery iron method, the furnace contents were cooled slowly after firing which would have had the effect of removing the dendritic structure by annealing the steel as it cooled. There was a risk that if cooling was too slow that graphite would have had time to form which would have seriously affected the optical as well as physical properties of a watered crucible steel. Panseri (1965) noted graphite nodules in one watered steel blade that must have begun to be affected in this way.

A2.6 · Producing the Watered Pattern

It seems fairly clear that the processes by which wootz was produced usually varied between the wood-bloomery iron and cast iron - bloomery iron methods. The crucible steel may not always have been produced as a cast ingot although the intention was clearly to produce a very high carbon steel within the range 1.2 - 1.8% carbon above which cast iron rather than steel would have resulted. If we consider the ways in which a pattern may be obtained from these ultra high carbon (hyper-eutectoid) steels we can then see how these may be best matched to the variations in wootz production as well as the differences in the watered blades that survive. We can then compare these watered patterns with those obtained for pattern-welded weapons.

First of all we can consider what happens when a crucible containing a molten 1.5% carbon steel cools fairly rapidly from the fully molten state at about 1450°C (Fig 3i). As the temperature falls below approximately 1420°C dendrites of less carbon rich austenite would form first and a progressively more carbon rich matrix would solidify last. At approximately 1150°C the liquid matrix solidifies to form austenite. Where the carbon content is higher primary cementite needles may also be formed. As the austenite cools below 1000°C progressively more cementite comes out of solid solution and is deposited around the primary austenite dendrites. At 695°C when the carbon content of the austenite is down to approximately 0.8%, the carbon, except for 0.05%, is ejected from solid solution to form the eutectoid, pearlite. The primary austenite dendrites also revert to the eutectoid pearlite. If the surface of a wootz ingot cooled from the liquid state in this way were polished and etched the primary dendrites and the infil matrix both consiting of pearlite would appear dark whereas the layer of cemetite around the primary dendrites would appear white.

If, however, for the same 1.5% carbon steel the crucible temperature never rose beyond approximately 1200-1300°C then a dendritic (cast) structure would not have resulted because the primary dendrites of austenite could not have formed. Within this temperature range the crucible contents would have been a partially molten mixture of austenite grains plus liquid. The austenite grains would increase in size the longer the temperature was maintained. In this case when the temperature falls below approximately 1150°C the remaining liquid will freeze to form a network of austenite with a higher carbon content around the existing nuclei. Below 1000°C progressively more cementite will come out of solid solution to form a network around the austenite grain boundaries and at 695°C the remaining austenite breaks down to form the eutectoid pearlite. If a wootz ingot made in this way were polished and etched the cementite network would appear white with a dark pearlite infil. In this case the slower the cooling down through the austenite range, the larger the austenite grain size will be and, therefore, the larger the cementite network. This effect has been reproduced using modern hypereutectoid steel (Sherby and Wadsworth 1985, 95-98).

In each case the product will be the same whether the original crucible charge was charcoal and wrought iron, or cast and wrought iron. The important variables are the highest crucible temperature, and speed of cooling down through the austenitic range. When the rate of cooling is sufficiently slow and the resultant austenite grain size is large the iron carbide may not always have time to migrate to the grain boundaries and, if this happens, a series of cementite needles will form along the crystal planes of the austenite to give a Widmanstatten structure. At least one wootz ingot (with a carbon content of about 1.6%) has been shown to have this structure (Tylecote 1962, Pl XXVIII). Where this structure is found in wootz ingots it may usually have been the result of the heat treatment of the ingot, probably by reheating it to well above the upper critical point (possibly to about 900-1000°C)

These are the main possibilities for the formation of a pattern within a wootz ingot but we may now examine how finished watered blades (or plates for armour) may have been produced from ingots of wootz. The surfaces of a number of watered blades, and at least one cross section, have been examined microscopically (Smith 1960, 18-20; Tylecote 1962, 295). It is clear from these investigations that for the surviving blades the pattern usually consists of a network or laminated distribution of spheroidal cementite granules in a matrix of pearlite which may itself be in a spheroidal form. In the watering of these blades the distinctive pale areas are actually a mixture of cementite granules and pearlite whereas the dark areas are all pearlite.

The network of cementite formed as the wootz ingots cooled meant that the ingots could not be forged at normal forging temperatures, approximately 1000-1100 C, because the brittle cementite would cause the metal to shatter, as happened when European smiths first tried to work Indian wootz ingots (Belaiev 1918, 417). Wootz ingots are limited to being forged gently, approximately within the range 650-850°C (dull cherry-red, see Table 6) as below this range the metal is not sufficiently ductile. Above 723°C the cementite network will have already begun to dissolve although the dissolution will at first be slow (Sherby and Wadsworth 1985, 98). Panseri (1965, 33) reckons that the lower temperature limit for forgeability is about 800°C. The smiths forging the wootz would have had to rely on the colour of the metal as a guide to its temperature. It seems likely that a smith would have needed to continue forging the metal down to the lowest possible temperature limit for forgeability as too prolonged a reheating time (or too many reheatings) would have increased the likelihood that some of the cementite network would break down into more stable graphite nodules to the detriment of the final pattern as well as the softening of the blade. Graphite nodules have been observed on one early seventeenth century watered steel sword blade (Panseri 1965, 28). Tavernier, in 1679 (Bronson 1986, 22) reports that it (wootz) could not be forged above cherry red while Scott (Pearson 1795) and Hunter (1875, 246) also reporting from India both say that forging was not practicable above a dull cherry red.

Gentle forging is required to break up the cementite network which is continuous (or nearly so) in the wootz ingots whether present as dendrites, needles or as a network around the former austenite grains. The brittle cementite network is broken up by gentle forging into spheroidal particles dispersed in pearlite. This greatly improves the flexibility of the metal which otherwise would be far too brittle. The presence of the cementite however means that much of the hardness is retained.

Once the cementite network of a wootz ingot has been broken up the properties of the metal are largely dependent on the structure of the pearlite matrix. A coarse lamellar structure will give a less flexible and more brittle metal than a fine grain pearlite. Reheating and forging at just above the lower critical point of 723°C would have had the effect of re-dissolving the pearlite to give a fine grain austenite and, on cooling, a fine grain pearlite. A piece of steel would, probably, need reheating many times before the desired blade shape was achieved. The effect of re-heating and cooling would have produced a similar grain sized pearlite matrix each time provided the re-heating was not too prolonged which is unlikely when the forging was being carried out at such a relatively low temperature. The state of the pearlite matrix is critical for the flexibility of watered steel blades. Fine grain pearlite will give good flexible properties and pearlite in this form has been reported for watered blades (Tylecote 1962, 295; Maryon 1960, 57). We can see from this that the state of the pearlite in these watered blades was dependent on the final re-heating above the lower critical point of 723°C.

As we have already seen the watered pattern on a finished blade is usually caused by the discontinuous network of spheroidal cementite particles in a matrix of pearlite, made visible when the surface is polished then etched. The form of the pattern is clearly dependent on the original form of the cementite network in the wootz ingot, the three main possibilities being:

a) Dendritic segregation (A2.6.1).

b) Grain boundary distribution of cementite (A2.6.2)

c) A layered distribution of cementite particles (A2.6.3)

A2.6.1 Dendritic segregation

The dendritic source of patterns is not very easy to recognise in a finished, watered blade although one 17th century Persian dagger from the Wallace Collection (no 1384 - see also Smith 1960, 17)) is unquestionably of dendritic origin. A virtually unaltered dendritic structure can clearly seen on the surface of this blade near the hilt. This has been distorted by forging to give a more familiar watered appearance further down the blade. However, the profile of this blade near the hilt is such that the blade cannot have been forged from either a flat cake-shaped or a hemispherical wootz ingot. In this case the original ingot must have been recast in the shape of a bar, with the approximate cross-sectional profile of the finished blade. Wootz ingots may often have been recast to produce blanks of the right shape for final forging. This would seem most likely to have been done at a more local or regional arms manufacturing centre because the shape of the blank would have to correspond approximately to that of the finished blade and that in turn would depend on local or regional styles. Recasting wootz ingots into sword or dagger blanks would have necessitated the use of a furnace with an efficient enough blast to reach the melting point of the steel, approx 1350-1450°C. Where wootz ingots were re-cast as blanks for watered blades, the eventual pattern is usually likely to have been one of dendritic origin unless extensive reheating well up into the austentic range (approx 1100 - 1150°C) was carried out.

Great care must be taken in the actual forging so that the distribution of the dendritic pattern will result in an even watering of the desired form as well as giving a blade of the right shape. Recast blanks would have been the ideal shape for even, final forging whereas the wootz ingots whether of the flat round cake shaped type or, more especially, the hemispherical shaped type are not suitable shapes from which to obtain an even watered pattern. In fact, it is hard to see how any of the watered patterns seen on the many surviving watered blades could have been obtained by forging the hemispherical wootz ingots. These ingots may usually have been intended to be recast as blanks for blades, or for the plates for armour, so that published sections of these wootz ingots which show either a dendritic or a network of cementite needles may be misleading as these structures would have been lost if the ingots were recast.

In the mid-nineteenth century Tschernev put forward an ingenious but incorrect method by which he thought curved swords with the famous Kirk Narduban or 'Mahomet's Ladder' pattern could have been produced from the radial dendritic structure in one of the disc shaped or plano-convex wootz ingots by removing the centre of the ingot then opening out the resulting disc so as to leave a curved piece of metal with the dendrites (mostly) in one plane - at right angles to the blade (Yater 1983, 10-11). The dendritic structure of the ingot, however, could never give rise to the rung pattern which is very regular and exactly at right angles to the blade and clearly could never have been forged to give the double rung pattern seen on some blades.

A2.6.2 Grain boundary distribution of cementite

A grain boundary distribution cementite around islands of pearlite may be, however, the source of many of the watered patterns on surviving sword and dagger blades. It seems the only feasible explanation for the concentric pools of light and dark areas described for some blades (Smith 1960, 19) The grain boundary forms of pattern have been successfully re-created in experiments using modern ultra-high carbon steels of between 1.3 and 1.9% carbon (Sherby and Wadsworth 1985, 94-99). Instead of hand forging, rolling mills were used to work the metal within the temperature range 650-850°C. These experiments produced quite convincing reproductions of the grain boundary patterns and the effect of the rolling was to break up the continuous cementite network into a discontinuous one of spheroidal cementite particles. The discontinuous networks of white cementite particles were however rather thinner than those visible on actual watered blades. The effect of rolling the experimental pieces at as high a temperature as 850°C may have been to partially redissolve some of the cementite at the former very large austenite grain boundaries only to be re-deposited at the much smaller new austenite grain boundaries as the metal cooled down to 695°C and the austenite reverted to pearlite.

Although not stated it would seem likely that these experimental pieces were rolled from straight bars of metal not from round, cake-shaped or hemispherical pieces similar to wootz ingots. Its easy to see that wootz in these forms was not in a shape suitable for producing a long sword or dagger blade with an even watered pattern.

The forging of a plano-convex wootz ingot at Gujerat in north-West India, has, however been described by Abbott (1847, 417 and figs 4-8) who saw one of these ingots being forged into a straight sword. Abbott's sketches show a plano-convex ingot approximately 5 inches (12.5cm) in diameter with a cast (dendritic) structure radiating from the centre. He says that the ingot weighed about 2 pounds (0.9kg) and was solid except for the upper central part which was porous. The ingot was held edgewise upon the anvil and forged, at red heat (possibly cherry red, 700-825°C) to produce a flattened bar so that upon further forging what had been the flawed centre of the bar became the back of the (single-edged) sword. After forging into shape the sword was filed, roughly burnished, heated to a dull red (dull cherry red = 700-750°C) heat and quenched, edge first, in oil. The blade was then tempered, burnished, degreased and etched with white vitriol with the resultant pattern reported as being very similar to the pattern of Isphahan in Persia. From the method described it would seem that a very distorted dendritic structure would have been the source of the pattern in this case.

A2.6.3 A layered distribution of cementite particles

The watering seen on a few blades shows some similarity to the relief map form of pattern-welding. One of these blades has been shown to consist of an alternately light and dark layered or laminated structure which under higher magnification consisted of dark layers of pearlite between pale layers of spheroidal cementite particles in a pearlite matrix (Smith 1960, 17). The appearance in transverse section shows how the laminated structure has been distorted in this direction although the enlarged photograph of the surface of the blade shows a recognisable wood grain pattern typical of a layered structure.

An inhomogeneous layered structure such as this cannot have been produced from one of the more homogeneous wootz ingots so far discussed. A wootz ingot with a laminated structure could, however, have been produced by placing a stack of thin iron plates, interleaved with crushed cast iron, in a sealed crucible and heating this in a furnace at about 1200°C, provided the furnace was fired just long enough for the iron plates to partially absorb carbon from the cast iron but not long enough to give a more homogeneous structure. This is an obvious possible variation to the 6th century AD Chinese 'co-fusion' method of making steel using a combination of wrought iron and cast iron in a sealed crucible. (Needham 1958, 26) This structure has been reproduced more recently in experiments designed to show the structures produced by both partial and complete dispersion of carbon from cast to wrought iron to give both layered and homogeneous steels (Whitaker and Williams 1969)).

A2.6.4 Three dimensional distribution of cementite - a possible source of watering?

A three dimensional distribution of cementite needles in a pearlite matrix is a structure that has been observed in one hemispherical wootz ingot (Tylecote 1962, PLXXLIII). There seems to be no way in which the intimately connected three dimensional network of cementite needles could be broken up and dispersed in such a way as to give the distorted lines of white cementite particles between the darker areas of pearlite which result in the watered patterns. It seems unlikely, therefore, that wootz ingots with this structure could have been forged to produce any of the familiar watered blades.

A2.6.5 Varieties of pattern and final polishing and etching

Egerton (1880, 60) divided the patterns recognised in Persia into four main types:

Kara Khorasan :- nearly black with fine undulating lines
Kara Taban :- brilliant black with larger watering and more grey in the tone
Kirk Narduban :- the (Mahomet's) ladder pattern, which has more or less distinct transverse markings at fairly regular intervals
Sham :- simple watered pattern which includes all the other varieties

He says that all these varieties are recognised in India plus an additional variety, *Zinjir* which refers to varieties of chain pattern watering.

Kara Khorasan and *Kara Taban* both refer to variations in appearance which must have been the result of different etching solutions having been used whereas *Sham, Zinjir* and *Kirk Narduban* all refer to differences in the form of the watered pattern. The *Kirk Narduban* or ladder pattern is the most obvious and easily recognisable form of pattern variation and is found in many surviving sword blades (for instance Smith, 1960, 21; Rawson 1968). The rung-like variations in the pattern are the result of local transverse distortions to one of the three basic forms of watering discussed above although different explanations as to how these rung-like distortions were achieved have been put forward. Smith (1960, 20) suggested that during the forging process horizontal grooves were filed at regular intervals across the blade which would have been further forged out and finally ground to give the correct shape.

This method would, however, have resulted in a less compressed pattern in the rungs of the ladder-like design and is the effect that can be seen on many south-east asian kris with relief-map pattern-welded blades. A more likely explanation of the compressed pattern seen in the Mahomets ladder pattern of many surviving watered sword blades is that during forging a series of transverse grooves were made using a blunt ended chisel or fuller and the blade then ground down (Panseri 1965, 63). This would have had the effect of compressing the pattern at intervals whichever of the three main forms of pattern-dendritic, grain boundary or layered - was present in the wootz metal before the final shaping of the blade.

After final polishing and cleaning the finished sword or dagger blades were etched to bring out the watered pattern. A solution known as *zaj* or *zag* has been known to have been used for this purpose since it was recorded by Al Biruni in the early 11th century. An analysis of 1816 found this substance to be impure basic ferric sulphate (Smith 1960, 22). Abbot (1847, 417) says that white vitriol - a solution of zinc sulphate - was used for this purpose in Gujerat in north-west India. Other locally popular solutions were presumably also used.

A2.7 Conclusions: The origin and purpose of watered crucible steel and its comparison with pattern-welding

From the evidence so far examined it would seem likely that the manufacture of the cast crucible steel known as wootz was already established in central Southern India, and possibly Sri Lanka as well, by about the 6th century A.D. It seems that southern India remained the centre of the industry although it was in use in Iran from the eleventh century or earlier and was also carried out in other parts of the Middle East, such as Egypt, in the thirteenth century.

Two main methods appear to have been used to make wootz. Each involved the heating of clay crucibles laid in a specially prepared bed or furnace filled with charcoal and fired using animal hide bellows powered by hand or foot. The methods are quite similar in that they involve the carburisation of bloomery iron in the crucibles to produce an ultra-high carbon cast steel of about 1.5% carbon which was forged at a low temperature to produce watered sword and dagger blades. It was also used to make other implements such as files and cutting tools for which the hardness of the metal was well suited. The two crucible methods varied in that one used dried wood, sometimes with leaves, whereas the other used cast iron as the source of carbon for the crucible carburisation process.

It would seem that the quality of wootz ingots could be rather variable which may be one reason behind the recasting and mixing of different cast crucible steels described by Chardin as happening in Persia in the early eighteenth century. A Wallace collection dagger (no 1384) shows that some blades must have been forged from blanks recast for this purpose. The forging of wootz into blades had to be carried out at a much lower temperature than usual (to western smiths) - between about 650 and 850°C - to prevent the loss of the watered pattern to the finished blade.

The watered pattern is likely usually to have derived either from a dendritic distribution of cementite (iron carbide) in the wootz ingot, bar or blank, or from a distribution of cementite (iron carbide) formed around very large grains of austenite (gamma iron) during an annealing or slow cooling process. Occasionally the pattern in a watered blade appears to have been the product of a rather different process such as the partial diffusion of carbon from cast iron into plates of wrought iron to give a homogeneous layered structure with a pattern similar in appearance to that of the relief map form of pattern-welding, especially popular in the south-east Asian kris type of dagger.

The usual watered steel pattern is derived from a fairly homogeneous distribution of cementite (iron carbide) in a very high carbon (hyper-eutectoid) steel, whereas the patterns found in Anglo-Saxon pattern-welded blades are the result of welding together pieces of low carbon iron usually with different low carbon alloys welded side-by-side so as to give an enhanced visual contrast when the surface was polished and etched. Forging techniques similar to those used to produce variations in the watered patterns such as the lateral 'rungs' of the *Kirk Narduban* or Mahomet's ladder form of pattern were also used to produce variations in the relief map form of pattern-welding common in south-east Asia from the thirteenth century onwards whereas pattern variations in Anglo-Saxon weapons were achieved by using complex welding and twisting techniques (see Appendix 1 and Chapter 7.4). There is no evidence to suggest that any watered blades owe their patterns to welding techniques even where the pattern is an inhomogeneous layered distribution of cementite in pearlite.

Bibliography

Ager, B and Gilmour, B 1988: 'A pattern-welded Anglo-Saxon sword from Acklam Wold, North Yorkshire', *Yorkshire Arch J*, 60, 13-23.

Aitchison, L 1960: *A History of Metals*. London: MacDonald and Evans

Alexander, DG 1984: 'The Swords of Damascus', *Waffen und Kostumkunde*, 131-138

Alfoldy, G 1974 (translated by Birley, A): *Noricum*. London and Boston: Routledge and Kegan Paul

Allan, JA 1979: *Persian Metal Technology 700 - 1300 AD*. London: Ithaca Press.

Antiens, AK 1968: 'Structure and Manufacturing Techniques of Pattern-welded objects found in the Baltic States', *JISI*, 206 (June), 563 - 71

Antejn, A 1982: 'The Mystery of Pattern-Surface Steel', *Nauka : technica* 6, 22-24, Abstracted: JHMS, 17 (2), 133

Anstee, J and Biek, L 1961: 'A study in Pattern welding', *Med Arch* 5, 71-93

Atkinson, RJC 1953: 'Technical notes on the construction of the swords, scabbards and shields', in Leeds, ET and Shortt, H de S, *An Anglo-Saxon Cemetery at Petersfinger, near Salisbury, Wilts* 55-60. Salisbury.

Bachmann, HG 1982: *The identification of Slags from Archaeological Sites*. Univ of London, Institute of Archaeology, Occasional Publication No. 6.

Backhuizen, SC 1977: 'Greek Steel', World Archaeology 9, 221-234

Bailey, FWJ 1972: *Fundamentals of Engineering Metallurgy and Materials*. London: Cassell

Baldwin Brown, G 1915: *The Arts in Early England. Vol III: Saxon Art and Industry in the Pagan Period*. London: John Murray

Bartlett-Wells H 1969: 'Contributions to the history of the heat treatment of steel (largely from the evidence of sword blades)', *J Arms and Armour Soc* 618, 217-240

Becker, G and Dick, W 1971: 'Iron pile shoe from the Roman bridge at Trier', *Arch Eisenhuttenwesen*, 42 (3) 223-227

Behmer, E 1939: *Das Zweischniedige Schwert der Germanischen Völkerwanderungszeit*. Stockholm: Akademisk Auhandling

Belaiev, N. 1918: 'Damascene Steel', *JISI* 97, 417-439

Berkelsen, H (ed) 1905-11: *Thioricks Saga at Bern*. Copenhagen

Biborski, M, Kaczanowski, P, Kedzierski, Z and Stepinski, J 1981: 'Two-edged swords from the cemeteries of the Przeworsk Culture at Chronielow Piaskowy, Province of Kielca and Gac, Province of Przemsyl', *Sprawozdania Archaeologiczne*, 33, 99-133. Abstracted in JHMS, 17 (2) 133

Biek, L 1963: *Archaeology and the microscope*. London: Lutterworth Press

Bidder, H.F. and Morris, J. 1959: The Anglo-Saxon Cemetery at Mitcham, Surrey Archaeological Collections, 56, 51-131

Biek, L 1983: 'The et hnic factor in archaeotechnology', in Aspinall, A and Warren, SE (eds). *The proceedings of the 22nd symposium on Archaeometry*, 303-313, Univ of Bradford

Bird, V and Hodges, H W M 1968: 'A metallurgical examination of two Early Swords from Luristan', *Studies in Conservation*, 13, 215-233.

Bohrie, C 1969: 'The development from damascus steel to Scharsach steel: the improvements of sword steels from the La Tène period to the late Middle Ages' *Archäeol Eisenhuttenwesen*, 40, 661-665. Abstracted in AATA, 1972

Bone, P 1989: 'The Development of Anglo-Saxon swords from the fifth to the eleventh century', in Hawkes SC, *Weapons and Warfare in Anglo-Saxon England*, Oxford Committee for Archaeology, 63-70

Bradley, R 1990: *A Passage of Arms*. CUP

Bramley, E and Lawton, C 1927: 'The gaseous cementation of iron and steel', *Carn Schol Iron and Steel Institute* 14,35-100

Brent, J 1863-5: 'Account of the Societies researches in the Saxon cemetery at Sarr' *Archaeologia Cantiana*, 5 (1863), 305-322; 6 (1864),157-185; 7 (1865), 307-321

Brewer, C 1976: 'Metallographic examination of six ancient steel weapons', *JHMS* 10 (1),1-10

Brewer, C 1979: 'Anglo-Saxon weapons', *Metals Australasia* 11(7),4-6

Brewer, C 1979: 'Anglo-Saxon weapons', *Metals Australasia*, 11(6), 22-24

Bronson, B 1986: 'The making and selling of Wootz, a crucible steel of India', *Archaeomaterials* 1 (1), 13-51

Bronson, B 1987: 'Terrestrial and meteoric nickel in the Indonesian kris', *JHMS*, 21 (1), 8-15

Brookes, N P 1979: 'Arms, status and warfare in late Anglo-Saxon England', in Hull (ed), *Ethelred the Unready*, BAR Brit Series, 59, 81-103

Bruce-Mitford, RLS 1978: *The Sutton Hoo Ship Burial, Vol 2 : Arms Armour and Regalia*. London: BM publications

Buchwald, VF and Mosdal, G 1985: 'Meteoric iron, telluric iron and wrought iron in Greenland', *Meddeleser orm Gronland,Man and Society*, 9, 3-49

Cahan, C 1948: 'Un traite d'armurerie compose pour Saladin', *Bulletin d'Ètudes Orientales*, 12, 103-163. Beirut

Chardin, J 1711: *Voyages en Perse et autres lieux d'Orient*. Amsterdam

Charles, J A 1977: 'The analysis of non-metallic inclusions in ancient iron', *PACT*, 1, 204-220

Charles, J A 1979: '*From, copper to iron: the origins of metallic materials*', *J of Metals*, 31, 7-14

Chickashige, M 1936: *Alchemy and other Chemical Achievements of the Ancient Orient*. Tokyo

Chilton, J P 1969: *Principles of Metallic Corrosion*. London : Royal Inst of Chemistry, Monographs for Teachers, No 4

Clarke, H (trans and ed) 1979: *Iron and Man in Prehistoric Sweden*. Stockholm: Jernkontoret

Cleere, H F 1972: 'The classification of early iron smelting furnaces', *AntiqJ*, 52 (1), 8-23

Cleere, H and Crossley, D 1985: *The Iron Industry of the Weald*. Leicester Univ Press

Clough R E 1985: 'The Bloomery Process - Observations of the use of rich ores and the production of natural steels', in Scott, BG and Cleere, H (eds) *The crafts of the Blacksmith*, 19-27

Clough, R E 1986: *Iron : Aspects of the Industry during the Iron Age and Romano-British Periods*, an unpublished Phd thesis, Univ. of London, Institute of Archaeology

Coe, MD and others 1989: *Swords and Hilt Weapons*. London : Weidenfeld and Nicholson

Coghlan, HH 1977: *Notes on Prehistoric and Early Iron in the Old World* (2nd ed). Univ of Oxford: Pitt Rivers Museum

Coghlan, HH 1957: 'A note upon iron as a material for the Celtic sword' *Sibrium* 3, 129-135

Coghlan, HH and Tylecote RF 1978: 'Medieval iron artefacts from the Newbury area of Berkshire: metallurgical examinations', *JHMS* 12 (1), 12-17

Condon, L O K 1971: 'Steel in antiquity: a problem in terminology' in Mitten, Pedley and Scott (eds) *Studies presented to George MA Hanfman*, 17-27. Cambridge (Mass): Harvard Univ, Fogg Art Mus.

Coomaraswamy AK 1908: *Medieval Sinhalese Art*. London : Essex House Press

Cowgill J, Neergard, M de and Griffiths, N 1987: *Knives and Scabbards. Medieval Finds from the City of London*. London: HMSO

Cramp, R 1957: 'Beowulf and archaeology', MedArch 1, 57-77

Crossley, DW 1981: 'Medieval iron smelting' in : Crossley (ed) Medieval Industry, CBA Research Report 40, 29-41

Crummy, P 1980: *Aspects of Anglo-Saxon and Norman Colchester*. CBA Research Report 39, 12-21

Davidson, HRE 1962: *The Sword in Anglo Saxon England: Its Archaeology and Literature*. Oxford: Clarendon Press

Davies, DJ and Oelmann, LA 1983: *The Structure, Properties and Heat Treatment of Metals*. London : Pitman

Denig, H 1990: *Alte Schmiedekunst Damaszenerstahl*. Kaiserslautern.

Dodd, B 1978: 'The making of old Japanese swords', *J Mech Work Technol* 2 (1), 75-84

Dowker, G 1887: 'A Saxon cemetery at Wickhambreux', *Archaeologia Cantiana* 17, 6-9

East, K, Larkin, P and Winsor, P. 1979: 'A Viking sword found at Chertsey', *Surrey Archaeological Collections*, 76, 1-9

Easton, S C and Wieruszowski, H 1961: *The Era of Charlemagne.* Princeton: D.Van Nostrand

Egerton, W 1880: *Handbook of Indian Arms.* London: Allen and Co.

Emmerling, J 1972: 'Technologisch Untersuchungen an eisernen Bodenfunden', *Alt Thür ngen*, 12, 267-320

Emmerling, J 1978: 'The technology of Roman swords from Buchlein', *Alt-Thüringen*, 15, 92-102. Abstracted in JHMS, 14 (1981)

Engstrom, R, Langton, SC and Engstrom, AL 1989: *A modern Replication based on the Pattern-welded Sword of Sutton Hoo.* Kalamazoo Medieval Institute Publications, Western Michigan University

Erhenreich, RM 1985: *Trade, Technology and the Iron Working Community in the Iron Age of Southern Britain.* BAR British Series, 114

Evison, VI 1956: 'An Anglo-Saxon cemetery at Holborough, Kent' *Archaeologia Cantiana* 70, 84-141

Evison, VI 1961: 'The kitchen area of Northolt Manor, Middlesex: The Saxon objects', *Med Arch*, 5, 226-230

Evison, VI 1964: 'A decorated seax from the Thames at Keen Edge', *Arch J*, 61, 28-36

Evison, VI 1965: *Fifth-Century Invasions South of the Thames* . London: Athlone Press

Fennell, KR 1957: 'Excavation of an Anglo-Saxon Cemetery at Hough on the Hill, Lincolnshire', *Journal of the RAF College, Cranwell,* 29 (2), 170-174

Field, FN 1982: 'Fiskerton' in White, AJ 'Archaeology in Lincolnshire and South Humberside, 1981', *Lincolnshire History and Archaeology* 17, 72

Foote, PG and Wilson DM 1970: *The Viking Achievement.* London: Sidgewick and Jackson

Forbes, RJ 1950: *Metallurgy in Antiquity.* Leiden : E J Brill

Forbes, RJ 1964: *Studies in ancient technology,* Vol 9. Leiden: E J Brill

France-Lanord, A 1964: 'La fabrication des épées de fer gauloises', *Rev Hist Sider*, 5 (4), 315-327. Abstracted in AATA (1966-67)

France-Lanord. A 1949: 'La technique du damas soude dans les épées mérovingiennes et carolingiennes', *Revue historique de la Lorraine*, 86, 26-33

France-Lanord, A 1949:' La fabrication des épées damasees aux époques mérovingienne et carolingienne", *Pays Gamais*, 10, 19ff

Frey, E 1988: *The Kris: Mystic Weapon of the Malay World.* Oxford: University Press

Gale, DA 1989: 'The Seax', in Hawkes, SC. *Weapons and Warfare in Anglo-Saxon England* Oxford Committee for Archaeology, 71-83

Ganiaris, H and Gilmour, B 1989: 'A leather sheathed and pattern welded knife' (from Pudding Lane), in *Aspects of Saxon and Norman London*, Museum of London

Gardner, GB 1936: *Keris and Other Malay Weapons*. Singapore: Progressive Publishing Co

Gilmour, B J J 1975: *Technology of swordblade making*, unpublished undergraduate dissertation, University of London, Institute of Archaeology

Gilmour, B J J 1984: 'Sword and pommel', in Rogerson, A and Dallas, C *Excavations in Thetford 1948-59 and 1973-80*. East Anglian Archaeology Report No 22, 105-106 ·

Gilmour, B J J 1984: 'X-Radiographs of two objects: the weaving batten (24/3), and the sword (40/5)', in Hills C, Penn K, and Ricketts R. *The Anglo-Saxon Cemetery at Spong Hill, North Elmham, Part III: Catalogue of Inhumations*. East Anglian Archaeology Report No 21, 160-165

Gilmour, B J J 1986: 'A Late Anglo-Saxon sword from Gilling West, N. Yorkshire: The blade', *Med Arch* 30, 93-96

Gilmour, B J J 1987: 'Structural aspects of the blade deduced from radiographs' in Green, B. Rogerson, A and White, SG, *The Anglo-Saxon Cemetery at Morningthorpe Norfolk*, A2-A3

Gilmour, B 1989: 'A pattern-welded knife (from Aldersgate)' in *Aspects of Saxon and Norman London*. Museum of London

Goodsall, RH 1966: *A Kentish patchwork*, 9-16. London: Constable

Goodway, M 1987: 'Phosphorus in Antique Iron Music Wire', *Science*, 236 (1987), 927-932

Goodway, M and Fisher, RM 1988: 'Phosphorus in low carbon iron: Its beneficial Properties', *JHMS*, 22 (1) 21-23

Gowland, W 1899: 'The early metallurgy of copper, tin and iron', *Archaeologia*, 56, 27-38

Gowland, W 1903: 'A note of the composition of two ancient British iron currency bars', *Proc Soc Antiq* 20, 194

Gowland, W 1912: 'The metals in antiquity', *J Royal Anthropological Inst* 4, 235-287

Graham-Campbell, JA 1980: *The Viking World*. London: Francis Lincoln

Greaves, HG and Wrighton, H 1957: *Practical Microscopical Metallography*. London : Science Paperbacks

Greener, W 1835: *The Gun*. London: Longman
Greener, W W 1910: *The Gun and its development* (9th edition). London: Cassell

Greensmith, J T 1978 : *Petrology of Sedimentary Rocks*. London: George Allen and Unwin

Gregory, E & Simonds, E N 1942: *The Structure of Steel*. London: Blackie and Sons

Grieg S 1923: *Merovingisk og Norsk, enegge Sverd fra VII og VIII Aarhundrede.* Kristiania

Hansson, T and Modin S 1973: 'A metallographic Examination of Some Iron Findings with a High Nickel and Cobalt Content', *Early Medieval Studies*, 5, 5-23

Hawkes, SC 1980: 'The two seaxes', in Crummy P, *Aspects of Anglo-Saxon and Norman Colchester*, CBA Research Report 39, 19-20

Hawkes, S C (ed) 1989: *Weapons and Warfare in Anglo-Saxon England* . Oxford Committe for Archaeology

Hazel, PJ 1981: 'The pedite gladius', *Antiq J*, 61 (1) 73-82

Hedges, R E M and Salter, C J 1979: :'Source determination of iron currency bars through analysis of the slag inclusions', *Archaeometry*, 21, 161-176

Henger, GW 1970: 'The metallography and chemical analysis of iron-bar samples dating from antiquity to modern times', *JHMS*, 4 (2), 45-52

Hennig, E 1983: 'Technologische Untersuchungen an Schwerten der Völkerwanderungszeit aus Schlotheim' (Technological investigations on swords from the migration period from Schlotheim), *Alt Thüringen*, 19, 83-98

Hermelin, E, Tholander, E and Blomgren, S : A prehistoric nickel-alloyed iron axe, *JHMS*, 13 (2), 69-94

Heyne, B 1814: *Tracts Historical and Statistical on India.* London

Hills, C, Penn, K and Rickett, R 1984: 'The Anglo-Saxon Cemetery at Spong Hill, North Elmham. Part III: Catalogue of Inhumations', *East Anglian Archaeology*, Report 21. Norfolk Archaeological Unit

Hill, D 1981: *Atlas of Anglo-Saxon England* . Oxford

Hiromu, T 1980: 'Development of the Japanese sword', *Jour of Metals* 32 (2), 63 - 73

Hodges, H W M 1964: *Artifacts.* London : Baker

Hodges, H W M 1971 : *Technology in the Ancient World.* London: Penguin

Hodges, R 1985: 'Beginnings of the Medieval Iron Industry in Western Europe', in *Medieval Iron in Society*, Stockholm Symposium

Hoffmeyer, AB 1961: 'Introduction to the history of the European sword', *Gladius* 1, 30-75

Howe, M 1978: 'From the Museum' (Whittlesea sword) *Durobrivae*, 7, 22-24

Holland, T H 1893: 'Iron Resources and Iron Industries of the Southern Districts of Madra Presidency', *Imperial Institute Handbook of Commercial Products*, 8 (1893). Calcutta

Holland, T H 1892: 'Preliminary Report on the Iron-Ores and Iron-Industries of the Salam District' *Records, Geological Survey of India* 25 (1892), 3, 135-159

Horbacz, T J 1976: 'A sword with images of Mars and of Victory from the collection of the State Archaeological Museum in Warsaw', *Wiadomosci Archeologiczne,* 41 (3), 281-291. Abstracted in JHMS, 12 (1978)

Horn, W and Born, E 1980: *The Plan of St Gall.* Univ of California Press

Hunter, A 1875: 'Metal-work amongt the Hindoos', *Art Journal* 14, 45-48, 149-51

Ilkjaer, J and Lonstrup, J 1976: *New excavations in Illerup Ada, Kuml, 1975* 99-115 (in Danish). Abstracted in JHMS 12 (1978), 1

Jacob, A 1985: *Les armes blanches du monde islamique.* Paris

Jankuhn, H 1959: Nydam and Thorsberg Moorfunde der Eisenzeit, Neumunster

Janssens, M 1957: 'Essai de reconstruction d'un procède de fabrication des lames d'épées damassées', *Studs in Cons* 3, 93-106

Johnson, G (trans) 1963: *The Saga of Gisli.* Univ of Toronto Press

Kirpicnikov, AN 1986: 'Russische Waffen des 9-15 Jarhunderts', *Waffen und Kostumkunde,* 1, 1-14

Klaeber, F (ed) 1941: *'Beowulf and the Fight at Finnsberg',* New York and London

Knox R, 1963: 'Detection of iron carbide structure in the oxide remains of ancient steel', *Archaeometry,* 6, 43-45

Kolchin, B A 1953: *Metallurgy and Metalworking in Ancient Russia.* Moscow. Published for the Smithsonian Institution, in translation, by Israel Program for Scientific Translations, Jerusalem (1967)

Krishara 1905-11 : *Sturlunga Saga* . Kongelige Nordiska Old skriftsselskal Copenhagen

Lang, J 1985: 'The Technology of Celtic Iron Swords', in Scott, BG and Cleere, H (eds) *The Crafts of the Blacksmith,* 61-72

Lang, J 1988: 'Study of the metallography of some Roman swords', *Britannia,* 19, 199-216

Lang, J and Ager, B 1989: 'Swords of the Anglo-Saxon and Viking Periods in the British Museum : A Radiographic Study', in Hawkes S C *Weapons and Warfare in Anglo-Saxon England,* Oxford Committee for Archaeology, 85-122

Lang, J and Price, J 1976: 'Iron tables from the late Roman glass making sites at Merida (Badajos) in Spain', *J Arch Science,* 2, 289-296

Lang, J and Williams, AR 1976: 'The hardening of iron swords', *J Arch science,* 2, 199-207

Larkin, P 1983: 'The Chertsey Viking Sword', *Popular Archaeology* 4, 5

Leeds, ET and Shortt, H de S 1953: *An Anglo-Saxon Cemetery at Petersfinger, near Salisbury, Wilts.* Salisbury : South Wilts and Blackmore Museum

Leeds, ET and Harden, DB 1936: *The Anglo-Saxon Cemetery at Abingdon, Berkshire.* Univ of Oxford, Ashmolean Museum

Leoni, M 1975: 'Celtic sword blades', *Sibrium*, 22, 105-125

Leppaaho, J 1964: *Späteisenzeitliche Waffen aus Finnland: Schwertinschriften und Waffenverzierungen des 9-12 Jarhunderts.* Helsinki

Liebgott, N K 1976: *Middelalderens vaben.* Copenhagen : National Museum

Lorrange, AL 1889: *Den Yngre Jernalders Svaerd Et Bidrag til Vikingetidens Historie og Teknologi.* Bergen Museum

Loyn, HR and Percival, J 1975: The Reign of Charlemagne. London: Edward Arnold

Liversidge, D 1989 : Paris conference, 1989, unpublished lecture.

Maddin, R 1985: 'The Early Blacksmith', in Scott, BG and Cleere, H (eds) *The Crafts of the Blacksmith*, 7-17

Magne de Marolles 1788: *La Chasse au Fusil* Paris. Also an English version of the same work: *An Essay on shooting*, London, 1789 (listed) and 1791 (2nd ed.) - an ananymous translation usually accredited to Acton.

Maryon, H 1961: 'Early Near Eastern steel swords', *Amer J of Archaeol*, 65, 173-18

Maryon, H 1960: 'Pattern-welding and damascening', *Studies in Conservation*, 5, 25-36 and 52-59

Maryon, H 1948: 'A Sword of the Nydam Type from Ely Fields Farm, Near Ely', *Proc Cambridge Antiquarian Soc*, 41, 73-76

Masalski, 1841: ' Preparation de l'acies damasse en Perse'. *Annuaire du Journal des Mines de Russia*, (1841), 297-308

Maxwell-Hyslop, KR and Hodges, HWM 1966: 'Three Iron Swords from Luristan', *Iraq*, 28, 164-176

McGrath, JN 1973: 'A note on the classification of Celtic swords', *Jour Arms and Armour Soc*, 7, 263-265 and Plates 69-71

McGrath, JN 1968: 'A preliminary report on the metallographic examination of four fragmentary early Iron Age swords from Llyn CerrigBach, Anglesey', *BHMS*, 2(2) 78-80

McDonnell, JG 1989: 'Iron and its alloys in the fifth to eleventh centuries AD in England', *World Archaeology*, 20 (3) 373-382

McDonnell, JG 1988: 'Ore to Artefact - A study of early iron working technology', in Slater, EA and Tate, JO. *Science and Archaeology, Glasgow 1987.* BAR British Series 196, 283-293

Meaney, A 1964: *A Gazeteer of early Anglo-Saxon burial sites.* London: George, Allen and Unwin

Minghin, W 1983: *Das Schwert in frühen Mittelalter* (The early medieval sword). Stuttgart: Konrad Theiss

Mills, JVG (trans and ed) 1970: Ma Huan, Ying-Yai Shang-han. *The overall Survey of the Oceans' Shores.* London: Hakluyk Society, Extra Series 42

Modin, S and Pleiner, R 1978: 'The metallographic examination of locks, keys and tools', in *Excavations at Helgö V : 1, Workshop 2*. Stockholm

Morris, W 1962: *Volsunga Saga*. London: Macmillan

Nadolski, A 1962: 'Ancient Polish Arms and Armour, Part 1', *Arms and Armour Soc*, 4 (1) 29-40

Needham, J 1958: *The Development of Iron and Steel Technology in China*. London : Newcomen Society

Nigam, ML 1975: 'A catalogue of arms and armour in the State Museum, Hyderabad', *Andhra Pradesh State Museum Series No 13*. Hyderabad, India

Oakshotte, RE 1960: *The Archaeology of Weapons*. London: Lutterworth Press

Oakshotte, RE 1964: *The Sword in the Age of Chivalry*. London : Arms and Armour Press

O'Leary, T 1982: ' A viking period sword from Bath', Still Trowelling (Newsletter of the Ancient History Book Club), No 6

Page, R I 1964: 'Appendix A: The Inscriptions' in Wilson, DM. *Anglo-Saxon Ornamental Metalwork 700-1100 in the British Museum*. London: British Museum Publications

Panseri, C 1965: 'Damascus steel in legend and in reality', *Gladius*, 4, 5-66

Panseri, C and Leoni, M 1967: 'Research on an iron spearhead from the Etruscan sanctuary of Fanum Voltumnae, fourth to third century BC', in Levey, M (ed) *Archaeological Chemistry, A Symposium*, 205-229. Philadelphia

Percy, J 1864: *Metallurgy. Vol 2, Part 1 - Properties of Iron: Iron Ores: Direct Reduction Process*. London: John Murray (Facsimile ed, Hist Met Soc)

Percy ,J 1864: *Metallurgy; Vol 2, Part 3 - Wrought Iron, Steel*. London: John Murray (Facsimile ed., Hist Met Soc)

Perring, D 1981: *Early Medieval Occupation at Flaxengate, Lincoln*, Lincoln Archaeological Trust: The Archaeology of Lincoln, Vol 9 (1)

Petersen, J 1919: *De Norske Vikingesverd* . Kristiania

Petzow, G 1972: *Metallographic etching*. American Society for Metals

Photos, E 1989: 'The question of meteoric versus smelted nickel-rich iron: archaeological evidence and experimental results', *World Archaeology*, 20 (3), 403-421

Piaskowski, J 1960: 'An interesting example of early technology', *JISI*, 197, 336-340

Piaskowski, J 1961: 'Metallographic investigations of ancient iron objects from the territory between the Oder and the basin of the Vistula river', *JISI*, 198, 263-282

Piaskowski, J 1964: 'The manufacture of medieval damascened knives', *JISI*, 202 (2), 561-568

Piaskowski, J 1969: 'Metallographic examinations of iron objects of pre-Roman and the Roman period found in the north-eastern territory of the GDR' (in German) *Ethnog Archaol Zeitschrift* 10, 301-322

Piaskowski, J 1970: 'The achievements of research carried out in Poland in the history of early technology of iron' (in Polish) *Archaeologia Polonia* 12, 187ff Abstracted in : JHMS, 7 (2) (1973), 63

Piaskowski, J 1971: 'Was iron with a high content of nickel smelted in antiquity?' (in Polish), *Zotchlani Wiekow*, 37 (1), 24-26. Abstracted in JHMS, 9 (1975), 2

Piaskowski, J 1972: 'Iron Technology in W Pomerania from late La Tene to early Roman Times' (in Polish) *Materialy Zachniopomorski*, 8, 81-135. Abstracted in JHMS, 11, 10

Piaskowski, J 1973: ' Metallographic examination of Iron objects of the La Tene period from Poiana and Popesti' (in Polish). Materials si Cercetoria Archaeologica, 10 87-95. Abstracted in JHMS

Piaskowski; J 1973: 'Iron Metallurgy in W Pomerania in antiquity (2nd century BC to 2nd century to AD) (in Polish), *Wiadomosci Huntnicze* 7-9, 260-265. Abstracted in JHMS 10 (1) (1976) 48

Piaskowski, J 1973: 'Eisen und Stahltechnologie der Völkerwanderungsziet im Gebiete zwischen Weichsel und Oder', *Early Medieval Studies*, 6, 29-41 (Antikvariskt archiv, 53)

Piaskowski, J 1974: *O stali damascenskiej*. Wroclaw

Piaskowski, J 1981: 'Examination of two Damascene Steel (Bulata) blades', in *Wiadomodsci Hutnieze*, 3, 37, 81-116 (in Polish). Abstracted in JHMS, 16, 2, 90

Piaskowski, J 1981: 'Classification of the famous damascene swords', *International Congress of the History of Turkish - Islamic Science and Technology, 14-18 Sept, 1981*.

Piaskowski, J 1982: 'Classification and Evaluation of the Technological Level of Ancient and Early Mediaeval Iron Manufacturing Centres', in Piaskowski, J and others, 'Ancient Iron Manufacture Centres in Northern Central Europe', *Archaeologia Interregionalis*, 2, 7-27. Krakow-Warsaw

Piaskowski, J 1985: 'Proposals for the Standardisation of the Criteria for Determining Technological Processes in Early Iron and Steel Metallurgy', in Scott, BG and Cleere H, 1985.

Piaskowski, J 1985: 'Iron and steel technology on the territories of Poland in the 11th-14th Century AD', in *Medieval Iron in Society*, papers presented at the symposium in Norberg, May 6-10, 1985. Stockholm: The Historical Metallurgy group of Jernkontoret, Jernkontorets Forskning Series H35

Piggot, S 1965: *Ancient Europe*. Edinburgh : Univ Press

Piggott, V C, McGovern, PE and Notis, MR 1982: ' The earliest steel from Transjordan',
Masca J, 2 35-39

Pleiner, R 1962: *Stare Europske Kovartstvi*. Prague

Pleiner, R 1963: 'Rediscovering the techniques of early European blacksmiths', *Archaeology*, 16, 234-242

Pleiner, R 1969: 'Experimental smelting of steel in early medieval furnaces', *Pamatky Archaeologicke*, 60, 458-487

Pleiner, R 1973: 'Metallography of early artefacts: the problem of welding together iron and steel', *Early Medieval Studies*, 6, 17-28 (*Antikvaris kt arkiv*, 40)

Pleiner, R 1980: 'Early Iron Metallurgy in Europe', in Wertime, TA and Muhly, JD *The coming of the Age of Iron*, 375-415

Pleiner, R (ed) 1981: *Frühes Eisen in Europe.Acta des 3 Symposium des Comite pour la siderurgie ancienne de l'UISSP*, Schaffhausen: Peter Meili

Pleiner, R 1983: 'Zur Technik der Iron Messerklingen Aus Haitabu', *Berichte über die Ausgrabungen in Haitabu*, 18, 63-92

Pleiner, R 1985: 'Problems in the Standardisation of Metallographic Investigations of Archaeological Iron Objects', in Scott, BG and Cleere, H *The Crafts of the Blacksmith*, 179-180

Puraye, J 1968: *Damascus Barrels*. Liege (trans by Norris, F)

Rao, KNP, Mukajee JK and Lahri AK 1970: 'Some observations on the structure of ancient steel from South India and its mode of production', *BHMS*, 4 (1), 12-17

Rao, KNP 1982: 'Iron and steel technology in India in ancient and medieval periods', *Metallurgist and Materials Technologist*, 14 (10), 468-470

Rao, KNP 1983: 'Iron and steel technology in India in ancient and medieval periods', *Metallurgist and Materials Technologist* ,15 (5), 245

Rawson, PS 1968: The Indian Sword. London: Herbert Jenkins

Reed Hill, RE 1973: *Physical Metallurgy Principles* (2nd ed). New York, London: D Van Norstrand

Reed, T 1921: 'Primitive iron smelting in China', *Iron Age*, 108, 451

Read, T 1934: 'The early casting of iron', *Geographical Review*, 24, 544-554

Rehder, J E 1989: 'Ancient carburisation of iron to steel', *Archaeomaterials* 3 (1), 27-37

Richardson, H 1934: 'Iron, prehistoric and ancient', *American J of Archaeology* 38 (4), 555-583

Richardson, FD and Jeffes, JH 1949: 'The thermodynamic background of iron and steel making processes, I - The blast furnace', *JISI*, 163, 397-420

Rickard, T A 1939: 'The smelting of primitive iron', *American J of Archaeology* 43, 85ff

Roesch, K and Kuhn, H H 1976: 'Reconstruction of bloomery iron smelting and working' (in German), *Arch Eisenhuttenwesen*, 47 (1), 5-8. Abstracted in JHMS, 11 (1977),1

Richmond, IA 1953 : The Roman Fort at South Shields: A Guide. South Shields Public Library.

Rogerson, A and Dallas, C 1984: 'Excavations in Thetford, 1948-59 and 1973-80', *East Anglian Archaeology*. Report 22

Rollason, EC 1973: *Metallurgy for Engineers*. London : Edward Arnold

Rosenquist, AM 1968: 'Sverd med klinger ornert mod figurer i kopperlogeringer frå eldre jernalder i Universi tetets Oldsaksamling', *Saertrykk fra Universitetets Oldsaksamlings Arbok* 1967-8, 143-199

Rostoker, W and Duvorak JR 1965: *Interpretation of Metallographic Structures* . New York and London : Academic Press

Sache, M 1978 : 'Die Restaurierung von Damaszenerstahl', *Arbeitsblätter*, 1, 113-123

Salin, E 1957: *La Civilisation Mérovingienne: Part 3, The Techniques*. Paris

Saltzman, LF 1967: *Building in England down to 1540*. Oxford : Clarendon Press

Sambhasiva, IVS 1901: 'Report on Prospecting Work in Parts of the Chitaldroog and Tumkur District' *Records, Mysore Geology Dept*, 2, 102-116

Samuels, LE 1980: *Optical Microscopy of Carbon Steels*. American Society for Metals

Sawyer, PJ 1978: *From Roman Britain to Norman England*. London: Methuen

Schaaber, O 1964: 'Metallurgical examination of ancient bloomery steel objects from Magdalensberg', *Archaeol Eisenhuttenwesen*, 35, 502-506.

Schlenker, BR 1974: *Introduction to Materials Science*. Sydney, London, New York and Toronto : John Wiley

Schmidt, B 1969: 'Theodoric the Great and the damascened swords of the Thuringians' (in German), *Ausgrabungen und Funde*, 14 (1), 38-40

Schubert, H R 1957: *History of the British Iron and Steel Industry from c450 BC to AD 1775*. London : Routledge and Kegan Paul

Schurmann, E 1959: 'Examination of Nydam swords', *Arch Eisenhuttenwesen*, 30, 121-126

Schurmann, E and Schroer H 1959: 'Harte - und Gliihversuche au dem Klingenbruchstuck eines Nydam - Schwertes', *Arch Eisenhuttenwesen*, 30, 127-130

Scott, BG 1971: 'Applications of metallographic examination of iron artefacts to Irish archaeology', *Ulster J Arch*, 34, 87-95

Scott, BG 1974 : 'Notes on the development of metallographic studies of ancient iron', *JHMS*, 8, (2)

Scott, BG 1974 : 'The application of techniques of physical examination to archaeological research', in Scott, BG (ed); *Perspectives in Irish Archaeology*, 107-119

Scott BG 1974: 'Some notes on the transition from bronze to iron in Ireland', *Irish Archaeological Forum*, April, 1 (1), 9-24

Scott, BG 1976: 'Metallurgical and chemical studies on a group of iron artifacts from the excavations at Greencastle, Co Down', *Ulster J of Archaeol* 39, 42-52

Scott, BG 1976: 'Remnant metal structures in corrosion products from an early medieval iron knife', *Irish Archaeol Research Forum* 1976, 61-64

Scott, BG 1977: 'Metallographic study of some early iron tools and weapons from Ireland', *Proc Royal Irish Academy* 77 (12) 301-317

Scott, BG 1983: 'Some problems in the Reconstruction and Interpretation of Indo-European Metallurgical Vocabularies', *Offa*, 40, 19-28

Scott, BG and Cleere, H (eds) 1985: *The Crafts of the Blacksmith.* UISPP Comite pour la Siderurgie Ancienne, Symposium, Belfast, 16-21 September, 1984

Scott, D 1987 : *Metallography of Ancient Metallic Artifacts.* London : Institute of Archaeology, Summer Schools Press

Semiatin, S L and Lahoti G 1981 : 'The forging of metals', *Scientific American*

Sherby, O D and Wadsworth, J 1985: 'Damascus Steels', *Scientific American*, 252 (2), 94-99

Singer C, Holmyard, EJ and Hall, AR 1956: *A History of Technology* Vol 1. Oxford

Smallman, R E 1963: *Modern Physical Metallurgy.* London: Butterworth

Smith, C S and Gnudi, M T 1942: *The Pirotechnia of Vannocio Biringuccio*, New York : The American Institute of Mining and Metallurgical Engineers

Smith, C S 1957: 'A metallographic examination of some Japanese sword blades', in Panseri (ed) *Symposeum La Technica di Fabbricazione delle Lame di Acciaio Presso gli Antichi*, Quaderno II, 1957, 41-64

Smith, C S 1960: *A History of Metallography.* Chicago: Univ of Chicago Press

Smith, C S 1967: 'The interpretation of the microstructure of metallic artefacts' in *Application of Science in the Examination of Works of Art*, 20-52. Boston Museum of Fine Art

Smith, C S (ed) 1968: *Sources of the History of the Science of Steel, 1532-1768.* Cambridge (Mass) and London : The Society for the History of Technology and the MIT Press

Smith, C S 1971: 'The techniques of the Luristan Smith', in Brill (ed), *Science in Archaeology*, London : MIT Press

Snodgrass, A M 1980: 'Iron and Early Metallurgy in the Mediterranean', in Wertime, TA and Muhly, JD *The Coming of the Age of Iron*, 335-374

Stead IM Hartwell AP, Lang J R S and La Niece S 1980: ' A Iron Age sword and scabbard from Isleham', Proc Cambridge Antiquarian Soc, 70, 61-74

Stead, J E 1918: 'Iron, carbon and phosphorus', *JISI*, 97, 389-415

Stone, G C 1931: *A Glossary of the Construction, Decoration and Use of Arms and Armor.* New York

Straube, H 1973: in Guyan, W U, Pleiner R, and Fabesova, R (eds) *Die Versuchschmelzen und ihre Bedeutung fur die Metallurgie des Eisens und dessen Gerschichten*, UISPP Comite pour la Siderurgie Ancienne, Symposium, 9-12 November 1970

Straker, E 1931: *Wealden Iron.* London : Bell

Swanton, M J 1973 : *The Spearheads of the Anglo-Saxon Settlements.* London: R.A.I

Tavadze, F N, Sarrak, U I and Svanishvili 1975: 'The mechanical properties and the nature of the fracture of archaeological iron', *Akad Nauk Gruz SSR* 80 (2) 409-412

Tavernier, J B 1679: *Les Six Voyages de Jean Baptiste Tavernier - en Turquie en Perse, et aux Indes.* Paris

Tavernier, J B 1688: *Collections of Travels through Turkey into Persia and the East-Indies.* London

Thalin, L 1973: 'Notes on the Ancient Iron Currency Bars of Northern Sweden and the Nickel Alloys of Some Archaeological objects', *Early Medieval Studies*, 5, 24-41, Antikvariskt arkiv, 40

Thalin, L 1973: 'Notes on the ancient iron currency bars of Northern Sweden and on the nickel alloys of some archaeological objects', *Early Medieval Studies* 5, 24-49 (Antikvariskt archiv 50)

Tholander, E 1971 : 'Evidence of the use of carburised steel and quench hardening in LBA Cyprus' *Opuscula Atheniensia*, 10, 15-22

Tholander, E 1979: 'A study of the technology behind nickel alloyed prehistoric steel having a laminated structure', in Ryan, M (ed), *Proc. of the Fifth Atlantic Conference* Dublin

Tholander, E 1982: 'How ancient technology could influence the properties of iron and steel', *PACT*, 7, 477-486

Thompson, M W 1967: *Novgorod the Great.* London

Thomsen, R 1971 : 'Metallographische Untersuchungen einer wikingerzeitlichen Lanzenspitze aus Haitabu (Metallographic study of a Viking spearhead from Haitabu)', *Ausgrabungen in Haitabu*, 5, 58-83

Thomsen, R 1971: 'Metallographische Untersuchung an wikingerzeitlichen Eisenbarren aus Haithabu (Metallographic study of Viking iron ingots from Haitabu)', *Ausgrabungen in Haitabu*, 5, 9-29

Thomsen, R 1971: 'Metallographische Untersuchung an drei wikingerzeitlichen Eisenaxten aus Haithabu (Metallographic study of three Viking iron axes from haithabu)', *Ausgrabungen in Haitabu*, 5, 30-57

Thomsen, R (forthcoming): *Roman weapons from Illerup and Nydam*

Todd, M 1975: *The Northern Barbarians 100 BC - A.D. 300* . London : Hutchinson

Tomtlund, J-E 1973 : 'Metallographic Investigation of 13 Knives from Helgö', *Early Medieval Studies* 5, 42-63. Antikuariskt arkiv, 40

Treharne, R F and Fullard H 1969: *Muirs Historical Atlas : Medieval and Modern.* London : George Philip and Son

Trueman, A E 1971 : *Geology and Scenery in England and Wales* . Pelican

Turner, T 1893: 'The production of wrought iron in small blast furnaces in India', *JISI*, 44, 162-181

Turner, W B 1841: 'Answers to Queries concerning the Manufacture of Cast Steel', *Reports and Abstracts, Committee for the Investigation of the Coal and Mineral Resources of India,* Appendix 2, London

Tweddle, D 1984 : 'The Acomb sword pommel', *Interim*, 9 (3), 20-23. York Archaeol Trust

Tylecote, R F and Owles, E 1960 : 'A second century iron smelting site at Ashwicken, Norfolk', *Norfolk Arch* 32, 142-162

Tylecote, R F 1962 : *Metallurgy in Archaeology.* London : Edward Arnold

Tylecote, R F 1968 : *The solid phase welding of metals.* London : Edward Arnold

Tylecote, R F 1968 : 'The phosphorus content of iron from the bloomery site at West Runton, Norfolk', *BHMS*, 2 (2), 83

Tylecote, R F, Austen, J N and Wraith, A E 1971: 'The mechanism of the bloomery process in shaft furnaces', *JISI*, 342-64

Tylecote, R F 1972: 'A visit to Sweden', *BHMG*, 7 (1), 23-25

Tylecote, R F and Thomsen, R 1973: 'The segregation and surface enrichment of arsenic and phosphorus in early iron artefacts', *Archaeometry*, 15, 193-198

Tylecote, R F 1976: *A History of Metallurgy* . London : *The Metals Society*

Tylecote, R and Black, J W B 1980 : 'The effect of hydrogen reduction on the properties of ferrous materials', *Studies in Conservation*, 25, 87-96

Tylecote, R F 1981: 'The earliest iron in Europe', in Pleiner, R 1981, 21-24

Tylecote, R F 1981: 'The medieval smith and his methods', in Crossley, D W (ed) 'Medieval Industry', *CBA Research Report 40*, 42-50

Tylecote, R F and Gilmour, B J J 1986: *The Metallography of Early Ferrous Edge Tools and Edged Weapons*. BAR British Series, 155

Tylecote, R F 1986: *The Prehistory of Metallurgy in the British Isles*. London : The Institute of Metals

Tylecote, R F 1987: *The early history of metallurgy in Europe.* London and New York: Longman

Validi, A Z 1936 : 'Die Schwerter der Germanen, nach arabischen Berichten des 9-11. Jahrhunderts', *Zeitschrift der Deutschen Morgenlandischen Gesellschaft*, 90 (N.F 15), 19

Verhoeven, J D 1987: 'Damascus steel. Part 1 : Indian Wootz steel', *Metallography* 20 (2), 145-51

Verhoeven, J D 1987 : 'Damascus steel. Part II: Origin of the damask pattern', *Metallography*, 20 (2), 153-180

Voss, R F 1976 : 'The variants of the torsional pattern of twisted damascening. Part II' (in German), *Neue Museumskunde*, 19 (4), 227-284

Wadsworth, J and Sherby, O D 1980: 'On the Bulat - Damascus Steels Revisited', *Progress in Materials Science*, 25 (1) 35-38

Wadsworth, J, Dong, W K and Sherby, O D 1986: 'Welded Damascus Steels and a New Breed of Laminated Composites', *Metal Progress*, 61-67

Waldbaum, J 1980: 'The first archaeological appearance of iron and the transition to the Iron Age', in Wertime T A and Muhly J D (eds). *The Coming of the Age of Iron*, Yale Univ Press, 69-98

Watson, J, Anstee, J and Biek, L 1982: 'The swords and pieces of equipment from the grave : scientific and technological examination', in Bennett P, Frere, SS and Stow,S. *Archaeology of Canterbury. Vol 1 : Excavations at Canterbury Castle*, 188-190

Webster, G 1982: 'The sword and pieces of equipment from the grave : description', in Bennett P, Frere SS and Stow S. *Archaeology of Canterbury. Vol 1: Excavations at Canterbury Castle* 185-188

Wells, H B 1969: 'Contributions to the history of the heat treatment of steel (largely from the evidence of sword blades)', *Arms and Armour Soc* 4 (8) 217-238

Wertime, T A and Muhly, J D (eds) 1980: *The Coming of the Age of Iron.* New Haven and London : Yale University Press

Westphal, H 1986: 'Unusual welding techniques and decorations in two 8th century saxes. Restoration, investigation, documentation' (in German), *Arbeitsblätter*, 1, 217-224

Wheeler, R E M 1927: *London and the Vikings*, London Museum Catalogue, No.1
Wheeler, R E M 1935 : *London and the Saxons*, London Museum Catalogue, No.6

Whitaker, P and Williams T H 1969: 'An examination of a north Indian sword (firangi) in the collections of the Pitt-Rivers Museum, Oxford, and experiments in the forge welding of low carbon strips', *BHMG*, 3 (2) 39-45

Whitelock, D 1930: Anglo Saxon Wills. Cambridge Studies on Legal History

Williams, A R 1977 : 'Methods of manufacture of swords in medieval Europe : illustrated by the metallography of some examples', *Gladius*, 13, 75-101. Madrid

Williams, A R 1977 : 'Roman arms and armour : a technical note', *J Arch Science*, 4 (1), 77-87

Williams, H W 1935 : 'A sixteenth century German treatise, *Von Stahel und Eysen*, translated with explanatory notes', *Technical Studies* 4 (2) 64-92

Wilson, D M 1960 : *The Anglo-Saxons*. Pelican

Wilson, D M 1964 : *Anglo-Saxon Ornamental Metalwork 700 - 1100*, Catalogue of Antiquities of the Later Saxon Period, Volume 1. British Museum Publications

Wilson, D M 1965 : 'Some neglected late Anglo-Saxon swords', *Med Arch*, 9,

Wilson, D M 1970 : *The Vikings and their origins*

Wilson, D M 1980 : *The northern world : history and heritage of northern Europe. AD 400-1100*. London

Wood, C 1893 : 'Discussion of Turner's Paper on the Production of Iron in Small Furnaces in India' *JISI* 44, 2, 177-180

Wormald, F 1953 : *The Utrecht Psalter*. Utrecht

Wulff, H E 1966 : *The Traditional Crafts of Persia*. London and Cambridge, Mass : M I T Press

Wyndham-Hulme, E 1940 : 'Part II. The crucible processes of the East', *Transactions of the Newcomen Soc*, 21, 23-30

Yater, W M 1982: 'The legendary steel of Damascus Part I : a review of the literature', *The Anvils Ring*, 10 (1), 3-8

Yater, W M 1983 : 'The legendary steel of Damascus, Part II : how it was made in the East', *The Anvils Ring*, 11 (2) 2-13

Ypey J 1982 : ' Europäische Waffen mit Damaszierung', Archäologisches Korrespondentzblatt, 12, 381-388. R.O.B 176

Ypey, J 1982: 'Flugellanzen in niederlandischen Sammlungen', (Winged spearheads from the Netherlands), *Rijksdienst voor het Oudheidkundig Bodemonderzoek*, Amersfoort.

Ypey, J 1983 : 'Rekonstructsversuch der schwertklinge von Sutton Hoo', *Archäologisches Korrespondenzblatt*, 13, 495-498

Ypey, J 1984: ' Some Viking Age swords from the Netherlands' (in German) *Offa*, 41, 213-222

Yule, H 1903 : *The Book of Ser Marco Polo* (3rd ed). London

Yumoto, J M 1958 : *The Samurai Sword : A Handbook*, Rutland (Vermont) and Tokyo

Zaky, A R 1961 : 'Introduction to the study of Islamic arms and armour', *Gladius*, 1, 17-29

Zaky, A R 1979 : 'Medieval Arab Arms', in Elgood, R (ed) *Islamic Arms and Armour*, 203-216 London : Scolar Press

Zimjakov, N M 1976 : 'Technology of iron objects of the Yelukayev Collection', in Kemerovo, *Yuznaya Sibir v skifo - armatskuyu epokhu*, 106-114. Abstracted in *JHMS*, 15 (1981), 1ff