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An Archaeometallurgical Study of Early Medieval Iron Technology. An examination of the quality and use of iron alloys in iron artefacts from Early Medieval Britain.

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**AN ARCHAEOLOGICAL STUDY OF EARLY MEDIEVAL
IRON TECHNOLOGY**

**An examination of the quality and use of iron alloys in iron
artefacts from Early Medieval Britain**

Volume 1

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submitted for the degree of
Doctor of Philosophy

Division of Archaeological, Geographical and Environmental Sciences
University of Bradford

2010

An Archaeometallurgical Study of Early Medieval Iron

Technology

An examination of the quality and use of iron alloys in iron artefacts from
Early Medieval Britain

Key Words

Iron, technology, Early Medieval, metallography, smithing, alloys, phosphorus,
manufacture, status, metallurgy

Abstract

This project presents a study of iron technology in Early Medieval (fifth to eleventh centuries AD) Britain through the examination of iron found in settlement contexts. This is a period characterized by significant cultural, political and social changes. The effect of these changes on iron technology has never been investigated on a large scale. Previous studies on iron focused either on individual sites or on single artefact types, and did not provide any clear multi-region interpretive framework. A longstanding problem has been in identifying the extent of usage of a key alloy: *phosphoric iron*.

This research project examined iron assemblages from eight settlement sites of varying size, culture, economic and social status from across Britain. From each settlement a mixed assemblage of iron artefacts was sampled, including edged tools, items of

personal adornment, construction materials, and craft tools. Analysis was by traditional archaeometallurgical techniques alongside SEM-EDS elemental analysis. Alloy usage, specifically relating to phosphoric iron, was examined and the manufacturing techniques assessed. It was shown that elemental analysis is the *only* reliable method to determine the presence of phosphorus in iron and demonstrated that the traditional phosphoric indicators as observed during optical microscopy are insufficient. Results were subjected to a series of comparisons based on settlement size, the inferred social status, and cultural affinities.

The results demonstrate the high technological level of iron artefact production across the country. All areas had access to the full range of iron alloys and employed a highly developed range of smithing techniques. Phosphoric iron was a prevalent alloy in this period. Based on these results, a model of the Early Medieval iron industry is generated, suggesting a vibrant economy in which both local and traded irons were significant.

Acknowledgements

I would like to thank my supervisors Dr. Gerry McDonnell and Dr. Tim Taylor for all of the guidance, patience, and unending support. I would also like to thank my family for their support despite all the ups and downs of the last five years. I love them dearly and couldn't have completed this work without them. I would like to thank my British family Paul Newnham, Rhiannon Draper, Dominic Smith, Vanessa Castagnino, and Catherine Illingworth for everything from being geeky with me to repeated proof reading to just being supportive in every way. They are lifelong friends and I only hope that someday I can support them like they have supported me.

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I would like to thank the trusts and museums that kindly provided the artefacts to be used in this study. These institutions included York Archaeological Trust, Avon Archaeology, Canterbury Archaeological Trust, Southampton Archaeological Unit, Worcestershire Archaeological Service, Worcester City Museum, The Wharram Percy Project, Winchester Museum and the Archaeology Field Unit.

List of Symbols and Abbreviations

ASTM

A Grain size gradient

Artefact #

Finds number or identification number assigned by the excavators

Clean?

Refers to the slag inclusion content
Clean = low (less than 1/5 of the section area contains slag) and Dirty = high (greater than 1/5 contained slag)

EDS

Energy Dispersive Spectroscopy

EE

Edge Effects

EMPA

Electron Microprobe Analysis

GB

Grain Boundary

High Carbon Steel (HC Steel)

Iron with $\geq 0.4\%$ Carbon

Hv_{0.2}

Average micro-hardness

Low Carbon Steel (LC Steel)

Iron with $\leq 0.3\%$ Carbon

P-iron

Phosphoric iron

SEM

Scanning Electron Microscope

WDS

Wavelength Dispersive Spectroscopy

Wt%

Weight percent

Chapter 1 – Introduction

Iron played an important role in the development of early Britain. By the Early Medieval period in Europe this material was intrinsically bound to all parts of daily life including craft production, agriculture, construction, hunting, personal adornment, and warfare (Ottaway 1992: 463). All of these activities include a range of different tools and equipment from specialized items such as augers to basic items such as nails. Each of these items requires specific manufacturing techniques and materials to produce a quality product. Previous research on early British iron focused primarily on edged tools and weapons while generally ignoring the variety of other iron artefact types regularly found in Early Medieval contexts, including the most prevalent of iron artefacts: the nail. This limited focus prevents a more thorough understanding of variations in manufacture between artefact types, the technologies employed by the smith, and a determination of the most commonly used iron alloys.

There were three major alloys used in Early Medieval British iron artefacts. These included phosphoric iron ($>0.15\text{wt}\%\text{P}$), ferritic iron (no alloying elements) and steel ($>0.1\%\text{C}$). Of the three, phosphoric iron received the little attention by archaeometallurgist despite its presence in archaeological assemblages dating Iron Age (Ehrenreich 1985) to the medieval period (McDonnell 1992). The iron alloy is defined as iron with a low carbon ($<0.1\%\text{C}$) content and high phosphorus ($>0.15\text{wt}\%\text{P}$) content. Previously limited attention was paid to this alloy due to the difficulty in identification. Often the alloy is identified based on an educated guess derived from the presence of

a few, potentially questionable, indicators that are visible during metallographic examination of etched sections. Previous research into phosphoric iron has been limited to the examination of artefacts from individual archaeological sites and the investigation of the mechanical properties of the alloy. There has been little research to assess the validity of the indicators used to characterise Phosphoric iron, to determine whether Phosphoric iron was a specialist alloy used for specific purposes or a general bulk alloy.

Previous studies in Early Medieval iron focused on either selected artefacts, often edged tools, from individual settlements, such as York (McDonnell 1992, Wiemer 1993), Hamwic (McDonnell 1987b), and Helgö (Lamm and Ludnström 1978), or were a multi-site (figure 1) examination of a specific artefact type, such as knives (Arrhaniu 1989, Blakelock and McDonnell 2007, Cowgill et al. 1987), padlocks (Gustafsson 2005), and weapons (Gilmour 2007). Despite the importance of such lines of study, it is difficult to derive significant inferences about the iron economy in Early Medieval from them.

1.1 Aims and Objectives

This project aimed to study iron technology in Early Medieval Britain with particular attention to the role of phosphoric iron in Early Medieval settlement contexts. The Early Medieval period (fifth-eleventh centuries AD) in Britain was a time of cultural, political and social change. Beginning with the end of Roman Britain in the late fourth

century (figure 2), the economy of Britain decayed and the political structure in former Roman areas changed to a more kingdom-based political and social structure. This change was further affected by the settlement of Germanic tribes from the continent which included the Saxons, Angles and Jutes, and later, the Danes. Each of these peoples introduced their culture, life style and industry to the descendants of the Romans and Britons. It was through the interactions of these different cultural groups that the foundation for the country now known as England was established. This period was one of diversity and change, with an influx of new ideas. A study of the iron economy of the period may provide insight into the influx and development of new technologies and the effects of that economy on everyday life within the individual cultures. To study the use and role of phosphoric iron in this setting, a variety of iron artefact types from across Britain were analyzed using archaeometallurgical analysis and the results formed the basis for models of alloy availability and craft specialization.

This analysis will focus on identifying and evaluating the properties and usage of alloys in use during the Early Medieval period, notably phosphoric iron in comparison to other ferric alloys. It will also determine which iron alloys were commonly available to the smiths and which alloys were reserved for more specialized use.

For this research the following objectives have been identified:

1. To identify iron artefact assemblages from a variety of Early Medieval settlements, i.e. differing in geographical location, site type, and status; suitable for laboratory analysis.

2. Create a classification scheme for the artefacts taking into account intended use, relative value, and the complexity of the manufacturing process(es).
3. Redefine phosphoric iron using conventional indicators (hardness, grain size, and ghosting) assessed against the elemental content as measured by electron microscopy.
4. Compare iron alloy usage, manufacturing techniques and quality between archaeological sites and artefact types and develop models for the Early Medieval iron economy in Britain.

1.2 Structure of the thesis

The thesis is structured in to 12 chapters, divided into two volumes and a disc, as follows:

Volume 1 – The Written Text

Volume 2 – The Figures, Tables, and Bibliography

Disc – Artefact Archive (Including artefact descriptions, SEM results, photos, x-radiographs, and section images)

Chapter 2 – Early Medieval Metallurgy

2.1 Ores

2.1.1. Introduction to Iron Ores

The iron ores of Britain are diverse and abundant with vast compositional differences (Percy 1864, Tylecote 1986: 124-128). This fact did not escape the Romans, who came to Britain and exploited the local resources to the extent that it is argued that they were mass producing British iron for the western part of the empire (Cleere and Crossley 1995: 66). When they left, the mining of iron ore greatly reduced but did not stop (Meredith 2006: 30). For the people who remained in Britain, iron making is believed to have reverted to a local production for local needs. This would imply the utilization of local ores and the variability of iron alloys based on local ore chemistry.

There are a couple impediments to researchers who are studying the iron ores used in the Anglo-Saxon period. First, there is little remaining evidence of iron mining from this period. Reasons for this include the possibility that production was too small to leave much evidence. Also, it is possible that the large scale iron industry that has existed ever since the Middle Ages has mined out any evidence left from the Early Medieval period. Another possibility is that the evidence from the period left little to differentiate itself from other periods. The second impediment is that the limited evidence of mining does not mean that people were not taking advantage of local ores.

Examination of the relationship between metallic iron and the iron ore was important to understand the origins of the alloying elements (i.e. Phosphorus and Arsenic) and their intentional/unintentional addition to the metal. This study, however, did not attempt to provenance the metallic iron.

2.1.2 Major Ore Types

There are four major types of ore found in Britain:

- Carbonate ores (FeCO_3): these ores have to be roasted before use in smelting to drive off the CO_2 and have been known to have a significant phosphorus component (Cleere and Crossley 1995: 32). They can be found in the Weald, the Coal Measures, and in the Jurassic Scarp that runs from the Cleveland Hills to Oxfordshire (Tylecote 1986: 125).
- Hematite ores (Fe_2O_3): these low phosphorus ores are found in Cumbria and in the Mendip Hills.
- Limonite ores ($\text{Fe}_2\text{O}_3 \cdot \text{H}_2\text{O}$ or $\text{FeO}(\text{OH})$): these ores are the largest group of ore in Britain and have a tendency to have a low phosphorus component (Walters 1999: 30). They are found in the Forest of Dean and in the South Wales coal fields (Tylecote 1986: 125).
- Bog iron ores: these ores, also known as secondary ores, are not derived from stone but are deposits formed in wet conditions by the biochemical oxidation of iron stone carried in solution. These ores consist of the mineral goethite ($\text{FeO}(\text{OH})$) and can be high in manganese and phosphorus. They are common throughout Britain (Tylecote 1986: 125).

2.1.3 Major Ores of Britain

In Tylecote's *History of Metallurgy* (1992) it was established that both bedded and secondary ore deposits have supplied ores for the smelting of iron in virtually all regions of England. Though some of the bedded ore deposits have undergone extensive examination by archaeologists (Cleere and Crossley 1995: 9-15, Meredith 2006: 13-6, Schrufer-Kolb 1999, Walters 1999: 30), the secondary deposits, often termed 'bog ores', also played a significant part in Early Medieval smelting. Thus, sites such as Millbrook in Sussex (Tebbutt 1982), the Ramsbury in Wiltshire (Haslam 1981), and Mucking in Essex (Clark 1993), which lie in areas of no known bedded deposits, produce extensive evidence of Saxon iron smelting. Therefore to attempt to provide a coherent overview of all ores available to Early Medieval iron smiths is impossible. Even in bedded ore regions, such as the Jurassic Ridge (Schrufer-Kolb 1999) it is unclear as to whether the Early Medieval smelted ores were exploiting the raw bedded ores or a secondary 'bog ore' derived from the bedded ores. The secondary bog ores would have a different chemistry and mineralogy to the published data relating to the bedded ores. This would be reflected in the resulting iron produced in the furnace, in particular the phosphorus and arsenic contents, which have both been suggested to originate in the iron ore (Castagnino 2008: 84, Vallbona 1997: 175).

This research is not focussed on investigating specific links or connections between ores, slags, blooms and finished products; hence detailed consideration of specific ores relating to each site is beyond the scope of this work. However broad generalities can

be considered and explored using specific examples including the Weald, the Forest of Dean and bog iron ores found in Northern England. These ores were selected because they were geographically adjacent to the sites under investigation and had archaeological evidence of use during the first millennium AD.

The Weald

The Weald (figure 6) is one of the largest and most famous areas of iron production in Britain. During the Roman period it was a hub of activity with intensive mining and smelting, believed to be part of the diverse and international iron economy that supplied the Roman Empire (Cleere and Crossley 1995: 83). By the end of the Roman period, mining in this area is believed to have ceased and the area became deserted. It is not until the seventh century AD that settlers began using the area for pastures. If smelting began again at this time it would have been for local use, which was mostly agricultural in nature. The smelting site at Millbrook (Tebbutt 1982) has been the only site dated to the Anglo-Saxon period found in the Weald.

Within the Weald there are three different sources of ore associated with archaeological remains. The largest and most exploited of which is the ironstone from the Wealden Beds. The second is concretionary ironstone, which is locally called Shrave or Crowstone. The third is an iron stone from Clay-with-Flints, a drift deposit on the chalk of the North Downs (Cleere and Crossley 1995: 6).

The Forest of Dean

The Forest of Dean's major ore source was a carboniferous limestone that outcrops on the northern, eastern, and the western sides of the forest (figure 7). During the Roman period, these outcrops were all in use (Walters 1999: 125).

Other ores in the area include the sandstones and Wentlock limestone north of the main Forest of Dean, as well as bog iron ores immediately to the west in the hills of Gwent, which were also in use during the Roman period.

Bog Iron Ores

Bog iron ores are abundantly found in Britain (Tylecote 1986: 125) and most likely have been exploited throughout the history of iron smelting. These bog iron ores were secondary ore deposits, derived from the weathering of local primary iron minerals deposits. The chemical process that changes the iron minerals into bog ores can be variable based on environment and the elemental composition of the iron minerals, creating variability in the elemental composition of the bog ores. Most of these ores, however, contain high levels of phosphorus which could have been transferred into the metal during smelting (Vallbona 1997: 60).

2.1.4 Additives

In her thesis on exploring the origin of phosphorus in phosphoric iron, Vallbona (1997) concluded that although phosphorus could have come from the ore, it may have also come from the addition of apatite, in the form of calcified bone, to the mix during the

smelt. This practice of adding ingredients during the smelt is plausible and maybe probable, but there are challenges presented in determining what producers may have been adding and in what quantities. It is also difficult to determine if the addition of additives affected the elemental composition of the resulting iron bloom.

2.2 Iron Production

Despite the collapse of the large scale iron industry of the Roman period (Cleere and Crossley 1995: 79-84, Walters 1999: 45) it has been postulated that iron production continued in Britain, but on a much smaller scale to suit local needs (Pleiner 2000: 274, Walters 1999: 125).

The following presents a review of the theory of Early Medieval iron production and a summary of the archaeological evidence for iron smelting in the period.

2.2.1 The Bloomery Furnace

The bloomery furnace was the most common method of smelting in Britain until the widespread use of the blast furnace in the fifteenth century (Cleere and Crossley 1995: 108, Craddock 1995: 250). In this charcoal-fuelled furnace, iron was produced in the solid state by reduction of the iron oxides from the ore (Craddock 1995: 241). The bloomery process was inefficient, necessitating the use of high grade ore.

The furnace itself (figure 8) is a cylindrical combustion chamber, fed at the top with fuel and ore, and equipped with openings at the base for the bellows and slag tapping (in the case of the slag tapping furnaces).

Bloomery furnaces from the Early Medieval period are classified into two types: slag tapping and slag block (figure 8) (Cleere and Crossley 1995: 39, McDonnell 1989, Pleiner 2000: 149). In the slag tapping furnaces there is an opening built into the furnace wall to allow the molten slag to escape while the furnace is in operation. This reduced the amount of slag in the bloom (Craddock 1995: 243) and increased the life span of the furnace structure. Tapped slag furnaces had been in use in Britain during the Roman period and there is evidence that they continued to be used in the post-Roman period at places such as Ramsbury, Wiltshire (Haslam 1981) and Shakenoak, Oxfordshire (Crossley 1981: 29). Slag block furnaces either had a hollow built in the bottom of the furnace for the slag to pool or allowed the slag to collect at the front of the furnace. British slag block furnaces were found at Aylsham, Norfolk (Crossley 1981: 29), Mucking, Essex (McDonnell 1989) and Romsey, Hampshire (McDonnell 1988a) as well as other sites dating to the Early Medieval period. These furnaces are similar to a technology used in northern Germany (Crossley 1981: 29), Poland and southern Scandinavia (McDonnell 1989).

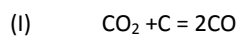
2.2.2 The Smelting Process

Ores consist of two components: the iron compound (oxide/carbonate) and a non-metallic component, known as gangue, which consists of sand, silts, and clays (Wiemer

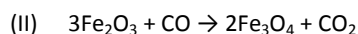
1993: 56). It is the objective of the smelting process to physically and chemically separate the iron from the gangue to form a silicate slag and reduce the separated iron oxides to metallic iron. Both processes require different operating parameters within the furnace. These parameters include a reducing atmosphere to chemically reduce iron oxide to metal as well as maintain high temperatures to liquate the slag.

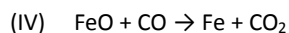
Initially the ore may have been crushed and screened to separate the lighter gangue from the heavier more metallic bits (Pleiner, 2000:113). In the next step, the ores were roasted to temperatures between 400-800°C to drive away the CO₂. This was especially important in the cases of carbonate ores (FeCO₃). During roasting microcracks were created in the ores to allow greater penetration of the reducing gases (Killick and Gordon 1988).

The furnace was prepared by filling it with charcoal and heating it to above 1100°C (Pleiner 2000: 135). The ore was slowly added in small quantities over time while a constant flow of air was provided by the bellows. In order to reduce the Fe₂O₃ into metallic iron a reducing agent is needed. In this case the agent is carbon monoxide (CO), derived from the CO₂ in the system at high temperatures (II).

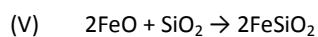


The smelting of iron:





The resulting CO_2 is released as a gas and escapes. At the same time it is necessary to separate the gangue; however, the melting temperature of silica (SiO_2), the main component of sand and clay, is much higher than the temperature that is produced within the furnace. FeO from the ore itself was used to reduce its melting temperature to form fluid slag. The slag is dominated by the silicate phase and has a liquidus in the range 1100-1200°C, but the slag viscosity when molten (i.e. above the liquidus) is heavily dependent on the relative proportion of the major phases present. These phases include the silicate phase, the free iron oxide and glassy phase, particularly the free iron oxide phase (Crabb pers comm.).



After a run of variable length of time dependent on the size of the structure, the furnace was allowed to cool and the resulting bloom of metallic iron was removed.

2.2.3 Slag and Bloomery Furnaces

In archaeological excavation, smelting slag has been found more often than the furnaces with which they were associated. The most common forms of slag include the free-flowing slag from the tap, the slag at the furnace bottom underneath the tap

opening, and the slag blocks from the slag pits below the furnace (Pleiner, 2000: 149, Buchwald 2005: 185).

2.2.4 Refining

Once the bloom has been removed from the furnace it must be given to a smith to be processed before the iron can be used to create objects. At that point it is spongy and still contains significant amounts of slag in its voids. The smith then repeatedly hammers and heats the bloom to remove the remaining slag and voids until it is a solid block of metal (Crew 1991).

Often a further step in smithing takes place where the billet, or consolidated block of metal, is broken down into rods or bars that are easily transportable for trade and the construction of other iron objects (Crew 1991).

2.2.5 The Archaeology of Early Medieval Smelting

Lacking written evidence, it has been archaeology that has built a picture of the Early Medieval iron industry. For this period, however, the archaeological evidence of iron production is scarce, with approximately 10 identified smelting sites across the entirety of Britain. However, small amounts of smelting slag have been found at settlement sites throughout Britain, including Stafford, Lincolnshire (Mahany et al. 1982), York, Yorkshire (McDonnell 1992: 476), Maxey, Northamptonshire (Crossley 1981: 29), and Thetford, Cambridgeshire (Wallis et al. 1995). Due to the identification of so few smelting furnaces, it is impossible to generalise and discuss the use and

development of the technology over this period. From the slag and the few furnace remains that have been found there is evidence for the use of both slag tapping furnaces and non-slag tapping furnaces (Cleere and Crossley 1995: 42, McDonnell 1989). Beyond the substructure of the furnaces, however, there is little evidence to say how tall furnaces originally were or what shape they took above ground (Craddock 1995: 243, Tylecote 1992: 49).

2.2.6 Alloy Manufacture

It is the careful manipulation of the smelting furnace during iron production that determines both the quality of iron and the composition of the iron alloys, such as phosphoric iron and steel (Craddock 1995: 248, Vallbona 1997: 180). Using the evidence from the excavation of bloomery smelting sites, ethnological data from Africa (David et al. 1989, Schmidt and Avery 1983, Schmidt and Childs 1985), and documentary evidence from colonial American bloomeries (Killick and Gordon 1988: 243-70), archaeologists have tried to reconstruct the smelting technologies (Crew 1991, Killick and Gordon 1988, Sauder and Williams 2002). Through these experimental smelts, archaeologists have learned that variations in furnace structure, control over temperature, a constant airflow, the composition of the ore and the addition of specific additives all affect the iron alloys produced (Whiteley 1926: 280). These experiments have shown that high carbon steel could have been produced in a bloomery furnace by adjusting the ore/fuel ratio and the temperature within the furnace (Killick and Gordon 1988). Phosphoric iron may have been created by the addition of the mineral apatite, $\text{Ca}_5(\text{PO}_4)_3(\text{OH}, \text{F}, \text{Cl})$, possibly in the form of burnt

bone, to the smelt or through the reduction of high phosphorus bearing ores, such as bog ore (Vallbona 1997: 13). In many of these experimental cases, however, archaeologists have found that differing conditions within different parts of the furnace can produce a bloom of heterogeneous iron (Serneels and Perret 2003, Vallbona 1997: 13).

2.3 Iron Working

2.3.1 The Early Medieval Smithies

The evidence of British Early Medieval smithing is sparse. Only a few actual smithy structures have been identified dating to this period (McDonnell et al. forthcoming-a). These smithies were identified at the urban site of Hamwic, Southampton, and the rural sites of Wharram Percy in East Yorkshire, Gauber High Pasture in North Yorkshire, and Ribbleshead also in North Yorkshire (McDonnell 1989: 67). Smithing slags, however, have been found at most Early Medieval settlement sites (McDonnell 1989), including the sites examined in this research, suggesting that smithing, even for just occasional repairs, was a common practice.

Smithy Models

This limited evidence of the smithing process can, along with analysis of the finished iron objects, provide insights into the capabilities and status of the smith. A prime example of this is research conducted for the Middle Saxon site of Wharram Percy (McDonnell et al. forthcoming-a) where analyses of smithing slag, stock iron bars, and completed artefacts were used to develop a series of testable models that provide

insight into blacksmithing specialization and the local iron economy. McDonnell et al. developed the following models:

a) This smithy has a self-sufficient mode of production where the ore is smelted within the settlement or landscape and then the resulting iron is used by the local smith in the creation of objects. The evidence for this model includes finding the raw materials (such as ore) and smelting slags, and possibly furnaces, in the local area, as well as evidence of smithing.

b) This smithy does not manufacture its own iron but imports stock iron in the form of bars to use in object construction. This could be a full or part-time smith of varying levels craft skill. Evidence for this type of smithing includes the presence of stock iron, smithing debris, and the occasional unfinished object.

c) This part-time smithy just repairs iron objects that have been imported into the settlement. The supporting evidence for this type of smith includes small amounts of smithing debris and the occasional repaired object. No stock iron or evidence of smelting should be present in the assemblage.

It was determined that the site of Wharram Percy was an example of the second model due to the lack of smelting furnaces and debris and the presence of smithing debris, stock iron, and finished objects.

2.3.2 The Smithy Complex

Little is known of the smithing complex during this period. The limited archaeological evidence suggests that the smithing hearth, taking either the form of a pit or a raised platform (Pleiner 2006: 122-131), was filled with charcoal, charcoal ash, and smithing slag, and hearth bottoms (HBs). The hearth would be constructed with bellows and tuyères, used to heat iron to up to 550°C for cold working, up to 1000°C for shaping, and as high as 1200°C for welding, all accomplished in at least a partly reducing atmosphere (Pleiner 2006: 66). Outside the hearth there would be a supply of fuel (charcoal), a water bosh for cooling the iron, an anvil, and iron working tools (Pleiner 2006: 131-134).

Associated with the smithy would be the residues generated during the smithing process, which include smithing slag lumps, the characteristic hearth bottom and broken vitrified hearth lining, and most importantly hammerscale (McDonnell 2001: 493-506). Hammerscale has been found on the floor of the smithy immediately adjacent to where the anvil stood. Hammerscale was the metal lost as the result of oxidation on the surface as the iron was reheated and worked (Pleiner 2006: 110, Tylecote 1986: 240, Whenlock 2002). It consists of iron oxides, including magnetite (Fe_3O_4) and hematite (Fe_2O_3), that develop as a skin on the iron when heated to 520-580°C (McDonnell 1986). When the metal is worked the oxides come off as laminar plates up to 1mm thick. There is also a globular form of hammerscale that is the result of heating the iron to 1100-1200°C and welding, at which time droplets of oxides fly off (Pleiner 2006: 115).

2.3.3 Smithing Waste

These residues from the smithing process, including charcoal, fuel ash, hammerscale, and smithing slags, are often all that survive of a smithy site. The most diagnostic of these residues is the hearth bottom, which forms by the accumulation of slag below the mouth of the tuyère (McDonnell 1991).

Smithing slags consist of three major phases: a silicate phase (most commonly fayalite), an iron oxide phase, and a glassy phase that contains alkali metal oxides (McDonnell 1988b).

2.3.4 Key Smithing Techniques

Hot working

Hot working is the forging of iron when it is plastic above its recrystallization temperature. Being above the recrystallization temperature allows the metal or alloy to recrystallize during deformation, keeping the yield strength and hardness low and ductility high (Samuels 1999: 438).

Cold working

Cold working is the forging of iron below its recrystallization temperature (560°C). Forms of cold working include drawing and hammering. Cold working results in an increase in hardness and yield strength, but it reduces ductility and impact strength (Scott 1991: 139).

Normalizing

Normalizing is the heating of the metal to temperatures around 500-800°C to reverse the effects of cold working. This is accomplished by recrystallization of the metal, restoring the ductility and malleability of the metal (Henderson 1953, Samuels 1999: 442).

Welding

Welding is the joining of two metals by heating and joining the separate parts with no solder applied (Scott 1991: 145). A fluxing agent, such as quartz sand, is used to react with the iron oxides on the surface of the metal to form a fayalitic slag that inhibited further oxidation and was removed during hammering as spheroidal hammerscale (Pleiner 2006: 110-112).

2.3.5 Heat Treatments

Quenching

This is the act of quickly cooling a metal or alloy from temperatures between 770-900°C, depending upon the carbon content, by plunging the hot metal into cold water or oil (Pleiner 2006: 67).

Slack Quenching

Slack quenching is the formation of transformation products other than martensite, such as ferrite and bainite, as a result of quenching at a rate slower than the critical cooling rate (Totten et al. 1993: 20).

Tempering

This is the reheating of quenched high carbon steels to temperatures around 450-650°C in order to reduce the brittleness of the metal that was caused by the quenching (Samuels 1999: 449, Scott 1991: 145)

Chapter 3 – Iron Alloys

3.1 Introduction to the Alloys

Carbon, phosphorus and arsenic are three iron alloying elements commonly found in Early Medieval iron, either individually or in combination. The presence of any of these three alters both the microstructure and the mechanical properties of iron, creating alloys suitable for different applications.

3.2 Carbon in Iron

3.2.1 Definition

The iron-carbon alloy known as steel contains 0.1-2.0wt% carbon. The microstructure varies with carbon content (figure 9). At temperatures below 727°C, steel containing up to 0.8% carbon has a hypoeutectic microstructure with a combination of ferritic grains and pearlite. As the carbon content increases, the ratio of granular ferrite/pearlite decreases. At 0.8wt% carbon the microstructure is at the eutectoid point and is 100% pearlite. In iron with carbon contents above 0.8%C the microstructure is hypereutectic with a combination of pearlite and cementite, with increasing cementite as the carbon content increases (Samuels 1999: 7-9). The addition of carbon also significantly increases the hardness of iron (table 1).

Heat treatment changes the microstructure of steel. When iron contains greater than 0.3wt%C it can be rapidly cooled/quenched and the microstructure changes from austenite to bainite or martensite instead of pearlite. These microstructures are dramatically harder and more brittle than pearlite.

3.2.2 Manufacture

Archaeometallurgists have argued that in the Early Medieval period there were three possible processes for the manufacture of steel: the creation of 'natural steel'; cementation; and through the decarburization of cast iron. However, there is not enough evidence to indicate which method was most common.

1.) 'Natural steel' is heterogeneous steel produced from the carefully controlled bloomery smelt. It was necessary to maintain a high CO/CO₂ ratio within the furnace, which was accomplished by controlling the fuel to ore ratio. This would carburize some of the iron particles, lowering their melting temperatures and forming drops of molten cast iron. These drops would fall on to the forming bloom and their carbon would diffuse, creating heterogeneous 'natural steel' (Craddock 1995: 236). Successful examples of the making of high carbon steel using the bloomery process have been found during ethnographic re-enactment of smelting in Africa (David et al. 1989). Opponents of this theory believe that in practice this process was difficult to control, only creating heterogeneous steel when it was successful (Rehder 1989).

2.) McDonnell (2000) suggested that early smelters may have had the ability to create liquid iron within the bloomery furnace, using similar techniques to those used in the manufacture of natural steel. This liquid steel would freeze to cast iron (iron with 2-4% Carbon) and would need to be decarburized so that it might be used. McDonnell suggests that very clean high carbon steel seen in the knives from Southampton is the result of decarburizing cast iron.

3.) Steel may also have been made during forging. Two different techniques were used depending upon the starting materials available. Steel was created from wrought iron through a process called cementation which was the solid state addition of carbon to iron. This process is also known as carburization or case hardening. This was accomplished by encasing the iron in an organic substance, such as charcoal dust or plant remains, then placing it in a clay container to protect the metal from oxidization, and heating it to approximately 950°C for an extended period of time (Pleiner 2006: 66, Scott 1991: 138). The greatest drawback of this process is that it is slow and, since the carbon enters from the surface, the core often remains uncarburized.

A second way of creating steel in the forge is the carbon diffusion method. This diffusion occurs when a piece of steel is welded to a piece of ferritic iron, allowing the carbon to diffuse across the weld. This technique was often used when “piling” alternating plates of wrought iron and steel to create a homogenized piece of steel.

3.2.3 Steel in the Early Medieval Britain

Carbon-iron alloys are common in Early Medieval edged tools (Blakelock and McDonnell 2007, Tylecote and Gilmour 1986: 37), but were rarely used as complete artefacts (table 2) (Tylecote and Gilmour 1986: 38). Blakelock and McDonnell (2007) demonstrated that the most common knife construction was a combination of a high carbon steel tip with a phosphoric/ferritic back. Tylecote and Gilmour (1986: 2) have suggested that this was due to high carbon steel being expensive, probably as a result of the difficulty of manufacture.

3.2.4 Heat Treated Steels in the Early Medieval Period

Heat treatment, as described in Section 2.3 on Early Medieval Iron Working, was a specialised craft tool used to greatly increase the hardness of high carbon steel. Table 2 shows that heat treated steels were found in approximately sixty percent of the knives examined from British Early Medieval settlements. Heat treatment was also identified in iron from Early Medieval Sweden at the site of Helgö (Pleiner 1978) indicating that the technology was not limited to Britain.

3.2.5 Terminology

Steels are often broken down into two categories: low and high carbon steels. Low carbon steels (**LC Steel**), containing between 0.1-0.3% carbon, and do not change structure when heat treated. High carbon steels (**HC Steel**), containing 0.4-2% carbon, are altered by heat treatment.

3.3 Phosphorus in Iron

In modern iron alloys phosphorus is considered “treacherous” (Stead 1915) due to its detrimental effects on the mechanical properties of the alloy (Goodway 1987, Gouthama and Balasubramaniam 2003, Tylecote 1986: 144, Vallbona 1997: 34). As a result modern iron alloys generally contain less than 0.05wt%P (Gouthama and Balasubramaniam 2003, Stewart et al. 2000c) and the effects of phosphorus on the iron microstructure have received little attention by modern metallurgists. Significantly higher amounts of phosphorus (0.05-0.5wt%P) are found readily in archaeological irons (Godfrey 2007: 24, Stewart et al. 2000a), inspiring archaeometallurgists to further examine the alloy.

3.3.1 Archaeological Definition of Phosphoric Iron

‘Phosphoric iron’ (**P-iron**) is a term coined by archaeometallurgists to describe an iron alloy with very low carbon (<0.1wt%C) and a relatively high phosphorus content. The exact parameters for the amount of phosphorus in iron required to classify it as phosphoric iron are rarely specified in publications, but the few that exist vary between 0.05wt%P (Stewart et al. 2000a), >0.1wt%P (Vega et al. 2003), 0.1wt%P (Godfrey 2007), and 0.2wt%P (McDonnell et al. forthcoming-a). These vary due to differences in analytical methods used for measurement of phosphorus and the nature of the study in which they are presented.

Often archaeometallurgists do not have the capacity to measure the elemental composition of every iron artefact and they have to rely on metallographic indicators to determine the presence of phosphorus. The identification of phosphoric iron has relied on a significant change in metallographic structure and/or physical properties that set phosphoric iron apart from ferritic iron. Though still granular the addition of phosphorus may cause an increase in the grain size and hardness values, an apparent resistance to etchants, and a watery effect that is visible when the alloy is etched with Nital, called “ghosting”.

This project defined phosphoric iron as an iron alloy with very low carbon ($<0.1\text{wt.\%C}$) and a relatively high ($0.15\text{--}1.5\text{wt.\%P}$) phosphorus content; however, as one of the aims for this research was to determine a new definition for phosphoric iron using analytical data along with the appearance of indicators, this definition will be re-examined in the discussion in Section 8.2.

3.3.2 Manufacture of Phosphoric Iron

The increased levels of phosphorus in iron are due to the diffusion of phosphorus from highly phosphoric ores, such as lake or bog ores, into the bloom during smelting (Godfrey 2007: 18, Piaskowski 1989, Vallbona 1997: 178). Buchwald and Wivel (1998) and Godfrey (2007) investigated the partitioning of phosphorus from the ore into the metal and slag. Godfrey determined a ratio of ore to metal of 1:0.7 and ore to slag between 1:1.2 and 1:1.8. Buchwald and Wivel looked at the ratio of slag to metal and found a 20:1 relationship. The resulting phosphorus content in the metal is often

heterogeneous due to non-equilibrium conditions within the furnace, variations in the temperature, the CO partial pressure, the amount of carbon that has diffused into the metal, and the presence of phosphate phases (Vallbona 1997, Vega et al. 2003). The time at smelting temperatures, as well as the amount of time for cooling, also effects the distribution of phosphorus within the bloom (Godfrey 2007: 209, Gouthama and Balasubramaniam 2003, Vallbona 1997: 180, Vega et al. 2003).

3.3.3 Phosphorus in the Crystal Structure

It is necessary to refer to the Fe-P and Fe-C phase diagrams to understand the interactions of phosphorus, iron and, where present, carbon within bloomery iron and how they affect the mechanical properties of the material as well as its microstructure.

Phosphorus exists substitutionally within the iron lattice structure, making the segregation of the phosphorus atom a very slow process (Buchwald and Wivel 1998, Vallbona 1997: 182). The movement of phosphorus through the iron lattice occurs more easily within the austenite microstructure (*fcc*), or γ -iron (present at temperatures above 900°C) than it does in the ferritic microstructure (*bcc*), or α -iron (that dominates lower temperatures) (Piccardo et al. 2004, Vallbona 1997: 36). Phosphorus is considered a ferrite stabilizer (Stewart et al. 2000c). It shrinks the austenite, or γ -field, on the Fe-C (figure 9) phase diagram, allowing ferrite to exist at much higher temperatures, as seen on the Fe-P diagram (figure 10a). Metallurgists have found that at temperatures between 900-1100°C, where there is the presence of a combination of austenite and ferrite, phosphorus segregates to the austenite grain boundaries (Stewart et al. 2000c). When this iron is rapidly cooled, the entire

microstructure transforms to ferrite and the phosphorus does not have time to dissipate into the rest of the microstructure, leaving areas of both high and low phosphorus. This has been cited as the cause of the watery feature seen in the iron microstructure called “ghosting” (Chen et al. 2003, Gouthama and Balasubramaniam 2003, Stewart et al. 2000c). A slower cooling rate or extended high temperature annealing allow the phosphorus time to diffuse within the ferrite microstructure, homogenizing the phosphorus content and improving the mechanical properties of the metal (Gouthama and Balasubramaniam 2003).

Carbon exists interstitially instead of substitutionally in the ferrite lattice (Samuels 1999: 8). Due to its size (P atomic radius: $0.77\text{\AA}$ and C atomic radius: $1.09\text{\AA}$) and positioning within the lattice structure, the diffusion of carbon in iron is faster than that of phosphorus (Vallbona 1997: 26). However, phosphorus and carbon are indirectly in competition within the iron lattice structure. Vallbona (1997:27) explains “the presence of one of the elements in solid solution in the iron distorts the lattice and impedes the diffusion of the other”. Erhart and Grabke (1981) established that the solubility of carbon in iron decreases with increasing phosphorus content. Due to the heterogeneity of the iron, there is uneven distribution of phosphorus and carbon in iron, which results in areas of low carbon/high phosphorus and vice versa. This is most apparent at the grain boundaries (Suzuki et al. 1983). Hansel and Grabke (1986) noted that carbon also segregates to the grain boundaries, competing with phosphorus for the position.

3.3.4 Mechanical Properties and the Working of Phosphoric Iron

The primary reason for limiting the amount of phosphorus within modern alloys was the resulting “cold shortness” (brittle when cold worked) of the product (Goodway 1987). Research into this embrittlement has related it to phosphorus segregation to the grain boundaries when it is heated to temperatures above 900°C for an extended period of time, reducing ductility between the grains and promoting inter-granular fracture (Gouthama and Balasubramaniam 2003, Suzuki et al. 1984). The amount of embrittlement is also dependent on the heat treatment history of the metal (Gouthama and Balasubramaniam 2003, Stewart et al. 2000a). Experiments have shown that this embrittlement was increased when the alloy was quenched instead of slow cooled, preventing the diffusion of the phosphorus back into the ferritic microstructure (Hopkins and Tipler 1958, Stewart et al. 2000a).

Alloying experiments demonstrated a slight increase in carbon within the phosphoric iron, resulting in a reduction of the embrittlement making the metal more readily workable (Goodway 1987, Hopkins and Tipler 1958, Stewart et al. 2000a, Suzuki et al. 1984); however, embrittlement worsens with significant amounts of both phosphorus and carbon (Gouthama and Balasubramaniam 2003) in the microstructure. This is the result of the precipitation of carbides that act as sites for fracture initiation (Suzuki et al. 1984).

In most archaeological artefacts there is no evidence of brittleness in the phosphoric iron microstructure (Buchwald 2005, Godfrey 2007: 230, Vallbona 1997: 184). Vallbona (1997) suggested that this was the result of the presence of slag in the archaeological

artefacts provided a sort of temper to prevent large scale fracturing. Gordon (1988) suggested that in phosphoric iron up to 0.3wt%P the distribution of slag inclusions helped determine the mechanical behaviour of the alloy.

3.3.5 Indicators

Specific metallographic indicators are used to identify the presence of phosphorus in iron. Only more recent studies that included elemental analysis have quantified the amount of phosphorus in artefacts displaying phosphoric indicators (Chen et al. 2003). The physical indicators that are used for identification of the presence of phosphorus in iron include an increased hardness from that of ferritic iron, an enlargement of grain size, a resistance to carbon diffusion into the metal, a watery effect that is visible when the alloy is etched with Nital, called “ghosting”, and its apparent corrosion resistance (McDonnell 1992).

Ghosting

One such feature that may be the result of phosphoric iron segregation is a watery effect seen microscopically on Nital etched sections, called ghosting. First noted by Stead in 1915, ghosting has been used almost exclusively to identify phosphoric iron. Elemental testing has shown that ‘ghosted’ areas tend to be higher in phosphorus than other areas in the specimen (Chen et al. 2003, Gouthama and Balasubramaniam 2003, Stewart et al. 2000c). Gouthama and Balasubramaniam (2003) attributed ghosting to both the segregation of phosphorus at high temperatures, as described earlier, and local dephosphorization due to the presence of fayalitic slags (also noted

by Chen, 2003). Stewart et al. (2000c) further determined that the ghosting features were caused by a surface relief and dramatic changes in phosphorus content due to the etchant preferentially attacking the prior phase. Buchwald and Wivel (1998) suggested another mechanism for the formation of ghosting was through oxidation during welding where the phosphorus concentrations are increased in the remaining metal as the iron oxidizes away.

To study the causes of ghosting, researchers have used copper-based enchants such as Stead’s reagent and Oberhoffer’s reagent to visually reveal the phosphorus distribution within the iron/steel microstructures (Piccardo et al. 2004, Stewart et al. 2000b). Oberhoffer’s reagent has also been used to examine the distribution of arsenic in iron alloys (Stewart et al. 2000b). The etchants selectively deposit copper on low phosphorus/arsenic areas, leaving the high phosphorus/arsenic areas appearing white.

Oberhoffer’s reagent

1g Cupric Chloride
0.5g Stannous Chloride
30g Ferric Chloride
30ml Nitric Acid
500ml H₂O
500ml Ethanol

Stead’s reagent

10g Cupric Chloride
40g Magnesium
20ml HCl
1,000ml Alcohol

Hall (2008) demonstrated that these etchants were more sensitive to slight variations in phosphorus content than a Scanning Electron Microscope with an EDS, which has a

detection limit of 0.1wt% for phosphorus. This was reinforced by Stewart's (2000) finding that Oberhoffer's reagent can detect differences of 0.05wt% phosphorus.

The ghosting effect has been found to take on particular morphologies. These morphologies, or ghosting structures (section 5.5.12 p.63), are evidence of microstructural changes that occurred when the alloy was heated between 900-1100°C. At that temperature both austenite and ferrite were present and phosphorus segregates to the austenite grain boundaries. The resulting microstructure is dependent on how long the metal was heated and how rapid the metal was cooled (Gouthama and Balasubramaniam 2003, Stewart et al. 2000c).

Stewart et al. (2000a, 2000b, 2000c) examined ghosting through experimentally heating and cooling iron – phosphorus alloys with between 0.1wt%P and 0.4wt%P. They found that the structures seen in the ghosting are best described by the Dubé classification system (figure 11) where reconstructive transformation causes the austenite to form at the ferritic grain boundaries as (A) allotriomorphs, (B1) Widmanstätten side plates, (B2) allotriomorphs with side plates, (C1) idiormorphs along the grain boundaries, and (C2) idiormorphs within the grains. Increased temperature caused the Widmanstätten side plates to grow with less space between them and gain a larger aspect ratio, while prolonged heating caused all of the austenitic structures to become spheroidised. Similar structures were identified by Buchwald (2005: 315), Chen et al. (2003), Gouthama and Balasubramaniam (2003) and Slater (2008: 62).

Slater (2008: 63) also identified a non-phosphoric ghosting structure that resulted from heavy deformation of the grains, often seen in wire.

Hardness

The presence of phosphorus within the iron microstructure increases the hardness of the ferritic microstructure (Buchwald and Wivel 1998, Chen et al. 2003, Godfrey 2007: Gordon 1997). The cause of the increase in hardness, however, has received little attention, though several studies have investigated the relationship between phosphorus content and the tensile properties of the metal (Buchwald and Wivel 1998, Chen et al. 2003, Goodway 1987, Gordon 1997, Hopkins and Tipler 1958, Stewart et al. 2000a). Gordon (1997) found a positive relationship between the increase in phosphorus content and increase in hardness values in carbon-free phosphoric iron. Buchwald and Wivel (1998) found that phosphoric iron had a flow stress and tensile strength close to that of mild steel.

Besides the phosphorus content, other factors that affect the hardness of iron include heat treatment, slag content, cold working, and the precipitation of nitrides and carbides (Gordon 1997, Gouthama and Balasubramaniam 2003, Stewart et al. 2000a). Stewart et al. (2000a) demonstrated that heat treatment in particular can increase the hardness values of phosphoric iron. In archaeological iron it was almost impossible to determine how much of each of these factors affected the particular area that was

tested for hardness. Further research needs to be conducted to study the interaction of these factors and determine which factors are most dominant.

Grain Size

The researchers like McDonnell (1992), Stewart (2000a), and Vallbona (1997) have noted a marked increase of grain size in phosphoric iron (ASTM 1-4) from that of most ferritic iron (ASTM 4-8). This increased grain size was one of the two most commonly used indicators of phosphorus during optical microscopy (McDonnell 1989). Vallbona (1997:183) suggested that the large grain structure is the result of a slow diffusion rate of phosphorus at smithing temperatures. Stewart (2000a) attributes the large grains to the stabilization of ferrite in austenitic temperatures, postulating that this extends the time for the ferrite grains to grow.

Alternatively, Gouthama and Balasubramaniam (2003) discussed that the presence of phosphorus in iron reduces grain size. Chen et al. (2003) attributed this to a limitation of grain growth caused by the presence of a film of Fe-P that forms at the grain boundaries.

Corrosion and Etch Resistance

Archaeometallurgists have noted that phosphoric iron appears to be resistant to corrosion and better preserved than the other iron alloys (Balasubramaniam 2002, Chen et al. 2003, Godfrey et al. 2003, Gouthama and Balasubramaniam 2003, Piaskowski 1989, Vallbona 1997: 33). Corrosion resistance is considered analogous to

the etch resistance of the alloy when etched with 2% Nital, as they both may be manifestations of the same property (Stewart et al. 2000c, Vallbona 1997:182, Whiteley 1921). Often other iron alloys have to be over-etched before the grains within the phosphoric iron become visible. Etching is chemically attacking the metal surface to reveal the grain boundaries by removing material that has been smeared during polishing the metallic surface (Scott 1991). It is possible that phosphorus increases the cohesiveness between grains (Gouthama and Balasubramaniam 2003), lessening the space between grains and making it more difficult for the material to exist between the grains, thus impeding both corrosion and etching.

3.3.6 Phosphorus and Carbon

Though previous studies have focused on the impact of phosphorus within the iron microstructure, these studies have avoided the effects caused by the addition of carbon on both the mechanical and physical properties of the alloy.

Gouthama and Balasubramaniam (2003) and Stewart et al. (2000c) each conducted experiments on the formation of ghosting using Fe-P alloys, but neither of these experiments included Fe-P-C alloys to determine the effects of carbon on the phosphorus distribution, particularly in the dual phase environment.

Vega et al. (2003) also conducted experiments with the working of phosphoric iron to test its mechanical properties, but they too did not include Fe-P-C alloys in their experiments.

Godfrey (2007) took a different experimental approach and used an Iron Age highly phosphoric bloom for smithing experiments and found that ghosting is altered during the smithing process smithing. The problem of the iron being cold-short only occurs in iron with more than 0.7wt%P with an uneven phosphorus distribution. Godfrey points out that this amount of phosphorus is rarely seen in archaeological iron which explains why evidence of brittleness is not often seen in archaeological iron.

Despite the limited attention given to this in experiments, archaeologists such as Slater (2008) have noted that age precipitates in the form of carbon, which had precipitated at the ferrite grain boundaries, were seen to enhance the effect of ghosting at the grain boundaries, suggesting a relationship between ghosting and carbon content.

3.3.7 Phosphoric Iron in Early Medieval England

In the Saxon period, phosphoric iron appears to have been specifically chosen by the blacksmith either for its unique mechanical properties or as a decorative addition in visually pleasing artefacts, such as those that have been pattern welded (figure 12) (Godfrey et al. 2003, Ottaway 1992: 589, Tylecote and Gilmour 1986: 171, Vallbona 1997: 31).

3.3.8 Colour and Selection of Phosphoric iron

The most definite examples of intentional use of phosphoric iron were when it has been found alongside ferritic iron in pattern-welded items, as was seen in knife 2951 from Coppergate, York (McDonnell 1992) and in several Anglo-Saxon knives analyzed

by Tylecote and Gilmour (1986). However, this does not imply that smiths were always intentionally using phosphoric iron instead of ferritic iron in their work. Even though early smiths may have understood the differences in iron alloys from the way they handled during working, phosphoric iron and ferritic iron were often used for the same purposes in the same types of objects, as was seen in the knives from Anglo-Scandinavian York (McDonnell 1992) and Saxon Southampton (McDonnell 1987a, McDonnell 1987b), making it impossible to establish if intentional selection took place.

Phosphoric iron has been called the silvery iron (Piaskowski, 1989), a feature that made it useful in decorative creations, such as pattern-welded objects.

3.3.9 Provenance

The presence of phosphorus in iron is directly linked to the presence of phosphorus in the ore (Piaskowski 1989, Vallbona 1997: 185) and it has been postulated that it can be used to provenance the iron (Lyngstrom 1997, Piaskowski 1989). As phosphorus partitions between the ore and the slag (Buchwald 2005, Gouthama and Balasubramaniam 2003), it is difficult to compare the phosphorus contents of the metal or the slag inclusions with the content of the ore (Buchwald 2005: 164). In Britain the problems with using phosphorus for provenance were compounded by the prevalence of high phosphorus secondary ores, such as bog ores. However, regions of low and high phosphorus primary ores may be reflected in the phosphorus content of locally produced iron.

3.4 Arsenic in Iron

3.5.1 Arsenic in Iron

Arsenic in iron behaves in a similar fashion to phosphorus. It is a substitutional element in the iron crystal structure. Similar to phosphoric iron, arsenical iron is etch resistant and increases the hardness of the metal. The Fe-As phase diagram (figure 10b) is very similar to phosphoric iron (figure 10a), demonstrating that it also stabilizes ferrite when heated within the austenite range and inhibits the diffusion of carbon, but not to the same degree as phosphorus (Castagnino 2008: 2). Arsenic generally appears in low quantities within archaeological iron (0.005-0.05% As) and hence there is no clear evidence for its presence in the metallographic structure (Castagnino 2008: 10, Tylecote and Thomsen 1973). This necessitates the use of analytical techniques that can examine the elemental composition of the iron, such as an SEM-EDS or electron microprobe analysis, to identify the presence of arsenic within iron objects.

The presence of arsenic in archaeological iron is most commonly noted in association with metallographic features termed “white weld lines” (Castagnino 2008: 1, Tylecote and Thomsen 1973) and as a known impurity found in the bulk metal in relatively small/trace quantities (Buchwald 2005: 160)

Tylecote and Thomsen’s 1973 paper on *The Segregation and Surface-Enrichment of Arsenic and Phosphorus in Early Iron Artifacts* is still the seminal paper on the topic of arsenic in archaeological iron. The paper focuses on the white weld line phenomenon, with a brief discussion as to how the origins of the element in the bulk metal (Tylecote

and Thomsen 1973). The authors suggest that arsenic could come from iron ore with a high arsenic content. The presence of arsenic in the metal would cause problems during smithing as the resulting alloy would suffer from brittleness during hot working and be very difficult to forge. Once the element is in the metal it would also be difficult to remove enough arsenic to overcome this problem.

3.5.2 Arsenic in Weld Lines

Arsenic is commonly encountered in weld lines known as “white weld lines”. This phenomenon is a prominent white line seen at welds, often containing other impurities, including nickel. The bright colour of the weld line is due to the etch resistance of the arsenic/nickel-enriched iron, allowing adjacent areas to etch while leaving the weld as bright metal. Examples of arsenic use in weld lines were found in artefacts recovered from excavations in Anglo-Scandinavian York (McDonnell 1992), Saxon Southampton (McDonnell 1987a, McDonnell 1987b) and Anglo-Saxon Wharram Percy (McDonnell et al. forthcoming-a).

There are two major theories concerning the presence of arsenic in white weld lines. The first theory is one of arsenic enrichment at the surface of the iron due to oxidation removing the metallic iron while but leaving the arsenic in increased concentration at the surface edge of the microstructure (Tylecote and Thomsen 1973). This theory assumes the presence of arsenic in the metal already and a significant amount of oxidation of the surface iron, resulting in heavy iron loss. The second theory argues for the intentional addition of arsenic during welding (Abdu and Gordon 2004, Castagnino 2008: 96). This theory requires access to an outside source of arsenic, such as

arsenopyrite (FeAsS), and asks the question, “how was it possible for smiths to readily use arsenic in a process that would necessarily have produced toxic fumes?”

Tylecote and Thomsen supported the hypothesis that white weld lines were not the result of the smelting process but from oxidation of the iron during smithing that concentrates the arsenic left behind along the surface of the metal. However, Castagnino (2008) has re-examined the white weld line phenomenon in Early Medieval British iron artefacts and concluded that it was unlikely that a smith would allow the loss of the large amount iron necessary for oxidation to create the high arsenic content seen in white weld lines. Further, the smiths would probably favour a reducing environment to keep the exposed iron surfaces clean for welding, preventing the conditions under which oxidation would occur.

The theory of an outside source of arsenic also been considered. Tylecote and Thomsen (1973), despite favouring the oxidation theory, did suggest the use of arsenical ores as the brazing agent in the weld lines. Castagnino (2008) explored this theory, noting that most arsenical minerals also contain sulphur, which was present in the artefacts examined from Britain, and suggested that it was possible that the ores were at temperatures that would burn off the sulphur while leaving the arsenic intact. To complicate matters, however, Abdu and Gordon (2004), investigating the white weld lines in their first and second centuries AD iron artefacts from Kush, now part of modern day Egypt, noted the lack of arsenic in local ores, indicating that either these white weld lines were not caused by the use of high arsenic ore or there is a factor that archaeologists have not considered.

Castagnino (2008) also made several interesting observations about the properties of arsenic in white weld lines. She noted that the presence of arsenic does not completely impede carbon diffusion, as carbon can be seen on either side of the weld line in many artefacts. However, the extent to which carbon diffuses is determined by the amount of arsenic present. Also, despite high concentrations of arsenic causing iron to be brittle, the concentrations seen in these weld lines ($\leq 2.4\text{wt\% As}$) are too low to cause embrittlement, allowing the welds to be further worked without cracking.

Ultimately, as Castagnino noted, not enough work has been done on arsenic-iron alloys. With the identification of arsenic limited to elemental analysis, the arsenic in many archaeological artefacts has gone unnoticed. While the white weld line studies have begun to address the behaviour of arsenic in iron, extensive further research is necessary to begin to understand the relationship between arsenic and iron.

Chapter 4 – Artefact Construction Techniques

4.1 Introduction

Previous studies in early iron metallurgy have focused on a few common types of iron artefacts, mostly edged tools, weaponry and bars. These studies have developed typological systems to describe the differences within each object type. Many of the artefacts within this study have not benefited from the same kind of extensive analysis of their manufacture; in fact, this may have been the first metallographic study in which they were examined. These objects will be described and their uses outlined at the end of this chapter. The rest of the chapter will focus on the artefact typologies that have been well established.

Most archaeological artefacts have been categorized based on their exterior appearance. The intricacies, such as whether a knife back is curved or straight, are integral in a general classification system. This form of classification is usually determined using x-radiographs and drawings of the artefact by a specialist who is experienced in the iron artefact typologies in use. In archaeometallurgy other levels of analysis are used to really understand the quality of the iron alloys, the skill in manufacture, and the effectiveness of heat treatments, improving both our understanding of the artefact's use and the reasons for its subsequent discard.

It should be taken into consideration when discussing typologies that these items have been handmade and construction can vary due to many factors, including personal preference, differences in manufacture techniques and/or availability of materials.

4.2 Major Artefact Types

A list of major iron artefact types based on use can be found on Table 3.

4.2.1 Edged Tools

This category was primarily based on knives, though other edged tools many have been constructed similarly (i.e. axes, pick heads, etc.).

The most common edged tool found at archaeological sites was the knife. Knives were used in nearly every aspect of daily life from cooking to hunting to woodcarving and were found not only in settlements (McDonnell 1987a, McDonnell 1987b), but were also discovered in many Anglo-Saxon graves (Blakelock and McDonnell 2007). Edged tools were the most extensively studied type of iron artefact from Anglo-Saxon and Anglo-Scandinavian contexts (Blakelock and McDonnell 2007, Lang 1988, McDonnell 1992). On a macro-scale these artefacts have been classified based on the shape of their back and blade (Arrhenius 1970, Arrhenius 1974, Blakelock and McDonnell 2007, Ottaway 1992: 484, 558-78), while archaeometallurgists have created a classification system based on the construction of the blade by comparing the alloy placement within a cross-section (figure 13) (Tylecote and Gilmour 1986: 3). Blakelock and McDonnell (2007) determined that knives from fifth-eleventh century settlements

were most commonly manufactured using a Type 2 butt-welded construction with a cutting edge of high carbon steel welded to a phosphoric, ferritic or piled back.

4.2.2 Nails

Nails have not been studied to the same extent as edged tools, despite being found in much greater quantities. There are no standard typologies of nails from the Anglo-Saxon and Anglo-Scandinavian contexts beyond groupings based on head shape and inferred use that are found in individual site reports with variable definitions (Ottaway 1992, Stamper and Croft 2000: 607-15). The only metallographic study on British nails was conducted by Angus et al. (1962) on the nails excavated at Inchtuthil Roman fort in south-western Scotland. In this examination, Angus et al. established a typology for Roman nails, which were found to be constructed to standard sizes and shapes. The metallography of a cross-section of the entire length of the nail was used to identify construction techniques of the head and point. They found that most often the nails were constructed from heterogeneous tapered bars that were heated and inserted into a die. The head was subsequently hammered into shape. The irregularity of shape and size of post-Roman nails does not fit Angus et al.'s typology and may have been constructed using different techniques. Angus et al.'s sampling technique of nails, however, clearly leads to the understanding of construction and could do so again for this study.

4.2.3 Stock Iron

Stock iron, also known as trade iron, usually in the form of billets and bars, was the intermediate stage between the bloom and the finished artefact. This was the form in which iron was traded from producer to smith. This trade allowed areas without local iron sources access to the full range of iron alloys. The Iron Age currency bars from Britain (Crew 1991) are an important archaeological example. Further metallurgical analyses of stock iron included the examination of bars from Anglo-Scandinavian contexts from York, UK (McDonnell 1992) and from Norse contexts Helgö, Sweden (Tomtlund 1978c). Selective smithing of the bloom can provide bars that are exclusively one alloy or, more commonly, bars can be a heterogeneous mix of alloys. In a few cases ancient smiths created bars that were a piled combination of specific alloys. Once the bars were procured by the smith they were used to construct the other artefact mentioned here.

4.2.4 Other Craft Tools

The construction of tools from other crafts included needles for sewing, fishhooks used in fishing, spoon augers used in woodworking, and awls used for working surfaces or piercing small holes in leather. Previous analysis of this category of iron artefacts has been limited the two important but limited archaeometallurgical studies that fall under this category include McDonnell's (1992) examination of Anglo-Scandinavian tools from York and Modin and Pleiner's (1978) examination of Norse tools from Helgö.

The needles and fish hooks were exceptionally thin and were usually constructed from one thin piece of wire-like metal. These artefacts required stock material of exceptional quality. The presence of inclusions in this iron would have made the metal brittle, impeding the drawing process (Goodway 1987). These exceptionally thin pieces of metal involved a different technique of manufacture than the rest of the other artefacts examined in this study. The medieval wire was created by wire drawing, strip drawing, and swaging (Slater 2008: 426), all of which involve repeated cold working and annealing. For a more detailed account of the manufacturing technology of wire see Slater (2008) and McDonnell (1992).

The spoon auger (figure 14) was a specialized tool used by woodcarvers for drilling holes in wood. Five incomplete augers or spoon bits were found at Coppergate, York (Ottaway, 1992:532). The handles rarely survive but were probably fitted transversely on the tang. McDonnell (1992) conducted metallographic analysis on one such spoon and found the tip was composed of heat treated high carbon steel.

4.3 Less Common Iron Artefacts

Table 4 shows the categories of Anglo-Saxon iron artefacts selected because they have not previously undergone extensive metallographic analysis.

Most of these artefact types are much less common at archaeological excavations than those described previously. Many of them, however, have been classified using their

exterior shape typology. A brief description of the items and their usage is provided below. Within this thesis the description of these items will be augmented with metallographic analysis to begin to understand their quality of material and construction.

4.3.1 Dress Fittings

The Dress Fittings category is for ironwork that was associated with clothing. In this study the artefacts that fall into this category include belt buckles, dress pins, and dress hooks. All of these items have been previously assigned a typology based on their physical appearance. Belt buckles (figure 15a) have been found in both Anglo-Saxon and Anglo-Scandinavian contexts, associated with graves and horse riding equipment (Ottaway 1992: 682). This artefact type is more often constructed of non-ferrous materials including copper alloys, silver, bone and boar's tusk (Rogers 1993: 1375), the vast majority of iron Anglo-Saxon buckles were oval shaped and worn around the waist (Marzinzik 2003: 10). Dress pins are found in both Anglo-Saxon and Anglo-Scandinavian contexts, but are more commonly found constructed of non-ferrous metals or bone (Ottaway 1992: 693-5). They show regional variation in both style and material (Rogers 2007: 126). The most common styles have spherical, polyhedral, ringed, or other decorative heads with a long thin shank that is sometimes twisted. Dress hooks (figure 15b), also called tags, are thin triangular shaped sheets of metal with two piercings at one end and a hooked point at the other. These are often found at sites dating from the seventh to the eleventh centuries AD (Dalwood and Edwards 2004, Riddler 1998: 387), with decorative ones from the ninth-tenth centuries

AD (Ottaway 1992: 697) These hooks were often used to hold ties on shoes and purses (Rogers 2007: 134).

4.3.2 Construction Materials

The construction materials examined in this thesis include rivets, joiners dogs, ferrules and staples. Nails should also be in this category, but as they are found in larger quantities and have been selected for individual analysis they were described in Section 4.2.2. Construction materials are generally not considered high quality items and have received only cursory attention by both archaeologists and archaeometallurgists. They were consistently used in construction throughout the fifth-eleventh centuries by all the inhabitants of Britain.

An rivet is a small sheet of metal used in conjunction with a nail to connect two materials together. Examples of rivets can be found in Ottaway (1992:615). A joiners dog is a piece of iron designed to hold things together like a vice, often used in woodworking in order to join planks. An ferrule is a sheet of iron that has been wrapped around something to hold it together or to something else, often used at the base of wooden poles and shafts to protect them from wear. An staple is a strip or band of iron bent and pointed at both ends, which were used to hold pieces of timber together. Two Anglo-Scandinavian staples from Coppergate, York, were analyzed metallographically (McDonnell 1992).

4.3.3 Riding Equipment

Riding Equipment includes ironwork associated with both on the animals and the riders. Many of the artefact types previously described can be associated with this category, but horse bits and spurs are uniquely designed for riding. Equestrian equipment has been found in both Anglo-Saxon and Anglo-Scandinavian contexts (Ottaway 1992: 407-9), however, none have been analyzed metallographically. Previous studies have focused on the style of these items as part of studies on Anglo-Saxon and Anglo-Scandinavian warfare and the history of equestrian arts (Williams 1952).

4.3.4 Miscellaneous

The Miscellaneous category is for iron artefacts of known type that do not fit into other categories.

Arrowheads, normally classed as weaponry, are used in both warfare and hunting. Several classification systems have been developed for arrowheads from Anglo-Saxon (Dalwood and Edwards 2004) and Anglo-Scandinavian (Wegraeus 1973) contexts. Their construction was dependent upon their purpose (Ottaway, 1992: 710) with wide blades designed for maximum blood loss of the hunted animal and thinner heads that are designed to pierce armour or protective clothing during battle. Only one Anglo-Scandinavian iron arrowhead has previously undergone metallographic analysis (McDonnell 1992: 714).

4.3.5 Keys and Locks

Locks were used widely in Britain as early as the Roman period (Manning 1985: 52) and have been found at both Anglo-Saxon (Dalwood and Edwards 2004: 164) and Anglo-Scandinavian (Ottaway 1992: 657-668) contexts. Early locks consisted of two forms: the fixed lock, which was integrated into the object it is locking, and the padlock, a portable mechanism. This study focused on padlocks. The most common type of padlock in use in the ninth-eleventh centuries AD was the barrel padlock, of which there were two types (figures 17) (Ottaway, 1992:665-667). One type (figure 16a) had a keyhole and slit along one end of the outer casing. The bolt, when the lock was secured, was held in place by two leaf springs. When the key was inserted and moved up along the slit the springs were compressed and the bolt would slide out. The other type of bolt lock (figure 16b) had the key hole at the bottom and the leaf springs were attached to the bolt itself. When the key was inserted it flattened the springs so the bolt could be removed. Similar locks have been identified at the Swedish Norse sites of Helgö (Tomtlund 1978a) and the Garrison in Björkö (Gustafsson 2005). Metallographic examination of the padlocks and springs from Helgö (Modin and Plainer 1978) revealed that they were constructed of wrought iron and mild steel with evidence of cold working.

For each lock type there was a specific style of key. The two major types of keys in used during the fifth to eleventh centuries including ones that needed to be rotated to move the bolt and ones that required the compression of springs (Ottaway 1992:667-

678). Figure 17 shows an Anglo-Scandinavian key examined metallographically by McDonnell (1992). Other keys from the period were sometimes decorated or plated with tin and other metals.

4.3.6 Hooks

Hooks have a variety of uses and forms. They could fit into many of the categories presented here, from dress fittings to construction materials. Typologies can be found in Ottaway (1992:651-653) and Manning (1985:35), though only the wire hooks have received previous metallographic analysis (Slater, 2008).

4.3.7 Unidentified Artefacts

There were several iron artefacts that remain unidentified (UI) but were sampled for this research. These artefacts were chosen for metallographic analysis to provide more data about the alloys and quality of metal that was generally available within the settlement.

Chapter 5 – Methodology

5.1 Archaeological Site Selection

Sites were selected from archaeological excavations of both urban and rural Early Medieval settlements. These sites needed to fulfil the comparative requirements of the aims and objectives:

- The settlements needed to be from different regions across England
- The settlements included a selection of both high and low status sites
- The excavations need to have ten or more iron artefacts of moderate preservation
- The excavations should not include cemeteries or other ceremonial sites

Ultimately sites were selected based upon availability and be able to fulfill the above requirements.

5.2 Artefact Classification System

To address the objectives of this study it was necessary to sample a selection of artefact types from each site. This selection focused on edged tools, nails and stock iron, while including a variety of other artefacts to create a broader sample of each of the assemblages.

An initial classification system based on the object's inferred use and the complexity of construction was created to aid in artefact selection. Artefacts were separated into three classes and, where possible, an even selection of each class was chosen. Examples of these artefacts can be seen in Figure 19.

Class 1 – This class was composed of iron artefacts that could have been complex to manufacture, are decorative or appeared to have required higher quality material for construction. This category focused on edged tools such as knives, axes, and chisels with a smaller selection of iron used in clothing such as decorative pins and tabs, iron used in crafts such as needles and punches, and iron used in complex items such as keys and locks.

Class 2 – This class was composed of iron artefacts less likely to be constructed of high quality materials or have complex construction. This category focused on nails and contained a smaller selection of ferrules, sheets, rivets, hooks, and staples.

Class 3 – This class was composed of stock iron artefacts in the form of bars and billets. These artefacts were included to provide insight as to the alloys and quality of materials local smithies used to create artefacts such as those in Classes 1-2.

Unidentifiable Iron (UI) (only used in the Thetford assemblage) – Iron artefacts whose use could not be determined were also included to gauge the range of alloys available in that particular site, but was not included in the interpretation of site status and the artefact comparisons.

This classification system was preliminary (i.e. to be tested and revised after analysis).

A thorough discussion can be found in Chapter 8.

5.3 Artefact selection

Specific artefacts were selected based on type and level of preservation. This was determined through visual examination, testing for magnetic properties and determining the amount of surviving metal, as determined through X-radiography.

In the case where the settlement had undergone previous archaeometallurgical analyses, sections from these artefacts were re-analysed using the specific analytical methodology designed to fulfil the specific requirements of this project.

5.4 Artefact Recording

5.4.1 Photo Imaging

Each of the artefacts to be sampled was photographed in the state in which they were received using a digital camera.

5.4.2 Measurement

The artefacts were then weighed (gram) and their dimensions measured (millimetre) before sectioning.

5.5 Analytical methodology

5.5.1 X-radiography

Each artefact was tested with a magnet to assess the presence of metallic iron in the artefacts. All artefacts indicating the presence of metallic iron were then radiographed using an HP Cabinet X-ray System, Faxitron series, at 120kV for 2, 3 or 6 minutes, depending on the thickness and density of the sample. Radiographs were taken with a working distance of 25cm using lead screens and processed by the author in a dark room. X-radiographs provide a wealth of data including location and extent of corrosion (hence indicating the presence of surviving metallic iron for sectioning), evidence of weld lines, distribution of slag inclusions, distinct X-radiograph pattern of high carbon steel, and evidence of non-ferrous inlay.

The X-radiographs were scanned to make a digital copy for presentation in this thesis. This was done with an Agfa FS50B scanner along with RADView Workstation software with a pixel pitch of 50 microns in a high quality scan mode.

5.5.2 Sampling Technique

After examination of the X-radiographs, areas with a significant amount of metal and areas where information about the manufacture technologies could be examined (i.e. the examination of the cutting edge of knives), were chosen to be sampled. The sampling placement varied based on artefact type and remaining metal. Examples of where the major artefact types were sampled can be seen in Figure 20.

The artefacts were sampled by removing a section of metal using a microslice diamond wafering blade and jeweller's piecing saw. Where possible, in addition to the normal cross-section, a longitudinal section was also removed.

Each section was mounted separately in Buehler VariDur acrylic cold-setting resin and then labelled with the site code and the finds number (table 5). These mounted sections were ground on successively finer silicon carbide papers and polished to a one micron diamond finish using polishing pads.

5.5.3 Optical Analysis and Imaging

The mounted sections were photographed and then examined in the polished condition using a Nikon Optiphot Reflected Light microscope that has an E-Rec Electronics digital camera with Fire-I imaging software. Key observations focused on the state and distribution of slag inclusions, corrosion and weld lines.

Sections were then etched for 5-15 seconds with Nital, a 4% solution of nitric acid in alcohol. Etching the metal surface with acid removes the polished smear layer of the surface of the metal and attacks specific features, e.g. grain boundaries, to reveal the microstructure below. With this etchant it is also possible to see features generally associated with phosphoric iron including ghosting and etch resistance.

The etched sections were again examined and photographed. A complete photographic schematic of each sample section was created using a 2.5x or 5.0x objective lens depending on the size of the section. Areas of interest, including weld lines, ghosting and other key features were also photographed using a 10x or 20x objective lens.

5.5.4 Manufacture Classifications

Artefact sections were analyzed and the structures classified as being composed of the following manufacture techniques:

Evidence of cold working

This indicated that either elongation of grains, Neumann bands, or significantly high hardness values existed in the section.

Heat Treatment

This indicated that either bainite or martensite present in the metallography of the section indicating the heat treatment of high carbon steel.

Carburized

This indicated a thin layer of steel was present along the exterior of the section.

Piled

This indicated a series of thin layers were welded together to make the part of the section.

Composite Construction

This indicated the presence of two or more alloys separated by weld lines in a manner that intentional placement during construction of the object (i.e. knife construction typologies).

Single Alloy Construction

Only one alloy was present in the structure.

Heterogeneous Structure

This indicated that several alloys existed within the section that were not separated by a weld line and were not the result of carburization.

5.5.5 Micro-hardness Testing

Hardness testing is a technique that tests the metal's ability to resist penetration, indentation, or scratching. In metallurgy this was done by applying a specific pressure for a specified period of time using a Vickers diamond indenter and then measuring the size of the indentation. This measurement was then compared to a standard.

The sample sections then underwent hardness testing using a Buehler MicroMet 5101 Vickers micro-hardness tester with a load of 200g for 15 seconds. Areas selected for hardness testing included areas containing the individual alloys and any other interesting features that has been identified and recorded earlier using the optical microscope. A minimum of three tests per section were taken for single alloy artefacts. The majority of the artefacts, however, contained multiple alloys and the numbers of tests increased pro-rata.

5.5.6 Grain Size Analysis

Grain size analysis was conducted using a standard scale of grain sizes (ASTM) to measure the size of grains in ferritic, phosphoric, and arsenical iron. This was performed at a standard magnification (10x objective) using a specialized lens insert with the different ASTM standard grains sizes delineated on it for optical comparison with the metallic grains. Grain size analysis focused on areas immediately adjacent to the hardness tests.

5.5.7 Material Quality Analysis

Material quality was assessed through visual inspection of the microstructure. Items were classified as “clean” when they contained a low number of slag inclusions and the majority of those slag inclusions were small (figure 18b). Items were classified as “dirty” when approximately 1/5 of their microstructure consisted on slag inclusions (figure 18a).

5.5.8 SEM/EDS Analysis

Artefact sections were then examined for elemental composition using a FEI Quanta 400 scanning electron microscope (SEM) with an Oxford Instruments INCA x-sight energy dispersive spectrophotometer (EDS) calibrated with a cobalt reference standard. The SEM was operating at 20kV acceleration voltage with filament at saturation (2.20 A), a working at a distance of 10mm and a variable spot size of 5-6 nm. The spectra were then quantified using the Oxford Instruments SEMQuant software system. The data was gathered for 50 live seconds allowing for a ‘dead-time’ of up to 40%. The limits of detection using this technique are only to one decimal place; if there is less than 0.1% of any element the machine will be unable to detect it with confidence. The machine is also not calibrated to measure carbon content and was only used to measure P, Fe, As, and Ni concentrations.

Where possible two or more tests were taken next to every hardness test enabling a direct comparison between micro-hardness, grain size and elemental composition. Further tests were taken from interesting features such as ghosting and weld lines.

5.5.9 Electron Microprobe Analysis (EMPA)

It was important for the study of phosphoric iron to improve on the limitations of the SEM/EDS in the detection and measurement of phosphorus. To accomplish this, selected artefacts were re-analysed with the EPMA to compare results and create a calibration for the data from the SEM.

Wavelength dispersive spectrometry (WDS) was used on 5 artefacts for further analysis of elemental composition. Artefacts were coated with a layer carbon 20nm thick before testing. The analyses were taken using 15kv accelerating voltage, a 20nA beam current. Both a pure iron and apatite standards were utilised. A count time of 50 live seconds was used to obtain detection limits of 0.001% for phosphorus.

5.5.10 SEM/EMPA Calibration

When using the EDS system on the SEM to measure the amount of Phosphorus in a sample the results are presented to 0.001wt%P with an error between ± 0.04 -0.08wt%P, however the confident detection limit to the EDS is only to 0.1wt%P. For this study that level of confidence was insufficient, as previous studies conducted by Chen et al. (2003), Gouthama and Balasubramaniam (2003), and Stewart et al. (2000c) have examined phosphorus contents to 0.01wt%P or better using X-ray fluorescence (XRF), Wavelength dispersive X-ray (WDS), and wet chemical analysis (using ICTP-AES) respectively, and steps needed to be taken to increase confidence in the SEM data presented in this study.

Limitations of expense and equipment availability deemed it unpractical to use a machine such as the EMPA, with a detection limit of 0.001wt%P, for all analyses. Instead the EMPA was used as a comparison to determine if the detection limit of the SEM/EDS was good enough to be confident about results down to 0.01wt%P.

This comparison was accomplished by conducting analyses of selected artefacts containing different phosphorus contents (0wt%P, 0.3-0.4wt%P, and 0.6-0.8wt%P) with both the SEM/EDS and the EMPA (table 6). A graph of these results as presented below (figure 21) demonstrated that the SEM/EDS results can be confidently interpreted to 0.05wt%P when the total phosphorus content is above 0.1wt%P.

These results demonstrate the SEM/EDS system produces significantly similar results to EMPA except when values are lower than 0.1wt%P. These results show that the phosphorus content as measured by the SEM/EDS system when the total content is above 0.1wt%P can be confidently to a precision of 0.01wt%P.

5.5.11 Stead's and Oberhoffer's Reagents

Both the Stead's reagent and the Oberhoffer's reagent are etchants applied to iron and steel to examine the distribution of phosphorus within the microstructure. Both etchants were utilised using the same techniques as Nital, where a freshly polished clean metal surface was submerged in the etchant for 10-15 seconds. The section was

then washed using tap water, sprayed with ethanol to remove excess moisture, and then dried using a hot air blower.

Alloy Determinations

Alloys were determined based on a combination of optical analysis, hardness measurements and elemental composition.

5.5.12 Ghosting Structure Identification

A system of classifying ghosting features was established after preliminary research revealed that a variety existed. This classification was developed independently from the previous classifications which were based on experimental results using pure phosphoric iron conducted by Gouthama and Balasubramaniam (2003) and Stewart et al. (2000a). For this study it was necessary to develop a new classification which incorporates the complexity of the elemental composition of the archaeological bloomery iron. This classification scheme was entirely based on observations of ghosting in the microstructure. This scheme will be examined more closely, along with associated analytical data, in the discussion.

Ghosting often takes different shapes often appearing shaped like grains, ripple-like, needle-like, Widmanstätten-like, dendritic, and laminar. The following classification indicates the placement of these shapes within the microstructure.

Major Ghosting Structures Classification

Grain Boundary (GB) - This form of ghosting appeared as out-line of the equiaxed grain boundaries. It can exist as along the current grain boundaries (figure 22b) or in the shape of grain boundaries from a previous structure over laying the current structure (figure 22a).

Inter-granular (figure 23) – This form of ghosting occurred as ghosted areas with non-granular structures that are not restrained by grain boundaries.

Edge Effects (figure 24) – This form of ghosting occurred along the edges of the phosphoric iron where meets other, often non-ferritic, alloys.

Slag Inclusion (figure 25) – This form of ghosting occurred immediately surrounding slag inclusions.

Pearlitic (figure 26) – This form of ghosting occurred immediately surrounding areas of pearlite in a hypoeutectic, often low carbon, steel.

5.5.11 Synthesis of Data

The resulting microstructures, micro-hardness values, grain size measurements and elemental composition data were used in interpreting the composition and construction of the iron artefacts. This allowed for comparisons to be made between different types of artefacts.

Individual artefact descriptions, analyses, photos, X-radiographs, drawings and section maps will be included in accompanying DVD organized by Site and Finds Number.

Chapter 6 – Evidence for the Medieval Period

6.1 - Introduction

Our current knowledge of the Early Medieval period is a combination of the information presented by a handful of semi-contemporary written sources and archaeological evidence. Presented in this chapter are a brief summary of the written sources and a description of the archaeological evidence.

6.2 - The Written Record

The written record from the Early Medieval period is exceptionally sparse. Four major texts have been used to derive the history of early post-Roman Britain. These texts include the writings of Gildas and Bede, as well as the Anglo-Saxon Chronicle and the Domesday Book. Another contemporary resource used by historians is the poetry of the Early Medieval period.

Gildas (c.AD 516-570), also known as Saint Gildas, was a sixth century cleric (James 2001: 63). Gildas is known for his work *De Excidio et Conquestu Britanniae* or *On the Ruin and Conquest of Britain* which chronicles the end of Roman Britain and the arrival of the Angles and the Saxons (James 2001: 94-95). The work was a three part sermon condemning the acts of his contemporaries, both secular and religious. The only textual account from Britain directly addressing the history of the post-Roman era,

Gilda's work provides insights into how the native Britons viewed the Romans and the invading Germanic tribes (Campbell 1982: 33); nevertheless, the writer's bias and lack of date and place name detail has brought into question the validity of the chronicled historical events.

Bede (c.AD 672/3-735), also known as Saint Bede or the Venerable Bede, was a monk at the Northumbrian monasteries of Saint Peter at Monkwearmouth and at Saint Paul's at Jarrow (Campbell 1982: 70-79). His most famous work, the *Historia Ecclesiastica Gentis Anglorum* or the *Ecclesiastical History of the English People* was completed in AD 731. Its five volumes followed the history of Christianity in England from its introduction up until the time of Bede himself. Key sections included the story of Augustine's mission to England in AD 597, which brought Christianity to the Anglo-Saxons, the progress of Christianity in Kent, the first attempts to evangelize Northumbria, the success and failures of missionaries from Iona and Lindisfarne (James 2001: 147). However, the chronicle also laid out an extensive history of Britain laying out the political and social parameters and describing changes that occurred after the end of Roman Britain. Bede added the names and dates from Gildas' accounts, as well as collecting information from as many other contemporary sources as possible to create a thorough account of the people and the period (Campbell 1982: 78). Although Bede's work also has its biases (James 2001: 14), it contains a vast quantity of information from a period where few other written sources exist, and this gives the work a special importance.

The Anglo-Saxon Chronicle was a compilation of annals drawn from earlier sources chronicling the history of the Anglo-Saxons (Campbell 1982: 26). The annals were created late in the ninth century, probably in Wessex (Arnold 1997: 17), during the reign of Alfred the Great (Reynolds 1999: 28). Multiple manuscript copies were made and distributed to monasteries across England and were independently updated. In one case, the chronicle was still being actively updated in AD 1154. The Chronicle is best known for its accounts of the development of Wessex (figure 5), the political scene of the Late Anglo-Saxon period, and the social upheaval caused by the Scandinavians beginning in the eighth century AD (Reynolds 1999: 28). The Chronicle is not unbiased and different versions contradict each other; however it is one of the most important historical sources for the period in England following the departure of the Romans and up until the decades following the Norman Conquest.

The Domesday Book (the Book of Judgement) is the record of the great survey of England completed in AD 1086, executed for William I of England (Reynolds 1999: 55). The book included information about the status of all settlements during the eleventh century AD. It is notable that, as in the case of Wharram Percy (Stamper and Croft 2000), it provides the first written record of the existence of many, particularly smaller, settlements. It was designed to determine ownership and assess the worth of each parcel of land to define the extent of the king's holdings and thus how much tax landowners owed (Lapidge et al. 1999: 144). The account did not include a history of land ownership or provide a long detailed account of each settlement.

The Poetry from the Early Medieval period was a combination of history, folk tradition, Christian textual and illustrative imagery, composed into stories of heroes and adventures (Reynolds 1999: 32). The most famous of these stories is *Beowulf*, preserved in an eleventh century manuscript; it is believed to be set in the eighth century, and tells a tale of Danish warrior king (Hall, 2007: 192). This type of epic-poetry provides large amounts of cultural and social information (Campbell 1982: 54-5).

6.3 - The Archaeology

The archaeology of Anglo-Saxon Britain is complex. It was initially firmly set within a historical support position, but it expanded, especially in the 1960s and 70, to investigate many sites for which no textual data existed and lead to the creation of an independent, non-textually based Anglo-Saxon archaeology. This tension, between the historical information and a purely archaeological record has been exasperated further skewed by preservation and investigation biases. This means that the study of the period is challenging, with a range of different specialist views which the archaeometallurgist must negotiate. The following therefore provides a relatively sparse outline of the kinds of archaeological data currently available and their generally agreed significance.

6.3.1 - Settlement types

Rural settlements – It would seem that the majority of known early Anglo-Saxon settlements appear to be rural (Wilson 1976: 58), the settlement at Mucking

being the prime example (Hamerow, H. 1993). Collapse of the Romano-British economy, which led to the collapse of many urban centres and the return to an agrarian way of life would make this acceptable. These settlements are the most difficult to detect due to their relocation in the eighth century. Whether this has been lost due to re-use of the land or 'settlement shift' in the fifth to seventh centuries AD (Hamerow 2004: 121) is unknown, especially as full-scale excavation today is now a rarity.

Royal settlement – These are settlements that have been given royal patronage, fortified, and sometimes re-used walled Roman towns, such as Winchester, Bath, Exeter (Wilson 1976: 123), Canterbury and Dorchester (Blair, 2005: 279).

Ecclesiastical/Monastic – These settlements appear from the seventh to ninth century and are communities that build up around holy orders, with the primary focus on a church. They are built on prominent geographical sites York, Ripon, Beverley, Winchester and Canterbury (James 2001: 153).

Wic – These are urban towns and trading centres, sometimes known as emporia. These centres include Hamwic, London, Ipswich and York (Hamerow 2004: 149, James 2001: 197).

Burh – These are fortified towns created by Alfred the Great to protect his lands from the Danish attacks. Alfred's son Edward the Elder continued his father's policy of establishing fortified towns (Reynolds 1999: 86), and he and his sister

Aethelflaed of Mercia built a new double row of burhs along the old Roman road of Watling Street, which lined the border of the Danelaw as it ran from London to Chester (Campbell 1982: 162).

6.3.2 - Types of archaeological evidence

The major finds found at Early Medieval sites in Britain included evidence of timber buildings, both sunken and posthole (Milne and Richards 1992: 89), occupation debris, Saxon coinage (sceatts and stycas), pottery, knives, bone combs, quern stone, metal objects, and metal working debris (James 2001: 15).

Archaeology – Saxon

The archaeology of the fifth-seventh centuries AD is characterized by furnished inhumation and cremation cemeteries, such as Spong Hill (Hill 1980), and small farmsteads (Reynolds 1999: 23). Dress of the occupants indicates loosely defined fifth century communities developed regional identities in the sixth century (Halsall 1995: 57). In the seventh century high status settlements with wealthy burials have been interpreted as evidence of kingships (Campbell 1982: 48).

The conversion of the English to Christianity in the seventh century (Campbell 1982: 45) is marked by a wealth of Saxon churches, the most famous being St Mary's, Deerhurst (Gloucestershire) (Rahtz 1976), though many of these contain re-used of Roman stonework robbed from the local Roman settlement, as seen at St Paul's at Jarrow (Campbell 1982: 74).

Many settlements from the Early Medieval period have been excavated for including Winchester, Hamwic, Canterbury, York, and Worcester. To find a detailed description of these settlement sites please refer to the individual site reports in Chapter 7 (p.73).

Archaeology – Anglo-Scandinavian

There is a difficulty with what is actually deemed ‘viking’ in the archaeological remains of this period, so caution is needed (see below). Yet there are distinct aspects of Scandinavian influence in the archaeological record. The tenth/eleventh century AD hogbacks of St Thomas’, Brompton, North Yorkshire (Hadley 2002: 15) are the clearest example. These stone hogbacks, or grave-markers, are neither Scandinavian nor Saxon, but a new form of commemoration of incomers displaying their identity in death (John 1982: 164).

Anglo-Scandinavian archaeology is allied with craft specialisation, as seen in abundance at Coppergate, York (Addyman 1982: 166-7). In terms of dress, some objects are most definitely of Scandinavian origin: the tortoise brooch, with its distinctive filigree construction, and the trefoil brooch (Hall 2007: 44-9).

Archaeology - Place name evidence

This evidence has often been used to determine the origins of a piece of land, be it a settlement or a single field (Lapidge et al, 1999: 367-71). Names are given to places of dwelling either by those that live there or by those who view them (Hadley 2002: 14-

15). As a result Scandinavian influence is regularly determined by the name endings of settlement, for example the use of -thorp or -by added to the end is a cultural identifier (James 2001: 217). However, caution is advised in the use of place names. The largest known group of Scandinavian burials, both inhumation and cremation, were found at Ingleby in Derbyshire despite its translation as “the place of the English” (Wormald 1982: 162).

6.3.3 - Difference in evidence: Anglo-Saxon vs. Anglo-Scandinavian

As stated above, caution must be advised when attempting to separate what is Anglo-Saxon and what is *Anglo-Scandinavian* in the archaeological record (Hadley 2000: 15). What is evident is that Scandinavian influences are seen on what are normally considered to be Saxon objects: Christian stone crosses, metalwork such as dress and horse fittings, cutting edged tools together with craft specialisation in working with bone and antler (comb making) horn (light fittings), leather (clothing), amber and jet (Hall, 2007: 44). Influence of design shows a culture of *Anglo-Scandinavian*: the Saxon and Danish had a solid Germanic identity in common thus allowing for this syncretism of cultures to take hold readily (Hadley 2000: 16). In York all artefacts of the period are described as ‘Anglo-Scandinavian’ in origin as they demonstrate a combination of Anglian and Scandinavian.

Chapter 7 – Site Summaries

7.1 Introduction to the Site Summaries

This research project examined iron assemblages from eight Early Medieval sites distributed across Britain (figure 1). These sites were selected because of both their diversity and their location (see figures 1-5 for maps). Aspects such as settlement size, site status, and region were all important factors in site selection. Table 120 summarizes each of these aspects for each of the sites. Another major factor that was taken into consideration with each of the site was period of settlement within the six centuries upon which the project focused. Figure 47 shows the timeline of site settlement, demonstrating that though many of the sites were inhabited at different points in time, the majority were contemporary during the eighth to ninth centuries AD.

A full description of each of the sites including settlement location, historical background, archaeology and a summary of the assemblage analyses are given below.

7.2 Brent Knoll, Somerset

Brent Knoll is an isolated hill that stands 140 meters high (Young 2009) and has a 360° panoramic view of the Polden Hills to the south, Glastonbury Tor to the east, the Mendip Hills and Cheddar Gorge to the northeast, the Bristol Channel and Wales to the

west and the Quantock Hills to the southwest (figure 27). The current village of Brent Knoll lies at the southwest base of the hill.

Brent Knoll sits in the wet land of central Somerset (Warnes 2009), called the Somerset Levels (Warnes 2009). Until the drainage of the Levels, throughout the Roman and Medieval periods, Brent Knoll was an island. During the Early Medieval period, the area surrounding the knoll remained marshy and suffered regular flooding.

7.2.1 Early Medieval Brent Knoll (a rural settlement)

Inhabitation of Brent Knoll began with an Iron Age hill fort that stood on the summit of the knoll (Young 2009). In the Roman period it was known as The Mount of Frogs and served dual purposes as a part of a chain of coastal watch towers as well as the home of a Roman temple (Warnes 2009).

There is very little information about rural Brent Knoll during the settlement tenth-twelfth centuries AD. In the Domesday Book, commissioned by William I in 1086, the settlement at the base of the hill was listed as containing 250 people (Warnes 2009).

In relation to the history of the greater area of Somerset, rural Brent Knoll was far from the larger settlements of Somerset that existed during the tenth-twelfth centuries and life there may not have been significantly affected by change in power after the Norman Conquest (Warnes 2009).

7.2.2 Archaeological Excavation

The archaeological excavation of Brent Knoll was conducted by Avon Archaeological Unit during Christmas 2006-2007 (Young 2009). The site was situated in the garden at the former vicarage (St. Michael's House). The excavation uncovered evidence of habitation from the Period I: the Roman period (third-fourth centuries AD), Period II: the Early Medieval period (eighth-tenth centuries AD), Period III: the Saxo-Norman period (eleventh century AD) and Period IV: Medieval period (twelfth century AD). The iron artefacts examined in this study were recovered from Periods III and IV.

In Period III (eleventh century) an earthfast building was situated on a slight terraced area existed on the north end of the site. The true extent of the building was not defined; however, the interior elements were identified. There was an obvious floor surface of compacted clay and silts and a partially filled depression within a rectangular pit that was filled before the building went out of use. At some point the building was remodelled and partition wall was put in. There was also a selection of other contemporary features including a drainage gully and several small pits outside the building.

In Period IV (twelfth century) settlement on the site was short-lived. Archaeological evidence included a scattering of twelfth century ceramics and a twelfth century boundary ditch cutting across the north-eastern corner of the Saxon Norman building, believed to have been abandoned by this time.

7.2.3 Local Iron Working

No evidence of iron smelting or smithing was uncovered from this excavation. This suggests that either the iron at Brent Knoll was all imported or that iron smithing occurred outside the excavation area. The nearest contemporary settlement with known iron smelting and metal working was the Royal settlement at Cheddar (Rahtz 1979) approximately ten miles from Brent Knoll. There were, however, iron deposits near Brent Knoll in the Mendip Hills that were exploited during the Roman period along with the more plentiful lead deposits that made the region famous (Todd 2007). This area would also be plentiful in local bog iron ore.

7.2.4 Artefact Types Selected

Due to the small number of iron artefacts (12) excavated at this site, artefact selection was based on the capability to identify the artefact type and/or the amount of remaining metal. Ten of the artefacts (table 7) were selected for analysis from the three major classes.

7.2.5 Analysis Results

A summary of the metallurgical analysis of all the artefacts is provided in Table 9. This demonstrates that the smiths supplying the Brent Knoll site were utilising the full range of iron alloys available in the Saxon period, similar to contemporary sites such as Coppergate, York (McDonnell 1992). The analysis has provided improved artefact identification and is evidence for artefact manufacture on the site.

Class 1

The Class 1 artefacts included several categories of artefact types, including two edged tools: knife BN300 and knife BN301, another tool: punch BN329, a dress fitting: dress pin BN324, and weapon: arrowhead BN333.

Manufacture

The two knives from the Class 1 assemblage, knife BN300 and knife BN301, demonstrated two different manufacture typologies. Knife BN300 was a Type 1 construction with a central spheroidised carbide pearlitic high carbon steel band and a phosphoric iron back. While Knife BN301 was a Type 4 construction with a martensitic outer sheath around a ferrite core with extensive carbon diffusion and high ferrite hardness values indicating cold working.

The section from punch BN329 indicated that the tool was completely composed of high carbon steel, in the form of spheroidised carbide pearlite.

Dress pin BN324 was manufactured from a single piece of phosphoric iron. A slightly higher hardness value, $Hv_{0.2}$ 200, and elongation of slag inclusions indicate working, but the presence of equiaxed grains suggests that the object was normalized after working.

Arrowhead BN333 was constructed from heterogeneous phosphoric iron, with a small central slag-rich area that was ferrite.

The spheroidised pearlite, phenomenon seen in knife BN300 and punch BN329, occurs when the metal has been heated to 500-600°C for a long period of time, causing the pearlite to lose its normal structure and form the spheroidal particles of cementite. There is not sufficient evidence to suggest that this occurred during manufacture or afterwards.

Alloy usage

The alloy usage of the Class 1 artefacts was summarized in Table 8.

Most of the artefacts in this class contain steel in some form; however, high carbon steel use in manufacture varies dramatically from the heat treated knife BN301 to the overheated punch BN329. What is clear in the Class 1 artefacts is that high carbon steel was most often a separate piece of metal welded to a ferritic/phosphoric iron back or core.

Phosphoric iron was found in three of the artefacts from the Class 1 assemblage. In pin BN324 the alloy composed the whole microstructure, while in arrowhead BN333 it composed most of the heterogeneous microstructure and in knife BN300 the alloy was used in both the sides and back. The hardness values for knife BN300 and arrowhead BN333 were normal for the alloy (around $Hv_{0.2}$ 160) and the grain size for all the phosphoric iron in the assemblage was between ASTM 5-6.

Ferritic iron was seen in only two of the Class 1 artefacts. In knife BN301 ferrite was used as the core of the Type 4 manufacture. In arrowhead BN333 ferrite only exists as a small area in a heterogeneous structure.

Quality of Materials

While most of the artefacts in this category had clean microstructures, knife BN300 and arrowhead BN333 were very dirty, with lots of slag inclusions.

Class 2

The Class 2 (table 10) artefacts included three nails and a hook.

Manufacture

All three nails were constructed from bars that contained a heterogeneous combination of phosphoric iron, ferritic iron and steel. The one exception was the tip of nail BN334, in which the even distribution of steel on the exterior of the tip of the nail could have been the product of carburization during manufacture.

The structure of nail BN310 was unusual due to the different alloys appearing to be naturally welded together, with clear weld lines present. This manufacture could have been created during the consolidation of the bloom or the bar may have been originally manufactured for other uses.

Both nail BN310 and nail BN334 had relatively high arsenic values with nail BN310 (0.4wt%As), limited to a specific ferritic area within the microstructure, and nail BN334 (0.2-0.6wt%As) throughout the entire microstructure.

Hook BN304 was composed of a ferritic body with a eutectoid steel insert in the tip that could be classified as a Type 2 construction manufacture typology.

Alloy Usage

The alloy usage of the Class 2 artefacts was summarized in Table 11.

Quality of Materials

All of the Class 2 artefacts were clean with very few small slag inclusions.

Class 3

Class 3 (figure 10) included only one tapering iron bar.

Manufacture

Artefact BN333 was the only artefact in Class 3 and it was classified as an unfinished tool. The artefact originally appeared to be just a tapered iron bar. Upon metallographic analysis, however, the tapered tip was found to have a partial Type 1 construction of hypereutectoid steel with a estimated carbon content above 1%C. As a result this bar was then identified as an unfinished tool, due to the lack of heat treatment of the high carbon steel and an unidentifiable tool shape. A cross section of

the back showed a dirty banded structure that included bands of phosphoric iron, ferrite and low carbon steel. The slag inclusions were most abundant between the individual bands.

Alloy Usage

The alloy usage of the Class 3 artefacts was summarized in Table 12.

Artefact BN333 had bands of low carbon steel along the back and a hypereutectoid steel cutting edge. It also had phosphoric iron and ferrite present in its banded structure.

Quality of Materials

Artefact BN333 was very dirty, with lots of slag inclusions.

7.2.6 Phosphoric Iron in Brent Knoll

Phosphoric iron was found in many of the artefacts from this site. Table 14 shows the properties of the phosphoric iron from each of the artefacts in which it was present.

The phosphoric iron was used intentionally as the back of knife BN300 and to create entire artefacts such as the dress pin BN324 and the arrowhead BN333. In the rest of the artefacts the phosphoric iron existed heterogeneously with the other alloys, as it may have existed in the bloom.

The major phosphoric iron indicators, including ghosting, etch resistance, and large grains have been indicated in Table 14. Ghosting and etch resistance were present in all but nail BN317 and not present in any of artefacts not containing phosphoric iron. Large grains (ASTM 3), however, were also seen in one of the ferritic artefacts, hook BN305.

Phosphorus and Carbon

Significant levels of phosphorus were found in the high carbon steel of three of the artefacts (table 13): knife BN301, tapering iron bar BN311, and punch BN329. In all of these the phosphorus levels were in the region of 0.1-0.2wt% phosphorus. Both knife BN301 and knife BN329, however, did not have phosphoric iron in their microstructures.

7.2.7 Arsenic in Brent Knoll

Both nail BN310 and nail BN334 contained significant (>0.4wt%As) amounts of arsenic present in the metal.

Nail BN310 (figure 28, table 15) contained a specific area of the cross-section microstructure where arsenic was the primary alloying component of the metal, separate from areas of phosphoric iron and ferrite. The microstructure of this artefact was determined to not be intentional, but a natural product possibly from the bloom.

Nail BN334 (figure 29, table 16) contained a significant arsenic content throughout its heterogeneous structure.

7.2.8 Summary and Class Comparison

Manufacture

The manufacture techniques summarized in Table 17 indicate that there was no evidence for cold working or piling in the Brent Knoll assemblage. Carburization was visible in nail BN334, a Class 2 artefact. Heat treatment was visible in knife BN301 from Class 1.

The intentional construction of iron artefacts from multiple alloys (i.e. knife constructions) was visible in the two knives from Class 1 and the hook in Class 2. The rest of the assemblage was constructed by either heterogeneous iron or single alloy construction.

Alloy Usage

In terms of alloy usage, all classes (table 18) contained the full range of alloys available in the Early Medieval period; however, Class 1 also demonstrated heat treatment of steel. No single alloy appeared to be used significantly more than the rest.

Alloy usage in terms of amount of alloy used in the construction of individual artefacts is summarized in Table 19. Only two whole objects were constructed completely from

a single alloy, both from Class 1. These artefacts were constructed from phosphoric iron and high carbon steel. Four other artefacts had a dominant alloy present in their construction: one ferrite, one phosphoric iron, and two low carbon steel. These artefacts may have had slight carburization, decarburization, or dephosphorization. These artefacts tended to be heterogeneous in nature.

Quality of Materials

Table 20 shows that the Class 1 artefacts were a mixture of clean and dirty, while the Class 2 artefacts were all clean and the Class 3 artefact was dirty.

7.3 Christ Church, Canterbury, Kent

Canterbury (figure 30) is located in east Kent about six miles inland from the southeast coast of England on the River Stour.

7.3.1 Early Medieval Canterbury (An urban royal and ecclesiastical settlement)

Previously the Roman city of Durovernum Cantiacorum, the whole or part of the city was abandoned at the beginning of the post-Roman period (Lapidge et al. 1999).

During the fifth and sixth centuries AD the area of Kent was claimed by the Jutes, from Jutland, the Danish mainland (James 2001: 107). During this period, the population of Kent was most likely a mixture of native Britons, Jutes and lesser amounts of other

Germanic peoples. The kingdom of Kent, the first Anglo-Saxon kingdom of Britain, was established in AD 449 and by the end of the sixth century AD Canterbury became the capitol, named Cantwaraburh (meaning Kentish Stronghold) (Lapidge et al. 1999).

In AD 597 Augustine, sent by Pope Gregory the Great, arrived in Kent to convert the Kentish King, Æthelberht, and the people of England (James 2001: 132). Augustine established the base for the Roman church in Canterbury, built new churches, including the Cathedral of Christ Church, and restored former Roman churches in the region.

After conversion, Pope Gregory chose Canterbury over London to be one of the two archbishop seats in England, the other being York, and made Augustine the first Archbishop of Canterbury. In the seventh century AD Canterbury became a mint for coins of the archbishops and then for the kings of the eighth and ninth centuries.

The city developed with its centre and many of its important buildings within the Roman walls. Since most of the houses were constructed of timber, major fires occurred in the city in AD 619, AD 624, AD 756 and AD 1067. Canterbury also suffered during the Kentish revolt against Mercian rule in AD 796-8 and was later sacked by the Scandinavian armies in AD 850, AD 851, and AD 893, then repeatedly threatened during the second surge of Scandinavian activity in tenth and early eleventh centuries. In AD 1011 the Scandinavians burnt the cathedral and held the king for ransom.

The city prospered in the late tenth and eleventh centuries AD, with an estimated population of 8000 in AD 1011.

The ever-changing political power of the period was integral to the capitol city of Kent. In AD 686 the Kingdom of Wessex seized control of Kent, but the people revolted and for a time there were multiple rulers. In AD 725 the King of Mercia claimed the throne of Kent and the kingdom remained under Mercian rule until Mercia was taken over by Wessex in AD 825. The kingdom was ruled by kings nominated by Wessex until the Norman invasion.

7.3.2 Archaeological Excavation

Canterbury Archaeological Trust excavated an area of Christ Church College in spring of 1995. Two trenches were opened near the north angle of the boundary wall of St. Augustine's Abbey. The archaeological deposits from the eighth and ninth centuries came from Trench A. The trench covered an area of 24m by 25m on the west end of the site and uncovered evidence from four broad periods, including prehistoric, Roman, Middle Saxon and Medieval. The Saxon deposits included a number of features, mainly rubbish pits, cess-pits, and post-holes; they also including a ditch sequence and several un-interpreted features.

The Middle Saxon finds were separated over three phases; Phase 1, 2, and 3. Finds were sparse in Phases 1 and 3, so the iron artefacts were primarily selected from Phase 2, dating from the early eighth to mid ninth centuries AD.

7.3.3 Local Iron Working

One of the most important aspects of the Christ Church College excavation was evidence of iron working from the Middle Saxon period. Large quantities of evidence were recovered, including smithing slag, hammerscale, bars and strips; however no Middle Saxon furnaces or hearths were identified (Riddler 1998).

7.3.4 Artefact Selection

Artefacts were selected based on artefact type and quality of preservation. Post-excavation analysis has not begun on the excavation; hence, other than the broad dates given above there is no detailed contextual information. However, all the artefacts were confirmed to be from Phase 2 contexts (early eighth to mid ninth centuries AD). Table 21 describes the selected artefacts.

7.3.5 Analysis Results

A total of 19 artefacts from Canterbury were sampled; of these eight were from Class 1, seven were from Class 2 and four were from Class 3. The Class 1 artefacts included a variety of different categories of artefact types, including edged tools, clothing accessories, drawn wire tools (i.e. needle and fishhook), and security related equipment. Class 2 was slightly less diverse, including several nails, staples, a fitting and a tack. Class 3 contained three bars and a billet.

Class 1

Class 1 artefacts (table 22) included three edged tools, two dress fittings, a needle and a key.

Manufacture

The knives from Canterbury were of Type 2 and Type 4 construction. The Type 4 knives, with steel encasing iron cores, were not common for this period (Blakelock and McDonnell 2007); however, knife CC397 demonstrated they are known to have high quality heat treated steel. Type 2 knives, such as knife CC829, were the most common knife construction in Early Medieval England. Knife CC397, a Type 4, and knife CC829, a Type 2, also contained banded non-steel structures constructed from many pieces of iron; while knife CC48-447, a Type 4, was constructed of just two or three different components. The back of knife CC48-447 was clearly a piece of phosphoric iron, while a band of pearlite across the middle of the section indicated a weld line mid-section; however, the tip was phosphoric iron encased in pearlite.

The other artefacts in Class 1 demonstrate several different types of construction. The clothing tab, needle, and belt buckle ring were constructed from a single piece of iron that has been shaped into the final object. Only the needle showed evidence of cold working through elongated inclusions and grains. The clothing tab was composed of a single alloy. The belt buckle was constructed of a single piece of phosphoric iron with a very small area along the edge with 0.1%C, probably due to carburization.

The lack of indicators of heavy cold working, such as distortion of grains and increased hardness levels, for all but needle CC258 should be noted.

Alloy usage

The alloy usage of the Class 1 artefacts was summarized in Table 24.

The use of steel in Class 1 was not ubiquitous. Steel was found to be present in all of the knives, with the high carbon steel in knife CC397 having undergone heat treatment. The high carbon steel in the knives shows intentional use of the alloy. Several of the other artefacts also contain some steel both low and high carbon; however in each of these the use of steel appears to be more incidental, due to carburization during production (i.e. smelting or smithing process).

Phosphoric iron was found in all but one of the Class 1 artefacts. Its use was the primary component of the non-edged tools and the back/core of the edged tools. In knife CC829 and the key, it was the larger grained bands of the banded structure.

Ferritic iron was found in four of the Class 1 artefacts. The clothing tab was the only artefact completely composed of this alloy. In knife CC829 and key CC211 ferrite was present in bands within the banded structure; it is not clear if this use was intentional.

Quality of Materials

The quality of material is measured by how clean from inclusions it is. In this assemblage it was found that the quality of materials was mixed. The edged tools

demonstrated clean high carbon steel, but the banded construction of knife CC829 had large amounts of inclusions both within and between bands. Knife CC397 was slightly cleaner, with most of the inclusions between the bands. Knife CC48-447 was cleaner partially due to the lack of a banded structure. This dirty banded construction can also be seen in the construction of the key. Both the clothing accessories (i.e. the buckle and the clothing tab) were constructed from individual pieces of dirty metal. The cleanest of the Class 1 artefacts was the needle, where inclusions would have caused material failure when the needle was drawn during manufacture.

Class 2

The Class 2 artefacts (table 23) included three staples, two nails, a fitting and a tack. The fitting was an iron object that looks similar to a modern karabiner. Similar contemporary objects were identified at Coppergate, York (Ottaway 1992), including a fitting (Ottaway 1992: 630), a hasp (Ottaway 1992: 644), and a horse bit mouthpiece link (Ottaway 1992: 705)

Manufacture

All of the Class 2 artefacts except fitting CC214, tack CC324 and nail CC211 were constructed from individual bars that had been shaped to form the final object. The majority of these items were constructed from heterogeneous bars of phosphoric iron that had undergone some exterior carburization. Of the three staples only one, staple CC230, does not fit this pattern; instead the bar from which it was constructed consisted of a folded banded phosphoric/ferritic iron structure. This folded structure was part of the manufacture of the original bar. Nail CC211 was phosphoric iron with a

piece of high carbon steel welded to it. Nail CC418 also differed from the other Class 2 artefacts by being completely constructed of ferritic iron.

Fishhook CC161 was also composed of a single, almost homogenous, ferrite.

Tack CC324 was composed of two separate pieces of metal welded together at the joint where the head meets the shank. The material that forms the head was similar enough to that of the shank that they were probably made from the same bar. The elongation of grains and slag inclusions indicated extensive working in the tack head.

Fitting CC214 was of a more complicated design and more sections are needed to establish the complete manufacture of the object. The section taken for this project revealed that the handle/strip was composed of a single piece of folded iron. This single piece of iron had a banded structure, but is primarily phosphoric iron with some carburization along the inside fold and on the terminating ends of the piece of iron.

Alloy Usage

The alloy usage of the Class 2 artefacts was summarized in Table 25.

Steel was present in the Class 2 assemblage. It was mostly high carbon steel, but not of the same quality as in the Class 1 artefacts, such as the knives. The steel in the Class 2 artefacts appeared to be mostly due to carburization of phosphoric/ferritic bars to varying extents. This carburization is seen in four of the Class 2 artefacts. Steel, both low and high carbon, was also present heterogeneously in one other artefact.

Ferrite existed in minor amounts heterogeneously along with phosphoric iron in three of the artefacts and it existed exclusively in nail CC418 and fitting CC214.

Phosphoric iron was the dominant alloy in the microstructure of all but one of the Class 2 artefacts. None of the artefacts, however, were completely composed of the alloy.

Quality of Materials

Most of the Class 2 objects were manufactured with medium to poor quality materials. Many contained amount of larger inclusions, which increased corrosion. Staple CC359 and nail CC418 were the cleanest structures.

Class 3

The Class 3 artefacts (table 27) from Canterbury included three bars and a billet.

Manufacture

There were three bars and one billet form the Class 3 stock iron assemblage. Bar CC292 and billet CC977 were composed of an individual alloy. Bar CC363 was composed of phosphoric iron and high carbon steel welded together. The last of the bars, bar CC299, may have been something other than a bar, based on its unusual construction. This bar was manufactured from two bands of phosphoric iron, possibly one band folded over, that were folded inwards and the exterior of the structure was slightly carburized.

The high hardness values for bar CC292 and elongated slag inclusions may reflect cold working, but the grains are not distorted and there are no other indications of cold working.

Alloy Usage

The alloy usage of the Class 3 artefacts was summarized in Table 26.

Steel is present in two of the bars; bar CC299 had a slightly carburized low carbon exterior and bar CC363 had a band of 0.4%C steel welded to a band of phosphoric iron.

There was very little ferrite in the Class 3 assemblage. Bar CC292 was primarily composed of phosphoric iron with a small area of ferrite with only slightly less phosphorus than the rest of the structure.

Phosphoric iron was found in all of the artefacts from the Class 3 assemblage. In all but bar CC363, phosphoric iron dominated the microstructure, and in bar CC363 it was present equally with medium carbon steel.

Quality of Materials

The quality of metal in Class 3 was fairly high with very few inclusions. All of the objects, however, suffered from heavy corrosion. Bar CC299 was especially vulnerable due to the space between the two folded bands that comprised the structure of the section.

7.3.6 Phosphorus in Canterbury

Phosphoric iron was found in 17 of 19 artefacts from this assemblage (table 28). Often it either comprised the entire microstructure or was the core material used in the manufacture of the object. Despite obvious use as the non-steel iron in composite objects such as the knives, there was no indication whether or not it was phosphoric iron preferentially selected for use instead of ferritic iron.

Phosphoric iron indicators are present in the majority of the artefacts. Ghosting was found in the phosphoric iron of 16 artefacts. The grain size averages ranged from 1 to 6 on the ASTM scale. Etch resistance was seen in ten of the artefacts, including one that did not contain phosphoric iron. Hardness values ranged between Hv_{0.2}140 to Hv_{0.2}220. The higher hardness values are well above the average and may be the result of work hardening.

A variety of ghosting structures were visible, including: slag inclusion ghosting, edge effect ghosting, inter-granular ghosting, pearlitic ghosting, and grain boundary ghosting. Slag inclusion ghosting was the most prevalent.

Phosphorus and Carbon

Significant amounts of phosphorus were found in both low carbon and high carbon steels in all three classes (*table 29*). In all cases phosphoric iron was also found in the artefact.

In the low carbon steel, phosphorus contents were generally higher when the carbon content was low, the exception being knife CC48-447 where the phosphorus content was 0.3wt%P and the carbon content was 0.2%C. The low carbon steel hardness levels did not appear to increase with increased carbon or phosphorus content.

In the high carbon steels, phosphorus contents as high as 0.61wt%P were present. The hardness levels were as expected in high carbon steels. Knife CC397 was heat treated with phosphorus content of 0.39wt%P and a carbon content of 0.8%C.

7.3.7 Arsenic in Canterbury

Elemental analysis of bar CC299 (figure 31) showed relatively high amounts of arsenic existing within the phosphoric iron of this artefact. The analysis results indicate high arsenic levels at Hv 1 and Hv 4 (Table 30).

7.3.8 Summary and Class Comparison

Manufacture

Evidence of manufacture was prevalent in the iron assemblage from Canterbury. Heat treatment was only seen in two artefacts from Class 1, both knives. Evidence of cold working was seen in two artefacts, one from Class 1 and the other from Class 2. Evidence of carburization was visible in all three classes. Evidence of piling, however, was only present in two artefacts from Class 1.

The intentional construction of iron artefacts from multiple alloys (i.e. knife constructions) was visible in six of the iron artefacts: four from Class 1, mostly knives, one nail from Class 2, and one bar from Class 3. The remaining artefacts were created from a single bar of either heterogeneous iron or a single alloy. Both single alloy and heterogeneous construction were present in all classes.

Alloy Usage

In terms of alloy usage Classes 1 and 2 utilized the range of alloys available; however, only the Class 1 artefacts contained heat-treated steel. The Class 3 artefacts had significantly less low carbon and high carbon steels than other two classes. Phosphoric iron was seen in all but two of the artefacts, one Class 2 and one Class 3. While both ferrite and steel were only present in approximately half of the artefacts. Alloy usage, in terms of how much of the artefact was constructed by a single alloy, are seen in Table 33. Four entire artefacts were constructed with a single alloy, two phosphoric iron and two ferritic. Phosphoric iron was also the dominant alloy in almost a third of the rest of the assemblage, often with small areas that were either slightly carburized or dephosphorized. Ferrite was only present in small amounts in almost a third of artefacts. Steel was dominant in one artefact, bar CC363, and present in small amounts in almost a third of the rest of the assemblage.

Quality of Materials

Table 34 shows that thirteen of the nineteen artefacts were clean with only small and sparse slag inclusions. The other six artefacts contained larger and many more inclusions.

Four of the eight artefacts from Class 1 artefacts were clean, while five of the seven artefacts from Class 2 artefacts and all four of the Class 3 artefacts were clean. If cleanliness reflects quality of metal, it is possible that the dirty Class 1 artefacts reflect a lower quality of object and the clean Class 2 artefacts reflect a higher quality of building materials. The Class 3 artefacts could easily be used to create the higher quality Class 1 and Class 2 artefacts.

7.4 Six Dials, Southampton, Hampshire

Southampton (Figure 32) is situated at the northern most point of the Southampton Water at the confluence of the River Test and River Itchen, with the River Humboldt joining just to the south. The Middle Saxon port town of Southampton (*Hamwic*) occupied an area of 42-45ha on the west bank of the River Itchen 0.3km northeast of the medieval walled town (Brisbane 1988: 101).

7.4.1 Saxon Southampton (*Hamwic*) (an urban market town)

Although there was a Romano-British settlement upstream from Hamwic, there has been no evidence uncovered of activity between the fifth and eighth centuries AD

(Andrews 1997: 252). Occupation began just prior to AD 700 (Andrews 1997: 20). The Saxons formed a settlement centred on what is now the St Mary's area of the city and, from the street layout, the settlement underwent rapid but controlled development during the early decades of the eighth century AD (Andrews 1997: 252). The origin of Hamwic may have been part of an initiative by the king of the West Saxons, Ine (AD688-726), to both gain control of a coastline and to establish a trading centre (Andrews 1997: 252, Brisbane 1988: 107). It has been estimated that between 4500 and 18,000 people lived in Hamwic at its height (Andrews 1997: 253). The social status of the population and the extent of Hamwic's importance in the Kingdom are still under debate (Andrews 1997: 255); however, that it gave its name to the hinterland, Hampshire, and its size indicate a great level of importance (James 2001: 199).

There are very few contemporary references to Hamwic. Instead, much of the history of the settlement comes from the archaeology (summarized below). The excavations have revealed imported goods from the far reaches of Britain, the Low Countries, Northern France, Frisia, and Denmark (Andrews 1997: 254).

The archaeological evidence showed that the settlement suffered almost complete abandonment by c. AD 900 (Andrews 1997: 255). The excavators believe that the reasons for this abandonment included depletion in trade due to civil wars amongst Charlemagne's heirs, Scandinavian raids from 840 onwards that made it unsafe for the population to remain, and the re-emergence of nearby Winchester as an important urban centre.

By the tenth century a new fortified settlement slightly south west of Hamwic, which became medieval Southampton, had been established (Brisbane 1988: 101).

7.4.2 Archaeology

The Six Dials excavation occurred for intermittent periods between April 1981 and August 1983 (Andrews 1997: 8). The excavation at Six Dials was 0.75km north east of the Medieval Bargate (north gate), within Nicholstown in Saint Mary's parish (*figure 32*). In relation to Middle Saxon settlement of Hamwic, the Six Dials site was 0.7km from the Saxon waterfront. The excavation area was approximately 5000 square meters (Andrews 1997: 1).

The excavation uncovered an early boundary ditch and street system, predating the buildings built along them (Andrews 1997: 31). These streets were straight, approximately 5 meters wide and up to several hundred meters in length. At Six Dials three streets were found: one north-south and two east-west. The properties along these streets remained relatively fixed for the duration of the settlement, with boundaries determined early in the development of the settlement (Andrews 1997: 46).

Over 68 Middle Saxon structures were identified at Six Dials (Andrews 1997: 49). All of these were rectangular timber buildings for domestic or industrial use. Complete ground plans were identified for approximately half of the structures. The remaining

structures either partially lay outside the excavation area or were partially destroyed during the intervening centuries.

7.4.3 Local Iron Working

Several hundred kilograms of iron working debris were found at Six Dials (Andrews 1997: 222). Most of this was in the form of smithing slag; however, hearth bottoms, hammerscale, fuel ash slag, other waste products, charcoal, heath/furnace lining, hearths, tools, and raw iron in the form of blooms, bars and rods have all been found at Hamwic (Andrews 1997: 222).

Two smithing complexes were identified by the large quantities of slag and charcoal. Both were on the north east corner of the junctions between the north-south and east-west streets. The structures associated with the smithies were an open-fronted shed or shelter along with a more substantial building. The structures for both of the smithies were associated with two structural phases. Both complexes were established in the early eighth century AD, remaining until the first half of the ninth century. Iron working appeared to be centred around one or more pits in each of the smithies. Neither smithy had any evidence for waist level hearths and no other features were found associated with the smithies (Andrews 1997: 223).

There was no evidence of iron smelting at Hamwic; however, one of the raw iron used by the smiths in Hamwic may have come from Romsey, 14km north west of Hamwic (Andrews 1997: 222)

7.4.4 Artefact Selection

A previous investigation of the ironwork from Southampton was conducted by McDonnell (Mack 1998, 1987a, 1987b). The investigation focused on the edged tools from the site. The sections from the knives previously investigated by McDonnell were reanalyzed for this project using the analytical techniques described in Section 5.5 (p.55). Further artefacts from Southampton were selected for this study in order to represent a wider range of artefact and class types. It was found that these artefacts were in a poor state of preservation, limiting the number of artefacts available for successful analysis. Table 35 summarizes the artefacts selected for analysis/reanalysis in this project.

7.4.5 Analysis Results

A total 19 artefacts from Southampton (table 35) were analyzed. These artefacts included 11 that were from Class 1, six from Class 2 and two from Class 3. The Class 1 artefacts included a variety of different categories of artefact types, including edged tools and a drawn wire tool (i.e. needle). Class 2 included one hook and five nails. Two bars made up Class 3 artefacts.

Class 1

The Class 1 artefacts included seven knives, an axe, a needle, a chisel, and a bill hook. The analysis and description of these artefacts can be seen in Table 36.

Manufacture

The Class 1 edged tools included six Type 2 knives composed of high carbon steel tips, three of which were heat treated, and heterogeneous or piled phosphoric iron/low carbon or high carbon steel. Only knife SOU99-92 was created from a single bar of heterogeneous iron with carburization along the outside of the tip and not of Type 2 construction. Chisel SOU169-1858, axe SOU24-22, and bill hook SOU31-92 all were composed of Type 3 construction with piled phosphoric iron, low carbon and high carbon steels. Axe SOU24-22 also contained heat treatment toward the tip and bill hook SOU31-92 included both bainite and tempered martensite.

Needle SOU31-1137 differed from the other Class 1 artefacts with a ferritic structure slightly carburized along the outside.

Alloy Usage

The alloy usage of the Class 1 artefacts was summarized in Table 38.

High carbon steel (>0.4%C) was present in five of the Class 1 artefacts. In the six Type 2 artefacts high carbon steel was used as the knife tip and in the three artefacts with piled structures it existed as either individual bands or as exterior carburization. In heterogeneous knife SOU99-92 high carbon steel was due to the carburization of the knife tip. Heat treatment of these high carbon steels was present in three of knives SOU169-540, SOU169-610, and SOU99-38, axe SOU24-22, and bill hook SOU31-92.

Low carbon steel (0.1-0.3%C) was present in nine of the Class 1 artefacts. In the Type 2 knives it was either a component of the heterogeneous structure, carbon diffusion from the high carbon steel tip or carbon in the welds of a piled structure. In the three artefacts with piled structures the low carbon steel existed as bands within the structure and in both needle SOU31-1137 and knife SOU99-92 the low carbon content was due to the carburization of the exterior of the object.

Phosphoric iron was present in ten of the Class 1 artefacts. In the Type 2 knives phosphoric iron was often the main component of the back structure either as the dominant part of a heterogeneous alloy, as a single alloy knife back with slight carburization, or as part of a piled structure. The three piled artefacts contained phosphoric iron as bands within the structure. In knife SOU99-92 the alloy was the largest component of the heterogeneous structure.

Ferrite was present on four of the Class 1 artefacts. Only needle SOU31-1137 was almost completely ferritic. In the other three artefacts ferrite was a minor component of heterogeneous structures.

Quality of Materials

Five of the eleven artefacts contained clean iron with only small slag inclusions. The other six artefacts were dirty with either a large amount of slag, especially at the weld lines of the piled structures, or large slag inclusions in the heterogeneous iron. Of the six Type 2 knives four were clean, while all of the Type 3 knives were dirty due to high

slag content present in the welds. The needle was very clean with almost no slag inclusions.

Class 2

The Class 2 artefacts included five nails and one hook. The analysis and description of these artefacts can be seen in Table 37.

Manufacture

Hook SOU31-1015 had a piled microstructure of heterogeneous phosphoric/ferritic iron with carbon present between the bands.

All of the Class 2 nails were constructed from individual bars except nail SOU31-1899, which was constructed from a piled bar of phosphoric iron with some carburization along the shank. Nails SOU31-1742, SOU31-1960 and SOU31-551 were constructed from primarily phosphoric heterogeneous iron that also contained small amounts of other alloys. The heterogeneous iron of nail SOU31-551 had been folded in on itself before the nail was shaped, as indicated by the squared shank exterior despite the interior fold. Nail SOU31-402 was completely composed of phosphoric iron with some minor carburization along one edge.

Alloy Usage

The alloy usage of Class 2 artefacts was summarized in Table 39.

Phosphoric iron was present as the primary component of the structure in all six of the Class 2 artefacts. In hook SOU31-1015 and nail SOU31-1899 the alloy composed most

of the bands in the banded structures. In nails SOU31-1742, SOU31-1960 and SOU31-551 phosphoric iron composed most of the heterogeneous structures. Nail SOU31-402 was the only artefact almost completely made of phosphoric iron.

Low carbon steel was present in three of the Class 2 artefacts: as carbon in the welds of the piled structure in hook SOU31-1015, as part of the heterogeneous structure in nail SOU31-1960 and as slight carburization in nail SOU31-402. High carbon steel was present in two of the Class 2 artefacts: as carburization of the shank of nail SOU31-1899 and as carbon in the fold of nail SOU31-551.

Ferrite was present only as a small component of the heterogeneous structure in three of the Class 2 artefacts: hook SOU31-1015 and nails SOU31-1742 and SOU31-1960.

Quality of Materials

Three of the Class 2 artefacts contained only clean metal with few slag inclusions: hook SOU31-1015) and nails SOU31-402 and SOU31-551. The rest of the nails contained significantly more slag inclusions SOU31-1742, larger slag inclusions SOU31-1960 or slag stringers SOU31-1899.

Class 3

The Class 3 artefacts from Southampton included two bars. The analysis and description of these artefacts can be seen in Table 37.

Manufacture

One of the bars SOU31-2110 was heterogeneous iron of mostly phosphoric iron with areas of ferrite and low carbon steel. The other bar SOU31-814 was heavily ghosted phosphoric iron with some exterior carburization.

Alloy Usage

The alloy usage of the Class 3 artefacts was summarized in Table 40.

Steel was present in the Class 3 artefacts as areas of low carbon steel in a heterogeneous matrix and high carbon steel carburization of an otherwise single alloy bar. Phosphoric iron was present as the main component of both the heterogeneous iron bar and the slightly carburized single alloy bar. Ferrite was only present as a component of the heterogeneous structure.

Quality of Materials

Both bars were clean metal with very few slag inclusions.

7.4.6 Phosphoric iron in Southampton

Phosphoric iron was found in 18 of the 19 artefacts (95%) examined from Southampton. In 13 of these artefacts phosphoric made up more than half of the structure. In the remaining five artefacts phosphoric iron was still a large component of the microstructure. There were no artefacts with only small amounts of phosphoric iron. Table 41 shows a summary of phosphoric iron usage and the indicators present in each of the artefacts.

The phosphoric iron indicators (table 42) present in the Southampton artefacts included ghosting in 17 of the 18 artefacts with phosphoric iron, large grains (ASTM 1-3) in 13 of the artefacts, and etch resistance in six of the artefacts. The micro hardness values averaged $Hv_{0.2}$ 169 and ranged $Hv_{0.2}$ 123 to $Hv_{0.2}$ 228, all significantly higher than un-worked ferritic iron.

All of the major ghosting structures were present in the Southampton artefacts (*figure 33*). Grain boundary ghosting and inter-granular ghosting were the two most prevalent forms.

Phosphorus and Carbon

Phosphorus was present in the steel from 13 of the Southampton artefacts (table 45). The low carbon steels with phosphorus were often due to the carbon diffusion from high carbon steels or the carburization of phosphoric iron. In three of the artefacts it was part of the heterogeneous structure. The phosphorus in the high carbon steels was found in three artefacts: twice as part of heterogeneous iron and once as part of a heat-treated Type 2 knife tip.

7.4.7 Arsenic in Southampton

Significant amounts of arsenic were present in knife SOU98-38 (*figure 34*), particularly in the non-steel knife back.

Elemental analysis (table 43) showed that high arsenic values were found at Hv3, the white weld line, in low carbon steel at Hv4, in ferrite at Hv5 and in phosphoric iron at Hv7.

7.4.8 Comparison with Previous Analyses

Table 44 summarizes McDonnell's (1987a, 1987b) analysis of all of the edged tools from the Southampton assemblage, including the ten edged tools re-examined in this study. This shows that the frequency of heat treatment in the analysed Southampton edged tools was 74%. Phosphoric iron, which McDonnell identified without elemental analysis, was present in 37%, or seven of the iron artefacts; however, the elemental analysis of the ten edged tools conducted in this study showed that all ten contained phosphoric iron, emphasizing the need for elemental analysis in alloy identification. Ghosting was reported in only one of the artefacts examined by McDonnell. This also differed from the re-evaluation in which nine of the ten edged tools examined in this study contained ghosted structures, one of which also demonstrated ghosting in non-phosphoric iron knife SOU99-92.

7.4.9 Summary and Class Comparison

Manufacture

Table 46 shows that there was a dramatic difference in artefact manufacture between classes. The Class 1 artefacts were mostly of composite construction, with only two exceptions: needle SOU31-1137 and knife SOU99-92. The Class 2 artefacts contained two heterogeneous piled structures and the rest were of single bar construction with

either heterogeneous iron or a slightly carburized single alloy. Many of the composite construction artefacts from Class 1 contained knife backs of similar to the Class 2 artefacts, using either heterogeneous iron or carburized single alloys. The Class 3 bars, heterogeneous SOU31-2110 and phosphoric SOU31-814, were also similar to the Class 2 assemblage and the Class 1 knife backs, needle SOU31-1137 and knife SOU99-92.

Evidence of cold working and heat treatments were only present in Class 1 artefacts. Slightly less than 50% of the Class 1 artefacts, all edged tools, were heat treated. Only one artefact bill hook SOU31-92 showed evidence of cold working; however, the increased hardness levels in the ferrite from all three classes (table 47) indicates most of the ferrite bearing artefacts were cold worked at levels below 40% reduction.

Alloy Usage

Table 48 shows the differences in alloy usage between the different classes. Both Class 1 and Class 2 contained the full range of alloys available in the Early Medieval period. Only the Class 1 artefacts, however, contained heat-treated steel. High carbon steel was seen in 68% of the artefacts from Southampton. All the Class 1 artefacts contained high carbon steel, while only 33% of the Class 2 artefacts and half of the Class 3 artefacts contained high carbon steel. The low carbon steels were also predominantly in the Class 1 artefacts, with 33% of Class 2 and half of the Class 3 artefacts. Both phosphoric iron and ferrite were prevalent in all three classes. Ferrite, however, was found in the smallest number Southampton artefacts (8/19 artefacts or 42%).

It should be noted that the presence of ferrite and low carbon steels in many of the artefacts was due to them being part of a heterogeneous structure and therefore not through specific alloy selection by the smith.

Alloy usage in terms of how much of the artefact was constructed by a single alloy is seen in Table 49. Phosphoric iron was the largest component in many of the artefacts. It was often used as either an individual alloy bar or as the largest component of the heterogeneous bar that was welded to high carbon steel, in composite artefacts, or shaped into single bar objects such as nails. The other alloys were used as smaller parts of heterogeneous structures or in composite compositions. Needle SOU31-1137 was the only artefact with no phosphoric iron.

Quality of Material

Table 50 shows that just over half of the artefacts were of clean metal. Approximately half of Class 1 and half of Class 2 were clean, while all of Class 3 were clean. If cleanliness reflects quality of metal, it is possible that the dirty Class 1 artefacts reflect a slightly lower quality of object and the clean Class 2 artefacts reflect a higher quality building materials. The Class 3 bars could easily be used to create the knife backs of the Class 1 artefacts and the higher quality nails of the Class 2 artefacts.

7.5 Brandon Road, Thetford, Norfolk

Early Medieval Thetford was located at the meeting point of the rivers Little Ouse and Thet (Wallis et al. 1995) (figure 35). Archaeological excavation has shown that the Early and Middle Saxon settlement was near Red Castle Furze and Thetford Castle, to the west and east of the modern town centre. The Late Saxon settlement developed to south of the river in late ninth century AD.

7.5.1 Early Medieval Thetford (A rural settlement)

Early and Middle Saxon remains have been uncovered in four separate excavations in Thetford near the Brandon Road site (Atkins and Aileen 2002: 3). These remains may have been part of a single settlement that lay along the Little Ouse valley over an area of at least 800m by 200m. Archaeologists have noted an increase in population density west of the modern town during this period (Wallis et al. 1995). The Early and Middle Saxon settlement was identified near Redcastle Furze (Andrews 1995) and Brandon Road (Dallas 1993). Thetford in the Middle Saxon period was not a substantial town; however it may have been an important one (Wallis et al. 1995).

By the early tenth century AD the settlement had expanded considerably, including the area south of the river, and the population significantly increased (Wallis et al. 1995). The town had its own mint (Welch 1992) and was encircled by a defensive bank and ditch on both north and south of banks of the river. This urban expansion included the development of markets in late ninth-early tenth centuries AD under Scandinavian rule (Hadley 2000: 31).

By the time of the Domesday survey the town ranked as the sixth largest in England and was the seat of the bishopric between AD 1071 and AD 1094 (Wallis et al. 1995). In the late eleventh century AD the town went into decline and the settlement south of the river was abandoned.

7.5.2 Archaeological Background

The Brandon Road excavation (Atkins and Aileen 2002) was located 2.4km west of modern Thetford town centre, on the south bank of the river Ouse. The area was a rural settlement outside of Early Medieval Thetford with occupation dating from the fifth to ninth centuries AD.

The excavation at Brandon Road uncovered early Saxon activity (fifth to seventh centuries) that included seven sunken buildings, two post-hole structures, five ovens, and pits. The buildings may have been deliberately located around a rectangular space. These buildings were abandoned and the site reverted to fields confined within north to south boundary ditches in the Middle Saxon period (eighth to mid ninth centuries). These ditches were later replaced by a large enclosure containing an industrial oven complex, two possible buildings, and a large midden. This industrial complex contained metalworking waste. The enclosure appears to have been short-lived and was overlain by a post-hole structure and the former boundaries filled with iron objects and metalworking waste. Ultimately the site was abandoned by the middle of the ninth century AD.

7.5.3 Iron Working

Metalworking debris was present in the backfill of one of the fifth-seventh century AD buildings (Atkins and Aileen 2002: 22-3). The debris included smelting and smithing slags, hammerscale, fragments of hearth or furnace structures, metalworking tools (chisels and punches) and a hoard of scrap metal. The majority of the debris was found in secondary deposits and dumping layers. There was a concentration of metal working activity in the southwest corner of the excavated area. Very little charcoal was found; however, the two sunken structures and the industrial complex are still believed to be places of metalworking.

7.5.4 Artefact Types Selection

The iron artefacts from Thetford were the first sampled in this research project. The sampling selection of the Thetford assemblage differed from the other sites due to a re-focusing of the research aims and objectives over the course of the project. The sampling for Thetford included Roman artefacts and UI iron. These Roman artefacts included a knife, a belt buckle, and a strip, whose reports will be included in Appendix I. The data from the Roman artefacts will be included in the examination of the properties of phosphoric iron, but not included in the rest of the discussion. The UI artefacts, however, will be included.

7.5.5 Analysis Results

A total 24 artefacts from Thetford were sampled (table 51). Eight were from Class 1, seven were from Class 2, two were from Class 3, and four were UI artefacts.

Class 1

The Class 1 artefacts include three edged tools Thet271, Thet427, and Thet203-4, two other tools Thet241 and Thet249, and two clothing accessories Thet286 and Thet414. The analysis and description of these artefacts can be seen in Table 53.

Manufacture

Each of the edged tools in the Class 1 artefacts, including two knives and a chisel, had a different construction. Knife Thet271 consisted of a central band of phosphoric/ferritic iron sandwiched between piled low carbon and high carbon (bainitic) bands, creating a structure that could have been classified as either a reverse Type 1 or a Type 3. Similarly chisel Thet203-4 with its central band of high carbon steel sandwiched between piled bands of phosphoric iron and ferrite also has a structure that could have been classified as either a Type 1 or Type3. Both knife Thet271 and chisel Thet203-4 exhibited elongated ghosting structures and slag inclusions despite the presence of equiaxed grains, indicating heavy working before being annealed. Knife Thet427 was constructed in a similar fashion to a Type 2 blade construction. The artefact was composed of four pieces of phosphoric iron with the phosphoric tip butt welded to a back constructed from the other three pieces with small amounts of ferrite at the weld lines.

The other tools in the Class 1 assemblage included punch Thet241 and awl Thet249. Punch Thet241 was constructed from a single heterogeneous piece of iron. Awl

Thet249 was constructed from a high carbon steel piece welded to a two pieces of ferrite with large amounts of carbon diffusion.

The two buckles were significantly different. Buckle Thet286 was a clean ferritic bar with some carburization along the exterior edge and buckle Thet414 was dirty phosphoric iron with small areas of ferrite with a series of high slag inclusion natural weld lines.

Alloy Usage

Evidence of all three iron alloys could be seen in the Class 1 artefacts. Table 52 shows the number of artefacts with the specified amount of each alloy present in the microstructure.

Steel was present in all but two of the artefacts in the Class 1 assemblage. In the two edged tools containing steel the alloy was used as a component in the piled structure; however only chisel Thet203-4 contained a central steel cutting edge. Both of the other tools, punch Thet241 and awl Thet249 had steel components. Punch Thet241 had a central area of high carbon steel ($>0.3\%C$) diffusing outward into the rest of a heterogeneous structure. Awl Thet249 had a high carbon steel component welded to several pieces of ferrite, which subsequently experienced carbon diffusion. Only one of the buckles had steel present as the result of exterior carburization along one side.

Phosphoric iron was present in five artefacts from the Class 1 assemblage and in three of these artefacts it comprised more than half of the microstructure. In the edged tools

phosphoric iron was the central band of knife Thet271, made up the majority of the structure in knife Thet427, and was part of the piled outer structure of chisel Thet203-4. Phosphoric iron was not present in either punch Thet241 or awl Thet249 and only present in buckle Thet414 as part of its heterogeneous structure. The phosphoric iron grain sizes for the Class 1 assemblage ranged from ASTM 4 to ASTM 6, with relatively normal hardness values ranging from Hv_{0.2}121 to Hv_{0.2}156.

Ferritic iron was present in six of the artefacts from the Class 1 assemblage. In buckle Thet286 the alloy composed most of the structure with slight carburization along one edge. Three of the other artefacts contained ferrite as a small component of a heterogeneous structure; while knife Thet271 and chisel Thet203-4 had ferrite bands as part of a piled structure.

Quality of Materials

The quality of Class 1 iron was generally good. Only two of the artefacts contained dirty metal. Belt buckle Thet414 contained many small and large slag inclusions, especially along natural welds. Knife Thet427 had numerous slag inclusions at the weld lines as well as medium to large inclusions within the iron components.

Class 2

The Class 2 artefacts include a loop pin, a ferrule, a rivet, two joiners dogs, five nails, and an unknown tool. The analysis and description of these artefacts can be seen in Table 54.

Manufacture

The loop pin was a ferritic with a central area of grain size ASTM 5 bounded on both sides by smaller grained ferrite (ASTM7-8) with grain boundary pearlite. Ferrule Thet176 was constructed from an inner band of heterogeneous phosphoric/ferritic iron welded to an outer band of low carbon steel. Rivet Thet198 was very corroded, making the structure difficult to determine, but the iron present was a heterogeneous phosphoric/ferritic iron with an area of low carbon steel at one end. Both of the joiners dogs were constructed from heterogeneous bars. Joiners dog Thet199 was a low carbon steel bar with areas of high carbon steel and Joiners dog Thet237 was mostly ferritic with a small area of phosphoric iron.

The five Class 2 nails were each made from a single bar that had been shaped. Three nails Thet277b, Thet287 and Thet334, were constructed from heterogeneous bars. Nail Thet277a and nail Thet287 were a combination of phosphoric iron, low carbon steel and high carbon steel; while nail Thet334 was a combination of phosphoric iron and ferrite. Two other nails Thet277a and Thet302 were completely phosphoric and completely ferritic with slight carburization along the edges.

Unknown tool Thet248 was identified by the excavators as a tool possibly used for fishing with two heterogeneous phosphoric/ferritic iron hooked ends joining at a shank that contained a heterogeneous banded structure of phosphoric iron, high carbon steel and ferrite.

Alloy Usage

Evidence of all three iron alloys could be seen in the Class 2 artefacts. Table 55 shows the number of artefacts with the specified amount of each alloy present in the microstructure.

High carbon steel ($>0.3\%C$) was present in five of the Thetford Class 2 artefacts. In bar Thet287 high carbon steel was the primary component with only a small area of ferrite along one side. High carbon steel in the other four artefacts was either due to carburization nail Thet277a and nail Thet302, or was small part of heterogeneous structure joiners dog Thet199 and tool Thet248.

Low carbon steel ($0-0.3\%C$) was present in six of the Class 2 artefacts. In five of these artefacts the alloy was only a small component of greater structure, while joiners dog Thet199 was almost completely composed of low carbon steel.

Quality of Materials

Six of the Class 2 artefacts contained clean iron, more than half of the Class 2 assemblage. These artefacts included heterogeneous and banded artefacts. The five dirty artefacts contained large slag inclusions, many slag inclusions or large amounts of slag trapped in welds and folds.

Class 3

The Class 3 assemblage includes two bars. The analysis and description of these bars can be seen in Table 58 on the following page.

Manufacture

Bar Thet209 consisted of a single alloy composition while bar Thet228 was a banded structure with multiple alloys.

Alloy Usage

Evidence of all three iron alloys could be seen in the Class 3 artefacts. Table 56 shows the number of artefacts with the specified amount of each alloy present in the microstructure.

Steel was present in bar Thet228, in the form of bands of low and high carbon steel. Phosphoric iron was also present in bar Thet228 containing as large grains (ASTM 2) and average hardness ($Hv_{0.2}178$) bands. Bar Thet209 was completely composed of Ferrite with an average hardness of $Hv_{0.2}101$ and average grain size of ASTM 4.

Quality of Materials

The iron found in the bars from Thetford was fairly clean; however, the inclusions between bands in bar Thet228 were abundant with several large inclusions.

Unidentified Iron Artefacts (UI)

Four unidentified artefacts included two identified as strips and two identified as iron fragments.

Manufacture

The UI assemblage included a piled ferritic/low carbon steel sheet fragment, a banded ferritic strip slightly carburized and cold worked on either end, a tapering strip of phosphoric iron completely encased in high carbon steel, and a heterogeneous fragment with areas of phosphoric iron, low carbon steel and high carbon steel where the metal has been folded and slight exterior carburization from the chisel set.

Alloy Usage

Evidence of all three iron alloys could be seen in the UI artefacts. Table 57 shows the number of artefacts with the specified amount of each alloy present in the microstructure.

Steel was present in all four artefacts of the UI assemblage. Sheet fragment Thet210 had low carbon steel within its piled structure. Strip Thet322 was a phosphoric band completely encased in high carbon steel. Chisel set fragment Thet203-5 had steel as part of its heterogeneous iron with higher carbon concentrations in the natural folds. Both strip Thet305 and fragment Thet203-5 had some exterior carburization.

Quality of Materials

The UI artefacts show generally clean iron with few large slag inclusions. Fragment Thet203-5, however, had both areas of clean iron and areas with lots of little slag inclusions. More inclusions were present at the fold.

7.5.6 Phosphoric iron in Thetford

Phosphoric iron was found in 56% of the 23 artefacts in the assemblage (table 59). Only one, nail Thet277a, was completely composed of the alloy. Another two, buckle Thet414 and knife Thet427, were almost all phosphoric iron except for small areas of ferrite. In the edged tools of the Class 1 artefacts the alloy was the central band of knife Thet271 and part of a piled structure chisel Thet203-4. In ferrule Thet176 and tapering strip Thet322 the phosphoric iron was a non-steel component specifically welded to a steel (low and high carbon) component. In joiners dog Thet237 and nail Thet334 phosphoric iron existed only in small areas in a generally ferritic structure. In rivet Thet198, nail Thet277b, and fragment Thet203-5 the alloy was one of many in a heterogeneous structure. Finally in bar Thet228 phosphoric iron existed as bands within a greater banded structure.

There was no evidence in the assemblage of specific selection of phosphoric iron over ferrite; however, as seen in knife Thet271, chisel Thet203-5, ferrule Thet176 and the tapering strip Thet322 phosphoric iron was used as the non-steel component of the structure.

The phosphoric iron indicators present in the Thetford assemblage (table 61) included ghosting, etch resistance, a few instances of large grains, and hardness levels above Hv_{0.2}124. The presence of ghosting was identified in all but one of the phosphoric iron artefacts. Etch resistance was observed in nine artefacts, two of which had extremely low phosphorus contents. On average the grain size of phosphoric iron ranged from ASTM 4 to ASTM 6, with only a few instances of larger grains.

The ghosting structures present in the Thetford assemblage (figure 36) included grain boundary, inter-granular, edged effects, and slag inclusion ghosting. No pearlitic ghosting was present in the Thetford assemblage. Slag inclusion ghosting was the most common ghosting structure.

Phosphorus and Carbon

Significant amounts of phosphorus were detected in the steel of eight of the artefacts from Thetford (table 60). The Class 1 artefacts and the chisel set fragment contained phosphorus in high carbon steels between 0.4-0.7%C. These phosphorus contents were relatively low at 0.16-0.21wt%P. The unknown tool Thet248 contained a significant phosphorus content of 0.41wt%P in the 0.4%C steel structure. In the rest of the artefacts the phosphorus varied between 0.17 and 0.62wt%P within the low carbon steel.

7.5.7 Arsenic in Thetford

None of the artefacts from Thetford showed significant amounts of arsenic.

7.5.8 Class Comparison

Manufacture

Evidence of manufacture of iron assemblage from Thetford is summarized in table 62.

Evidence of cold working was only visible in two of the artefacts, joiners dog Thet237 and strip Thet305. Increased hardness values, however, were seen in the ferrite of many of the artefacts. Table 63 shows the average hardness value of ferrite for each class. The increased values for Class 1, Class 2 and UI artefacts indicate that artefacts from these classes have undergone cold working to less than 40% reduction.

Heat treatment was only present in one of the Class 1 artefacts, knife Thet271. This reverse Type 1 knife was constructed from two bands of bainite sandwiching a central phosphoric band. Evidence of carburization was visible in three Class 1 artefacts, one Class 2 artefact and one UI artefact. Evidence of piling was present in two of the Class 1 artefacts, one Class 3 artefact and one UI artefact. The piled knives of Class 1 were both classified as composite construction due to the specific placement of the steel in the structure, while the piled artefacts of Class 3 and UI did not appear to have an intentional structure.

There were more Class 1 artefacts of composite construction than in any of the other classes. The Class 1 artefacts included three edged tools and the awl. The Class 2 artefacts tended to require less complicated construction, often on the shaping of a single bar. Only one Class 2 artefact was composite, ferrule Thet176, which was constructed with an exterior low carbon steel shell welded to interior phosphoric/ferritic iron. One of the UI artefacts was also composite, tapering strip Thet322, indicating that it was intended for a specific use. The UI composite construction artefact consisted of a phosphoric iron completely encased in steel.

Single alloy construction was seen in one completely ferritic Class 3 bar Thet209. Heterogeneous iron was found in Class 1, Class 2 and UI artefacts; however, this mix of alloys composed the majority of the Class 2 artefacts.

Alloy Usage

All of the alloys were present in more of the Class 1 artefacts than in the other classes, with ferrite the most abundant alloy present in the entire assemblage. Table 64 shows the number of artefacts containing each alloy based on class and Table 65 shows the number of artefacts with the specified amount of each alloy present in the microstructure.

High carbon steel was present in all classes, but was most abundant in the Class 1 artefacts. This abundance may have been due to the use of high carbon steel as the cutting edges of the edged tools as well as the presence of steel in the heterogeneous iron used to construct the Class 1 artefacts. Table 65 shows that none of the artefacts contained large amounts of the alloying element. The steel present in the Thetford artefacts was due to two possible sources. In one source, the alloy was either welded to a non-steel structure, as a part of the Class 1 composite constructions, or as a result of carburization. The other source was as a component of a heterogeneous structure.

Low carbon steel was present in all of the classes. This may reflect the carburization of single alloy artefacts during manufacture or carbon diffusion that does not occur until the bar was used in object manufacture. Low carbon steel was present in high amounts

in three of the artefacts. In the other 13 artefacts the alloy was often as a small component of a carburized artefact, the result of carbon diffusion, or a component of a heterogeneous structure.

Phosphoric iron was the dominant alloy for six artefacts, two from Class 1 and four from Class 2, and a smaller component of eight other artefacts. In the Thetford assemblage the alloy was used as often in each class as ferritic iron and in similar distribution for each class.

Ferrite composed the entirety of two artefacts and was the dominant alloy in another six artefacts. It also occurred in small amounts in nine other artefacts.

Quality of Material

Approximately 70% of the Thetford artefacts contained clean iron (table 66), with the majority in Class 1. As compared to the other classes Class 1 and UI artefacts were well constructed with clean iron and clean welding techniques.

7.6 South Manor, Wharram Percy, Yorkshire

Wharram Percy is situated on the western edge of the chalk Wolds in North Yorkshire, England (figure 37).

7.6.1 Early Medieval Wharram Percy (a rural manorial settlement)

Most of what is known about Early Medieval Wharram Percy is derived from the Domesday Book compiled shortly after AD 1086 (Stamper and Croft 2000: 1). It states that Wharram Percy is the property of the king by 1086 with two manors and nine carucates (approximately 4.4km²) of land. At the time of the Domesday Book, however, there was no attempt to investigate the prior history of the settlement (Stamper and Croft 2000: 3). The multiple excavations of the village of Wharram Percy have been the only source of information prior to AD 1086.

The area around Wharram contained several high-status settlements during the Roman period (Milne and Richards 1992: 90). Villas have been found at Wharram Grange and Wharram-le-Street with mosaics and traded goods from Gaul, Spain, possibly Italy and other parts of England. These estates may have survived into the fifth-sixth centuries AD. A third villa may have been present at Wharram Percy itself, possibly in the area of the north manor. Roman finds have been found in the excavations of both the North and South Manors (Milne and Richards 1992: 90, Stamper and Croft 2000: 195), indicating a significant Roman building somewhere on the plateau (Stamper and Croft 2000: 196).

There was a hiatus in evidence of habitation during the Early Medieval period (Stamper and Croft 2000: 196). By the sixth century AD several dispersed Anglo-Saxon structures, including both sunken-featured structures and posthole structures, existed in the area of Wharram Percy (Milne and Richards 1992: 93). The evidence of occupation increased and by the eighth century AD there was evidence of a number of

timber buildings and a smithy centred around the South Manor area (Milne and Richards 1992: 94); however, the layout of the settlement remained unplanned. Due to the evidence indicating weapons repair at the smithy, non-ferrous metal working, Tating-type pottery, long distance trade goods, sceats, and sculpted stone, the settlement by this period was interpreted as high status (Stamper and Croft 2000: 199). The excavators have also speculated that during the eighth century Wharram Percy may have been a part of a monastic or privately owned estate (Stamper and Croft 2000: 200).

By the ninth and tenth centuries AD the origins of the manors present in post-Conquest Wharram Percy may have been established (Stamper and Croft 2000: 195).

7.6.2 Archaeology

Excavations around the village of Wharram Percy have happened sporadically since the 1950's (Stamper and Croft 2000: 16). The excavation of the South Manor is the most recent, occurring over ten seasons between 1981- 1990. The excavation was carried out under the auspices of the Medieval Village Research Group, the Medieval Settlement Research Group, and the Department of Archaeology, University of York, under the direction of John Hurst (Stamper and Croft 2000: xi).

The Middle Saxon segment of the excavation contained large amounts of evidence for occupation (Stamper and Croft 2000: 27). Numerous postholes indicated the presence of at least one complete building (Stamper and Croft 2000: 29). This building had an

identifiable doorway, a hearth feature, and an exterior privy hut. Two major ditches and an array of pits were also found on the site. These contained large amounts of Middle Saxon pottery as well as both domestic and industrial finds. Many of these finds were associated with key areas within the site, including a large domestic area, a smithy, and a pit that researchers believed to be used for rituals (discussed below).

Though previously large amounts of evidence from the Late Saxon have been found in other parts of Wharram Percy, only a small handful of pre-Conquest artefacts were found during the South Manor excavation, indicating that this area was not in use.

7.6.3 Local Iron Working

The excavation of the South Manor of Wharram Percy uncovered a Middle Saxon smithy (Stamper and Croft 2000: 32). This smithy included two main features: a heavily burnt area, including a block of burnt limestone, and a depression identified as a smithy dump. A series of postholes indicated a possible structure bounded one edge of the smithy area. Smithing finds included 78.8kg of smithing slag, 12.9kg of hearth bottoms, 14.2kg of hearth lining material, 7.5kg of fuel ash and cinder, and a small amount of hammerscale (McDonnell 2000: 156-159). Also found in the smithy was associated debris, including stock iron bars and iron nails.

A forthcoming chapter (McDonnell et al. forthcoming-a) discusses the analysis of the smithy material conducted by the author and associated researchers. The

metallographic analysis of the nails and bars, however, was conducted for this research project and the results are summarized below.

No evidence of smelting was found at Wharram Percy.

7.6.4 Artefacts Selected

The artefacts from Wharram Percy (table 67) were analyzed for multiple projects, resulting in different sampling techniques and a larger quantity of data than several of the other sites. The knives were sampled and analysed by Blakelock (2006), while the bars were sampled and analysed by both the author and Chabot (2007). Finally the nails were specifically selected, sampled and analyzed for this project alone.

Despite earlier analyses, all the artefact sections underwent the same analytical analysis as describe in Section 3.5. Preservation at this site was very good.

7.6.5 Analysis Results

A total of 27 artefacts were examined from Wharram Percy. These artefacts included 8 Class 1 artefacts (knives), 10 Class 2 artefacts (nails), and 9 Class 3 artefacts (bars). Their microstructures can be seen in the sections below.

Class 1

The Class 1 assemblage included eight knives. The analysis and description of these artefacts can be seen in Table 68.

Manufacture

The knives (Blakelock 2006) from Wharram Percy were of Type 0, Type 2 and Type 3 constructions. The Type 0 knife, uncommon for this period, was made of a heterogeneous phosphoric/ferritic iron that has slight carburization along one edge. Five of the knives were of Type 2 construction with high carbon steel cutting edges in four of the five knives. The blade of knife WP159 was also heat-treated. Knife WP176 had heavily worn a low carbon steel edge and may have once contained a high carbon steel cutting edge. Three of the Type 2 knives have phosphoric iron backs and two have ferritic iron backs, one of which was pitted. There were three Type 3 knives, which were constructed by sandwiching a low-medium carbon steel between bands of phosphoric iron. In one of these artefacts, knife WP442, the phosphoric iron was pitted.

Alloy Usage

Evidence of all three iron alloys could be seen in the Class 1 artefacts. Table 71 shows the number of artefacts with the specified amount of each alloy present in the microstructure.

High carbon steel (>0.3%C) was used in the Class 1 artefacts as the steel cutting edge of the knife blade in Type 2 knives, it was welded to phosphoric or ferritic backs in Type 3 knives and it was sandwiched between phosphoric bands. Only in the Type 0/2

heterogeneous knife WP307 was the steel component not a separate piece of metal welded to a ferritic or phosphoric piece. Only knife WP159 showed signs of heat treatment.

Phosphoric iron was used in six of the eight knives, either as the knife back or as the sandwiching bands in the Type 3 knives. The hardness values ($Hv_{0.2}$ 142-185) are within average phosphoric iron range, while three of the knives showed large grains (ASTM 2-4).

Ferrite was found in four of the knives. Two of these knives, knife WP307 and knife WP176, the ferrite was present in the heterogeneous structure along with phosphoric iron. In the two other knives, knife WP308 and knife WP237, the alloy composed entire pieces of metal used in construction. Hardness values and grain size were only exceptional in knife WP308 where the hardness was high ($Hv_{0.2}$ 181) and the grain size was large (ASTM 3).

Quality of Materials

The metal in most of the knives was clean with small inclusions. Two of the knives, however, were of lower quality metal. Knife WP442 was a thinly piled structure with lots of inclusions between bands, which were pathways for corrosion. The individual bands appeared to be fairly clean. Knife WP472 differed from the rest of the knives by having a clean high carbon steel cutting edge welded to a phosphoric iron back that was high in slag inclusions both large and small.

Class 2

The Class 2 assemblage consists of ten iron nails. The analysis and description of these artefacts can be seen in Table 69.

Manufacture

All of the Class 2 artefacts were nails. The nails were constructed from a single piece of iron that had been shaped. Evidence of cold working was in the form of elongation of grains in nails WP218 and WP556 and increased hardness due to work hardening in nails WP160 and WP218. Further evidence of construction was found in nails WP160 and WP556 where the elongation ghosting and the slag inclusions show how the head was created by shaping the end of the bar from which the nail was made; however, the nails were not worked to the extent that the grain structure showed distortion. Nail WP556 also showed slight carburization ($<0.1\%C$) of the nail shank on one side.

Alloy Usage

Evidence of all three iron alloys could be seen in the Class 2 artefacts. Table 72 shows the number of artefacts with the specified amount of each alloy present in the microstructure.

High carbon steel was present in the heterogeneous structure along with low carbon steel only in nail WP394. Four other nails contained heterogeneous structures with low carbon steel (0-0.3%C) and ferrite/phosphoric iron. Only nail WP556 had obvious carburization.

Two of the artefacts, nail WP160 and nail WP218, were composed completely of phosphoric iron with heavy ghosting and increased hardness ($>Hv_{0.2}200$). Another artefact, nail WP556, was also constructed from ghosted phosphoric that but was slightly carburized and without increased hardness ($Hv_{0.2}177$). The rest of the nails containing phosphoric iron were constructed from heterogeneous bars containing other alloys. Grain sizes varied between ASTM 1-5.

Two of the artefacts, nail WP287 and nail WP532, were completely composed of ferritic iron. The three other nails with ferritic iron were of heterogeneous structure, two with pearlite and one with phosphoric iron. Hardness values varied between $Hv_{0.2}86-141$. Grain sizes were relatively small, ASTM 5-7.

Quality of Materials

There was variability in the quality of the materials used for the Wharram Percy Class 2 artefacts. Four of the nails were exceptionally clean, with only a few small inclusions. Three of the artefacts, nail WP218, nail WP394 and nail WP398, contained a slightly larger amount of inclusions and small areas where an increase in inclusions may have increased corrosion penetration.

Four nails were composed of lower quality metal with large amounts of slag inclusions. Two of these nails, nail WP219 and nail WP556, were formed from a single alloy with inclusions randomly distributed. The other two of these nails, nail WP287 and nail

WP550, contained large amounts of slag lines that were probably the result of the formation bars used to create the nails.

Class 3

Nine bars composed the Class 3 assemblage. The analysis and description of these bars can be seen in Table 70.

Manufacture

The majority of the iron bars were composed of heterogeneous structures with a mix of the alloys in no intentional distribution. Exceptions to this were bars WP95 and WP320, which were completely composed of phosphoric iron, and bars WP115 and WP299 which were either completely phosphoric or completely ferritic with small areas of carburization on their exterior. Finally, bar WP120 differed from the rest of the bars with a slightly banded structure of phosphoric iron sandwiching a ferritic/low carbon steel band with no visible weld-line. It was possibly a heterogeneous, natural structure.

Alloy Usage

Evidence of all three iron alloys could be seen in the Class 3 artefacts. Table 73 shows the number of artefacts with the specified amount of each alloy present in the microstructure.

High carbon steel was seen in two of the bars. In one incidence it comprised a core of a low carbon steel bar. In the second incidence it was the result of carburization of a

ferritic iron bar. The steel that was present in the rest of the artefacts was low carbon steel. The low carbon steel was either present as a heterogeneous component of the bar or due to carburization of the exterior of the bar.

Three of the bars were completely composed of phosphoric iron, one of which was slightly carburized. In bar WP260 phosphoric iron existed in a heterogeneous combination of multiple alloys. In bar WP547 phosphoric iron was naturally banded with ferritic iron. Hardness values were normal ($Hv_{0.2}$ 131-177) in all but bar WP320, which had a slightly elevated hardness of $Hv_{0.2}$ 205. Grain size varied between ASTM 2-6.

Ferrite was found in five of the bars. In bar WP299 the alloy comprised most of the bar but it had slight carburization along the outside. In bar WP260 and bar WP364 ferrite existed as one component of a heterogeneous structure. Bar WP120 contained ferrite mixed with low carbon steel in a central band within the structure. Bar WP547 contained a naturally banded mixture of ferrite and phosphoric iron. The hardness values for ferrite in the bars varied between $Hv_{0.2}$ 90-158, and the grain sizes remained relatively small (ASTM 5-8)

Quality of Materials

The material quality for Class 3 overall was poor. Six of the nine bars were classified as dirty, with large amounts of slag inclusions that increased the susceptibility of corrosion. The three remaining clean bars were not exceptionally clean, but contained

mostly small slag inclusions with a few larger inclusions. Only bar WP364 was significantly clean.

7.6.6 Phosphoric iron in Wharram Percy

Phosphoric iron was found in 18 of the 27 artefacts (66%) from this assemblage (table 74). It was found in four knife backs/flanks, in one banded structure, in seven complete objects and as a part of a heterogeneous structure in six of the objects. Despite obvious use as the non-steel iron in composite objects such as the knives, there was no indication that phosphoric iron was selected for use instead of ferritic iron.

Phosphoric iron indicators are present in the majority of the 18 artefacts containing phosphoric iron (table 76). Ghosting was found in phosphoric iron with grain size that ranged from ASTM 1 to 6. Thirteen of the artefacts with phosphoric iron contained grain sizes greater than ASTM 3. Etch resistance was seen in 10 of the artefacts, including one that did not contain phosphoric iron. Hardness values ranged between Hv_{0.2} 120 and Hv_{0.2} 224. The higher hardness values are well above the average and may be the result of work hardening.

A variety of ghosting structures were visible in the Wharram assemblage, including slag inclusion ghosting, edge effect ghosting, inter-granular ghosting, pearlitic ghosting, and grain boundary (GB) ghosting. Slag inclusion ghosting and inter-granular ghosting were the most prevalent (figure 38).

7.6.7 Phosphorus and Carbon

Table 75 shows that up to 0.6wt%P was found in both low carbon and high carbon steels in all three classes. This mixing occurred in heterogeneous structures and carburized phosphoric iron.

7.6.8 Arsenic in Wharram Percy

Arsenic was seen the white weld lines of knife WP159 and found throughout the microstructure of nail WP218 (figure 39). The analysis results for nail WP218 can be seen in Table 77. These show that the nail head has between 0.3-0.8wt%As along with a phosphorus content of 0.2-0.3wt%P. The nail also exhibited increased hardness levels (up to Hv_{0.2}292) that may indicate work-hardening.

7.6.9 Summary of Alloy Usage and Class Comparisons

Manufacture

Evidence of manufacture is summarized in Table 78 based on class.

Evidence of cold working was only visible in two of the Class 2 artefacts, nail WP218 and nail WP556. Increased hardness values, however, were seen in the ferrite of many of the artefacts. Table 79 shows the average hardness value of ferrite for each class, indicating that artefacts from all classes show evidence of cold working.

Heat treatment was only present in one of the Class 1 artefacts. Knife WP159 contained a tempered martensitic tip welded onto a phosphoric iron knife back.

Evidence of carburization was visible in one Class 1 artefact, two Class 2 artefacts and two Class 3 artefacts. Evidence of piling was present in two of the Class 1 artefacts, as either part of a Type 3 structure and as a knife back in a Type 2 construction.

Composite constructions were only found in seven Class 1 knives. Single alloy construction was seen in four of the Class 2 artefacts and two of the Class 3 artefacts. Heterogeneous iron was found in all three classes; however, this mix of alloys composed the majority of the Class 2 artefacts.

The assemblage of Class 3 stock iron could have been used to create objects similar to those found in Class 1 and Class 2.

Summary of Alloy Usage

In the Wharram Percy assemblage all alloy types were present (table 80), along with one case of heat-treated steel. Phosphoric iron was found in the largest number of artefacts in all three classes, with ferrite slightly less common. Steel was more abundant in the Class 1 artefacts, due to its use in the cutting edges of the edged tools. The low carbon and high carbon steels present in Class 2 and Class 3 were components of the heterogeneous iron.

Table 81 shows the number of artefacts with the specified amount of each alloy present in the microstructure. In this assemblage the use of phosphoric iron was used to create the majority of single alloy objects and objects where the alloy comprises the

majority of the structure. Ferrite was the other alloy used to create single alloy objects. Both low carbon and high carbon steels only comprised less than 50% of most of the artefacts in which they were used.

Quality of Material

Table 82 summarized the quality of the iron for each of the classes. The quality of the metal in Class 1 and Class 2 was high, with only a few artefacts constructed from metal with large amounts of slag inclusions. Class 3 differed from the other two classes by containing less than half of the iron with clean metal. This may indicate specific selection by the smithy of clean bars for object manufacture.

7.7 Winchester, Hampshire

Winchester is the county of Hampshire, in Southeast England (figure 40). The city is located along the River Itchen in the western end of the South Downs.

7.7.1 Early Medieval Winchester (An urban royal and ecclesiastical settlement)

In 70AD the Romans built the town known as Venta Belgarum, naming it after the previous inhabitants, the Belgae (Beaumont 1997: 30). By the fifth century AD the Roman town went into decline (James 2007: 46).

Resettlement of the area by the Saxons occurred in the sixth century AD and the settlement took on a new name, Wintaceaster, “ceaster” being the term for a former Roman walled site (Beaumont 1997: 39).

Conversion of the West Saxons occurred in AD 635 following the arrival of the missionary Birinus (James 2007: 49). By the mid seventh century a Minster church called the Old Minister was built inside the Roman walls of Winchester (Beaumont 1997: 40). In AD 676 the Bishop of Wessex moved his seat to Winchester and the Old Minster became a cathedral (James 2007: 49). In AD 686 the city replaced Dorchester-on-Thames as the *de facto* capital of the ancient kingdom of Wessex. Although it was not the only town to have been the capital, its status was established by King Egbert as the main city in his kingdom in AD 827 (Yorke 1995: 310).

Late in the ninth century Alfred the Great, of Wessex, made Winchester into a burh (James 2007: 49), repairing and rebuilding the city to fortify it to fight the Danes. This rebuilding laid the streets out in a grid pattern, overlaying the pre-existing Roman street plan.

In the early tenth century AD Alfred's successor founded a second Minster church in Winchester, called the New Minster, and Alfred's widow founded a nunnery known as the Nunnaminster (Beaumont 1997: 44). (It was later called St Marys Abbey). The royal palace and a mint were also built during this period (Beaumont 1997: 43). Later in the tenth century the monastery attached to the Old Minster church was reformed and became St. Swithun's Priory (James 2007: 58). By the end of the tenth century

Winchester may have had a population of about 8,000 and there were suburbs outside Westgate and Northgate (Hinton 1990: 91). Winchester remained the capital of Wessex and then became the capital of England until the Norman invasion (James 2007: 64).

7.7.2 Archaeological Excavation

Each of the four artefacts involved in this study comes from a different excavation. The notes on the later Saxon strata are briefly described here:

New Road – This excavation was situated in a suburban area west of the Roman city walls. The Oram's Arbour ditch that skirted just outside the walls was still a significant feature (1.2-1.6m in depth) in the later Saxon period. The late Saxon evidence includes pits from the ninth and tenth centuries AD, as well as property demarcations dated to the end of the tenth century AD.

Sussex Street - This excavation was situated in a suburban area west of the Roman city walls. A layer of chalk and clay from the construction of the city defences in the ninth century AD underlay later Saxon deposits. Evidence of extensive occupation during the late Saxon period existed on Sussex Street, including pits, property boundary features, timber structures and a hearth.

Victoria Road – This excavation was situated in a suburban area north of the Roman city walls. The archaeological finds consisted of one timber building, along with a series

of property boundary ditches and pits. By the eleventh century AD the building and property boundary ditches went out of use, while the area continued to be used for pits in declining numbers (Rees et al. 2008).

The Brooks – This excavation was situated in the northeast quarter of the historic city of Winchester (Scobie et al. 1991). The site was bounded on the south by middle brook street and west by upper brook street, both of which have their origin in the late Saxon period. No evidence for occupation between post roman and late Saxon periods. The collapse of the river management left most of the site unsuitable for occupation, prior to the reorganization of the water courses in the ninth century AD. Dark soil was found on the southern side of the excavation, but several buildings and burials were discovered on the western side of the site. Unfortunately, poor preservation of these buildings made interpretation difficult. The two east-west burials contained two adult males, one between the ages of 25-35 and the other 15-21. Following the demolition of the buildings, a series of intercutting pits and postholes were identified dating to tenth-twelfth centuries AD.

7.7.3 Local Iron Working

Iron working evidence has been found at excavations of Nunnaminster dating to late ninth century (Beaumont 1997: 41). Further evidence of iron working was found at the excavations of as Castle Yard and Wolvesey Palace (Biddle 1990: 135). This ironworking consisted of small scale smithing. The Castle Yard excavation was situated on the major North-South street of the Anglo-Saxon period. The ironworking evidence from this site

included furnace debris such as furnace bottoms, magnetic waste with wood ash, flooring in which iron can be detected and iron fragments including nails, horseshoes and iron plates (Biddle 1990: 136). These deposits dated from the late ninth to mid tenth century AD. The evidence from Wolvesey Palace included iron working waste, mostly smithing slag, was found with during the excavation of the pre-conquest Episcopal palace (Biddle 1990: 137).

7.7.4 Artefact Selection

The knives from Winchester, previously sampled and analyzed by Rulton (2003), were included in this study to provide insight into another important settlement of the study period and because of their availability. Re-analysis was necessary to employ the analytical methodology developed specifically for this research project to provide a comparable data set. During the sampling process Rulton found that most of the knives were poorly preserved which limited sampling to eight knives. In the period since the original analysis, active corrosion claimed many of the mounted sections, resulting in only four knives available for re-examination.

7.7.5 Analysis Results

A summary of the artefacts from Winchester is provided in Table 83. These results demonstrate that the smiths either at Winchester or supplying the Winchester sites were utilising the full range of iron alloys available during the later Saxon period and at contemporary sites such as Coppergate, York.

Class 1

The four knives from Winchester make up the Class 1 assemblage. Table 87 summarizes the analyses of the Class 1 artefacts.

Manufacture

Table 84 demonstrated the different manufacture techniques were used in the iron knives from Winchester.

Knife NR8 was a classic Type 2 manufacture with a ferritic back and a heat treated steel cutting edge. Knife SXS93 was a classic Type 1 manufacture with a central band of pearlite sandwiched between heterogeneous phosphoric/ferritic iron bands. Knife BRI4154 was a pattern-welded blade made-up of alternating bands of high carbon steel and phosphoric iron. Knife VR8580 was too heavily corroded to determine manufacture. The small portion of the knife back that remained had a band of ferrite welded to a band of pearlite indicating that the knife was neither a Type 0 nor Type 5.

Knife NR8 demonstrated evidence of cold working in the form of Neumann bands present at the edge of the knife back.

None of the artefacts were composed of a single alloy and the heterogeneous structures existed either as a component in an intentionally manufactured structure, knife SXS93, or as piece of an unknown construction, knife VR8580.

Alloy Usage

The alloy usage of the Class 1 artefacts was summarized in Table 85. Winchester has the full range of alloys available in the Saxon period.

High carbon steel was used intentionally and differently in each of the knives. In knife NR8 the steel tip was also heat-treated. The placement of the steel in knife NR8 was as the high carbon steel cutting edge of a Type 2 knife and some carbon diffusion across the weld line. In knife SXS93 a central steel band was sandwiched between non-steel alloys with decrease carbon content from the knife tip to the knife back. In knife BRI4154 high carbon steel formed the cutting edge and alternating bands within the pattern welded structure. In knife VR8580 steel was a large component of the heterogeneous structure of the iron bands and along the weld line, but no cutting edge remained to determine its use within the overall knife structure.

Phosphoric iron was used in three of the knives, but never as the dominant alloy. In knife SXS93 it existed heterogeneously with ferrite to make up the bands on either side of the steel. In knife BRI4154, it alternated with the steel in a pattern-welded structure. Then in knife VR8580 it existed heterogeneously in one of the two bands welded together.

Ferrite was found in two of the Winchester knives. In Knife NR8 the alloy composed the entire knife back and in knife SXS93 it was part of the heterogeneous structure along with the phosphoric iron bands that composed the sides of the knife.

Quality of Materials

Three of the knives of Winchester were clean with only small inclusions; however, the piled structure of knife SXS93 had significant amounts of slag present in the welds between the bands of metal.

7.7.6 Phosphoric iron in Winchester

Table 86 summarizes the analysis of phosphoric iron in the Winchester assemblage. The phosphoric iron indicators were not present in all occurrences of phosphorus in the microstructure. Grain size varied greatly between different knives. Etch resistance was only seen in one of the artefacts. Hardness values averaged in the general phosphoric iron range (between $Hv_{0.2}$ 150-180). The last detectable characteristic, ghosting was present in two of the three knives; however, the area phosphoric iron in knife VR8580 is too small to determine if the metal contained ghosted structures before it corroded.

Phosphorus and Carbon

Table 88 demonstrated that high phosphorus levels were seen in the high carbon steels of two of the iron knives: knife NR8 and knife VR8580.

7.7.7 Arsenic in Winchester

There were only trace amounts of arsenic in the iron knives from Winchester.

7.8 Deansway, Worcester, Worcestershire

Worcester is situated in the English West Midlands on the eastern bank of the River Severn (figure 41).

7.8.1 Early Medieval Worcester (an urban and ecclesiastical settlement)

The Anglo-Saxon name for Worcester was Weogornaceaster (Dalwood and Edwards 2004: 19). The settlement was locally important through the fifth-sixth centuries. It lay within the defences of the preceding Roman town and was situated in an area under the control of the Britons until the seventh century AD. The earliest churches of Worcester were built during this period. In the seventh century AD this area became part of the Anglo-Saxon Kingdom of Hwicce, and an Episcopal see was founded in Worcester in AD 680. The Kingdom of Hwicce was then taken over by the kingdom of Mercia in the late seventh century. Most of what was known about Worcester between the ninth and eleventh centuries AD related to the cathedral and the church. The bishops headed the elite of the settlement from the late seventh century AD, having a civilian settlement of craftsman and traders providing goods and services to the church.

In the ninth century AD Worcester became a burh (Dalwood and Edwards 2004: 22), or fortified town, to help defend Mercia. This burh was designed to be both a defensive

post and a market town, where the profits were divided between the church and the Kingdom of Mercia.

7.8.2 Archaeological Background

Excavation (Dalwood and Edwards 2004) began in 1988 in an area in Worcester City Centre between Deansway, High Street and Broad Street by the Deansway Archaeological Project. The excavation included finds dating from the Prehistoric to Modern periods. The evidence from the post-Roman early to middle Anglo-Saxon period (fifth to late ninth centuries AD) showed limited occupation with evidence of the use of the land for pasture (Dalwood and Edwards 2004: 54).

In the late Anglo-Saxon period (late ninth to late eleventh centuries AD) there is evidence of the development of the burh of Worcester (Dalwood and Edwards 2004: 55). The defences, consisting of a rampart with a ditch, were constructed in the late ninth century AD. Occupation evidence included rubbish pits, cesspits, and timber buildings in the southern part of the excavation area. This indicated the urban development in the settlement.

A vast variety of archaeological finds was uncovered in the late Anglo-Saxon settlement. These included evidence of crafts such as metalworking, lime production, tanning and cloth working (Dalwood and Edwards 2004: 57).

7.8.3 Iron Working

Some evidence of metalworking was found during the Deansway excavation. For the period between fifth and eleventh centuries AD approximately 535.3kg of smelting slag and 18.9kg of smithing slag were excavated at Deansway (McDonnell and Swiss 2004: 375-376). It is, however, unclear whether smelting and smithing activities occurred within the town or if they occurred elsewhere and the slag was imported into the settlement (McDonnell and Swiss 2004: 376).

7.8.4 Artefact Types Selection

Artefacts were selected based on artefact type and quality of preservation. Preservation of the metal was very poor and limited the number of artefacts suitable for analysis.

Stock iron was not included in the artefact selection from Worcester. The analysis of stock iron was added to the project aims during a mid-project refocusing after the assemblage from Worcester had already been examined. A summary of the selected artefacts can be found in Table 89.

7.8.5 Analysis Results

A total 12 artefacts from Worcester (table 89) were analyzed. These artefacts included six from Class 1, five from Class 2 and one from Class 3. The Class 1 artefacts included a variety of different categories of artefact types, including edged tools, security

implements, and a dress fitting. Class 2 included five nails. A single strip fragment composed the Class 3 assemblage.

Class 1

A variety of artefact types comprised the Class 1 assemblage (table 90), including edged tools (a pick head and two knives), clothing accessories (the hook tag), and security elements (a padlock and a key).

Manufacture

The edged tools included a Type 2 knife, a knife tang that could be from a Type 2 knife, and pick head that had a heat treated Type 5 construction. Hook tag DW5657 was comprised of a banded combination of phosphoric and ferritic iron with elongated slag inclusions and ghosting, suggesting heavy working. Key DW6302 and the small section of padlock DW6411 were composed of a single alloy, low carbon steel and ferrite respectively.

Alloy Usage

Evidence of all iron alloys could be seen in the Class 1 artefacts. Table 92 shows the number of artefacts with the specified amount of each alloy present in the microstructure.

All three of the edged tools contained high carbon steel (>0.3%C) components, one was completely steel, one had a steel cutting edge, and one a steel component welded to a ferritic component. Pick head DW16758 contained steel that was heat-treated to

produce a martensitic point. Key DW6302 was also completely constructed from homogenous 0.2%C low carbon steel.

Phosphoric iron was present in one Class 1 artefact, hook tag DW5657, in a naturally banded structure with ferrite. The phosphoric iron had medium sized grains (ASTM 6) and hardness values that were typical for the alloy ($Hv_{0.2}$ 178).

Ferrite was present in four of the artefacts: in the two knives it composed the knife back, it made up the entire padlock section, and it was present in the naturally banded structure of the hook tag. The ferrite in knife tang DW17304 has elevated hardness values ($Hv_{0.2}$ 183) that may indicate work hardening and possibly be influenced by elevated arsenic content (0.3-0.4wt%As).

Quality of Materials

Most of the Class 1 artefacts were very clean with only a few slag inclusions. The exception to this was knife tang DW6489, which had a clean steel edge welded to a ferrite back with a large quantity of both large and small inclusions.

Class 2

Class 2 was composed of five iron nails. Table 91 summarizes the analyses of the Class 2 artefacts.

Manufacture

All but one of the nails appeared to be constructed from a single bar with various compositions. Two nails DW6319 and DW6477 were constructed from a single alloy, ferrite and high carbon steel respectively. Two other nails DW5609 and DW5646 were constructed from bars that were either a heterogeneous or a banded combination of low carbon steel and ferrite. Only nail DW5602 was constructed of two pieces of iron with a steel head welded to the ferritic shank.

Alloy Usage

Evidence of all iron alloys could be seen in the Class 2 artefacts. Table 93 shows the number of artefacts with the specified amount of each alloy present in the microstructure.

Steel was present in four of the five artefacts in this category. The compositions varied from one hundred percent steel, nail DW6477, to mostly steel, nail DW5646, to elements of steel diffusing into ferrite nails DW5609 and DW5620. In nail DW5620, the steel component was welded on.

There was no phosphoric iron present in the Worcester nails.

Ferrite was present in four of the five nails, which were either completely composed of the alloy, like nail DW6319, or the alloy was heterogeneously mixed with steel as in nails DW5609 and DW5646. The shank of nail DW5420 was ferritic with a steel head causing some diffusion. The ferritic hardness values are relatively high for the alloy

(Hv_{0.2}124-184) indicating that the nail was work hardened. Grain sizes ranged from ASTM 3 to ASTM 8.

Quality of Materials

Four of the Class 2 artefacts were clean with small slag inclusions. Nail DW6477 was dirty with larger and a greater amount of slag inclusions.

Class 3

There was only one Class 3 artefact sampled, a strip fragment. From the shape of the object it may have been an unfinished object. Table 91 summarizes the analyses of the Class 3 artefacts.

Manufacture

The strip was a single piece of slightly carburized ferritic iron.

Alloy Usage

Evidence of three iron alloys could be seen in the Class 3 artefact. Table 94 shows the number of artefacts with the specified amount of each alloy present in the microstructure.

Steel was present as carbon diffusion in the single artefact in this category.

Ferrite was the major component of the single artefact in this category. The average hardness value from this ferrite was relatively high $Hv_{0.2}150$, which may be due to work hardening; the average grain size was moderately large at ASTM 3.

Quality of Materials

The strip was composed of very clean iron with very few slag inclusions.

7.8.6 Phosphoric iron in Worcester

Table 95 demonstrates that phosphoric iron was only found in one of the artefacts from Worcester. Hook tag DW5657 was constructed using a naturally piled structure with a mix of phosphoric and ferritic bands.

The phosphoric iron indicators included areas with ghosting and etch-resistant areas.

Some etch resistance was also seen in non-phosphorus rich iron artefacts.

Ghosting structures included some minor inter-granular ghosting.

Phosphorus and Carbon

There was no steel with significant amounts of phosphorus (0.1%P) present in the Worcester assemblage.

7.8.7 Arsenic in Worcester

None of the artefacts from Worcester contained significant amounts of arsenic (>0.2wt%As).

7.8.8 Class Comparison

Manufacture

Table 96 summarizes the manufacture of the artefacts from Worcester. The Worcester assemblage contained one heat-treated artefact in Class 1, pick head DW16758, one carburized artefact in Class 3, artefact DW6317 and no distortion of granular structure to indicate cold working; however increased ferrite hardness values (table 97) indicate cold working below 40% reduction.

The composite construction of iron artefacts from multiple alloys (i.e. knife constructions) was visible in four of the artefacts: the three Class 1 edged tools and one of the Class 2 nails. The tip of the Class 3 artefact, believed to be an unfinished tool, could also be classified as an intentional construction; however, the back of the artefact appears more heterogeneous. The rest of the assemblage appeared to be constructed from a single piece of iron that was either a single alloy or heterogeneous. The four single alloy objects were present in the Class 1 and Class 2 assemblages. The four heterogeneous objects were split between all three classes: Class 1 contained one heterogeneous artefact, hook tag DW5657, Class 2 contained two heterogeneous nails, and Class 3 contained the strip fragment previously discussed.

Alloy Usage

All of the alloys were present in more of the Worcester artefacts than in the other assemblages, with ferrite the most abundant alloy present in the entire assemblage.

Table 98 shows the number of artefacts containing each alloy based on class and Table 99 shows the number of artefacts with the specified amount of each alloy present within the microstructure.

Steel was present in almost 70% of the assemblage. Only three of the intentionally constructed artefacts of Class 1 contained high carbon steel, while four of the Class 2 nails and the Class 3 contained high carbon steel.

Phosphoric iron was only present in one Class 1 artefact, hook tag DW5657. In this artefact it was heterogeneously mixed with ferritic iron.

Ferritic iron was on-steel iron alloy mostly used in the Worcester assemblage. Nine of the artefacts contained ferrite, the vast majority of the each class.

Table 99 shows the alloy usage summary for the twelve Worcester artefacts. The four artefacts with single alloy construction consisted of two completely ferritic structures, one low carbon steel and one high carbon steel. Another four artefacts were manufactured with a dominant alloy, two of which were ferritic, one low carbon steel and one high carbon steel. These artefacts were often slightly carburized or decarburized. The rest of the artefacts were a combination of alloys either due to intentional manufacture, banded structures or heterogeneous.

Quality of Material

Table 100 shows ten of the 12 iron artefacts from the Worcester assemblage had clean iron. The two artefacts that were classified as dirty were knife tang DW16758 from Class 1, in which only the ferritic component contained a high number of slag inclusions, and nail DW6477 from Class 2, in which the entire structure contained large slag inclusions.

7.9 Coppergate, York, Yorkshire

The modern city of York lies at the confluence of the Ouse and the Foss, in North Yorkshire, England. Anglo-Scandinavian Jorvik was situated within the area now enclosed by the medieval city walls, along many of the streets adjacent to River Ouse (figure 42).

7.9.1 Anglo-Scandinavian York (*Jorvik*) (a capital and ecclesiastical urban centre)

The area of York was settled in AD 71 by the Romans who built the legionary fortress of Eboracum (Wiemer 1993: 17). At the end of the Roman period the area was settled by the Angles and the settlement renamed Eborwic. The city served as an Anglo-Saxon trading port and the capital of the Kingdom of Northumbria, occupying the area that is currently north eastern England and southern Scotland, until the ninth century AD (Hall 1994: 16, Wiemer 1993: 20).

The Anglo-Scandinavians (Danes) captured the Anglo-Saxon settlement of Eoforwic in AD866 (Booth 1990, Campbell 1982: 166), which they renamed as Jorvik, and spent the next several years strengthening York's defences, partially refortifying the Roman city walls (Davies 2003). They installed a puppet king in York who ran the city and the surrounding area while they subdued the Midlands and East Anglia (Hall 1994: 16). They returned to York in AD 876 and settled, replacing the puppet king with a Danish ruler and began to exert influence on the structure, religion, and architecture of the city. Soon the Danish army was back to conquering England, taking Mercia the next year and planned to take Wessex (James 2001: 224). In AD 878, however, Alfred, king of Wessex, repelled the invaders out and eventually came to an agreement with the Danish leader, Guthrum, giving the Danes control over the area from Essex to Cheshire. The area became known as Danelaw (Hall, 1994:16) and would be ruled from their capital at York, now called Jórvik (James 2001: 197).

The city of Jorvik flourished as the capital city of the part-nautical part-agrarian trading culture and rapidly grew over the next century. Within the city there existed a combination of Anglo-Saxon and Danish cultures adopting elements from both societies (Wiemer 1993: 22). After Alfred's death, the struggle between the Danes of York and Wessex began again (James 2001: 241) and in AD 910 the Danelaw, being allowed to retain self-government, came under the rule of the Anglo-Saxon king in Winchester (Campbell 1982: 165). York retained its Danish kings throughout the first half of the tenth century. The last king of Anglo-Scandinavian Jorvik was Erik Bloodaxe, the former king of Norway, who was expelled from York in AD 948, leaving York in the

hands of the English (Hall 1994: 20). The city of York was then led by a series of earls and archbishops of Scandinavian decent (Hall 1994: 20).

In the end of the tenth century AD, the areas of England outside of Danelaw once again come under attack from Anglo-Scandinavians, and in AD 1016 all of England came under control of the Danish King Cnut (Campbell 1982: 174). In AD 1042 the rule of England reverted back to the house of Wessex and York was ruled by a series of governors/earls until the Norman Conquest. By the time of the Domesday Book York had an estimated population of 10,000 and was the second most important city in England (Hall, 1994:33).

7.9.2 Archaeology

The excavation of 16-22 Coppergate, York, occurred between 1976 and 1983. The excavation site was an area 1000 square metres sitting on the land between the Rivers Ouse and Foss. The site is bounded on the west by Coppergate and to the east by the River Foss (figure 42). Evidence was uncovered of occupation from the Roman period through to the modern day, with the Anglo-Scandinavian deposits dating from the ninth to eleventh centuries AD.

In the post-Roman period the excavation area showed no evidence of occupation (Ottaway 1996: 460). Activity or settlement recommenced on an occasional basis in the mid to late ninth century AD. Evidence from this period included domestic debris, a series of postholes, and some pits with human remains. In the early tenth century AD

there was evidence of a realignment of boundaries, possible building remains, and pits filled with organic materials. By around AD 930/5 four tenements were distinguishable. These were defined by wattle fences, which were not continuous to the River Foss end of the site. It is unclear why these divisions did not extend that far. Each tenement contained buildings of post and wattle construction with their gable ends facing the street. These buildings averaged 4x4 metres in size and showed signs of frequent repair and rebuilding. Hearths were found in all four of the tenements. Behind the buildings yards were used for workshops, waterholes or pits. Large amounts of evidence of metal and leather working were found in these rear workshops.

The finds from c. AD 975 to the mid-eleventh century AD demonstrated a change in construction to sunken structures replacing the former ground level buildings. These buildings disrupted the earlier deposits, but stratification could be clearly seen in the work areas in the rear of the tenements.

The strata were clearly dated for the tenth century AD and later deposits using a combination of coins, pottery, archaeomagnetic dating and dendrochronology.

7.9.3 Iron Working

Ironworking evidence was found at Coppergate (McDonnell 1992: 471). This included evidence of both smelting and smithing, the quantities of which are summarized in Table 101. The evidence was present in all the Anglo-Scandinavian contexts. The

largest concentrations of both iron smelting and smithing occur in the period between AD 930/5 and AD 975 (McDonnell 1992: 477).

7.9.4 Artefact Selection

The selection of artefacts from this site came from two different sampling sessions. The first was by McDonnell (1992) as part of the post-excavation analysis of the large assemblage of iron from the excavation at Coppergate, York. The 19 artefacts re-analyzed in this study included six knives, eight blanks/stock iron, a key plate, two punches, a spoon auger and an arrowhead. These artefacts were chosen based on the preservation and availability of the artefacts' original sections, the diversity of artefact types, and the presence of pattern welding.

The second sampling included the selection of nine iron nails, also from the Coppergate excavation, for full analysis by the author. Nails were selected using the criteria presented in the methodology.

A full summary of the artefacts can be found in Table 102.

7.9.5 Analysis Results

A total 28 artefacts from York were sampled; of these 11 were from Class 1, nine were from Class 2 and eight were from Class 3. The Class 1 artefacts included a variety of different categories of artefact types, including edged tools, weapons and security items. Class 2 was comprised only of nails and Class 3 was comprised only of bars.

Analysis included an examination of the manufacture of each artefact, the identification of the alloys present, and an assessment of the quality of materials used in artefact construction. All alloys were identified using a combination of metallographic analysis, hardness values, and elemental analysis. Material quality was assessed through visual inspection of the microstructure. Items were classified as “clean” when they contained a low number of slag inclusions and most of those slag inclusions were small (figure 18b). Items were classified as “dirty” when approximately 1/5 of their microstructure consisted of slag inclusions (figure 18a).

Class 1

The Class 1 artefacts (table 103) included six knives, two punches, an auger, an arrowhead and a key. All of the Class 1 artefacts were previously examined by McDonnell (1992) and were re-examined to suit the parameters of this study.

Manufacture

The Class 1 York knives included two Type 0s, a Type 1, a Type 2, a Type 3 and a pattern-welded blade. The two Type 0 knives Yo3810 and Yo12229 were completely composed of phosphoric iron. The Type 1 knife Yo5802 consisted of a central band that was low carbon steel degrading into phosphoric iron sandwiched between heterogeneous bands of phosphoric/ferritic iron. The Type 2 knife Yo10395 contained a tempered martensitic tip welded to a piled ferrite/bainite back, and the Type 3 knife Yo4070 contained thin bands of ferrite sandwiched between broad bands of 0.5%C high carbon steel and 0.2%C low carbon steel. The pattern-welded blade Yo3859 was

constructed from the full range of alloys available with a heat-treated steel tip welded to a back constructed with separate pieces of ferrite, phosphoric iron, high carbon steel and low carbon steel welded to a central band of low carbon steel.

The two punches were each of different construction. Punches Yo1638 had a heterogeneous banded structure of bainite, tempered martensite, pearlite, and ferrite converging towards the tip. Punch Yo7454 contained a ferritic core with a steel sheath welded around it. Spoon auger Yo9439 was constructed from a steel core wrapped in piled phosphoric/ferritic iron. Key Yo6295 was composed of a heterogeneous ferrite with areas of phosphoric iron. High hardness values ($Hv_{0.2}194$) for the ferrite suggest possible work hardening. Arrowhead Yo11067 contained a structure similar to a Type 1 with a central steel band sandwiched between sides of heterogeneous ferritic iron.

Alloy Usage

Evidence of all iron alloys could be seen in the Class 1 artefacts. Table 106 shows the number of artefacts with the specified amount of each alloy present in the microstructure.

High Carbon steel ($>0.3\%C$) was present in six of the Class 1 artefacts. In punch Yo1638, knife Yo4070, and knife Yo10395 the alloy was a component of the banded structure. In pattern-welded knife Yo3859 the high carbon steel composed the tip, the central band, and a few other bands in the back. In spoon auger Yo9439 the alloy formed the core of the structure. In Type 2 knife Yo10395 the alloy composed the heat treated tip.

In the Type 1 structure of arrowhead Yo11067 it formed the central band of the structure.

Low carbon steel (0-0.3%C) was present in seven of the Class 1 artefacts. In the heterogeneous piled structures of punch Yo1638, knife Yo4070, knife Yo10395, and arrowhead Yo11067, low carbon steel was present either as bands or along the welds. It was present as either single alloy bands or as the result of carbon diffusion from high carbon steel bands in pattern-welded knife Yo3859. Punch Yo7454 was composed of a ferritic core encased in a sheath of the low carbon steel and spoon auger Yo9439 had minor amounts of low carbon steel (0.1%C) along the exterior of the ferritic/phosphoric casing as the result of slight carburization.

Phosphoric iron was present in seven of the Class 1 artefacts. Knives Yo3810 and knife Yo12229 were completely composed of the alloy. In pattern welded knife Yo3859 the phosphoric iron was a component of the heterogeneous bands in that comprised the knife back. The alloy comprised a large part of the piled structure in knife Yo5802, the piled outer sheath of spoon auger Yo9439 and the piled knife back of knife Yo10395. The alloy was also the primary component of the heterogeneous structure of key Yo6295.

Ferrite was present in eight of the Class 1 artefacts. In key Yo6295, punch Yo7454, and arrowhead Yo11067 the alloy was a major component of the structure. In key Yo6259 ferrite was the primary alloy in the heterogeneous iron, in punch Yo7454 the alloy composed the core of the artefact and in arrowhead Yo11067 it composed the two

flanks of the Type 1 structure. The remaining five artefacts contained ferrite a part of a heterogeneous banded/piled structure or, as in the case of knife Yo3859, as part of the pattern-welded structure.

Quality of Materials

Only four of the York Class 1 artefacts were wholly constructed of clean metal and manufacture. These four included knife Yo4070, key Yo6295, knife Yo10395, and punch Yo1638. The rest of the Class 1 artefacts were dirty either due to a large amount of slag inclusions in the iron or at the welds in the piled structures. In the case of the pattern-welded knife Yo3859 most of the metal was fairly clean with only small slag inclusions; however, also present were small pieces of dirty metal and a large slag content in the welds.

Class 2

The Class 2 artefacts comprised nine nails. These artefacts were sectioned as part of study and have not been analyzed previously. The analysis and description of these artefacts can be seen in Table 104.

Manufacture

Each of the York nails was constructed from a single iron bar. These nails fall into three categories of construction: single alloy bars, carburized single alloy bars and heterogeneous bars. The nails from the single alloy bars included two phosphoric, nail Yo26171 and nail Yo28587, and one ferritic, nail Yo26736. The nails that were constructed from single alloy bars with slight carburization included two ferritic, nail

Yo8454 and nail Yo25990, and one phosphoric, nail Yo26247. Three nails Yo2920, Yo15404, and Yo27819 were constructed from heterogeneous bars.

Alloy Usage

Evidence of all iron alloys could be seen in the Class 2 artefacts. Table 107 shows the number of artefacts with the specified amount of each alloy present in the microstructure.

High carbon steel was present in five of the Class 2 artefacts. The alloy was only present in small amounts of each of the artefacts either as part of a heterogeneous structure (two artefacts) or as the result of carburization (three artefacts).

Low carbon steel was present in five of the nine Class 2 artefacts. It was either present due to carburization of a single alloy artefact (two artefacts) or a part of a heterogeneous structure (three artefacts). Only in nail Yo2920 did heterogeneous low carbon steel compose the entire section and in nail Yo15404 it composed most of the heterogeneous section.

Phosphoric iron was present in three of the Class 2 nails. Nail Yo26171 and nail Yo2858 were composed of heterogeneous phosphoric iron with small amounts of ferrite. In nail Yo26247 the phosphoric iron was present as the largest part of the heterogeneous structure.

Ferritic iron was present in six of the Class 2 artefacts. In nail Yo26736 was completely composed of ferritic iron. Two other nails Yo8454 and Yo25990 were mostly ferritic with some carburization. In the remaining three nails ferrite was a component of heterogeneous iron.

Quality of Materials

All of the York nails were constructed from clean bars of iron except nail Yo28587, which had several very large inclusions. The cleanness of the iron used in the York nails suggests that there was abundant high quality of iron in York.

Class 3

The Class 3 artefacts included eight bars (table 105). All of the Class 3 artefacts were previously examined by McDonnell (1992) and were re-examined for this study to suit the parameters of this study.

Manufacture

Four of the Class 3 artefacts, bar Yo8364, bar Yo8376, bar Yo9938 and bar Yo11352 were manufactured from heterogeneous iron. There were two single alloy artefacts: bar Yo11208, which was phosphoric, and bar Yo11550, which was ferritic. Bar Yo8439 was a single alloy bar of phosphoric iron with a small area of carburization and bar Yo8794 was of composite construction containing alternating phosphoric and ferritic iron.

Alloy Usage

Evidence of three of the iron alloys could be seen in the Class 3 artefacts. Table 108 shows the number of artefacts with the specified amount of each alloy present in the microstructure.

High carbon steel was present in three of the artefacts; in bar Yo8376 and bar Yo9938 as part of the heterogeneous structure and in bar Yo8439 as the result of carburization. While low carbon steel was present in none of the artefacts.

Phosphoric iron was present in six of the Class 3 artefacts. Bar Yo11208 was completely phosphoric iron and bar Yo8439 was mostly phosphoric with some carburization. Bar Yo8364, bar Yo8376, and bar Yo11352 contained phosphoric iron as part of the heterogeneous structure. Bar Yo8794 was welded in alternating bands within a composite structure.

Ferritic iron was present in six of the Class 3 artefacts. Bar Yo11550 was completely composed of ferritic iron. In the four heterogeneous bars ferritic iron was only a small component of the structure and bar Yo8974 was made of alternating ferritic and phosphoric bands in a composite construction.

Quality of Materials

Three of the Class 3 artefacts, heterogeneous bar Yo8364 and bar Yo9938, and phosphoric bar Yo8439, were composed of clean metal. The rest of the bars contained large amounts of small slag inclusions.

7.9.6 Phosphoric iron in York

Phosphoric iron was found in 16 of the 27 artefacts (59%) from York. The results of the analysis of the phosphoric are presented in Table 109. Six of the artefacts were almost completely manufactured from phosphoric iron. The alloy was also present in five of the piled artefacts, four of the heterogeneous artefacts and as bands in the knife back of the pattern-welded knife Yo3859.

The phosphoric iron indicators (table 111) present in the York artefacts included ghosting, in 50% of the phosphoric iron artefacts, large grains (ASTM 1-3) in nine of the artefacts, and etch resistance in eight of the artefacts. Four of the artefacts had etch resistance in iron with no phosphorus. The micro hardness values averaged $Hv_{0.2}$ 174 and ranged from $Hv_{0.2}$ 87 to $Hv_{0.2}$ 289, all significantly higher than un-worked ferritic iron.

Almost all of the major ghosting structures were present in the York artefacts (figure 43), with only pearlitic ghosting not present. Grain boundary ghosting was the most prevalent form of ghosting.

Phosphorus and Carbon

Phosphoric iron was found in the steel of four of the iron artefacts (table 110). In knife Yo4070, knife Yo10395, and the shank of nail Yo26247 the carbon content was part of

the heterogeneous structure, while in the head of nail Yo26247 and in blank Yo8376 the carbon content was due to carburization of the exterior of the nail.

7.9.7 Arsenic in Anglo-Scandinavian York

High arsenic levels were found in the iron of spoon auger Yo9439 (figure 44). The artefact was constructed with one of the upper piled edge containing a high arsenic content. Hv8 and Hv9 in Table 112 show relatively high arsenic contents in the middle of large bands of phosphoric iron. These areas were not in immediate contact with the white weld lines present in other parts of the artefact. The regions were etch-resistant and the region immediately around Hv9 demonstrated ghosting.

7.9.8 Comparing to Previous Analyses

The selection of the iron artefacts from the Coppergate excavation were originally analyzed by McDonnell (1992). This analysis included optical microscopy and hardness testing, but did not include elemental analysis. Table 113 is a brief summary of the artefacts analyzed by McDonnell (1992). The artefacts were organized by class. McDonnell's original analysis focused primarily on Class 1 and Class 3 artefacts with only a small selection from Class 2.

The results of McDonnell's analysis are summarized in Table 114. These results show heat treatment in 34 of the 96 artefacts from York (35% of the assemblage). Phosphoric iron, which McDonnell identified without elemental analysis, was present

in 61%, or 59 artefacts (61% of the assemblage). Ghosting structures were identified in 21 artefacts (22% of the assemblage).

Figure 45 compares McDonnell's results for each of the classes, demonstrating that heat treatment was used most often on Class 1 artefacts. Phosphoric iron was present in approximately half to two-thirds of all the classes and ghosting was also present in all classes, but most prevalent in Class 1 artefacts.

The re-analysis of 19 of these artefacts for this study included more extensive hardness testing, as well as elemental analysis of the individual alloys present within each sample. The results from this re-analysis were compared to McDonnell's original results based on the class. Figure 46 shows this comparison for the Class 1 (a) and Class 3 (b) artefacts, demonstrating that the application of elemental analysis for alloy identification and an intensive examination of ghosting structures produce different results than optical examination and hardness testing alone.

7.9.9 Summary and Class Comparison

Manufacture

Evidence of manufacture was prevalent in the iron assemblage from Anglo-Scandinavian York. Table 115 summarizes the results of manufacture based on class.

Evidence of cold working was only visible in two of the Class 1 artefacts: punch Yo1638 and arrowhead Yo11067. Increased hardness values, however, were seen in the ferrite

of many of the artefacts. Table 116 shows the average hardness value of ferrite for each class, indicating that Class 1 and Class 3 artefacts both show evidence of cold working while Class 2 does not.

Heat treatment was only present in three of the Class 1 artefacts. Knife Yo3859 and knife Yo10395 were constructed with martensitic tips welded on to the knife back. Punch Yo1638 was almost completely steel with small amounts of ferrite. Evidence of carburization was visible in one Class 1 artefact, two Class 2 artefacts, and one Class 3 artefact. Evidence of piling was present in four of the Class 1 and two of the Class 3 artefacts, but none in Class 2, which was primarily made up of single bar artefacts.

Composite construction was used for more Class 1 artefacts than the other classes. There were eight composite construction artefacts in Class 1. Of the other classes only one artefact, bar Yo8794 was also of composite construction. Single alloy construction was seen in two artefacts from each of the three classes. Heterogeneous iron was found in all three classes; however, this mix of alloys composed the majority of the Class 2 artefacts.

Alloy Usage

All of the alloys were present in more of the York artefacts than in the other classes, with ferrite the most abundant alloy present in the entire assemblage. Table 117 shows the number of artefacts containing each alloy based on class and Table 118

shows the number of artefacts with the specified amount of each alloy present in the microstructure.

High carbon steel was present in all classes, but was most abundant in the Class 1 artefacts. Table 103 shows that there was only one artefact, punch Yo1638, that contained large amounts of the alloy. In the rest of the artefacts it existed most often as a piece either welded to the structure, as in the Class 1 composite constructions, or as a component of a heterogeneous structure, as in Class 2 and Class 3 artefacts.

Low carbon steel was only present in Class 1 and Class 2, but not in the Class 3 artefacts. This may reflect the carburization of single alloy artefacts during manufacture or carbon diffusion that does not occur until the bar was used in object manufacture. Low carbon steel only composed one entire artefact, being found more often as a small component of the carburized artefacts, as carbon diffusion, and as a component of a heterogeneous structure.

Phosphoric iron composed the entire microstructure of two Class 1 artefacts, one Class 2 artefact and one Class 3 artefact. It was also the dominant alloy for another two artefacts, one Class 2 and one Class 3, and a smaller component of nine other artefacts. Despite not being the prevalent alloy, more artefacts were composed entirely of phosphoric iron than any of the other alloys.

Ferrite was not only the most abundant alloy for the entire assemblage; it was the most dominant alloy in each of the classes. Ferrite composed the entirety of two

artefacts and was the dominant alloy in another five artefacts, while it occurred in small amounts in 14 artefacts.

Quality of Material

Approximately half of the York artefacts contained clean iron (table 119), with the majority in Class 2. As compared to the other classes, Class 2 artefacts were composed from individual bars with no dirty welds or dirty iron welded on. The Class 3 stock iron could have been used to create some of the Class 1 artefacts, but only the clean heterogeneous or single alloy artefacts from Class 3 could be used to construct Class 2 artefacts.

7.10 Summary of Artefacts

Table 121 summarized the numbers of each artefact type examined in this study separated by class.

Table 122 summarizes the numbers of artefacts in the individual classes present at each site.

Further summaries based on site and an analytical comparison of the sites can be found in Section 8.6.

Chapter 8 – Discussion

8.1 Reviewing aims and objectives

8.1.1 Research Aims

This project aimed to study iron technology in Early Medieval Britain with particular attention given to the role of phosphoric iron in Early Medieval settlement contexts. To accomplish this, archaeometallurgical analysis of a wide variety of iron artefact types from across Britain was undertaken and used to create models of alloy availability and craft specialization.

This analysis will focus on identifying and evaluating properties and usage of alloys, notably phosphoric iron in comparison to other ferric alloys, in use during the Early Medieval period, and on determining which iron alloys were commonly available to the smiths and which alloys were reserved for more specialized use.

8.1.2 Research Objectives

Previous research (Blakelock and McDonnell 2007, McDonnell 1989, McDonnell 1992, Wiemer 1993) had established the presence of phosphoric iron as a key alloy in Early Medieval Britain. However, these studies focused on edge tools and relied heavily on metallographic characterization of phosphoric iron alloys with limited elemental analysis. For this study the following research objectives were identified:

1. To identify iron artefact assemblages from a variety of Early Medieval settlements, i.e. differing in geographical location, site type, and status, suitable for laboratory analysis.
2. Elaborate a classification scheme for the artefacts taking into account intended use, relative value, and the complexity of the manufacturing process(es).
3. Redefine phosphoric iron using the conventional indicators (hardness, grain size, and ghosting) assessed against the elemental content as measured by scanning electron microscopy with X-ray microanalysis.
4. Compare iron alloy usage, manufacturing techniques and quality between archaeological sites and artefact types and develop models for the Early Medieval iron economy in Britain.

These aims and objectives will be examined using the relevant data in the following discussion.

8.2 Artefact Construction Techniques

8.2.1 Single Alloy Construction

Single alloy artefacts were artefacts that were constructed from a single bar of one of the four major alloys: phosphoric iron, ferritic iron, low carbon steel and high carbon steel.

Use

Single alloy construction was seen in 16% of the total assemblage (23 artefacts). This form of construction required shaping through hot and cold working, but did not include welding or heat treatment. Table 123 shows a summary of artefact types, manufacture techniques, and alloy usage for the single alloy artefacts.

Artefacts

The single alloy artefacts consisted of variety of Class 1 artefacts, Class 2 nails and Class 3 stock iron.

Alloys used in Single Alloy Construction

Figure 48 shows single alloy artefacts were primarily composed of ferrite and phosphoric iron. Steel, including both low and high carbon steels, was rarely used in single alloy artefacts which may have been the result of limited accessibility to entirely steel bars or the alloy's selective use in composite construction artefacts. The three steel single alloy artefacts included two Class 1 artefacts, punch BN329 and key DW17274-6302, and one Class 2 artefact, nail DW17300-6477.

The only evidence of cold working apparent in the single alloy artefacts was visible in nail WP218 in the form of deformed grains.

Altered Single Alloy Artefacts

Many of the carburized and heterogeneous artefacts may have originally been constructed from single alloy bars that were subsequently altered by deliberate or unintentional carburization or decarburization occurring during manufacture. There were approximately 12 carburized artefacts that may have originally been of single alloy construction.

Material Cleanness

Single alloy artefacts demonstrate the smith's selection of individual alloy bars for use in construction. An aspect of this selection process will include an assessment of the cleanness of the metal. However, approximately half the single alloy artefacts from each of class were constructed from clean iron (figure 49). Indicating the class cannot be used to assess the quality the cleanness of iron.

There was no apparent pattern in clean versus dirty single alloy artefacts. Of the single alloy artefacts 13 were of clean metal, including the padlock and the key, the punch, six nails, the billet and two bars.

Conclusions

Single alloy construction artefacts required only the reshaping of individual bars to create the final product. The manufacture of these artefacts did not require highly skilled smiths. However, the selection of single alloy bars over heterogeneous bars demonstrated selective use of alloys.

8.2.2 Heterogeneous Alloys

The origin of heterogeneous iron can be the result of many different factors. These factors included the creation of bars were from a heterogeneous bloom, the result of processes such as carburization and decarburization during bar manufacture which may be unrecognizable once the bar was used in artefact manufacture, and the creation of bars from multiple bars/billets from of differing composition.

Table 124 is a summary of the artefacts types, manufacture, and alloy usage of the artefacts with heterogeneous iron.

Use

In this assemblage 57% of the total assemblage (80 artefacts) contained iron that could be defined as heterogeneous. Under this category there were three different groups of artefacts (figure 50): the 50 artefacts that were constructed from a single heterogeneous bar, the 19 artefacts constructed from multiple heterogeneous bars or piled, and the 25 artefacts that contained heterogeneous components in a composite construction.

Single bar, multi-bar, and composite constructions were each manufactured using different techniques. The heterogeneous single bar artefacts were manufactured much in the same way as the single alloy artefacts. The artefacts were shaped from a single piece of metal utilizing both hot and cold working to form the final object. The second

category, multi-bar construction, was composed of welded heterogeneous artefacts which were manufactured by welding multiple heterogeneous pieces of iron or piling and then shaping the metal through hot and cold working into the final object. The final category, heterogeneous components in composite constructions, were formed by welding heterogeneous pieces of iron to specific alloys using a specific construction, such as edged tool manufacture typologies, to create the final composite object. Of the three types of heterogeneous artefact construction the manufacturing technique most used was single bar construction.

Types of Artefacts

Heterogeneous iron was found in all classes of artefacts.

Class 1

Heterogeneous iron was used in the manufacture of 30 (52%) of the Class 1 artefacts. The majority of these artefacts were manufactured using composite construction (figure 51). In these composite construction artefacts heterogeneous iron was used as Type 2 knife backs or as piled components in other construction types. Fourteen (46%) of the heterogeneous composite construction artefacts contained piled structures, mostly in Type 1 and Type 3 constructions. The Class 1 heterogeneous artefacts with single bar constructions included a buckle, a tab, two knives, a punch, a key and an arrowhead. Key CC211 was the single Class 1 artefact entirely composed of a piled heterogeneous structure.

Class 2

Heterogeneous metal was present in 31 (64%) of the Class 2 artefacts. The manufacturing techniques used in Class 2 artefacts differed from Class 1 (figure 52), containing no composite constructed artefacts, and was primarily heterogeneous artefacts of single bar construction. The Class 2 heterogeneous artefacts included nails and object used in construction.

Class 3

There were 12 (48%) of the Class 3 artefacts; four with single bar construction, two with piled structures and one was of composite construction which was classified as an unfinished tool.

UI

Of the 3 unidentified artefacts 2 contained heterogeneous iron with one of single bar construction and two with multi-bar construction. One of the multi-bar artefacts contained piled structures.

Carburization and Piling

Carburization was seen in nine of the heterogeneous artefacts; however, many of the multi bar construction/piled heterogeneous artefacts contained small amounts of carbon along the weld lines.

There were 19 piled heterogeneous artefacts which fell into two construction categories: the five artefacts that were completely piled structures and the 14 artefacts that contained a composite construction that included a piled structure. The composite construction piled artefacts consisted of mostly edged tools and bar BN311. The major manufacture types included Type 1, Type 2 and Type 3 (figure 53). The Type 2 artefacts contained piled backs welded to steel tips.

The quality of manufacture of the piled artefacts fell into three categories: Clean metal and welds, clean metal and dirty welds, and dirty metal and dirty welds. Dirty welds demonstrate poor welding technique where large amounts of slag and sometimes carbon were introduced into the structure. Table 125 demonstrate that the metallic iron present in the piled structures tended to be clean despite the introduction of slag and carbon as the result of poor welding technique.

The Alloys Present in Heterogeneous Iron

Heterogeneous structures are by nature a combination of multiple alloys. All of the major alloys were found in heterogeneous structures in many different combinations.

Phosphoric iron/Ferrite Heterogeneity

The heterogeneity of phosphorus in iron, most prominently seen in ghosting, was another form of heterogeneity present in the iron artefacts. Many, mostly phosphoric iron, artefacts demonstrated areas of ferrite with increased slag content.

Heat treatment

Heat treatment was seen in six of the composite construction heterogeneous artefacts, bill hook SOU31-92, knife Yo10395, knife SOU169-610, knife SOU98-38, axe SOU24-22 and punch Yo1638. These artefacts included either piled structures or structures that were completely heterogeneous both containing high carbon steel as a major constituent.

Material Quality

Of the 80 artefacts containing heterogeneous iron, 58% contained clean metal. Figure 54 shows the class distribution of clean structures in heterogeneous artefacts. The low number of clean Class 1 artefacts, of which there were 15 out of 30 artefacts, may indicate that heterogeneous Class 1 artefacts were low quality and did not require clean metal. However, the Class 2 artefacts, of which there were 34, had the largest amount of clean metal (21 artefacts) suggesting that despite the choice of the smith to create nails and other construction objects using heterogeneous iron, there was still a need for these items to be created using clean metal. More than half of the heterogeneous Class 3 and UI artefacts were clean, reflecting the availability of the both clean and dirty metal.

Conclusions

Heterogeneous iron was commonly used in artefacts constructed from a single bar in the Early Medieval period. This mixed alloy iron was present in all classes of artefacts and in all different construction types. However, heterogeneous iron was used more

frequently in Class 2 artefacts than in Class 1, indicating less of a need for specific alloys usage in Class 2 items.

8.2.3 Composite Construction

Artefacts classified as composite constructions were objects intentionally constructed by combining multiple bars, often of different alloys, to form the final structure.

Table 126 is a summary of the artefacts types, manufacture and alloy usage in the composite construction artefacts.

Use

Composite construction was seen in 46 (33%) of the 140 artefacts. These artefacts were manufactured using the full range of techniques available to the smiths. Alloy selection, piling, carburization, welding, hot and cold working, and heat treatment were all found in artefacts of composite construction. The most common construction combinations were the edged tool manufacture typologies.

Artefact Types

The Class 1 artefacts were the largest group of composite construction artefacts, with 39 artefacts including 37 edged tools, an awl and an arrowhead. None of the dress fittings or security related artefacts were manufactured using composite construction. The Class 1 edged tools included 29 knives, an axe, a bill hook, two chisels, two

punches, an auger, and a pick. Figure 55 shows the distribution of manufacture types for the 37 edge tools with identifiable forms of composite construction (Typologies were defined in Section 4.2.1). All types of edged tools manufacture were present.

The largest group of edged tool manufacture were the 17 Type 2 knives. This finding is consistent with Blakelock and McDonnell's (2007) findings on the abundance of Type 2 knives during the Early Medieval period. The Type 2 knives consisted of a high carbon steel tip welded to a heterogeneous/ferritic/phosphoric back. A breakdown of the common knife back construction is presented in Figure 56. It was found that in the Type 2 knives heterogeneous knife backs were as common as single alloy knife backs. Considering that none of the knife backs were completely low carbon steel and no Type 5 knives existed, it is possible that the material of the knife backs were chosen for their non-steel component instead of a single alloy component or a particular alloy.

The other types of edge tool manufacture contained significantly fewer artefacts. The Type 1 edged tools, mostly pried with a wide central steel band, included a chisel and three knives. The Type 3 edged tools, entirely pried structures, included a chisel, an axe, a bill hook, a punch, and three knives. The Type 4 edged tools, a steel outer casing around a non-steel core, included a punch, a pick head and three knives. Only one Type 5 edged tool was identified, a pick head. There were two pattern welded knives, each with a unique construction, one, knife Win1454, with alternating steel and phosphoric iron and the other, knife Yo3859, with a steel tip and a back formed from low carbon and high carbon steels, phosphoric iron and ferritic iron.

Two other Class 1 artefacts with composite construction included Awl Thet249 and Arrowhead Yo11067. Awl Thet249 was constructed by welding a steel component to a ferritic iron and allowing carbon diffusion to create a decreasing gradient of carbon away from the weld. Arrowhead Yo11067 was a Type 1 style construction with a central steel band sandwiched between two bands of ferrite.

There were only three Class 2 artefacts manufactured using composite construction: nail DW16692-5620, ferrule Thet176 and hook BN305. In all three artefacts the manufacture included the welding of steel to ferrite or phosphoric iron in a manner that demonstrated purposeful use of the alloy. Nail DW16692-5620, was constructed by welding a steel head to a ferritic shank. The ferrule was constructed with a steel outer casing welded to a piled phosphoric/ferritic iron inner shell. The tip of the hook could be described as a Type 1 construction with a steel point inserted between two pieces of ferritic iron.

The Class 3 artefacts with composite construction included four bars. Three of these bars were composed of the welding of two or more single alloy bars together to create a composite bar. A composite construction bar could have been prepared for the manufacture of a specific composite object but was never finished. Bar CC363 and bar Yo9938 consisted of high carbon steel bands cleanly welded to a phosphoric or ferritic iron band. Bar Yo8794 was constructed using alternating bands of phosphoric and ferritic iron. Tapering iron bar BN311, also identified as an unfinished tool, was different from the other three bars with the tapered end constructed like a partial

Type 1 edged tool with a very high carbon steel welded to a heterogeneous phosphoric/ferritic iron.

Alloy Selection

Composite artefacts contain multiple alloys intentionally welded to form a structure that was intended for a specific use. These alloys were placed within the structure based on their specific properties; for example, the cutting edge of most knives was composed of high carbon steel due to its hardness and improved sharpening properties.

Class 1

Table 127 shows the presence of steel in all of the Class 1 artefacts. Low carbon steel was the second-most-prevalent alloy found in 79% of the Class 1 artefacts, often due to carbon diffusion from the high carbon steel components or carburization. Phosphoric iron and ferrite both are present in a little over half of the artefacts.

Figure 57 shows the alloy usage exclusively in the edged tools in Class 1. High carbon steel was present in all of the Class 1 edged tools as the cutting edge with only one exception; knife Thet271, where the steel was present in other parts of the piled microstructure. Low carbon steel was present in most of the edged tools and all of the other Class 1 artefacts.

In the Class 1 artefacts phosphoric iron was present in 27 (72%) of the 37 edge tools. Eleven of the Type 2 knife backs contained phosphoric iron, six of which were heterogeneous, one was piled and four of which were single alloy. In the other edged tools phosphoric iron was used as a component of heterogeneous or piled structures, the core of a Type 4, and the sides of a Type 1 knife.

In the Class 1 artefacts ferrite was present in 22 (59%) of the 37 edged tools. Eight of the Type 2 knife backs contained ferritic iron; two of which were heterogeneous, two were piled, and four of which were single alloy. In the other construction types ferritic iron was a component of the piled flanks in the Type 1 edged tool microstructure, a component of the piled microstructure of 3 of the Type 3 edge tools, and the core of 2 of the Type 4 edged tools. No ferrite was present in awl Thet249.

Alloy selection in Class 1 composite construction artefacts indicates that high carbon steel was reserved for the specific use as the cutting edge of edged tool, rarely used in other parts of these artefacts. The rest of the alloys were used in many combinations, indicating that it was less important as to what alloy composed the back of the artefact as it was to have a steel cutting edge. The pattern welded knives, particularly Y03859, also demonstrated an understanding the different alloys available through selective use of the alloys for different parts of the knives.

Class 2

The Class 2 composite construction artefacts included hook BN305, nail DW16692-5620, and ferrule Thet176. Table 128 shows the alloy usage in the Class 2 composite construction artefacts.

Steel was present in all of the Class 2 composite construction artefacts. Phosphoric iron, ferritic iron and low carbon steel were each present in two of the three artefacts. The use of high carbon steel in these objects is probably indicative of the use of the objects themselves. The hook contained a steel insert in the point, indicating this particular hook required a sharp point, possibly to use for scraping. The nail contained an unquenched high carbon steel head, possibly a product of reuse. The ferrule included a steel outer casing, which may have been used to strengthen the iron and retain the shape. Low carbon steel was present as slight carburization of the hook and carbon diffusion in the nail.

Phosphoric iron was only present in one of the Class 2 composite construction artefacts, the ferrule. In this object it served as a part of the heterogeneous piled inner ring. This heterogeneous non-steel interior may have been to provide contrast to the brittle steel outer casing.

Ferritic iron was present in the hook and the ferrule. In the hook it composed most of the structure and in the ferrule it consisted as part of the heterogeneous piled inner ring of the artefact.

Alloy selection in Class 2 composite construction artefacts indicates that despite the common use of this class of artefacts, smiths still created specialized versions of these artefacts, probably intended for specific uses.

Class 3

The Class 3 composite construction artefacts included tapering bar BN311, bar CC363, and blank Yo8794. Table 129 shows the alloy usage in the Class 2 composite construction artefacts.

Two of the Class 3 bars were composite construction artefacts composed of a high carbon steel band clearly welded to a non-steel component (one had phosphoric iron and the other contained ferritic iron). The cleanness of the weld and the iron indicated that this weld was intentional.

A third bar did not contain any steel, but was a banded structure of alternating phosphoric and ferritic iron. This structure may have been the result of folding bars of phosphoric and ferritic iron with intentional alternation of the two alloys.

The tapering bar/unfinished tool was a combination of heterogeneous phosphoric/ferritic iron with a high carbon steel welded to it to form a partial Type 1 tapered tip and low carbon steel was present as a part of the heterogeneous phosphoric/ferritic iron piled back. The use of the high carbon steel in the tapered portion indicated that it was of composite construction and probably intended to be finished into a tool.

Alloy selection in Class 3 composite construction artefacts could have been used by a blacksmith to create the Class 1 and Class 2 composite artefacts.

Conclusions

The selective use of high carbon steel in the composite artefacts demonstrated that it was a key component in complex manufacture and rarely used where it was not needed. The combination of steel with non-steel alloys shows an understanding and exploitation of the mechanical properties of the two different alloys.

Carburization

Minor exterior carburization could be seen in three of the composite construction artefacts: awl Thet249, chisel SOU169-1858 and hook BN305.

Heat treatment

All 13 of the heat treated artefacts were of Class 1 composite construction artefacts. Heat treatment was an intentional manufacture technique exclusively reserved for edged tools.

Material Quality

Approximately half of the 46 composite construction artefacts were identified as clean. This result suggests that it was not necessary for clean iron to be used in this form of construction artefacts despite selective use of alloys.

As composite construction includes specific selection of alloys, the material quality of the alloys may have been a factor in selection for use. Figure 58 shows the material quality of the alloys within composite construction artefacts. The high carbon steels were very clean, with the low carbon steel slightly less so, indicating that it was important not only to selectively use high carbon steel but that high carbon steel needed to be clean. Only approximately half of the phosphoric iron and ferritic iron was clean, indicating less of a need for clean material in the non-steel components of composite constructions.

Reuse/Recycling

Reuse and recycling must be considered when examining metal artefacts. The effort needed to mine, smelt and forge iron was extensive and, for those without the time or the means reuse and recycling may have been easier options. Unfortunately the archaeologically it is difficult to identify evidence of recycling within archaeological iron artefacts themselves. Recycling of iron is often associated with hordes of iron such as those found in Iron Age contexts (Bradley 1988) and in non-ferrous metals (Vassos and Vasiliki 1999). However, outside of horde contexts it is often difficult to identify reuse and recycling. In non-ferrous artefacts (Gale 1997), isotope analysis has been used to

identify recycling. Unfortunately isotope analysis does not provide the same quality of information for iron and would aid in recycling identification.

There are no established criteria for determining reused and recycled iron through the examination of iron artefacts (Northover 2009 pers. comm.). Considering that the iron has to be reworked to be reused, the process of recycling probably introduces new smithing slag inclusions and produces smaller artefacts. The original microstructure would be transferred to the new item. Each of these, however, presents problems that would impede identification of recycling. Large amounts of slag inclusions present in the microstructure may represent either the addition of new slag inclusions during smithing or iron that has not had all of the smelting slag removed or iron that was heavily worked. The latter would be impossible to see, especially would be if the artefact had been tempered.

The transfer of microstructure is currently the only means by which recycling of iron in artefacts can be identified. However, if the original object was a single alloy or a heterogeneous item, it would be impossible to recognize alterations to the microstructure that indicate that in the object was created through recycling. Nonetheless, the reuse of composite construction artefacts has only a slightly greater chance of being identified. Unless the artefact has a very clear composite construction microstructure that is an unusual combination of alloys and it can also be argued that such combination has no conceivable practical effect on the structure of the artefact. It must be concluded that recognizing reuse from the analysis of heterogeneous iron does not appear possible on the basis of current knowledge.

Of the 140 artefacts examined in this study none could conclusively be identified as recycled. Many of the artefacts examined here may have been recycled, but their structures could just as well be heterogeneous or the product of the smith combining the off-cuts to create objects.

Conclusions on Composite Construction

The Class 1 composite construction artefacts demonstrate both intentional alloy selection and material selection by the smith. The pattern welded knives contained both ferrite and phosphoric iron as separate components, confirming that the smiths could tell the two alloys apart. The selective use of high carbon steel indicated the importance of the iron-carbon alloy and possibly the rarity of the alloy. The abundant use of the other alloys and heterogeneous iron indicates that they were more common and possibly inexpensive. High carbon steel also tended to be cleaner than the other alloys, which may have been the result of selection or the process to create it.

8.3 Alloys and Alloy Use

8.3.1 The Alloys

Characterisation of the microstructures by optical and scanning electron microscopy demonstrates that there were a number of different alloys present in iron artefacts manufactured during the Early Medieval period. The following section describes in

detail the characteristics of these alloys. The critical question is, however, whether the alloys were manufactured and used deliberately.

8.3.2. Ferritic Iron

Ferritic iron, found in 60% of the assemblage (84 of the artefacts), was one of the three main alloys present in archaeological iron. Though the properties of ferrite have been studied extensively by modern metallurgists (Samuels 1999), ferritic iron in archaeological artefacts differs from modern pure iron due to its inherent impurities. The ferritic iron in this study was defined as iron with less than 0.1% carbon, 0.2wt% phosphorus and less than 0.4wt% arsenic; however, minor amounts of each of these alloying elements and others may have been present in ferrite.

Properties

Though this research project was not designed to examine the properties of ferritic iron as an alloy, aspects such as the grain size and hardness were important for comparison with the other alloys and to determine manufacturing techniques. These will be reviewed here.

The large grain size (ASTM 1-3) in a ferritic structure has been generally used as an indicator of phosphoric iron. The expected ferritic grain sizes are approximately ASTM 6-8. Figure 59 is a histogram showing the number of artefacts with each average grain size, demonstrating that ferritic iron in the artefacts from this study contained the entire spectrum of grain sizes; however, the largest concentration (36% of the

artefacts) were ASTM 6 and the average grain size was $ASTM\ 5 \pm 1$, falling well within the expected range. The larger grains may have been the result of very slow cooling rate that allowed the crystals extended time to grow (Scott 1990: 12-13).

The hardness of ferritic iron is an indicator of both manufacture and alloying. The expected hardness values for ferritic iron that has not been cold worked vary between $Hv_{0.2}\ 70$ and $Hv_{0.2}\ 100$. This value, however, increases based on the impurities in the iron and the amount of cold working that an object has undergone. The hardness of the ferritic iron from this study varied between $Hv_{0.2}\ 73$ -240. This large range can be accounted for in part by the effects of cold working (see Section 8.6.2), but in some cases this does not fully account for the increased hardness. The effects of the main alloying elements (i.e. C, P and As) are excluded. Other explanations that could account for increased hardness could include the presence of nitrogen, though no characteristic carbo-nitride needles were observed in this study, or the combination of very low levels of the main alloying elements (i.e. C, P and As).

Alloy Use in Manufacture

In Early Medieval artefact manufacture ferritic iron was used by the smith in two forms: as an individual alloy and as a component in a heterogeneous iron. Figure 60 shows that the number of artefacts constructed from bars that were either heterogeneous or single alloy. Of these, two single alloy ferritic bars and 14 heterogeneous/carburized iron bars contained ferrite.

Thirty-one artefacts contained ferritic iron from individual alloy bars were used in single alloy artefacts, composite construction artefacts and carburized ferritic artefacts (table 130).

Ferritic iron was used in the single alloy construction of nine artefacts, which included five nails, a clothing tab, a padlock and two pieces of stock iron. Nine more artefacts originated as single alloy ferritic iron objects that each underwent some carburization. These artefacts included a buckle, a needle, four nails, and two pieces of stock iron.

Ferrite was intentionally used as individual alloy components in 13 of the composite construction artefacts. Figure 61 shows the distribution of knife construction types for the composite artefacts containing ferrite. In the majority of these artefacts ferrite was used as the back (in Type 2 constructions), the flanks (in Type 1 constructions) or the core (in Type 4 constructions) of edged tools.

Ferrite was also present in 75% of the artefacts containing heterogeneous iron. The nature of Early Medieval heterogeneous iron has been discussed in detail in Section 8.3.2. In the artefacts containing heterogeneous iron ferrite was a major component of 15 piled microstructures and present in the heterogeneous iron of 15 composite construction artefacts.

Figure 62 plots the use of ferritic iron as an individual alloy versus its presence as part of heterogeneous iron based on class. Despite ferritic iron's presence in all of the classes, its individual use was only in approximately 20% of each of the three main

classes. In the rest of the artefacts containing ferritic iron, ferrite was part of a heterogeneous iron and was present in 30-40% of the artefacts from each of the three main classes. This indicates that ferritic iron was widely used; however, its intentional use as an individual alloy was significantly less than its use in heterogeneous iron.

An examination of the cleanness of ferritic iron showed 62% (52 artefacts) of the artefacts with ferritic iron present were clean. This percentage was maintained when the artefacts were separated into groups of ferrite from individual alloy components and ferrite in heterogeneous iron (figure 63).

8.3.3 Steel

Steel was the most important iron alloy of the British Early Medieval period. Its selective use as the cutting edges of edged tools and weaponry enabled a level of iron technology that exceeded all earlier periods (McDonnell et al. forthcoming-b). This project began to examine the types of steel available to smiths and the techniques used by smiths to further create steel in this Early Medieval iron assemblage.

High Carbon Steel (HC Steel)

High carbon steel (>0.3%C) was identified in 56% (78 artefacts) of the assemblage.

The Early Medieval smith would have received high carbon steel in three forms as single alloy bars, carburized ferritic/phosphoric bars, and as a component of heterogeneous iron bars. In the Class 3 assemblage there were no single alloy high

carbon steel bars present. There was one composite artefact, however, with a band of clean high carbon steel welded to ferritic iron that could be used in edged tool manufacture. There were five carburized bars and five heterogeneous bars containing high carbon steel. It is possible that the carburization was conducted by the smith to create bars with some high carbon steel to use in manufacture.

In the finished objects high carbon steel was present in the four forms: by itself in single alloy construction, as an individual alloy component used in composite construction items, as a component of a heterogeneous structure, and as the result of carburization. Of these four forms, steel was used (figure 64) primarily in composite construction.

Figure 65 demonstrates the forms of high carbon steel used in specific classes of artefact. In the Class 1 artefacts high carbon steel was present in 69% of the artefacts and was predominantly used as individual alloy components in composite construction artefacts. High carbon steel was a vital component of Class 1 edged tools, serving as the cutting edge. In Class 2, where it was not necessary for steel to be in any of the artefact types, high carbon steel was present in 50% of the artefacts in the form of carburized steel exteriors or as part of heterogeneous iron. In Class 3 high carbon steel was present in 37% of the artefacts, generally in the forms of carburized steel exteriors or as part of heterogeneous iron. This shift from use as an individual alloy in Class 1 artefact to use as carburization or in heterogeneous iron in Class 2 and Class 3 artefacts may represent a difference in the importance of steel to the artefacts. In Class 1 artefacts steel was needed for specific construction techniques, while in Class 2

and Class 3 objects steel may have been used as a strengthener, either to the exterior through carburization or within the interior by its presence in heterogeneous iron.

The heat treatment of high carbon steel will be covered in Section 8.5.1; however, the 14 heat-treated artefacts were all Class 1 edged tools. In all of these artefacts the steel was used as an individual alloy in a composite construction and was probably specifically selected for use in artefacts with the intention of heat treatment.

In high carbon steels intentional use included use as individual alloy components in composite construction artefacts and as single alloy artefacts. The combination of these composes 25% of the total artefacts from the assemblage. The presences of high carbon steel in heterogeneous iron and as the result of carburization are questionable as to whether it was intentionally used by the smith. There were both advantages (i.e. strength) and disadvantages (i.e. brittleness) to having high carbon steel present in the artefacts with heterogeneous iron and carburization. These structures were present in 31% of the artefacts. These results suggest that high carbon steel was used frequently in Early Medieval artefacts and that its intentional use was only slightly less frequent than its presence as carburization and in heterogeneous iron.

Low Carbon Steel (LC Steel)

Low carbon steel (0.1-0.3% C) was identified in 59% of the 140 artefacts.

Low carbon steels contain too low of a carbon content for heat treatment to alter the microstructure and therefore were used for entirely different purposes. This form of steel has many origins, most of which are directly related to smithing and not created during earlier bar formation; however, it is possible that the smith selected bars of low carbon steel for artefact construction. Only one artefact, key bit DW17274-6302, was completely composed of low carbon steel. Another artefact, punch Yo7454, contained a completely low carbon steel component in its composite construction. Low carbon steel can also be present in heterogeneous iron, of which there are five heterogeneous Class 3 bars containing low carbon steel and 38 other heterogeneous artefacts.

Low carbon steel can be produced during smithing by carburizing ferritic/phosphoric iron or through carbon diffusion from high carbon steel welded to low carbon, ferritic, or phosphoric iron. Carburization, either intentional or unintentional, was the cause of low carbon steel in 19 (14%) of the artefacts, while carbon diffusion was the cause of low carbon steel in 23 (16%) of the artefacts. Figure 66 compares the causes for low carbon steel in the artefacts from this study, demonstrating that low carbon steel is primarily found in heterogeneous artefacts.

It should be noted that low carbon steel was more likely to have been unintentionally present in iron artefacts than high carbon steel. To achieve the high carbon steel through carburization a significant amount of time was required. Low carbon steel, however, only required a small amount of carbon (0.1%C) to affect the microstructure and that could have easily occurred accidentally during the smithing process.

Figure 67 demonstrates the type of manufacture of low carbon steel used in specific classes of artefacts. The increase in carbon diffusion in Class 1 artefacts was probably directly related to the use of high carbon steel in edged tool construction. Heterogeneous iron was used in all classes and low carbon steel was a major component of the mixed alloy iron and also present in all classes. The slight carburization that produces low carbon steel occurred more in the Class 2 and Class 3 artefacts, possibly suggesting less need for precision in the manufacturing of these artefact types or that intentional carburization occurred to strengthen these items.

Clean iron was found in 63% of the low carbon steel artefacts. Table 131 shows the cleanness of the low carbon steel artefacts based on the type of manufacture. The artefacts that contained low carbon steel due to carburization and heterogeneous iron had the cleanest microstructures.

Carburization

Carburization was a slow process that required the iron to be in direct contact with carbon, often in the form of charcoal or other organic materials, at temperatures above 950°C. Carburization of the exterior surface of the artefact was identified in 27 (19%) of the artefacts examined in this study. Carburization, as it was defined for this particular research project, was identified as a gradient of steel along the exterior of the object.

Carburization can be both intentional and unintentional. Intentional carburization was defined as a layer of steel ($>0.1\%C$) along approximately half of the exterior of the object. Intentional carburization was found in 10 (7%) artefacts. Table 132 gives a list of the intentionally carburized artefacts, indicating the presence of low carbon and high carbon steel as a result of the carburization. Unintentional carburization was defined as small areas of carburization located randomly along the exterior of the object. During the working of an object at hot temperatures the iron may have accumulated small amounts of carbon from the charcoal of the hearth. It was also possible that surface loss due to corrosion may have obscured what would otherwise be classified as intentional carburization. Unintentional carburization was present in 17 artefacts, of which contained low carbon steel as the result of carburization and 59% (10 artefacts) of which contained high carbon steel.

Considering the determination of intentional versus unintentional was subjective, as it was impossible to truly determine intent, all artefacts that were questionable were placed in the unintentional category.

Steel Conclusions

Determining intentional usage of steel was very difficult. Using the criteria established above for the intentional use of steel, namely the use of the alloy as an individual component in composite construction, as a single alloy object, and as intentional carburization, it was found that 11 (8%) artefacts showed intentional use of low carbon steel (table 133) and 43 (31%) artefacts showed intentional use of high carbon steel.

Together these artefacts composed 39% of the total assemblage. Some of these artefacts contained both low carbon and high carbon steels.

The remaining artefacts with low carbon steel composed 50% of the total assemblage and the remaining artefacts with high carbon steel composed 26% of the total assemblage. The numbers indicate that the majority of low carbon steel usage could not be proven to be intentional, while the majority of high carbon steel usage could be.

8.3.4 Phosphoric iron

Phosphoric iron was a commonly used alloy in the Early Medieval Britain. 66% of the artefacts examined in this study contained significant amounts of phosphorus in their iron alloys. This abundance of phosphoric iron provided a large dataset from which to examine the properties of the alloy and how it was used in the Early Medieval period.

The Phosphorus Content of Early Medieval iron

Table 134 provides a list of the types of artefact containing phosphoric iron. The alloy was present in 68% of Class 1 artefacts, 63% of Class 2 artefacts, 75% of Class 3 artefacts and 50% of the UI artefacts. This indicated that phosphoric iron was abundant in Early Medieval Britain and used in all types of artefact construction.

Alloy Manufacture

Though this study did not directly investigate the manufacture of phosphoric iron, some of the results may aid in the understanding of how phosphoric iron was manufactured. The two major theories of manufacture include manufacture from high phosphorus ores, such as bog ores, and the addition of phosphorus-bearing minerals, such as apatite (Ca_3PO_4), which can be found in animal bone. The first occurrence may have been partially incidental, the alloy being one of the products local smelters got whenever they used those ores. As Godfrey (2007) and Vallbona (1997) noted in their experiments, some manipulation of the smelt may have improved the chances of highly phosphoric iron blooms. The second manufacture theory was the deliberate addition of additives during the smelt to create phosphoric iron. The existence of the steel with high amounts of phosphorus made it unlikely that the addition of phosphorus to the smelt was always intentional. The detrimental effects of combining significant amounts of phosphorus and carbon would make the iron undesirable and difficult to market, making intentional manufacture unlikely.

Artefact Manufacture Evidence

Working evidence

In several of the iron artefacts, specifically nail WP160 and nail WP556, indications of manufacture techniques could be derived from the deformation of the ghosting within the artefact. Figure 68 demonstrates this pattern of ghosting in nail WP556 in both (a) Nital and (b) Stread's Reagent. Stread's demonstrates that this effect is due to the distribution of phosphorus in the microstructure. A formerly lengthwise distribution of

phosphorus, as seen in the shank, was altered when the nail head was formed. The equiaxed structure of the grains indicated that the nail was normalized after the head manufacture, but the removal of ghosting would have required a more prolonged heating (Gouthama and Balasubramaniam 2003).

Metallographic evidence of cold working, such as the distortion of the granular structure beginning at 40% reduction, was seen in nine of the phosphoric iron artefacts. These artefacts included thinned items, such as needles and a key, as well as the heads of nails and a variety of other artefacts from all classes. A full description of the cold worked artefacts is included in Section 8.4.

Heat treatment

Evidence of heat treatment, in the form of heat-treated steels, was present in nine of the artefacts containing phosphoric iron. Table 135 displays the results of analysis for phosphoric iron in heat-treated artefacts. All of the artefacts were Class 1 edged tools, with phosphorus present in the knife backs of Type 2s, part of the piled structures of Type 3s, the central core of Type 4 and a part of the pattern-welded structure. Though heat treatment increases the hardness of steels in phosphoric iron, where the average hardness is around Hv_{0.2} 160, there was no significant increase in hardness as the result of heat treatment (see hardness values table 135).

One cause of ghosting was rapid cooling after the alloy had been heated for a prolonged period in the dual-phase region. This heat treatment, however, could occur

at any point in the production of the artefact and remain despite further treatments as long as it was not heated for a prolonged period to allow for the diffusion of the phosphorus. The heat treatment used to create heat-treated steels was unlikely to have been the cause of the ghosting structures due to rapid cooling preventing the time needed for segregation.

8.3.5 Phosphorus and Carbon

Relatively high phosphorus concentrations were found in both the high and low carbon steels from all sites except Worcester. Table 136 shows the number of artefacts in which phosphorus was present in steel. In low carbon steels the phosphorus was often present in the ferritic component of the normalised ferrite plus pearlite microstructure. In the high carbon steels, however, further research will be needed to discover where the phosphorus exists in the microstructure.

Figure 69 shows the distribution of phosphorus in steel versus the carbon content from artefacts. The measurements were limited to artefacts with phosphorus content greater than 0.1wt%P. The results show that high concentrations of phosphorus rarely exist in high carbon steels. However, lower phosphorus contents can exist in all steels.

Phosphorus Distribution in Steels

Once phosphorus was identified in high carbon steels, Oberhoffer's reagent was used on selected samples to determine phosphorus distribution within those steels. Canterbury knife CC397 was an example of a heat-treated steel knife tip containing

high phosphorus and low arsenic (figure 70a). Once etched with Oberhoffer's Reagent the structure (figure 70b) showed that the phosphorus content was more concentrated in the bainitic areas than in the tempered martensite. This was reflected in the SEM/EDS data as presented in Table 137. There were no significant variations in phosphorus content in the steel; however, metallurgists have previously noted the concentration of phosphorus in bands within steels (Stead 1915).

Carburization/Carbon Diffusion

There were 18 artefacts with carburization/carbon diffusion into phosphoric iron. Archaeometallurgists have always referred to phosphoric iron as a carbon inhibitor, pointing to the clean welds with steel that show no carbon diffusion across the weld line. Experiments conducted by Godfrey (2007) and Hall (2008), however, found the alloy easy to carburize. The results of this study reflect Hall's finding that it is possible to carburize phosphoric iron as seen in 14 artefacts, but there were also 11 artefacts that exhibited the clean welds of steel and phosphoric iron. This may be due to the need for specific conditions to be in place for phosphoric iron to be carburized. It is possible that welding is too quick a process for the carbon to diffuse into a crystal structure altered by the presence of phosphorus.

Another factor that may have aided some of the carburization of phosphoric iron was the local dephosphorization due to dual-phase segregation or absorption of phosphorus by slag inclusions. The low phosphorus ferrite in these areas would have allowed the carbon to diffuse freely. An example of this can be seen in unfinished tool

BN311A (figure 71) where the areas in the microstructure that are low in phosphorus have high slag inclusion content and are carburized, while the cleaner highly phosphoric iron directly adjacent was not carburized.

Conclusions

Phosphorus can co-exist with carbon in the iron microstructure. However, phosphorus is a carbon inhibitor and the conditions of heating and welding, specifically time and temperature, may be the determining factor that allows carbon diffusion into phosphoric iron.

8.3.6 Phosphoric iron Indicators

Phosphoric iron indicators have been used to identify the presence of the alloy without the use of elemental analysis. Previous studies have explored the causes of individual indicators, such as ghosting (Chen et al. 2003, Gouthama and Balasubramaniam 2003, Stewart et al. 2000c) and increased hardness values with increased phosphorus (Gordon 1997), but these studies did not consider these indicators in relation to each other, their abundance, and their effectiveness in identifying phosphoric iron.

The following indicator data were taken from the analysis of all phosphoric and ferritic test sites in the 140 artefacts. This included 541 test sites; the data from each was an average of two SEM/EDS tests per site.

Ghosting

Ghosting has been attributed to the segregation of phosphorus to the austenite grain boundaries when the alloy was in the dual-phase region of the phosphoric iron phase diagram (See figure 10) (Buchwald and Wivel 1998, Gouthama and Balasubramaniam 2003, Stewart et al. 2000c), as well as local dephosphorization due to the presence of fayalitic slags (Chen et al. 2003, Gouthama and Balasubramaniam 2003).

Ghosting was found in the phosphoric iron of 79 of the artefacts. This comprises 84% of the artefacts containing phosphoric iron. Table 139 demonstrates that ghosting was seen in over half of the artefacts in each of the classes and in approximately half of each construction type, except for heterogeneous artefacts, in which it was found in almost 70% of the artefacts.

Figure 72 summarizes the average phosphorus content for each of the ghosted areas in the 79 ghosted phosphoric iron artefacts. The results show that ghosting existed with all levels of phosphorus content. The majority of the test sites contained 0.3-0.5wt%P, with an average phosphorus content for ghosted areas of 0.4wt%P. However, ghosting has been proven to be the result of dramatic differences of phosphorus content in the iron (Chen et al. 2003, Gouthama and Balasubramaniam 2003, Stewart et al. 2000c, Vallbona 1997: 180) as demonstrated in Figure 73.

Figure 73a shows a ghosted area from nail WP556, from which the SEM/EDS elemental analysis results are presented in Figure 73b. These results confirmed that the

phosphorus content was highly variable in the ghosted structure with variations up to $\pm 0.4\text{wt}\%\text{P}$.

Ghosting Structures

The non-uniform distribution of phosphorus that causes ghosting occurred in a series of regular structures previously defined in Section 5.5.12. Table 140 shows how often these structures were found in the 94 phosphoric iron artefacts.

The two noted causes of ghosting, phosphorus segregation and slag inclusion absorption, were re-examined in light of the ghosting structure analysis.

Grain Boundary Ghosting

Grain boundary and Dubé ghosting structures (figure 74) were the direct result of segregation of phosphorus to the austenite grain boundaries and have been the subject of several previous studies (Gouthama and Balasubramaniam 2003, Stewart et al. 2000c). Depletion of the phosphorus at the grain boundary can be seen in Figure 75 and is supported by the phosphorus measurements. This ghosting structure was one of the most common, appearing in 41 artefacts. The most common Dubé forms were allotriomorphs and Widmanstätten-like structures that form at the grain boundary with needles cutting into the centre of the grains.

Inter-granular Ghosting

Inter-granular ghosting was often found in the form of a ripple-like effect overlaying the current granular structure. Stewart et al. (2000c) described a similar feature that

was the result of a coarsening and spherodisation of the clear Dubé structures with prolonged heating. This structure was the most common form of ghosting, seen in 45 of the ghosted artefacts. This type of ghosting commonly occurred as large ghosted areas (figure 76).

Edge Effect Ghosting

Edge effect ghosting was seen in 16 of the ghosted artefacts. This form of ghosting only occurred where phosphoric iron had been welded to carbon steel. It was possible that edge effect ghosting was the result of carbon diffusion into the phosphoric iron microstructure. As previous researchers have commented on, phosphorus and carbon are in competition in the microstructure (Vallbona 1997: 26). Despite this, the relationship between ghosting and carbon has never been studied. Though modern metallurgists have extensively studied the segregation of phosphorus in steel (Erhart and Grabke 1981, Hansel and Grabke 1986, Suzuki et al. 1983, Suzuki et al. 1984), their studies worked with phosphorus levels below 0.08wt%P (the modern definition of phosphoric iron (Bramfitt and Benschoter 2002: 248)) never approaching the significantly larger amounts of phosphorus found in archaeological iron. Archaeometallurgists have focused on the mechanical problems of carbon/phosphorus iron alloys (Goodway 1987, Gouthama and Balasubramaniam 2003, Stewart et al. 2000a). Further research is needed to study the causes of edge effects, particularly carbon diffusion in phosphoric iron in the quantities seen in archaeological iron.

Pearlitic Ghosting

Pearlitic ghosting (figure 77) was a new structure discovered during this study. This ghosting structure may be a clue into the relationship between phosphorus and carbon in archaeological iron. This was a halo of ghosting seen around pearlite. The testing of this ghosting showed a depletion of phosphorus immediately adjacent to grain boundary pearlite (figure 78). This ghosting structure could have been the result of the combination of phosphorus segregation to the austenite grain boundaries and the formation of pearlite from the austenite within the low phosphorus areas upon cooling.

Figure 78 shows the results of elemental analysis of an area of ghosted pearlite. These results demonstrate the decrease in phosphorus content immediately adjacent to the pearlite (test sites 2 and 6). The depletion of phosphorus around the pearlite was on the scale of 0.1-0.3wt%P with an average of 0.2wt%P. Also demonstrated was the significant phosphorous content of the pearlite itself (test sites 1 and 8), which was almost as high as the area outside of the ghosted halo. Further research is needed to investigate the causes of pearlitic ghosting.

Slag Inclusion Ghosting

Slag Inclusion ghosting, as seen in Figure 79, was the second-most-common structure found in the ghosted artefacts. This form of ghosting was often seen in artefacts that contained no other ghosting structures and has been attributed to the absorption of local phosphorus by silicate slag inclusions (Chen et al. 2003, Gouthama and Balasubramaniam 2003). The darkened areas around the slag inclusions in Figure 79

(b) confirmed a relationship between the slag inclusions and the metal in terms of phosphorus content.

The results from elemental composition analysis of a ghosted slag inclusion are presented in Figure 80 and Table 141. The phosphorus content is significantly lower immediately surrounding the slag inclusion, while the slag inclusion itself contains large amounts of phosphorus.

Slag inclusion ghosting was not always present around the inclusions found in phosphoric iron and may be related to the type of slag (i.e. smithing vs. smelting slags). Further research should investigate both un-ghosted and ghosted slag inclusions. It should also determine, if possible, what processes create slag inclusion ghosting, and how they are affected by heating and cooling regimes.

Ferritic Ghosting

Ghosting in ferritic iron ($<0.15\text{wt}\%\text{P}$) was found in 13 of the iron artefacts. This ghosting may have been the result of small amounts of phosphorus still present in the structure. The definition of phosphoric iron used in this study, iron with $0.15\text{wt}\%\text{P}$ or above, does not limit the indicators to iron with less than $0.15\%\text{P}$. It was still possible that phosphorus levels smaller than $0.15\text{wt}\%\text{P}$ could contain phosphorus-related ghosting.

Some researchers have suggested that ghosting could also be caused by elements that behave similar to phosphorus in the iron microstructure, particularly arsenic.

Elemental analysis of these ferritic ghosting structures, however, did not find significant amounts of such elements. Slater (2008: 421) suggested that heavy cold working (such as occurs during the drawing process) was another cause of ghosting in ferritic iron. Only one of the ghosted ferritic iron objects showed the deformation of grains associated with cold working over 40% reduction.

Ghosting Conclusions

Previous studies on ghosting have shown that it was caused by the use of heat treatment (Gouthama and Balasubramaniam 2003, Stewart et al. 2000c). This heat treatment involved prolonged periods of heating to allow the phosphorus to segregate. This prolonged heating is not the same heat treatment as that which was used on high carbon steel, which involved much shorter periods of heating. It is more likely that ghosting structures were caused by earlier heating and cooling cycles, as early as during the smelting process. The ghosting structures were robust and remain despite heating and cooling during manufacture (Gouthama and Balasubramaniam 2003, Stewart et al. 2000c). This was exemplified by the deformation of the ghosting in worked artefacts that were normalized after working. In light of the evidence of phosphorus inhibiting carbon diffusion in some artefacts, allowing carburization in others and the presence of edge effects as well as ghosted pearlite, the relationship of carbon and phosphorus is complicated and will require extensive further research.

Ghosted slag inclusions indicate a relationship between slag inclusions and the presence of phosphorus in the microstructure and may indicate smithing versus smelting slag in the microstructure.

Hardness

Several previous studies noticed a rapid increase in hardness in ferritic iron structures with the increase in phosphorus content (Chen et al. 2003, Gordon 1997, McDonnell 1983, Tylecote and Gilmour 1986: 11). Figure 81 plots the hardness values in the 541 phosphoric/ferritic iron test sites against the phosphorus content. Though there is a trend of increasing phosphorus content to hardness, the correlation was not significant ($r = 0.47$).

These results were to be expected considering the many other factors in the archaeological artefacts that can affect the hardness/phosphorus content relationship. These factors include work hardening, age hardening, and the presence of other alloying elements, such as carbon or arsenic. Each of these components individually would increase the hardness values in ferritic iron and are likely to have a similar effect in phosphoric iron.

Previous studies (Chen et al. 2003, Gordon 1997, Stewart et al. 2000a) have experimented with hardness/phosphorus relationships and did find that increased phosphorus content does increase hardness. These studies, however, were not directly comparable to archaeological iron. They were conducted with modern iron in controlled phosphoric alloys that contained no other alloying elements, such as trace amounts of carbon or arsenic that may alter the hardness values in archaeological iron.

Figure 82 demonstrates that there was no relationship between grain size and phosphoric iron hardness values.

Chen et al. (2003) noted that ghosted structures contained higher hardness values than un-ghosted areas. As Figure 83 demonstrates, the findings of this study did not find a large difference between the hardness of ghosted and unghosted structures. Theoretically, the hardness values increased with the increase of phosphorus content, as was seen in Figure 81. In ghosted iron the concentrations of phosphorus would have been higher in the former ferritic grains due to phosphorus segregation. This would have locally increased hardness values and the phosphorus-deprived areas at the former austenite grain boundaries would exhibit lower hardness values. The results of this research, however, revealed that the relationship between hardness values and ghosting was not predictable. Ghosting occurs with very small amounts of phosphorus and the hardness test was often too big to specifically test the phosphorus-high areas. Further research is needed to compare the hardness values of areas with high and low phosphorus in the ghosted structure.

There was no evidence of brittle fracture in these assemblages, despite the obvious evidence of high-phosphorus high-carbon alloys. If phosphoric iron was brittle, micro-cracks may be expected to form during manufacture/use life of the object. These cracks would have made the metal more susceptible to corrosion and less likely to survive to become part of the archaeological record.

Hardness Conclusions

There was a trend of increase in hardness with phosphorus content, but the effects of other factors such as cold working and carbon content must also be considered when interpreting increased hardness in archaeological iron.

Large Grains

In previous studies researchers have related phosphoric iron with large ferritic grains. Figure 84 shows the distribution of grain sizes in the phosphoric iron artefacts analyzed in this study. The results demonstrated that the grain size distribution of phosphoric iron was highly variable; however, 55 of the 94 phosphoric iron artefacts contained large grains (ASTM 1-3). Phosphoric iron rarely contained grains sized ASTM 6-7.

The distribution of ferritic iron grain size can be seen in Figure 85. The majority of ferritic grains were grain sizes ASTM 5-7 with very few grains sizes above ASTM 4 or below ASTM 7. Comparing the grain size distributions between phosphoric and ferritic iron, phosphoric iron had a different distribution of grain size, with a greater quantity of artefacts containing large grains and significantly less artefacts with grain size ASTM7-8.

Figure 86 graphs the grain size against the phosphorus content of all phosphoric and ferritic measurements taken during this study to determine if there was any relationship between the two variables. The results showed that phosphorus contents below 0.6wt%P contained all grain sizes. Higher phosphorus contents generally were present in larger grains, though the data also demonstrated that large grains could

exist in low phosphorus structures. This increased grain size was present in 19 of the ferritic iron artefacts.

Grain Size Conclusions

Phosphoric irons tended to have larger grain sizes, especially when high phosphorus contents were present. It should be noted, however, that ferritic iron also demonstrated large grain sizes but much less frequently.

Etch resistance

Resistance to etchants such as Nital was seen in the phosphoric iron of 38 artefacts and in non-phosphoric structures of 18 artefacts. Etch resistance was found in 56 microstructures of 55 artefacts. In 38 of these microstructures (68%) the etch resistance occurred in phosphoric iron, indicating that the presence of phosphorus is often the cause.

Table 142 shows that etch-resistance was present in artefacts from the three main classes, with approximately 40% of each class demonstrating etch resistance. Etch resistance was most prominent in composite construction but seen in all forms of artefact construction. It is unlikely that this effect is the result of artefact manufacture or artefact type, and more likely the result of alloy composition.

Etch resistance was found in non-phosphoric structures present in the artefacts from the three major classes and all manufacturing types (table 143). Etch resistance occurred in both ferrite and steel. In the ferritic etch resistance the phosphorus

content ranged 0.0wt%P-0.14wt%P and may account for some of the etch resistance. The presence of arsenic played a role in the etch resistance of many of the ferritic iron artefacts. The etch resistance in the steel artefacts, however, did not appear to be the result of either phosphorus or arsenic.

Etch Resistance Conclusions

Etch resistance was seen in both phosphoric iron artefacts and non-phosphoric iron artefacts. When the phosphorus content was low or nil, arsenic was identified in many of the etch-resistant structures.

Indicator Conclusions

The phosphoric iron indicators have been proven to be indicative of phosphoric iron. They, however, are not exclusive to phosphoric iron and elemental analysis is needed to validate the presence of phosphorus in the metal. Indicators such as ghosting and hardness can also provide information about the manufacture of the artefact.

8.3.7 Defining Phosphoric Iron

Archaeological alloys must be considered differently from modern alloys for two major reasons. First, archaeological iron most often contains small amounts of many different elements. Second, archaeological alloys are most often identified using optical microscopy and hardness testing without elemental analysis. For these reasons defining an “archaeological alloy” is not simply a definition of the elemental components, but a broader understanding of the physical attributes that help

archaeometallurgists realize that they are dealing with an alloy instead of a pure metal.

The key physical attributes to be taken into consideration for phosphoric iron include:

- Colour difference from that of ferritic iron
- Difference in hardness and brittleness from ferritic iron
- The propensity for containing the phosphoric iron indicators

The term “phosphoric iron” within this research had a very specific definition: iron with equal or greater than 0.15wt%P. Many of the artefacts tested had iron identified as ferrite that only contained slightly less phosphorus than the 0.15wt%. This caused difficulty in determining the phosphorus content necessary to identify phosphoric iron from ferritic iron. It was necessary, however, to set limits on phosphorus to ease the large-scale analysis of all the artefacts within this study. The definition of phosphoric iron is discussed below.

One of the key exercises of this research project was to establish if any of these attributes/indicators, or a combination, was a true indication of significant phosphorus content within the sample, specifically looking for the minimum amount of phosphorus at which these indicators begin to appear. It was found that individually most of these factors may not identify the presence of phosphorus within iron. This suggests that though they indicate the presence of phosphorus they need to be corroborated with elemental analysis to confirm if the alloying substance is present.

These results conclude that the definition of archaeological phosphoric iron used in this study ($>0.15\text{wt}\%P$) was acceptable. Though the indicators all occur in artefacts with less than $0.15\text{wt}\%P$, their frequency is significantly less than in artefacts with higher phosphorus contents. It should be noted, however, that even small amounts of phosphorus can affect the iron microstructure and that phosphoric iron indicators do not indicate how much phosphorus exists in the structure.

8.3.8 Phosphorus and Provenance

The data comparing the phosphorus content in artefacts from each of the sites show that the artefacts from Worcester, immediately in the vicinity of low phosphorus ore, had very little phosphoric iron. This is not proof of provenance, but does indicate that there is a relationship between local iron and local ore and, in an island like Britain where there are very few places with low phosphorus, low phosphorus in an assemblage of iron artefacts provides possibilities to the origin of the ore used to construct them.

Alloy Usage

Phosphoric iron usage did not differ greatly from that of ferritic iron. It was present in single alloy artefacts, as an individual alloy component in composite construction artefacts, and found in heterogeneous iron.

Figure 87 is a breakdown of phosphoric iron usage based on class and type of usage. Phosphoric iron as a component in heterogeneous iron was dominant in all classes; however, the use of the alloy as an individual component in composite construction was the second largest group in Class 1, followed by single alloy usage. In Class 2 and Class 3, the second largest usage was single alloy constructions.

Phosphoric iron was used for 12 single alloy artefacts. These artefacts included three Class 1 artefacts (two knives and a dress pin), five Class 2 artefacts (four nails and a tack), and four pieces of stock iron. Eight other artefacts were of single alloy construction with some exterior carburization, only one of which was identified as intentional. The carburized artefacts included one Class 1 artefact (a needle), three Class 2 artefacts (two nails and a fitting), and four pieces of stock iron. The 12 Class 1 and Class 2 artefacts originated as single alloy phosphoric iron bars that were shaped into the final form by the smith. The presence of the eight pieces of phosphoric iron stock iron indicates that the alloy was available in abundance for smithy use.

Individual alloy pieces of phosphoric iron were used in 12 of the composite construction artefacts. These artefacts included nine knives, two pieces of stock iron and one UI artefact. In the knives phosphoric iron was used as the flanks of one Type 1 construction, as the knife back of four Type 2 constructions, as the core of two Type 4 constructions and as a component in two pattern-welded knives. Both stock iron pieces contained bands of phosphoric iron welded to either ferritic iron or high carbon steel. The UI artefact was a composite artefact constructed from a core of phosphoric iron encased in high carbon steel. In all but two cases the use of phosphoric iron could

have been interchangeable with ferritic iron, and it is unclear if it was entirely intentional selection of the phosphoric iron over ferritic iron. What was intentional was the use of a non-carbon alloy in these composite construction artefacts. The two artefacts that defy this are pattern-welded knife (Yo3859) and bar (Yo8794), in which separate bands of phosphoric iron and ferritic iron were used within the construction.

Phosphoric iron was found as a component of heterogeneous iron in 60 artefacts. These were distributed across the classes and dominated the assemblage of phosphoric iron bearing artefacts.

Usage Conclusions

Defining intentional alloy usage was difficult for phosphoric iron due to its similar usage to ferritic iron. It is impossible to determine whether they were used interchangeably or selectively in artefacts such as the single alloy and composite constructions. With the other alloys it was assumed that individual alloy components in composite constructions were intentional, but the two artefacts (knife Yo3859 and bar Yo8794) containing individual components of both phosphoric iron and ferritic iron in composite construction are the only secure examples of the intentional use of the phosphoric iron. The differences between phosphoric iron and ferritic iron in workability and phase changes would have been noticed by the smith and alloy selection would have resulted from that knowledge, especially in composite construction. So the 32 single alloy, carburized single alloy and composite construction artefacts most likely demonstrated intentional use of phosphoric iron, leaving the 60 artefacts with phosphoric iron in heterogeneous structures.

8.3.9 Arsenic in Early Medieval Iron

Traditionally arsenic in iron has been only identified in the phenomenon called white weld lines. The white weld lines in the artefacts presented in this study were previously examined by Castagnino (2008) and not a focus of this study; however, during the examination of alloying elements present in the bulk iron of these artefacts significant amounts of arsenic ($>0.3\text{wt\%As}$) were identified in eight of the artefacts from six of the sites (table 144). These artefacts included a knife, a ferrule, an auger, four nails and one piece of stock iron. An analysis of the affects of arsenic on the properties of the iron as well as the use of arsenic in Early Medieval iron is presented below.

Arsenic in the Microstructure

Tylecote and Thomsen (1973) point out that the average arsenic content in archaeological iron is $0.005\text{--}0.05\text{wt\%As}$. In the eight artefacts with non-weld line arsenic concentrations were as high as $1.0\text{wt\%As}$. These significantly high levels of arsenic may have affected the resulting properties of the iron, such as increasing the hardness and preventing carbon diffusion (Castagnino 2008: 75); however, only two of these artefacts, nail BN310 and knife SOU98-38, contained ferritic iron with significant arsenic content; the other six artefacts contained arsenic in either iron-phosphorus or iron-carbon alloys. In both of the two artefacts with the iron-arsenic alloy, the alloy existed as a component of heterogeneous iron and was not an individual alloy specifically selected for use.

Table 145 demonstrates the hardness values for the alloys containing significant amounts of arsenic. In nail BN310 and knife SOU98-38 the hardness values of the ferritic areas containing As ($Hv_{0.2}140-180$) were significantly higher than ferritic iron but similar to the levels seen in phosphoric iron and may contain slightly increased values due to cold working, but there was no distortion in the grains. There was also no cracking to indicate brittleness and the grain sizes (ASTM 4-6) were similar to ferritic iron. In both areas the iron was etch-resistant. None of these traits are exclusive to arsenical iron; however the combination may provide an indicator that elemental analysis is necessary to identify the alloy.

The six artefacts with arsenic as well as phosphorus and/or carbon did not demonstrate significant differences from artefacts of the same phosphorus or carbon without arsenic. The average hardness of phosphoric iron with significant arsenic was $Hv_{0.2}204$, which is slightly higher than the average of phosphoric iron without arsenic ($Hv_{0.2}173$), and the average grains size (ASTM 4) was the same as regular phosphoric iron. The low carbon steel and un-heat-treated high carbon steel hardness values and grain size also did not show any significant change.

Besides the etch resistance, the addition of arsenic did not appear to alter the resulting microstructures of ferritic iron, phosphoric iron or steel, indicating that it is necessary to identify the presence of arsenic using elemental analysis on a system such as an SEM/EDS.

The Use of Arsenic in Early Medieval Iron

The presence of high arsenic levels in the iron was most likely unintentional. All but one of the artefacts contained the arsenic ($>0.3\text{wt\%As}$) in heterogeneous iron (table 146). The remaining artefact, nail WP394, was a phosphoric iron single alloy construction that contained significant levels of arsenic throughout the microstructure.

Manufacture

As discussed previously in Section 3.4 (p. 38), it had been postulated that the presence of arsenic in the white weld lines was the result of either the addition of arsenical minerals during smelting (Abdu and Gordon 2004), the enrichment of surface layers of iron due to oxidation (Tylecote and Thomsen 1973), or the use of iron ore as a brazing agent by the smith during welding (Castagnino 2008: 83, Tylecote and Thomsen 1973). It is plausible to assume that these may also be the origins of arsenic in the bulk metal.

The results of this analysis do not provide evidence as to why the arsenic was present in the iron. The addition of arsenic during welding would not have been the origin of arsenic in the general iron. Any added arsenic would require long periods at elevated temperatures to diffuse (Castagnino 2008: 82) and the very act of welding high carbon steel to a low carbon component necessitates expedience. Also, despite the presence of white weld lines in three of the artefacts with arsenic in the iron (nail BN310, knife SOU98-38 and Spoon Auger Yo9339), none contained a decreasing arsenic gradient from that weld line that would indicate arsenical diffusion.

Conclusions

Though arsenic may have been present in Early Medieval bulk iron, there is no evidence of its intentional use as an individual alloy. Instead the evidence suggests that arsenic was an impurity in the other iron alloys that slightly altered both the microstructure and the hardness properties. From the evidence presented above, this impurity may be a remnant of the ore from which it was created or the addition of an arsenical mineral during smelting and may be used as an indicator of the origin of the iron. If so, the presence of this impurity may indicate a shared origin of these widely distributed artefacts.

Significant further research needs to be done on both how arsenic entered the iron and the presence of arsenic in Early Medieval iron to determine if these hypotheses are true.

8.3.10 Alloy Comparison and the Common Alloy

The biggest complication in determining alloy usage is recognizing the difference between the intentional and unintentional use of alloys. With great respect for the Early Medieval smith's abilities to understand the materials that they used in their craft, it is entirely possible that not all artefacts required careful alloy selection. The presence of large quantities of heterogeneous iron in the Early Medieval artefacts examined for this study may be the result of this lack of need. In the following section the alloys are assessed based on overall presence and then broken down into alloy use that was clearly intentional versus alloy use that was somewhat more ambiguous.

General Alloy Usage

An assessment of general alloy usage ignores intent and examines the alloys based purely on whether they were present and in what quantity they were present. Tables such as Table 147 were included in all of the artefact summaries. This table was established by a visual examination of the microstructure assessing how much of each alloy was present. From this table it is apparent that all of the alloys were present. Phosphoric iron was present in the greatest quantity overall. It was the alloy most used for single alloy artefacts and had the highest quantity of artefacts where it dominated the microstructure. Ferritic iron was second in both the single alloy artefacts and as the dominant alloy in artefacts; however, both low carbon and high carbon steels, though present in few artefacts as single alloys or dominant alloys, were found in small quantities in over 40% of the total assemblage of artefacts.

Clear Intentional Use of the Alloys

Determining intention was quite difficult. Each of the individual alloys required unique criteria to define intent. In the end these criteria included the following:

Phosphoric iron

- Single alloy artefacts, individual alloy components of composite construction artefacts, and single alloy artefacts with carburization

Ferritic iron

- Single alloy artefacts, individual alloy components of composite construction artefacts, and single alloy artefacts with carburization

Low Carbon Steel

- Single alloy artefacts and individual alloy components of composite construction artefacts

High Carbon Steel

- Single alloy artefacts and individual alloy components of composite construction artefacts

The manipulation of carbon in the artefacts makes identifying intentional usage exceptionally difficult. The addition of carbon through carburization and carbon diffusion can change a single alloy artefact or an individual alloy used in composite construction into a more heterogeneous-looking structure. This addition may or may not have been intentional. Decarburization during working can cause an originally steel object to also appear heterogeneous. The decarburization may or may not have been intentional. For this reason the criteria for determining intentional manufacture of steel has been limited to items of clear intent and any questionable items are put in the unclear category.

Single Alloy Artefacts

Single alloy artefacts are the most basic form of artefact construction. They are constructed from a single bar of a particular alloy to be used to create the entire artefact.

It should be noted that the bars composed of single alloy iron were in much less abundance (4% of total artefacts) than bars of heterogeneous iron (11% of total artefacts).

Figure 88 shows the single alloy artefacts divided based on class. Ferritic and phosphoric irons have a significantly larger quantity of single alloy artefacts in all classes. Single alloy usage in the steels was focused on Class 1 and Class 2 artefacts, possibly the result of either a rarity in single alloy bars of steel or the product of the steel manufacture from otherwise ferritic/phosphoric bars during smithing through carburization and carbon diffusion.

An addition to the single alloy artefact category is single alloy artefacts with carburization. This category only applies to alloys that can be carburized (i.e. phosphoric iron and ferritic iron). Eight phosphoric iron artefacts showed carburization and seven ferritic iron artefacts were also carburized.

Components of Composite Artefacts

The second form of intentional alloy usage was individual alloy components of composite artefacts. These apply to artefacts that were clearly constructed by welding single alloy components together to form an identifiable composite construction (i.e. the knife blade construction typology).

Figure 89 shows the number of artefacts with each alloy as an individual component of composite construction divided by class. The Class 1 artefacts, which contained the

most composite construction artefacts, clearly dominated the all-alloy usage. The largest alloy group was high carbon steel, which was specifically used in edged tool constructions for the cutting edge. The other alloys were less vital to blade construction and were present as individual alloys in smaller numbers. In many blade constructions, for example Type 2 knives, heterogeneous iron was used in more knife backs (53%) than individual alloy components such as phosphoric iron (24%) and ferritic iron (24%).

Low carbon steel had the least individual alloy usage. Low carbon steel was mainly produced through carburization or carbon diffusion, and thus was found in many of the composite artefacts, making little need for it to be used as an individual alloy. The only case where it was used as such was in punch Yo7454 where the alloy was clearly welded around a ferritic core.

Total Intentional Alloy Usage

Table 148 demonstrates that high carbon steel was the alloy most clearly selected for use, most likely due to its use in edged tools.

Unclear usage

The selection of heterogeneous iron by the smith is difficult to assess because the smith may have chosen some dirty iron without any regard for the alloys present in the iron or the smith may have selected the heterogeneous iron based on the alloy that dominated the structure. For example three of the Type 2 knives have heterogeneous ferritic/phosphoric knife backs, which were probably selected for the non-steel

components. The two forms of heterogeneous selection are indicative of entirely different manufacture needs. However, neither form of selection can be proven to be intentional.

Other factors that make it difficult to discern intention in alloy usage are the effects of carburization, carbon diffusion, decarburization and dephosphorization. All of these processes may have occurred during manufacture, altering the original alloy and creating a situation where the alloy usage is unclear.

Overall 55% of the assemblage (62 artefacts) did not include any clearly intentional alloy usage.

The Common Alloy

The results show that all of the alloys (ferrite, phosphoric iron, low carbon steel, and high carbon steel), except for iron-arsenic alloys, were common and intentionally used.

8.4 Heat Treatment and Cold Working

8.4.1 Heat Treatment

Heat treatment was present exclusively in Class 1 edged tools. The 13 heat-treated artefacts included eight knives, axe SOU24-22, bill hook SOU31-92, punch Yo1638, and pick head DW16758. The heat-treated artefacts comprised 33% of the edged tools assemblage and nine percent of the total assemblage of artefacts from this study.

Through the examination of the blade construction (figure 90), the Type 2 knives were the largest group of heat-treated artefacts; however, all of the artefacts were heat-treated primarily on the cutting edge or tip, even if the artefact contained steel in other areas.

Heat-treated steels display several microstructures based on how treatment has been administered. Heat treatment was to the iron objects through the rapid cooling (quenching) of high carbon steels ($>0.3\%C$) from above A1 ($770-900^{\circ}C$) to ambient temperature by immersion in a large body of coolant relevant to the artefact size. The result is an increase in the hardness of the material. The resulting microstructures are known as martensite, which is brittle and has a hardness of greater than $Hv_{0.2} 700$, and bainite, which is cooled slightly slower and has a hardness of $Hv_{0.2} 200-600$. To remove the brittleness martensitic structures are often reheated to $450-650^{\circ}C$ (Samuels 1999: 427), which create a microstructure called tempered martensite that has a hardness of $Hv_{0.2} 500-700$. Slack quenching, the partial emersion of the metal in a quenching medium, allowed the metal to retain enough heat to act as the tempering heat. Table 149 summarizes the heat-treated microstructures from the artefacts in this study. The most prevalent heat treatment technique was the tempering of martensite, indicating that the smiths found it most effective to combine quenching and tempering.

All of the heat-treated steels were clean. Ten of the heat-treated artefacts contained steel that was exceptionally clean with very few slag inclusions. The iron used in these steels was the cleanest iron found in the artefacts in this study. The three heat-treated artefacts that did not contain this very clean iron, knife BN301, punch Yo1638 and

knife Yo10395, had slightly more inclusions in their microstructure. In punch Yo1638 and knife Yo10395 this increase in slag inclusions was a product of a Type 3 piled microstructure.

The combination of specific smithing technique (i.e. quenching and tempering) and the limited use of heat treatment in iron edged tools demonstrates that this was a specialized technique. The cleanness of the steel used for heat treatment indicates specific material selection and supports the conclusion of specialization.

8.4.2 Cold Working

Cold working is the forging of iron below its recrystallization temperature (560°C). The visible evidence of cold working occurs in two forms: the elongated/distorted grains in ferritic/phosphoric grain structures and the presence of Neumann bands. The former only occurred when the metal was reduced by more than 40% (Samuels 1999: 142) and the latter is the disruption of the crystal lattice as the result of shock due to cold working. This visible evidence was identified in nine artefacts (6%), with distortion of grains in seven artefacts (5%) and Neumann Bands present in two artefacts (1%).

The artefacts that contained evidence of cold working were found in Class 1 and Class 2. The Class 1 artefacts included needle CC258, bill hook SOU31-92, knife NR8, key Yo6295 and arrowhead Yo11067. Needle CC258 showed deformation of the granular structure that was a product of the drawing. Bill hook SOU31-92 and knife NR8 both contained Neumann bands as a part of their back/core microstructure. Key Yo6295

and arrowhead Yo11067 both showed distortion of their grain structure, which was a product of cold shaping.

The Class 2 artefacts included the fitting CC214, joiners dog Thet237, nail WP218, and nail WP556. All of the Class 2 artefacts showed deformation of grains along thinner areas that were reduced to create the final shape of the object. Fitting CC214 was folded and the deformation occurred at the folded ends from hammering the fold closed. Joiners dog Thet237 contained deformed grains due to the drawing of the pointed ends. Both nail WP218 and nail WP556 showed elongation along the outer area of the nail head due to formation.

Excessive cold working makes the metal brittle and can lead to cracking. This cracking then makes the metal more susceptible to corrosion and unlikely to retain metal for sampling, hence would be excluded from the archaeometallurgical record.

Another form of evidence is the increased hardness values due to cold working. Seventy-two (51%) of the artefacts examined contained ferrite with hardness values over Hv_{0.2} 110. Other causes of increased hardness in ferrite include the presence of small amounts (quantities smaller than can be detected by the SEM/EDS) of hardening elements such as carbon or phosphorus, and the presence of slag inclusions beneath the hardness test site. This circumstance does not occur often and the increase in hardness could be demonstrating that the use of cold working to finish objects was common during the Early Medieval period.

8.5 Class Comparison

The artefact classes established were based on traditional artefact typologies. In the case of iron artefacts these typologies focused on the identification of artefact use and, unlike ceramics, did not include material quality/manufacture/status implications. In the realm of ceramics these aspects of typology were established based on a combination of materials analysis and context, two things not often taken into consideration in iron artefact analysis; however, there is so much more information that the archaeometallurgical analysis can add to the archaeological interpretation of iron. One of the primary aims of this research project was to demonstrate the wealth of information available within the artefact that is directly applicable to site interpretation.

The artefact classification system for this study was developed to predict the presence of composite construction and quality of materials based on artefact typology. This system is tested through a class comparison, specifically looking at manufacture, alloy usage and material quality. The artefact classes and artefact typologies were then removed to strictly examine manufacture based entirely on microstructure, demonstrating the disadvantages of a class-based system. Finally the classification system examines how manufacture and material quality can add that extra information to fulfil the same kind of status information that ceramic studies can provide.

8.5.1 Class Summaries

The Class 1 artefacts were selected to include objects assumed to be of complex manufacture, objects that were decorative, and objects that required high quality material for construction. These assumptions were based on the combination of the results of previous archaeological analysis of edged tools as well as the modern expectation that decorative items, such as clothing adornments, would be made of quality materials. This class included items such as edged tools, dress fittings, security components, other specialized tools, and weaponry. A full list of the artefact types and the quantities of each artefact type are presented in Table 150.

The Class 2 artefacts (table 151) were selected to include objects that were assumed to be more utilitarian and of lesser quality and complexity than the Class 1 artefacts. These assumptions were based on the idea that these artefacts needed to be made in bulk and often bulk material is often of lower quality than the material used in Class 1 objects. This class was comprised of items such as iron used in construction, including nails, rivets and staples, as well as items such as hooks, pins, and ferrules. Another object put into this category was what was identified as an unknown tool. This item was included in this class due to its resemblance to the hooks in this category. A full list of the artefact types and the quality of each artefact type are presented in Table 151.

The Class 3 artefacts (table 152) were selected to include objects that were believed to be stock iron or objects that resemble stock iron, with the assumption that the latter has undergone limited alteration from its stock iron state. The stock iron was assumed to represent the materials the local smiths had available with which to create the

objects such as those found in Class 1 and Class 2. This implied that the Class 3 artefacts should have demonstrated less evidence of manufacture, such as composite construction and evidence of cold working, and would have instead contained a significant number of single alloy stock iron artefacts. The stock iron was present in two types (table 152) in the form of billets and bars.

The following compares the classes and assesses the validity of the assumptions that define each class.

8.5.2 Class Manufacture

The skill of the iron smelter and the iron smith is encapsulated in the artefact. Inefficient smelting and poor quality smithing will result in poor quality artefacts. On the other hand, highly controlled smelting followed by complex smithing, including heat treatments of quality steel, is apparent in many steel edged tools.

The two classes of finished iron objects, Class 1 and Class 2, represent the end product of the smithing process and therefore demonstrate the complete manufacturing process. The following is a comparison of the manufacturing techniques used in Class 1 and Class 2 artefacts.

To compare the sites and artefacts on a large scale, the construction types for the artefacts were simplified to three categories. The first category was single alloy construction, which also included single alloy artefacts that had some carburization

along the exterior. Single alloy artefacts were the result of specific selection of the alloy by the smith and therefore represent deliberate manufacture. The carburization, deliberate or not, came after this deliberate alloy selection. The second category was artefacts completely constructed from heterogeneous iron. The manufacture of artefacts from heterogeneous iron is more difficult to define as deliberate and does represent a different form of iron alloy selection than single alloy construction. None of the artefacts included in this category were part of composite constructions. The final category was composite construction. This category included any artefact, whether or not heterogeneous iron was present, which was constructed from the intentional welding of pieces of different iron alloys to form the completed composite artefact. Each individual artefact was ascribed to one of these three manufacture types.

Figure 91 compares these construction techniques for Class 1 and Class 2 artefacts, demonstrating that composite construction dominates the Class 1 assemblage while very few exist in Class 2 and heterogeneous structures dominate Class 2 and very few exist in Class 1. These results support the assumption that the Class 1 artefacts would have more complex construction than the Class 2 artefacts. The use of heterogeneous iron to create a large quantity of Class 2 utilitarian artefacts was logical. Class 2 artefacts could easily have been constructed in bulk heterogeneous iron that came directly from the bloom with very little working, as compared to single alloy iron that either required the smith to separate out the alloys from the bloom or were the result of deliberate manipulation of the smelting process to produce a single alloy bloom. The limited single alloy usage, though higher in Class 2, may indicate that single alloy

iron was difficult to obtain in large quantities or that it was more important for single alloy bars to be used in composite construction rather than on their own.

Further differences between the Class 1 and Class 2 artefacts included the heat treatment of high carbon steels and the use of piled structures in the Class 1 microstructures. Heat treatment was only present in 13 of the artefacts, all Class 1 edged tools. No major artefact types in the Class 2 artefacts either required high carbon steel or would benefit from heat treatment.

Piled structures, which were automatically classified as heterogeneous due to their mixed alloy structure, were found to be most abundant in the Class 1 artefacts (67%) compared with the other classes (6% in Class 2 and 7% in Class 3). This included 12 edged tools and two other Class 1 artefacts. This manufacturing technique was the result of combining multiple pieces of iron into a single piece or a repeatedly folded iron sheet. The use of piled structures in mostly Class 1 artefacts, however, suggests that it may have been a specialized construction technique (Leahy, 2003: 125). This form of manufacture may have been used for increased strength over single alloy components or the small amounts of carbon present in welds prevent carbon diffusion from the high carbon steel cutting edge.

What was clearly demonstrated in the comparison of the Class 1 and the Class 2 artefacts was that the Class 1 artefacts have undergone extensively more construction than those in Class 2.

There were significant differences in manufacture between the classes, both in terms of construction and manipulation of the alloys. Some of these differences, particularly the assumption that the Class 1 artefacts would contain more composite constructions, confirmed the assumptions used to define the differences between the Class 1 and Class 2 artefacts. Conversely, the prevalence of heterogeneous structures and the presence of composite construction in non-Class 1 artefacts suggest that artefact type cannot always predict construction.

8.5.3 Comparing Class Alloy Usage

Comparison of alloy usage is more complex than it appears. The alloys existed as single alloy componets, as part of a heterogeneous iron or as the result of carburization.

Figure 92 shows the overall alloy usage for Class 1 and Class 2 artefacts, ignoring artefact construction. There were no stark differences between the alloy usage in Class 1 and Class 2 artefacts. Within the Class 1 artefacts high carbon steel was the most prevelant alloy, while ferritic iron dominated the Class 2 artefacts. Steel was used in a larger percentage of Class 1 artefacts than in the Class 2 artefacts. This may be a result of intentional steel usage in composite construction, especially the use of high carbon steel as the cutting edges of edged tools.

Figure 93 shows the alloy usage without the heterogeneous iron in Class 1 and Class 2 artefacts. This figure includes single alloy artefacts, individual alloys in composite artefacts, carburization, and carbon diffusion. The Class 1 artefacts, which contained

less heterogeneous iron than Class 2, included a larger percentage of each of the four alloys with large quantities of both high and low carbon steels. High carbon steel in the Class 1 edged tools was used for two purposes. First, individual alloy components of high carbon steel were utilized as the cutting edge of the composite artefacts in this class. Second, when the high carbon steel component was welded to a non-carbon component the carbon diffusion across the weld line would extend the presence of carbon into the rest of the artefact.

8.5.4 Class 3

The Class 3 stock iron requires a different approach than the other classes. The stock iron, by definition, was intended for use in other artefacts. The evidence of manufacture and alloy usage in the stock iron must be considered in terms of how it was meant to be manipulated by the smith during object manufacture.

It should be noted that only the stock iron from Wharram Percy came from smithing contexts; the rest were bars identified from other parts of each of the settlements and may have been remnants of Class 1 and Class 2 type artefacts, such as the handles and tangs.

The manufacture techniques used on stock iron should be considered as preparation for use. Figure 94 shows the major forms of construction for the Class 3 artefacts with heterogeneous iron as the dominant form and single alloy construction just slightly less prevalent; however, 50% of the single alloy construction artefacts were

carburized, which, if used in composite construction, may appear to be heterogeneous in the final artefact. Carburization may have been used to create steel bars for use in composite and single alloy steel artefacts.

The two composite composition stock artefacts were constructed with intentional alternating banded structures; these structures along with the piled structure of one other bar may have been prepared for use in Class 1 artefacts.

Comparison of the Class 3 artefact manufacture (figure 94) to the other classes is more complicated than was generalized in Figure 91. The heterogeneous iron from Class 3 may have been intended for the construction of the heterogeneous artefacts, but it may have also been used for pieces of the 22 Class 1 artefacts and one Class 2 artefact that were of composite construction but contained heterogeneous iron. The single alloy Class 3 artefact also may have been destined for single alloy construction or as components in composite construction similar to those in Class 1 and Class 2. What is clear is that the Class 3 artefacts were present in enough quantity to create artefacts falling into all three major construction types.

An examination of the alloys present in the Class 3 artefacts demonstrates a slightly different picture. Figure 95 shows the overall alloy usage for the Class 3 artefacts. This demonstrates that all the alloys were present and phosphoric iron was the most abundant. Figure 96, however, shows the alloys present in the six non-carburized single alloy bars that would be used to create both single alloy artefacts and components of composite construction artefacts. There were no single alloy artefacts

composed of low or high carbon steel in Class 3. This may indicate that steel was either a product of the smithing process or that steel bars were always used and rarely deposited to be found in the archaeological record.

Ultimately the Class 3 stock iron could have been used to create some of the Class 1 and most of the Class 2 artefacts, but the individual alloy steel components used in the composite construction artefacts were not present in the Class 3 assemblage.

8.5.5 Cleanness of Iron

The cleanness of an artefact is not a simple thing to determine. In this study metal was defined as clean when it had slag inclusions covering less than 1/5 of the section. This had to be measured visually by the researcher to be able to differentiate between slag inclusions, corrosion, and etch pits.

Cleanness was also difficult to determine for entire artefacts constructed from different pieces of metal. A single artefact could be constructed from both clean and dirty components or the introduction of slag inclusions in welds can create a structure that appears dirty despite the use of clean iron. This issue was addressed during the assessment of the cleanness of iron in composite construction artefacts. In these artefacts the slag introduced at the weld lines was ignored and the focus was directed toward the cleanness of the metal itself.

Despite these difficulties the cleanness of the iron would have been a major issue for the smith when selecting iron to create the objects examined in this study. Clean iron would have been easier to work with, being able to be easily worked and presenting a finer object in consequence.

Class Cleanness Comparison

With the initial development of the classes, some of the Class 1 artefacts were selected based on the assumption that they would be of higher quality iron than the iron used in the Class 2 assemblage. These artefacts included the dress fittings and thinned objects such as needles. Figure 97 shows the cleanness of the Class 1 artefacts based on category, demonstrating that this assumption was not entirely true as all categories contained artefacts constructed from both dirty and clean iron. Instead, more than half of each category was clean. The vast majority of items related to security, such as locks and keys, and items categorized as other tools, such as needles, the awl and the punches, were constructed from clean iron.

While the Class 1 artefacts were assumed to be clean, the Class 2 artefacts were assumed to have been constructed in bulk from dirty cheap iron. Figure 98 compares the cleanness of the three main classes, demonstrating that these assumptions were false. More than half of all the classes contained clean iron, with the Class 2 artefacts containing the largest quantity of clean iron.

The cleanness of the iron almost certainly played a role in the selection of particular bars of iron to be used in manufacture. Comparing the Class 3 artefacts to the other classes demonstrated that the Class 3 stock iron could have been used to manufacture both the clean and dirty items in the other two classes.

Conclusions

The assessment of cleanness provides another level of interpretation to iron artefacts. It is clear that both clean and dirty iron were used to create most artefact types, possibly indicating lower and higher quality versions of the same artefact type.

8.5.6 Using Microstructures to Classify Artefacts

Construction is a major factor in studying other craft materials, such as textiles and pottery. In both cases it changes the interpretation of the object as well as the interpretation of where it was found. The following is an examination of the iron artefacts without their artefact typology, explicitly looking at their construction.

To accomplish this comparison, it was necessary to develop a manufacturing typology that would suit a broad range of artefacts and include the heterogeneous structures. This was accomplished using the knife manufacture typology created by Tylecote and Gilmour (1985) presented in Figure 13 as a template for the new typology.

Figure 99 shows the new typology system created to include as many of the artefacts used as possible. As with Tylecote and Gilmour's (1986) knife typology, each type

demonstrates an intentional manufacture, specifically including weld lines at the interface of two alloys. Small areas of carburization of the exterior have been ignored.

Table 153 demonstrates that heterogeneous microstructures were the most abundant throughout the assemblage. The second most abundant structures are the single alloy phosphoric Type 0's and the Type 2's, which were primarily Type 2 knives. The prevalence of the Type 3 constructions confirms the earlier discussion of piled structures being primarily in Class 1 artefacts.

It is not the more abundant types of construction that differ when all artefacts are placed into a construction typology, but the presence of the of Type 1's and Type 2's in Class 2 artefacts. These constructions are traditionally associated with Class 1 artefacts and their presence in the other classes suggests that the artefact typologies used to establish the classes may not indicate the level of technology of the artefact. The key example of this was the Brent Knoll hook (BN305), whose clean structure and high carbon steel inserted tip would normally be associated with a Class 1 edged tool; but hooks are associated with more utilitarian items, so this hook is a Class 2 anomaly. It is the quality of the manufacture of items such as the Brent Knoll hook that defy the convention that edged tools have to be obvious types such as knives, axes, and specialized tools that would have previously been overlooked.

Using this system the UI artefacts can be re-integrated into the archaeological record by considering the level of manufacture and quality of material. The UI artefacts of composite construction, i.e. the Type 4 constructions and piled structures, suggests

that they may belong in Class 1 despite their unknown usage. The UI artefacts were also mostly manufactured from clean iron, suggesting that they were not low quality items.

8.5.7 Re-integrating manufacture and material quality into the site interpretation

Cleanness of materials and smithing techniques can provide a level of information that can be directly applicable to site interpretation. If clean iron represents a higher status of artefact from the dirty iron, then the presence of clean nails may indicate a higher status in whatever it was used for. Dirty knives may indicate the opposite: that the owner of the dirty knife was of lower status than that of a clean one. This may also be true of composite construction: if an item has undergone composite construction it required more labour to create and is probably indicative of someone who could afford the inflation of cost as the result of that labour.

8.5.8 Re-addressing the classification system

At the beginning of this research it was essential to work with a typology of artefacts to establish a basis for comparison. The limited numbers of each artefact type created a need for larger groupings of artefacts and the classification was devised. As has been demonstrated, the classification system did not fully support the different levels of analysis possible with an analysis of both the construction and cleanness of the artefacts. The presence of clean nails and dirty knives, or composite construction hooks and heterogeneous knives, indicates that the iron artefacts are more diverse

and can provide so much more information if analysis does not simply focus on individual artefact types with the assumption that type is an indicator of manufacture.

8.5.9 Conclusions on Artefact Types and Classifications

Iron artefacts have been dramatically underestimated in what information they can provide archaeologists. Artefact type only provides a framework to which smithing technology and material quality can provide information on status and worth.

8.6 Inter-site Comparison

8.6.1 Introduction

Eight sites of differing status (table 120) and differing locations around England were examined in this project. These sites ranged from a small rural village (Brent Knoll) to combined royal and ecclesiastical settlements such as Canterbury, Worcester and York. The sites also differed in culture with Saxon occupation at all sites except at Anglo-Scandinavian York.

Figure 47 demonstrates the sites relative to the period from which the assemblages belong. Of the eight sites only Thetford included the Early Saxon period between the end of Roman Britain and the seventh century. The sites at Canterbury, Southampton, and Wharram Percy were inhabited during the Middle Saxon period (eighth-ninth

centuries AD). The remaining sites, including Brent Knoll, Winchester, Worcester and York, were inhabited in the Late Saxon period (ninth-eleventh centuries AD).

Besides the temporal differences between the settlements, there was also a spatial difference. The sites spread across what is now modern England, including both coastal and landlocked settlements. Many of these settlements, however, were port towns accessible by the rivers that criss-cross England. Figure 100 shows the distribution of the settlement sites in England, with the rural settlements indicated in green and the urban settlements indicated in red. Of the rural settlements only Wharram Percy was associated with royalty; Brent Knoll and Thetford were otherwise rural low-status settlements. Of the urban sites, only the market town of Southampton was not associated with either royalty or the church.

The assemblages from each of the sites differed in both numbers of artefacts from each class (table 154) and the types of artefact that composed the classes (see site summaries that were analyzed in Chapter 7). This variation made comparison challenging and required that many of the comparisons be based on percentages.

The following is a comparison of the sites based on manufacture, alloy usage and cleanness of material. The variables of period, region, and status play a large part in interpreting the changes and intricacies of the iron economy of the period. These results, however, are provisional and form the basis for future research.

8.6.2 Comparing artefact manufacture between sites

The manufacture of the iron artefacts was expected to differ between sites. Differences in site status and location would imply that there would be differences in the access of materials and craftsmen. Differences were also expected between Scandinavian-dominated York and large Anglo-Saxon settlements such as Southampton. The results of a detailed analysis of the assemblages revealed both similarities and differences that were unexpected.

Using the same the three major types of manufacture established in Section 8.6, each artefact was classified as being either of single alloy, heterogeneous, or composite construction. Figure 101 shows construction for all of the sites, demonstrating that the construction types were equally divided between manufacturing types; however, heterogeneous structures were slightly more abundant and single alloy construction was the smallest of the three groups.

Figure 102 shows artefact construction by site, demonstrating that the use of the three major forms of artefact construction varied from site to site. There were few distinctive similarities or differences based on urban/rural, region, and site status. The three non-royal sites, Brent Knoll, Thetford, and Southampton, all had significantly less single alloy construction than the other two construction types. Sites such as York and Wharram Percy, both in Yorkshire, had a similar distribution of manufacture to the average from all sites (figure 101); the rest of the sites vary widely. On a site by site basis, Brent Knoll showed equal levels of usage in heterogeneous structures and composite construction. Thetford had the highest usage of heterogeneous iron with

the smallest usage of single alloy construction. Wharram Percy had equal amounts of heterogeneous and single alloy usage, with low composite construction despite having one of the largest assemblages of knives. Worcester had the largest amount of single alloy artefacts with the smallest concentration of heterogeneous structures. York showed nearly equal amounts of all three alloys. Southampton had the highest usage of composite construction, possibly associated with the two smithies excavated at the site, with the second smallest usage of single alloy construction. Canterbury had the smallest amount of composite construction with a large number of heterogeneous structures. Finally Winchester, not featured in the figure, only consisted of four composite construction knives.

It is clear that there are significant variations in manufacture types between sites. The reasons for this variation, however, are unclear as there are few obvious commonalities between sites of similar construction. Further research should investigate manufacture at individual sites in greater depth, comparing larger numbers of artefacts.

Thetford also has the largest concentration of heterogeneous iron with Canterbury being the second largest.

The key differences in manufacture within the sites were visible when comparing Class 1 and Class 2 artefact construction, including the usage of heterogeneous and composite construction, as seen in an all-site assessment in the previous section on

class manufacture (Section 8.6.1). Also, specialist manufacture techniques such as heat treatment and piling were primarily found in the Class 1 assemblages.

Class 1 and Class 2 manufacture comparison (figure 103) demonstrates the major manufacture differences between the classes as well as the sites. Composite construction artefacts dominate all Class 1 assemblages but Brent Knoll. Brent Knoll demonstrated a slightly higher percentage of single alloy artefacts in the Class 1 assemblage. Heterogeneous structures dominate all Class 2 assemblages except Wharram Percy and Worcester. Both sites still contained large amounts of heterogeneous iron but it was equal to another construction type. Other than these two general trends there were no obvious trends between rural and urban assemblages, low and high status sites, and sites of different parts of the Early Medieval period.

Most of the previous work on Early Medieval iron has focused on knives and other edged tools. Blakelock and McDonnell (2007) summarise the metallography of the Early Medieval iron knives that had been previously published. Blakelock and McDonnell found that Type 2 knives were the most abundant in Early Medieval settlements. The data from this study show that 48% of the 33 knives in this study were of Type 2 construction (table 155). None of the other knife construction types were present in significant quantities. There were large variations between knife types at each site with wider selections at northern high status sites such as York and Wharram Percy. There were no significant patterns of change over time and no significant difference between urban and rural assemblages. Due to the limited and

varied sample selection per site further analysis is necessary to support the conclusions from this comparison.

Specialized manufacture techniques, including heat treatment and piling, were apparent in the Class 1 assemblage. Table 156 shows the use of these treatments per site, demonstrating that the use of both heat treatment and piling was high at sites such as Southampton and York. Other sites with more than one piled artefact were Canterbury and Wharram Percy. The commonality between all of the sites with a larger number of the specialist techniques was the larger number of Class 1 artefacts. This indicates that larger Class 1 sample sizes for the other sites investigated in this study may provide more evidence of local use of these specialized techniques. In the cases of York and Southampton, results of the previous analyses by McDonnell (1987a, 1987b, 1992) (table 157) demonstrated that heat treatment was seen in approximately 60% of each of the assemblages.

8.6.3 Site Alloy Usage Comparison

Each site had its own iron economy and the materials to which the local smiths had access were dependent on a combination of trade, local iron production and affordability. An examination of the quantities and diversity of alloys present at each site can begin to answer questions about alloy availability and specialist verses common alloys.

Figure 104 demonstrates there were only slight differences in overall alloy usage between sites except for two specific cases. Phosphoric iron was almost completely absent from the Worcester assemblage. The settlement of Worcester is situated on the edge of the Forest of Dean, whose iron ore contains almost no phosphorus and the lack of the phosphoric iron in Worcester may be an indicator that the settlement was using locally made iron. The only artefact from Worcester that did contain phosphorus was a hook used on shoes to hold the ties in place and could easily have been transported into the settlement by a passing traveller. Canterbury, containing the largest percentage of phosphoric iron, is situated on the edge of the Weald, which produces high phosphorus ores, and the large quantities of phosphoric iron may also represent the use of local iron.

When the heterogeneous iron is removed from the alloy usage (figure 105) a few other interesting aspects become apparent including the lack of phosphoric iron at Thetford and Worcester. Unlike the single heterogeneous artefact with phosphoric iron at Worcester, Thetford had 12 heterogeneous artefacts containing phosphorus but no phosphoric iron single alloy components were present in either the single alloy or the composite composition artefacts from the site. This may suggest that the local iron producers were not making phosphoric iron and that the heterogeneous iron was imported. The dominance of phosphoric iron usage in Canterbury remained.

Overall it is apparent that the steel was the most prominent alloy in the non-heterogeneous microstructures. This was a combination of the use of high carbon steel

in the Class 1 artefacts from all of the sites as well as the carburization and carbon diffusion that occurred during artefact manufacture.

8.6.4 Cleanness of Iron by Site

The cleanness of the iron may differ from site to site for several reasons. Possible reasons include: the local iron production may produce clean iron; the local smith had a preference for clean iron; or the settlement could afford more clean iron. In any case the cleanness of the iron was found to be variable from each of the sites (figure 106). All sites contained clean iron in more than half of their assemblage. The abundance of cleanness did not appear to be affected by rural and urban settings. The sites with the highest amounts of clean iron were Brent Knoll (a very rural village), Winchester (with a very small assemblage), and Worcester (an urban environment). The sites with the largest amounts of dirty iron were all urban with large assemblages and known for their international trade. These sites included Canterbury, Southampton and York.

Table 158 provides a closer look at the assemblages by dividing them into classes and calculating percentage of clean iron artefacts per class. This showed that in Brent Knoll dirty iron was only present in the Class 1 assemblage, while Class 2 and Class 3 were completely clean. Worcester and Wharram Percy showed high percentages of each class as being constructed from clean metal. The rest of the sites had approximately fifty percent clean iron in most classes with the occasional peak. These occasional peaks included the Winchester assemblage, the Class 2 assemblage of York, and the Class 3 assemblages of Canterbury and Southampton.

8.6.5 Observations and conclusions

A major impediment to a multi-site multi-artefact type comparison was the limitations due to sample size. Many of the sites had only one or two of a particular artefact type, specifically knives, that could be used in comparison to previous studies. This limitation was only highly apparent after the metallographic analysis had been completed and the form of manufacture identified. On a broader scale the variations in total assemblage and class size for each of the sites also inhibited solid comparisons. Generalizations, however, could be taken from the result of the study and further work can solidify its findings.

In the Early Medieval period several different peoples inhabited what is now known as England. These different cultures originated in different parts of Europe and lived different lifestyles. From this it is easy to imagine that each of these different cultures was using different iron production and smithing technologies. The data for this study, however, indicate that there were no major differences between the Anglo-Scandinavians and the Anglo-Saxons. The same manufacturing techniques and alloy usages were present in areas controlled by each culture. Even specialized manufacture techniques such as pattern welding were found in both Anglo-Scandinavian and Anglo-Saxon contexts. The iron was only slightly dirtier in the Anglo-Scandinavian settlement of York, but not significantly. These results indicate that Anglo-Scandinavian smiths had just as much skill and knowledge as the Anglo-Saxon smiths.

That technologies evolve through time is an accepted fact of life in modern times. Archaeologically we can see similar development over larger scales of time. At the end of the Roman period the technology underwent a change (McDonnell et al. forthcoming-b), but this change in iron manufacture technologies during the Early Medieval period was not apparent in the assemblages investigated. Only a greater percentage of heterogeneous iron in early Thetford and slightly greater percentages of composite construction in all of the later sites indicated a change in technology within the assemblages; however, the sample sizes were too small and limited data from the post-Roman period were available to give these observations weight. McDonnell and Blakelock (2007) identified a change from Type 2 knife construction to Type 1 knife construction over the Early Medieval period, but the knife assemblages within this study were also too small to support this observation.

Location has dramatic effects on available materials and access to trade. Rural settlements, such as Brent Knoll and Wharram Percy, would have had less access to trade goods than urban centres such as Southampton, York and Canterbury. The data in this study, however, demonstrate that all sites had access to complex smithing technologies and all of the alloys. This indicates that trade was vibrantly active, allowing remote sites such as Brent Knoll access to a full range of smithy products. Local iron production also would have affected alloy availability and cleanness. Settlements such as Worcester and Canterbury, which are situated close to major known iron ore sources, may have had more access to locally smelted iron, specifically ferritic iron in Worcester and phosphoric iron in Canterbury. Sites with very clean iron,

such as Brent Knoll and Worcester, would have probably been getting much of their iron from an individual source. Traded iron would show more variability in cleanness.

The status of each site was based on evidence of royalty and significant church presence during the Early Medieval period, leaving only Brent Knoll, Thetford, and Southampton as low status sites. There were very few major differences in the manufacture and alloy usage between the high status sites and the low status sites. Blakelock and McDonnell (2007) suggested that differences could be found in comparing knives between high status and low status sites; however, the knife assemblages between the sites in this study were too variable in size to be directly comparable. The only apparent difference was that in the Class 2 artefacts the lower status sites had slightly higher percentages of heterogeneous iron.

Except for the knife assemblages from Southampton, Wharram Percy and York, the rest of the sites did not contain enough knives to compare heat treatment and knife blade construction to the assemblages examined in Blakelock and McDonnell (2007). This resulted in difficulty in determining blade construction change over the Early Medieval period and variations based on urban/rural and site status; however, there were enough results to state that Type 2 knives were in greatest abundance and that none of the other forms of construction were exclusive to a single site.

Of all of the sites, Worcester stands out as having a selection of unique attributes. Worcester contained only one piece of phosphoric iron, with an abundance of the other alloys. The metal was 83% clean and 42% of the manufacture were single alloy

artefacts. This indicates a clean iron source for the local smiths who have the skills to manufacture both single alloy and composite construction objects. The single artefact with phosphoric iron was probably imported into the settlement, demonstrating that a small amount of trade was also present. The settlement was situated near a source of non-phosphoric iron ore and this low amount of phosphoric iron is evidence for local iron production. This site and others in the immediate area should be sampled to explore these unique attributes in further detail.

Ultimately it was concluded that each of the sites may have varied based on percentage of alloys present, dominant manufacture and cleanness; however, they were all very similar in many ways, demonstrating that the smithy skills were widely known and that alloys were widely available.

8.7 Iron economy model

8.7.1 The Old Model

During the Roman period in Britain the iron production economy was dominated by large production centres (Cleere and Crossley 1995: 57) with trade routes across Britain and links to the Continent. It was previously thought that with the end of the Roman period the vibrant iron economy reverted to local iron production for local needs (Pleiner 2000: 275). This meant that trade of iron across Britain would have been infrequent and resources limited. This also meant that smithing technologies would have been localized and variable depending on access to specialized smiths and

the necessary alloys. One of the aims of this research was to investigate this local production and trade model through the analysis of iron artefact sites across Britain of varying status and access to trade.

Evidence for the local production for local needs model would have included regional differences in alloy availability, variations in cleanness of the metal due to differences in iron production, and differences in manufacture techniques due to the capabilities of the local smith.

Alloy Availability

The alloy availability could have been affected by two factors: trade and local iron production. Access to trade would have varied from settlement to settlement depending upon location and settlement size. Large as well as influential settlements often had more access to trade than small rural settlements. Though it hasn't been directly proven that alloying elements such as phosphorus and arsenic originate from the iron ore, it has been considered a likely origin for these elements (Tylecote and Thomsen 1973, Vallbona 1997: 185).

Smithing Skills

The variation in smithing skills would be expected, considering small rural settlements would be assumed to have been less able to afford the specialist smiths than high status settlements. Also a local production model would demonstrate variability in manufacturing techniques, such as composite construction and the use of heat

treatment, between settlements due to cultural ties and access to trade. The Anglo-Saxon settlements in the western part of Britain would have had less influence from the Continent than eastern settlements, such as Canterbury, which the archaeological record has demonstrated significant trade ties. It was also possible that the Anglo-Scandinavian population in York would use different technologies from the Anglo-Saxons of Southern England.

Cleanness of Iron

Variations of cleanness of iron have many causes; however it is easier to make clean iron dirty than dirty iron clean. It is possible during iron production that smelters and bloom smiths followed a regime that kept any clean iron created in the smelt clean for use in iron tools. It is also possible that the process not be carefully controlled and only dirty iron produced. In a local production model this may be indicated by a large quantity of either clean or dirty metal. Another factor that may have affected the cleanness of the iron was the cost involved. If clean iron was more expensive than dirty iron, it was possible that settlements of higher status could better afford clean material.

8.7.2 Why the old model doesn't work

It is clear from the results of this study that the iron industry was not simply a local production for local needs economy. The archaeological data, however, provides evidence to re-assess the model.

Alloy Availability

Examination of the artefacts showed only slight regional differences in alloy availability. All of the sites' assemblages examined here contained all of the alloys. There was also evidence to suggest the use of locally produced iron. The presence of very little phosphoric iron at Worcester, which is situated next to the Forest of Dean (Cleere and Crossley 1995: 103), an area with iron ore that is low in phosphorus, and the presence of high amounts of phosphoric iron in Canterbury, situated in the Weald, an area of iron ore with high amounts of phosphorus (Cleere and Crossley 1995: 103), indicate that a significant portion of the iron at these two sites was of local origin. Conversely the presence of phosphoric iron at Worcester and ferritic iron at Canterbury supports a model in which trade also plays a role.

Iron Object Manufacture

Comparisons of manufacture techniques both specialised (i.e. heat treatment, piling and pattern welding) and general (i.e. composite construction) demonstrated that all of these techniques were widely known.

Composite construction was the form of manufacture that was the most labour intensive and utilized the largest range of smithing techniques. It is highly possible that these items required a more skilled smith than other artefacts. If this was indeed the case then these items may reflect either the presence of a skilled smith or trade items. Since composite construction items were found at all of the sites, including small rural

villages that are unlikely to have had their own highly skilled smith, these items are another example of evidence for trade of completed goods.

The presence of specialized smithing techniques such as heat treatment and piling at all of the sites indicates either that it was common for smithies to have these skills or that trade brought these items from places that did have a highly skilled smith. The former demonstrates that the technical knowledge was abundant across Britain and not localized, while the latter demonstrates that there was proliferate trade across Britain. Neither of these theories supports a model of local production for local needs.

Heterogeneous Iron

The wide use of heterogeneous iron presents has many implications. Heterogeneous iron has been considered a consolidated version of the iron bloom (Craddock 1995: 248). The direct usage of the bloom may indicate low skill local iron production where the resulting bloom had high amounts of heterogeneity, cheap iron that underwent limited bloomsmithing, or that alloy separation was unnecessary for the manufacture of the iron object. The first two theories support a local production for local needs model, while the third could exist in any economy.

Another possible form of manufacture for heterogeneous iron included the combination of pieces of iron containing different iron alloys consolidated into a single bar. This form of heterogeneous iron manufacture may indicate the smith had limited

metal resources and found it necessary to agglomerate what iron was available into an individual bar. This form of manufacture would also support a local production theory.

Ultimately the heterogeneous iron found in these assemblages was likely to be the result of local iron production or of limited metal resources.

Cleanness of Iron

All of the sites had approximately 60% or more artefacts containing clean iron. Only two of the site assemblages contained artefacts with over 80% clean iron: Brent Knoll and Worcester. Brent Knoll, being a rural village, does not support the theory that clean iron was more expensive and would not have been accessible to a poor rural village. Instead Brent Knoll and Worcester, which have already been suggested to have local iron production. However, the variety present at the other sites may reflect a model that includes trade.

Conclusions

Examination of the evidence reveals a complex combination of trade and local iron production. From this data it is unlikely that a comprehensive model can be established, but the results do provide the initial framework for establishing a picture of the Early Medieval iron economy.

8.7.3 Creating new models

Any model for the iron economy of the Early Medieval period would have to include mining, iron production, iron working, and iron object distribution. Since this project was designed to examine the iron objects that constitute the final part of the iron economy chain it was necessary to work backwards to determine economy. This will be accomplished using factors such as alloy availability and manufacture techniques to create a new model.

Mining

There is little evidence from mining in the Early Medieval period (Tylecote 1986: 179). Mining was not a component of this project; however, elemental analysis of the iron within the artefacts did provide some indications about the properties of the ore sources used to create them. The lack of phosphorus in the iron from Worcester, positioned at the edge of the Forest of Dean, is probably due to the low P bearing ores of the Forest of Dean carboniferous limestone (Walters 1999: 30). The presence of arsenical iron in artefacts from six of the sites indicates the use of a high arsenic bearing ore, such as those found in the Cumbrian Hematite from western Britain.

Iron Production

The model developed by this research project for Early Medieval iron production uses the production of the alloys as its focus. Alloy availability depends on a combination of the ore elemental composition, the control of the smelt, the heterogeneity of the bloom, and the subsequent bloomsmithing.

There is very little known about Early Medieval iron production. This lack of knowledge is the direct result of the small number (a little more than a dozen) of Early Medieval smelting furnaces found across Britain. In most cases only the base of these furnaces and some associated slag were found, providing little information of the structure as it existed when it was in use. There have also been no Early Medieval iron blooms excavated in Britain. Despite the extensive studies on bloomery furnaces (Cleere and Crossley 1995, Pleiner 2000, Schrufer-Kolb 1999), the process of direct iron production, and the analysis of the slag that remained, much of what is known about how these particular iron furnaces were built, the process of running them, and the iron they produced is speculation. Modern recreations of bloomery smelting furnaces are often based the measurements of the diameter of the base of archaeological bloomery furnaces with little information of the shaft construction (Crew 1991, Meredith 2006: 17). Though these recreations have proved that the basic process as outlined in Section 2.2 is most likely to be correct, there are many variables related to alloy manufacture that are unknown. These include ore selection, anything that was added to the smelt beyond the fuel and ore, and expert control of the smelting conditions. Despite carefully recreating bloomery smelting furnaces, modern archaeometallurgists do not have enough evidence to create complete replicas of the Early Medieval furnaces nor do they have the knowledge or experience needed to recreate the exact conditions in the furnace to manufacture iron blooms of the same quality and composition. Lacking the Early Medieval blooms to compare, it is impossible for experimental smelters to determine what conditions are necessary to achieve similar results.

This has direct implications to alloy manufacture. In research into the production of both phosphoric iron and steel during the smelting process, researchers concluded that conditions within the furnace needed to be carefully manipulated to control alloy manufacture (David et al. 1989, Vallbona 1997: 180). This manipulation would require both skill and experience for the smelters to produce the desired product.

The lack of British Early Medieval blooms also brings into question if it was possible to make blooms composed mostly of a single alloy or if all blooms were heterogeneous. Blooms found from the Roman period were heterogeneous iron with a steel component that contained between 0.3-0.8%C (Tylecote 1986: 144) and Early Medieval blooms from Europe were both single alloy and heterogeneous (Pleiner 2000: 236) but these blooms were few and may even represent unwanted iron, as good blooms would have been used by smiths for object manufacture. Experimental blooms have almost always been heterogeneous in nature, but this may be the result of unskilled smelting more than that being the only type of bloom to be produced in the past.

There is no evidence of bloomsmithing in the archaeological record and none from the Early Medieval period. Due to this lack of blooms, studies in bloomsmithing are composed of theory and the results of experimental work (Sim 1998: 17-52). Both of these methods, however, have focused on reshaping the bloom and removing the remaining slag (Cleere and Crossley 1995: 47, Pleiner 2000: 215-6, Sim 1998: 17), with little reference to how bloomsmithing could affect the microstructure of the metal

(especially in terms of alloys). It is this very effect on the microstructure that makes bloomsmithing important to the development of iron economy models.

The composition of the blooms (i.e. heterogeneous or single alloy) has important implications to modelling the processes of iron production, bloomsmithing and trade. In terms of the smelting process there are three different models to consider for the manufacture of Early Medieval iron. These models include:

1. A model where only heterogeneous blooms could be manufactured and these contained a selection of alloys that varied depending on the elemental composition of the local ore source.
2. A model where both heterogeneous blooms and single alloy blooms could be manufactured by a smelter through the control of the smelting process. This model also depends upon the elemental composition of the local ore source for the production of alloys, such as phosphoric iron.
3. A model where both heterogeneous blooms and single alloy blooms could be manufactured, but only specialist control over the smelt could create blooms composed mostly of a single alloy. This model also depends upon the elemental composition of the local ore source for the production of alloys, such as phosphoric iron.

The first model suggests an economy where it is possible to have a mostly local iron production, limited only by the elemental composition of the local ores. The link between elemental content of the ores and the elemental content of the resulting iron indicates that certain alloys, i.e. phosphoric iron, could only be produced in regions where the alloying element is present in the local ore. This means the phosphoric iron would need to be traded into regions that have no phosphorus in their local ore. The biggest problem with this model has to do with the processing of the heterogeneous bloom, which would require a smith of high skill to determine the alloys that compose the different parts of the bloom and split the bloom into those alloy components without overly decarburizing the high carbon steel. The results of this process would mean only small amounts of each alloy were produced in each bloom and for large single alloy items to be created would require combining many pieces of the same alloy from different blooms.

The second model has the production of both heterogeneous blooms and blooms composed of a single alloy from iron production sites to provide for all the metal needs for a local settlement. This model would only require the trade of alloys that are not manufactured in the region. In this model the bloomsmithing would not require the skill to separate the bloom into its components; rather, it would require the bloomsmith to have the ability to maintain the single alloy composition found from bloom to bar. An advantage that this model has over the first model was the availability of blocks of individual alloys to be used in large items without the need for welding.

The third model is similar to the second model with the manufacture of both heterogeneous blooms and single alloy blooms, but these single alloy blooms were produced by specialist smelters skilled at controlling the smelting conditions needed to create the single alloys. This model would indicate that the products of these specialized smelters would have had less availability than heterogeneous iron, probably retain a higher value and require trade to be distributed. The higher cost and the costs of travel for trade may prevent access to poorer communities.

Ultimately there is no way to choose between these models without more knowledge of the products of the smelting process. However, there are several important results of this project that need to be taken into consideration for further study.

- Heterogeneous iron is present in over 48% of the artefacts in each of the assemblages, across the range of archaeological sites examined, suggesting that it was a major product of the smelting process. Considering it was present in higher quantities in the Class 2 artefacts, which are more common than the Class 1 artefacts, suggests that it was relatively inexpensive and, at least in the case of Worcester, most probably the product of local iron production. Also, the amounts of heterogeneous iron used within a settlement did not appear related to the economic status of the settlement.
- Single alloy components were found in approximately 28% of the artefacts from each assemblage. These single alloy components were used regularly in

both Class 1 and Class 2 artefacts, and the use of the iron within artefacts did not appear dependent upon the economic status of the settlement.

Iron Working

Modelling iron working in settlements from the Early Medieval period includes an examination the Early Medieval smithies, of the technologies of the period, and blacksmith specialization.

Early Medieval smithing evidence was found at more of the sites examined in this study than smelting evidence. In the sites without an identifiable smithy it is very difficult to talk about the iron economy of the smithy itself as McDonnell et al. (forthcoming-a) did for Wharram Percy. The different types of smithies as described by McDonnell were outlined in Section 2.3.1. Unfortunately, the only two other sites used in this study that contained excavated smithies included Southampton and Winchester. The two smithies excavated at Southampton were similar to Wharram Percy and fit McDonnell's smithy model B, which included the import of iron from outside the central settlement. The smithy at Winchester fit McDonnell's model A, which included evidence of smelting. Table 159 briefly identifies whether smelting and smithing evidence were present for each of the sites. The rest of the sites with smithing evidence but no excavated smithy were difficult to fit into the models. Only the site of Brent Knoll had neither smelting nor smithing evidence, which indicates that all iron was imported in its final form. This indicates that at the majority of sites there was smithing taking place. Despite that, due to the presence of arsenical artefacts

spread over six different sites and evidence at Brent Knoll, trade in iron and iron objects was actively taking place across Early Medieval Britain.

Blacksmith specialization, in terms of manufacture techniques, demonstrated an iron economy where all alloys were widely available across Britain during the Early Medieval period. Smiths across Britain were skilled in the manufacture of composite construction artefacts, heat treatment and piling. Though the last two smithing skills were relatively rare (0-4 artefacts per site) and most likely specialized, they were reserved for artefact types that would fall into Class 1. Despite this specialization all of these techniques were available to all settlement types. Pattern welding, however, was a rare find that was only present in urban environments, both Anglo-Saxon and Anglo-Scandinavian. The distribution of black smithing techniques demonstrated a combination of trade and local iron production.

8.7.4 Conclusions

The development of models for the Early Medieval iron economy exposes clear gaps in current knowledge of iron in this period. There are four major factors that prevent creation of a comprehensive model that will define the iron economy of the Early Medieval period. These factors include the limited archaeological evidence of iron production from the Early Medieval period, a lack of understanding of the Early Medieval bloomery iron production process, its products, and how these products are dealt with during the subsequent bloomsmithing. What is clear is that there was a dynamic iron economy with evidence indicating some local iron production and some

trade. The extent of trade, however, will remain unknown until a greater understanding of iron production can be achieved.

Chapter 9 – Conclusions

9.1 Introduction

This research aims to add to knowledge of Early Medieval iron technology in Britain through examining iron artefact assemblages from eight settlement sites across Britain. This analysis was unique in Britain due to the range of artefacts and sites examined, allowing new perspectives of iron on large scale.

9.2 Iron in Early Medieval Britain

The results of this study also provide insight into the technological knowledge of the Early Medieval smiths. In general the Early Medieval smiths had the knowledge of all three major alloys, including phosphoric iron. These smiths could manipulate each of these alloys without causing the decarburization of high carbon steels or experiencing brittle fracture when cold working phosphoric iron. The products of these smiths were manufactured using three major artefact types of construction: single alloy, heterogeneous, and composite. The last of these construction techniques, composite construction, further displayed the smith's capability to select individual alloys and utilize their unique properties. The selective use of high carbon steel in the Class 1 artefacts demonstrates both knowledge of its properties and the careful use of what may have been a rare alloy.

Many smiths may also have had knowledge of heat treatment of these steels, but its occasional use suggests that it was a specialized technique and not general knowledge.

The multi-site comparison found that there were no major differences between the Anglo-Scandinavian and the Anglo-Saxon iron assemblages when comparing manufacturing techniques and alloy usage. Specialized manufacture techniques such as pattern welding were found in both cultural contexts.

Further, the data established that the overall British iron economy was a combination of local iron production and trade. The results showed that all sites had access to complex smithing technologies and the full selection of alloys (phosphoric iron, ferritic iron, and steel) indicating trade was active across Britain. There is also evidence to suggest that local iron production was active at settlements such as Worcester and Canterbury, where the phosphorus content in the local ore was reflected by the phosphorus content in the iron.

In the Early Medieval period, despite the dramatic changes such as the end of Roman control, the development of Kingdoms, the influx of new cultures, and the rise of the Christian church, the iron economy was vibrant and the skills of the blacksmith were known throughout Britain.

9.3 Phosphoric Iron

This research found that phosphoric iron was one of the three major iron alloys used in Early Medieval Britain. This result indicates that phosphoric iron was present in much larger quantities than previous studies (McDonnell 1987b, McDonnell 1992, Tylecote and Gilmour 1986) were able to identify. This discrepancy was due to the limitations in identification of the alloy. Previous studies used phosphoric iron indicators to distinguish between phosphoric iron and ferritic iron. These indicators included increased grain size, increased hardness, and the presence of ghosting. The results of extensive testing proved that though the phosphoric iron indicators were indicative of the presence of phosphorus in the iron, none of the indicators were exclusive to phosphoric iron. In many cases no indicators were present to identify the presence of phosphorus in the ferritic microstructure. It was concluded that the only way to determine the presence of phosphorus in iron is through elemental analysis.

During this study it was proven that phosphorus can co-exist with carbon in the iron microstructure. Furthermore, phosphorus does act as a carbon inhibitor and the conditions of heating and welding, specifically time and temperature, determine how much carbon can diffuse into phosphoric iron.

Implications

These results indicate that many of the preconceptions of phosphoric iron are invalid. These results show that archaeometallurgists cannot rely on phosphoric iron indicators

alone to identify the alloy, and that is vital to site interpretation to identify the alloy correctly, as shown in the multi-site research into the iron economy presented above.

9.4 New Avenues in Archaeometallurgy

This research included a study of cleanness in iron to determine aspects of quality, specifically the selection of clean metal for certain artefact type. However, due to limited contextual evidence for each of the artefacts, the small assemblages, and the results that show all sites had at least 60% clean iron, it is difficult to pinpoint patterns in the data. Despite this difficulty cleanness presents interesting new ways of examining the metal and its use in specific iron objects. It also provides data on site economics in the form of indicating unique assemblages, as in the site of Brent Knoll and its 80% clean iron artefacts.

This study established a manufacture typology for artefacts besides edged tools and established that it is possible to gain useful information from artefacts of unknown use. This information includes the detection of smithing technologies, possible reuse factors and can help identify common alloys.

The advantage of a multi-site study was the ability to discern and compare the unique attributes of the individual sites. Those attributes could then be used to successfully discuss the overlaying aspects of economy.

A multi-artefact type examination provides the capability to determine what manufacture techniques are unique to specific artefact types and which are used on a wider scale. This form of analysis, however, requires smaller numbers of each artefact type to be analysed and prevents an intensive investigation of the variations within an individual artefact type.

9.5 Concluding Remarks

This study presented a corpus of new data on Early Medieval Britain and was able to draw conclusions on iron alloys, manufacture and economy on a scale that has never been done before. In view of the successful results of this project, this style of research should be applied to other periods and locations.

Chapter 10 – Suggested Further Research

This project was designed to be a broad overview of iron in the Early Medieval period. The resulting data was of such large quantity that it could supply several more research projects of this size. The suggested further research presented below demonstrates the many angles from which this research can be expanded upon and the importance of this research to the fields of archaeology and archaeometallurgy.

1. The need for integration of context in the analysis of archaeological iron is paramount. The limited information provided to the specialists for their analyses only supports a determination of the metallurgy of the iron object while preventing a comprehensive interpretation of the archaeological artefact. This problem is often not rectified by the archaeologists after they receive the specialist report and fail to integrate the metallurgical information into the greater interpretation of an archaeological site. This problem demonstrates a clear lack of understanding by archaeologists as to what the iron analysis can provide their site interpretations and, without being able to answer significant archaeological questions, the archaeometallurgical analysis of iron artefacts is pointless. It is necessary for both the excavator and specialist to understand what archaeometallurgy can add to site interpretation. This PhD begins to demonstrate the use of such information and further work is necessary to continue to develop relationships between the context and the iron.

2. Previous studies have focused on edged tools. This project, however, demonstrated the advantages of examining the metallurgy of entire iron assemblages. Examining a variety of iron artefacts, therefore, allows for the overall understanding of both iron technologies and the overall iron economy. Other items such as the padlocks, though not as plentiful, demonstrate a level of specialized technology that may provide a greater understanding of the capabilities of the ancient smiths.
3. Further work examining large assemblages from individual settlements with large amounts of contextual information may provide a clearer picture of the importance of cleanness in the local iron economy and then a greater view of the larger iron economy.
4. This research demonstrated the benefits of examining the iron economy of a single period through the analysis of large assemblages from multiple sites within a geographical region. This type of study has rarely been undertaken in archaeometallurgy due to limited access to the suitable type of assemblage. Furthermore, such projects should be encouraged as they present a picture of the technologies available, the quality of materials and the access to trade during the period.
5. The necessity of extensive examination of the limited archaeological blooms in existence. The greater necessity is to examine archaeological bars and billets related to a smithy context, as these are supposedly the closest relation to the original archaeological bloom. From this we can begin to understand the

smelting process rather than experimental blooms which do not necessary represent the archaeological.

6. A common misconception in examining iron alloys in archaeological artefacts is that these alloys are comprised of multiple alloying elements. Without understanding how these elements, no matter how minimal, interact within the iron matrix, processes such as inhibiting of carburisation and etch-resistance may never be fully understood.
7. There are two directions this research could be expanded: geographically and temporally. Further research could involve a similar study that examines iron from the Early Medieval homelands of the Danes, Angels, and Saxons to establish origins of the technologies uncovered here. To temporally expand this research a similar study can examine either the Romano-British period or the Later Medieval period to determine the changes in technologies across Britain to follow the development and/or decline of alloy usage and smithing techniques.
8. The topic of recycling in bloomery iron is in need of concentrated investigation. There are many limitations to this line of research including establishing criteria for identifying recycled items. This research would require the development of new approaches to such determine these criteria using a combination of experimental research and, if possible, the development of analytical techniques designed to begin to identify recycling.

Appendix 1 – Glossary of Terms

Alloy – A substance having metallic properties and compound of two or more chemical elements of which at least one is a metal.

Allotriomorphs – A particle phase that has no regular shape (Bramfitt and Benscoter 2002: 246)

Annealing – A heat treatment process that involves heating the metal to soften the material and remove deformation resulting from cold working (Scott 1991: 137)

Blank – A bar of iron that serves as an intermediate between the bloom and blacksmithing. A black is the product of bloomsmithing.

Cementite – A very hard and brittle compound of iron and carbon corresponding the empirical formula Fe_3C – commonly known as iron carbide and possesses an orthorhombic lattice.

Cold working – The plastic deformation of a metal at the temperature low enough to cause permanent strain hardening. The treatment usually consists of rolling, hammering, or drawing at room temperature when the hardness and tensile strength are increased with the amount of cold work, but the ductility and impact strength are reduced (Scott 1991)

Carburization – Absorption and diffusion of carbon into solid ferrous alloys by heating, to a temperature usually above A_{c3} , in contact with a suitable carbonaceous material.

Corrosion – The chemical or electrochemical between material, usually a metal, and its environment that produces a deterioration of the material and its properties.

De-carburization – Loss of carbon from the surface layer of a carbon containing alloy due to reaction with one or more chemical substances in a medium that contacts the surface (Samuels 1999: 432)

Diffusion – The migration of one alloy or metal into another. Interdiffusion also occurs with the secondary metal migrating into the first. Usually heat is required for this process to occur (Scott 1990: 140).

Diffusion bonding – Bonding or joining of two metals by heating them together. Each will diffuse into the other, at different rates, creating a strong and permanent metallurgical bond (Scott 1990: 140).

Drawing - Drawing is the deformation process resulting in the reduction of the shape and cross sectional area of a metal work piece caused by pulling it through a die (Avitzur 1987: 80).

Ductility - The ability of a metal to be drawn or deformed (Scott, 1990: 140).

Embrittlement – Weakness in metal due to trace elements or quenching without tempering.

Etching – Subjecting the surface of the metal to preferential chemical or electrolytic attack to reveal structural details.

Etch Pits – Over etching, where inclusions jump out leaving a pit-effect.

Ferrite – Generally a solid solution of one or more alloying elements in the bcc polymorph of iron (α -Fe). Specifically in carbon steels, the interstitial solid solution of carbon in α -Fe.

Forge-welding – The welding hot metal by applying pressure or blows of the hammer.

Ghosting – The water appearance of some phosphoric iron microstructures after the section has been etched with Nital.

Grain – In crystalline metals, the grain is an area or zone of crystal growth in a uniform and homogeneous form. Most metals consist of grains and the grain boundaries are the interface between a succession of grains in the solid mass of crystals.

Hardening – Increasing hardness by suitable treatment. Usually involving heat and cooling. Where applicable, specific terms should be applied: age-hardening, case-hardening, flame-hardening, induction hardening, precipitation hardening or quench-hardening.

Heat treatment – Heating and cooling a solid metal or alloy in such a way that desired structures, conditions and properties are attained. Heating for the sole purpose of hot working is excluded from the meaning of this term.

Heterogeneous – A piece of metal consisting of multiple alloys that are of either natural occurrence or accidental manufacture.

Hot working – Deformation of the metal or alloy above the temperature necessary for plastic deformation (Scott 1991).

Idiomorphic – Crystals that have grown without restraint so that the habit planes are clearly developed (Bramfitt and Benscoter 2002: 270)

Interstitial – A small element that may occupy lattice spaces without causing too great.

Martensite – Often only used for the hard, needlelike component of the quenched steels, but more generally, any needlelike, hard transformation product of a quenched alloy (Scott 1990: 142).

Low Carbon Steel - Iron with up to 0.3% carbon. Working the metal has been physically altered by mechanical working.

Optical Microscopy - The examination of samples using a reflective light microscope.

Pearlite – A eutectoid mixture of with laminar plates of ferrite and intermetallic carbide

Phase Diagram – A diagram with the axes of temperature vs. composition showing the different phases of the structure of the metal over the range of conditions.

Phosphoric iron - An iron alloy containing little to no carbon and 0.2-1.5% phosphorus.

Sceats – Eighth century coins.

Slack quenching – quenching, by plunging metal in and out of water/oil, quickly.

Slag inclusion - Slag or dross entrapped in the metal.

Slag stringer – Small pieces of slag that have become incorporated into the metal and then are strung out as small elongated ribbons as the result of working the metal to shape it.

Strip drawing – Lengthening of a piece of metal by pulling it out whilst heating it.

Tempering – A heat treatment, reheating hardened steel to some temperature below A1 temperature for the purpose of decreasing hardness and/or increasing toughness. The process is sometimes applied to normalized steel.

Welding - A joint between 2 metals made by heating and joining the separate parts with no solder applied (Scott 1991).

Widmanstätten – The precipitation that is the result of one high temperature phase decomposing into two solid phases. This usually occurs at grain boundaries of the initial crystals and as plates of needles within the grains themselves. (Scott 1990: 20)

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