The Iron Economy of Wharram Percy - Modelling the Anglo-Saxon Iron Working Landscape

By McDonnell, G., Blakelock, E. and Rubinson S. with contributions by Chabot, N. Daoust, A.B. and Castagnino, V.

Introduction

The excavations in 1981-90 of Sites 59, 76, 84, 85, 90 and 93 in the South Manor Area recovered a substantial quantity of slag (113 kg) that led to the identification of the location of an Anglo-Saxon smithy. Very few smithies have been investigated from any period, and only a few Saxon examples can be quoted. The results were published in a decade ago (McDonnell 2000) as a distinct chapter in the site publication (*Wharram VIII*). This was an advance over many excavation reports in which the ironworking is presented as an appendix or in fiche, which belies the fundamental importance of iron to the society being researched. The chapter was still a very routine publication reporting the finds and considering the spatial and chronological distribution of the slag with some limited reporting of the slag composition. In the last few years the evidence for ironworking has been assessed from other excavations at Wharram and significant archaeometallurgical research has been undertaken on the slag and iron artefacts from the smithy.

This chapter will synthesise the new evidence gained from the analyses, but more importantly it re-interprets all the evidence in a more holistic way, setting the smithy in its landscape and considering how it functioned. It begins with an explication of three generic ironworking landscape models that can be applied to any site in any period. One of these models is proposed for the Anglo-Saxon smithy at Wharram. The second section considers the inputs into the smithy, the building materials, the fuel and stock iron. The third section discusses the operations conducted in the smithy and their associated evidence. The fourth section reconsiders the iron working evidence as well as the other artefacts from the smithy sites, and leads to a better identification of possible locations for the smithy building than was achieved in the original publication. The fifth section reviews the outputs from the smithy, based on the archaeometallurgical analyses of the artefacts. Section six discusses artefact wear and disposal. Finally section seven provides a discussion and conclusion to the study; this is followed by a list of terms and accompanied by Archive appendices detailing methodologies.

This chapter demonstrates the potential of integrated archaeometallurgical research. One great advantage of such a study is that it can identify a specific activity or craft taking place in a particular building at a particular point in time, an outcome rarely achieved for archaeology. However it must be noted that in the late 1980s excavation strategies for ironworking sites were only in their infancy; for example hammerscale, now regarded as an absolute essential indicator of smithing, was only just being recognised and recovered. The first detailed recovery and recording of hammerscale took place at Burton Dassett in Warwickshire in 1991 (Mills and McDonnell 1992) – although one of us (GMcD) has a strong memory of the late Leo Biek minutely examining the troweled surface at Wharram with his magnifying lenses.

Ironworking Models

Introduction

This section provides a brief review of the paucity of archaeological evidence for iron smelting and smithing in the Anglo-Saxon archaeological record, which is in stark contrast to our knowledge of the smithing technology and skills, a comment originally published by one of us over fifteen years ago (McDonnell 1989). Three models are proposed for the operation of the iron economy/landscape. These are not specific to the Anglo-Saxon landscape, but it is a period that can demonstrate the effectiveness of these models, despite the paucity of the record. The section concludes with the evidence that supports the model that applies to Wharram, in the current state of knowledge.

Ironworking in the Early Medieval Period

The complete manufacturing cycle of an iron artefact can be divided into three main stages: smelting of the ore to produce iron; the refining of the metal to trade iron and then the smithing of the iron to forge the artefact (McDonnell 1987a). Each of these stages require different inputs and generate different types of output and debris.

There are two methods to produce iron: the direct method in which iron metal is extracted from the ore in the solid state using a bloomery furnace, and the indirect process, which produces liquid steel or cast iron. In both processes the ore is reduced to metallic iron creating an iron slag of unwanted gangue material, but only in the indirect process does the iron become liquid (Buchwald & Wivel 1998, 45-46; Pleiner 2000, 131-133). The morphology of the slag produced during smelting often depends on the type of furnace used, which can also vary both regionally and chronologically, depending on the ore type (available and used), the available fuel and cultural traditions (Joosten 2004, 20-28; Pleiner 2000, 141-145). Very few Early Medieval smelting sites have been identified in England. For example there is no evidence for Early Medieval iron smelting in the Forest of Dean, and only one site, Millbrook (Tebbutt 1982), in the Weald, both of which areas were major centres for iron production in the preceding Roman and subsequent Medieval periods. Excavations of the few iron smelting sites discovered have revealed three types based on slag morphology.

The first group consists of tapped slag similar to that present in other periods, found at Flixborough, North East Lincolnshire (Starley 1999). The second group comprises the raked slag at Millbrook, Sussex (Tebbutt 1982) and Cherry Willinhgam, North East Lincolnshire (McDonnell 1987b) and the furnace slag type recovered at Ramsbury, Wiltshire (Haslam *et al.* 1980). The third group has a distinct ‘slag block’ morphology similar to slag found in Southern Scandinavia, North Germany and Poland (McDonnell 1989). Examples of slag blocks have been found at Romsey (McDonnell 1988), Mucking and Little Totham, Essex (Hamerow 2002, 189). Rural smelting sites such as Ramsbury and Flixborough are high status centres (Hamerow 2002, 189; Loveluck 1998), whilst others such as Bestwall, Dorset are typical Anglo-Saxon rural settlements (Slater and McDonnell 2002). There is scant evidence for urban smelting in the Early Medieval period with very small amounts of smelting slag found at York (Ottaway 1992, 477-478; Rogers 1993) and no evidence found at *Hamwic*.

On the other hand many Early Medieval settlement sites have produced some evidence for smithing. This is to be expected since smithies would have been required to manufacture and repair iron artefacts used by the communities. There are different levels of smithies, from permanent 'full-time' workshops to forges where occasional smithing operations were carried out. Even so the evidence from this period is sparse, as although there are numerous finds of iron smithing slag, very few smithy structures have been identified (McDonnell 1989; Stamper & Croft 2000, 155-166). Smithing slag has been found at a range of urban sites including York, London and Stamford but only at *Hamwic* has the smithy itself been identified (Andrews 1997; Ottaway 1992; Rogers 1993). Evidence for rural smithies has been found at a large number of settlements including West Stow (West 1985), West Heslerton, Catholme, Yarnton (Hey 2004) and Wharram Percy (Stamper & Croft 2000, 155-166). Smithing slag has also been found associated with smelting sites such as Romsey, Ramsbury, Flixborough (Starley 1999), Mucking (McDonnell 1988, 1989), Little Totham and Bestwall (Slater and McDonnell 2002)

Overall the evidence for Early Medieval iron smelting is poor. The sites that are known lie outside the main centres of Roman and medieval iron smelting, and are predominantly single furnaces producing relatively small amounts of metal. In stark contrast smithing slag is the most common ironworking residue found on Early Medieval settlement sites, suggesting that smithing was a craft carried out close to the consumer (McDonnell 1987a; Serneels and Perret 2003).

The smith required a stock of iron in the form of bars, billets and strips from which to produce iron objects, whether he was a specialist smith or a general village smith. Four basic types of iron were available: ferritic iron which contained few alloying elements (less than 0.1%); phosphoric iron containing between 0.15 to 1% phosphorus; steel which contains carbon as the main alloying element (McDonnell 1989), and a fourth, termed piled or composite iron, incorporating one, two or more of the single alloys (e.g. ferritic and phosphoric iron). The composite alloy may be formed ‘naturally’ by the traditional bloomery smelting furnace, or as a deliberate construction made by welding bars of the different alloys together.

Recent research has shown that phosphoric iron is present in significant quantities in most iron samples, suggesting that phosphoric iron was the product of many of the smelting sites. In contrast, iron with few alloying elements and steel appear to be rarer in the Early Medieval period and may have been produced at specialised smelting sites. In antiquity three methods may have been used to produce steel. One was directly from the smelting process by controlling the fuel to ore ratio. Another was by carburization of ferritic iron. The third method would be to produce liquid steel. Evidence from *Hamwic* suggests that high-quality high carbon steels (homogeneous high carbon content >1% carbon) were being produced by refining cast irons, although no residues from this process have been found (Mack *et al.* 2000).

Ironworking Models

Three models are proposed for the exploitation of iron:

a) The first model is the self-sufficient mode of production, in which the whole process from the smelting of the ore to the manufacture of the objects takes place entirely at the same settlement. This model allows for spatial separation of the processes, e.g. smelting in the ‘outfield’ and smithing within the settlement. The evidence for this model includes the raw materials (e.g. ore, fuel and clay), the remains of a smelting furnace and the resulting smelting slag. In addition to this evidence for the smithing of the artefact must also be present, including smithing hearth remains, smithing slag and stock iron.

b) The second model is that the settlement has a local smithy that is using imported stock iron in the form of bars to manufacture their own iron objects. The evidence for this model consists of smithing hearth debris, smithing slag and stock iron. The level of smithing activity may vary from a full-time smithy to one used occasionally.

c) The third model is that all iron artefacts were imported into the site from elsewhere. In this model there would be no evidence for smithing of new iron objects so there should be no stock iron present on the site. There could be some smithing slag, as occasionally imported iron objects may have needed to be repaired.

While it is possible that each of the above models can be independent of the others, it is equally likely that there could be a mixture of two or three models occurring at any one settlement. For example, some rarer iron alloys such as high-quality high carbon steel may have been imported into some smithy sites to create composite iron artefacts, even though the same site is smelting its own bulk iron. In addition the same site may also be importing some artefacts from sites elsewhere. With each of the above models it is possible that both repairing and recycling of iron objects was also taking place. In both cases there would evidence in the form of smithing slag.

The Wharram Percy Model

No smelting furnaces or smelting slag has been identified at Wharram Percy therefore the first model, the fully self-sufficient model, can be at present be excluded. There is evidence for a smithy with stock iron at the site. Trade iron was imported into the site from elsewhere to supply the smithy. There are several main scenarios. The first is that the iron was being imported from the Jurassic Ridge sources in North Lincolnshire where smelting evidence has been recovered at Flixborough (Starley 1999) and Cherry Willingham (McDonnell 1987). A slag block, typical of Saxon smelting technology resides in the garden of Scunthorpe Museum (Leahy pers. Comm.) and one is illustrated by Harold Dudley (1949). Secondly, the Wolds are surrounded by bog ores which were exploited in the Iron Age, e.g. North Cave (McDonnell 1988) and further a field (Halkon and Millet 1999), and may have been exploited in the Saxon period. A third option is that iron was sourced from further away e.g. from the North York Moors or West Yorkshire via markets such as those at Malton or Diffield.

The Inputs to the Wharram Smithy

Introduction

This section considers the materials required for a Saxon smithy to operate. There are misconceptions about where ironworking, in particular smithing was conducted. It is essential that smithing is carried out in low light levels to enable the smith to see the colour of the flame and most importantly the metal which provides the only temperature guide the smith has. It is envisaged that the Saxon forge comprised a roofed building dedicated to metalworking containing a raised blacksmith's hearth, hand or foot powered bellows, an anvil, a range of tools, stock iron and fuel. It is probable that, other than fuel, the smithy of today is little changed from its Saxon predecessor.

Stock Iron

Bar, or trade iron, is the intermediate stage between the bloom and the finished artefact. It is created by consolidating and shaping the bloom into bars for trade and use. These bars are then used by blacksmiths in the manufacture of iron objects such as tools, fixtures and fittings etc. They have been variously termed as trade iron, bar, blank or strip (e.g. Ottaway 1992, 492). The bars recovered from the smithy are probably smaller (Table 7.3.1) than trade bars, which would probably be c.40mm wide and 20mm thick of varying lengths. The bar fragment analysed from Coppergate (Ottaway 1992, 499, fig. 188, cat. no. 2073) is probably a scrap end of a more typical trade bar. Thus the material classified as bar at Wharram represents iron at an intermediary stage between the trade iron and a finished artefact.

Nine 'bars' were found in the Wharram Percy smithy, averaging 76mm in length, 5mm wide and 3mm thick, with tapered or scrolled ends; they probably represent end of bar, i.e. that final portion of a bar that was unusable. The bars were different shapes and thicknesses providing a selection based on what the smithy needed (e.g. WP320 was a curved bar and two, WP 260 and WP299, were classified as strip).

All the bars were sectioned and a sample prepared in the usual manner (see Appendix 1) they were examined using optical and electron microscopy and micro-hardness testing. The SEM analyses provided elemental analysis of the metal, in particular the phosphorus content and the oxide composition of the slag inclusions trapped in the metal. Previous research has demonstrated that three alloys were used in the Anglo-Saxon period in England (McDonnell 1989, Blakelock and McDonnell 2007): ferritic iron, phosphoric iron and steel. These alloys are not exclusive and may be combined either naturally (e.g. due to natural segregation during the refining of the bloom), or deliberately by combining and welding together bars of different composition, termed composite bars (Pl. 7.3.1). Thus an artefact may be manufactured from a single alloy or a combination of two or more alloys to make a composite artefact. In the case of bars, the archaeometallurgical research is undertaken to test whether the bars are single or composite artefacts.

The Wharram bars represent a selection of alloys. There are one ferritic bar, three phosphoric bars, two steel bars and three composite bars (Figure 7.3.1). Table 7.3.2 provides the basic metallurgy of the alloys, and it is worth noting that the data shows that the presence of phosphorus has a significant effect on the iron, increasing its hardness (Pl. 7.3.2). The ferritic bar has a hardness of 116Hv_{200}, compared to the highest value for the phosphoric bars of 205Hv_{200}, which is harder than the low carbon steel bar (130Hv_{200}). Two of the phosphoric bars show a low concentration of slag inclusions (i.e. are 'clean'), and the grain size of the phosphoric is larger than ferrite. A further attribute that is not apparent in the table is that the phosphoric iron would colour differently, which leads to its use in pattern-welding. The steel bars are of particular interest. These bars fit into two different categories due to their different carbon contents. The high carbon steel (maximum 0.8%C) seen in WP359, had the potential to have been heat treated to dramatically increase its hardness, making it ideal for the cutting edges of knives. The second steel bar (WP364) had a lower carbon content and would not have produced a cutting edge of the same quality.

Re-examination of some of the Anglo-Scandinavian bars recovered from the excavations from Coppergate, York (Fig. 7.3.1) shows that the composite bars dominate that assemblage, which can be interpreted as reflecting the heterogeneous nature of iron blooms produced by the bloomery process. This suggests that the single alloy bars were produced deliberately for specific functions, e.g. steel for cutting edges.

As part of a larger study (Chabot 2007) a detailed analysis of the slag inclusions in all nine bars from Wharram Percy was undertaken. The aim of this study was to test a model concerning the types of inclusion that may be found in iron artefacts. The model argues that a simple object such as a bar is a small number of processes away from the smelting process. Each process in the production of the artefact will alter existing slag inclusions or introduce new slag inclusions into the metal. Thus a simple artefact, such as a bar should contain a smaller range of compositions. In theory, the minimum number of inclusion types should be three, those deriving from the smelting process, the refining of the smelted iron, and those deriving from the smithing of the bar. Further characterising of the inclusion profile range within an assemblage of bars may indicate whether the bars derive from a single centre or multiple production centres. Bars generated by a single production would be expected to show the same range of inclusion profiles. These data must not, however, be used as a provenancing tool, with which to identify a production centre to a specific geological locality such as the Jurassic deposits of the North York Moors or North Lincolnshire.

The bulk oxide compositional data has been grouped into silicate oxides, glass oxides and FeOx (iron) oxides and presented on ternary plots. The inclusions in the ferritic bar group tightly along a trend line. Those from the phosphoric iron bars are more dispersed but are characterised by one tight group from WP115, which is low in FeOx suggesting one distinct production centre. The inclusion compositions of the two steel bars concentrate along two trend lines suggesting two distinct production centres. This data suggests that the Wharram smithy was accessing iron from at least five production centres.

Other resources

There are many other resources involved in blacksmithing that are vital to the creation of the finished product, such as building materials, fuel, clay, wood and leather for bellows. The most important are fuel and clay. Clay was needed to make crucibles and moulds (two fragments were recovered from the smithy) for non-ferrous metalworking. Most importantly it was required for the construction of the hearth, providing the lining for the hearth, especially around the tuyère (blow hole) area which was subjected to the highest temperatures. The forge envisaged at Wharram would be a raised hearth, perhaps waist high, built of stone and/or timber, with the hearth itself built of stone or timber lined with clay, and perhaps a base layer of sand. The hearth would have a set of bellows to provide forced draught to raise the temperature required for welding (1100°C). Such a structure is illustrated in the 9th Century Utrecht Psalter (Clarke 1979, 106; and http://psalter.library.uu.nl/).

The clay lining, especially around the tuyère, would have to be periodically replaced, perhaps weekly depending on the level of activity, as the internal hot face of the lining would fracture from the hearth due to chemical alteration of the clay and the high temperatures. A total of 14.2kg of hearth lining was recovered from the excavation; the quantity is compared with some other sites in Table 7.3.3, and shows that as a proportion of the total assemblage Wharram is comparable to other sites, though, given the presence of a smithy dump, a higher proportion may have been expected.

Charcoal was the fuel in use in this period for both iron smelting and iron smithing. A working smithy would probably require several kilos of charcoal per day, giving a yearly requirement of less than half a tonne. The experimental charcoal burn conducted by Wheeler and Powell at Dalby Forest, North Yorkshire utilised 4 tonnes of chopped wood to produce one tonne of charcoal (Wheeler 2004, Powell et al 2005), thus the smithy could have been supplied by a single large burn. Although charcoal flecking was present in the soils no identifiable fragments of charcoal were recovered from the South manor excavations.

A further resource is stone used for sharpening blades, Clark and Gaunt (2000, 104-109) reported on the hone stones from the South Manor Area excavations. These excavations produced the largest quantity of hones stones, with a particularly high concentration recovered from Sites 44, 59, and 76 (32 hones), associated with the smithy (Table 7.3.4). This represents 44% of those recovered from the whole of the South Manor Area excavations. There was no evidence for preference of a particular stone, with Site 59 the only site having examples of all five stone types present.

Craft Activity in the Smithy

Introduction

A wide variety of craft activities could have been carried out in an Anglo-Saxon smithy, ranging from ironworking, to non-ferrous metalworking and to other craft activities associated with the manufacture of metal artefacts. For example all iron knives had a non-metallic handle, made from bone, wood or antler, and these could have been produced by the smith or a different craftsperson. This section focuses solely on iron smithing and outlines the different processes involved in the manufacture of iron artefacts.

Manufacture

Creating objects from iron is a process that can be very simple or incredibly complex, depending on the quality of iron used and the final product required, from a simple nail to an elaborate composite blade which has been heat treated and decorated (Serneels & Perret 2003). Therefore in antiquity there were different levels of smith, from the general village blacksmith creating horse shoes to the master sword smith. The village blacksmith would have provided an important service to any community, both manufacturing and repairing iron items used either in the home or as agricultural equipment (Faull and Moorhouse 1981: 771-773). On the other hand the skills and techniques required to manufacture a pattern welded sword may have been known only to a select few smiths (Anstee & Biek 1961; Peirce 2002, Tylecote and Gilmour 1986, 1-3).

There are two stages of smithing; primary and secondary (Figure 7.3.2). The first, primary smithing is required to refine and consolidate the bloom and produce a billet. This is carried out by hammering the bloom, often while still hot, to remove adhering slag or to expel included slag and charcoal (Hedges & Salter 1979; Crew 1991; McDonnell 1991; Serneels & Perret 2003). Primary smithing or bloom smithing would almost certainly be carried out at or close to the smelting site and is therefore considered not to have been conducted at Wharram. Secondary smithing or 'forging' is the operation where the billet is shaped into a trade iron or bar, and subsequently the bar is manufactured into artefacts. This process is carried out by repeatedly heating the iron in a hearth and hammering it on an anvil to form the artefact, and may involve welding to join two or more components, e.g. steel edges to tools. During hot forging large amounts of metal are lost due to oxidisation, this forms a layer around the iron object and is removed during hammering, resulting in hammerscale (McDonnell 1986; Dungworth & Wilkes 2007; Pleiner 2006, 53-64). Therefore a flux may have been added to help dissolve the oxide film and prevent further oxidation (McDonnell 1987; Serneels & Perret 2003; Sim & Ridge 1998, 12), an essential process during fire welding.

Metallographic studies of knives and other objects have shown that there is a specific order used when manufacturing an object and therefore a 'chaîne opératoire' can be constructed. The manufacture of complex artefacts, in particular edged tools, utilises more than one type of alloy bar. In the case of edged tools, in particular knives, this enables a manufacturing typology to be established which demonstrates how the steel edge is introduced (Blakelock & McDonnell 2007; Tylecote & Gilmour 1986, 2-7). The majority of these methods of manufacture require the different iron alloys to be hot welded together. This occurs prior to the object being shaped, indicated by the large number of distorted weld lines found in knives. To weld pieces of iron together it is vital that the metal is heated to a temperature at which it is soft but not molten (c.1100˚C). Weld lines joining metals are often visible due to slag inclusions which get trapped between the metals during the smithing process. Some weld lines even have a distinct white colour (Pl. 7.3.3), which is due to arsenic and nickel enrichment, possibly indicating that during fire welding a 'fluxing' compound was added to create a better quality weld (Castagnino 2007).

Once the object is the desired shape the smith has more decisions to make, depending on the required function (e.g. a knife requires a sharp and hard cutting edge). The speed of cooling can control the formation of certain microstructures which increase the hardness of the metal. The most common form of heat treatment is quenching, where the still hot object is plunged into a liquid to cool it rapidly and to create an extremely hard cutting edge (Pleiner 2006, 65-70; Samuels 1999, 5-37; Scott 1991, 31-32; Tylecote 1990). In modern smithies this is usually done with water, but other liquids such as oil, milk, urine and even blood would have been just as effective and may have been necessary for the ritual or 'secret recipe' aspect of the smith's work (Maddin 1987). Once quenched the steel would also become brittle so it required tempering, heating to 500°C, which reduces the brittleness and its hardness (Samuels 1999, 5-37; Scott 1991, 31-32; Tylecote 1990). Cold working can also significantly increase the hardness of iron and its alloys (Swiss & McDonnell 2003). All the smithing processes generate slag as a waste products.

Iron Working evidence

A total of 113.4kg of ironworking debris was recovered from the South Manor Area (Sites 9, 44, 59, 76, 81, 84, 85 90 and 93). In the original publication this was classified into four major groups: Hearth Bottoms, Smithing Slag Lumps, Hearth Lining and Cinder/Fuel Ash Slag (McDonnell 2000). A re-assessment of some of the material in 2006-7 suggests that the identifications are correct, with the revision that the Cinder/Fuels Ash Slag would be re-classified as Smithing Slag/Cinder (i.e. it is smithing slag with a higher silica content). Other sites excavated at Wharram also produced slag but in small quantities. The distribution of slag by all sites is shown in Table 7.3.4.

Analysis of the distribution of slag on the South Manor sites shows a clear concentration in Sites 59 and 76, specifically within Phases 3, 4 and 5. In Phase 3 (Middle Saxon) the slag is distributed to the south of the main east-west ditches (Stamper and Croft 2000, 158 fig. 74). This would suggest that this represents the smithy dump, hence the smithy building is elsewhere: it is probably the structure identified as Building A and perhaps also its suggested predecessor Building B (see *Wharram XIII*, 124, fig.55). The smithy was established in Phase 2, the early part of Middle Saxon period. How long the smithy stood at this location is unknown as the slag spreads into phases 4 (Late Saxon) and 5 (Medieval). The presence of large quantities of hearth lining is strong evidence for the proximity of the smithy to the dumps, rather than the dumps being of slag re-used for foundations, levelling etc. Analysis of other assemblages indicates that the lining is friable and does not survive in recognisable form if transported and re-used.

The argument against a smithy building is the absence of extensive quantities of hammerscale. The South Manor Area was, however, excavated in 1977-8 (Site 44) and between 1981-90. Hammerscale was only beginning to be recognised in the mid-1980s and it was only in the very late 1980s that strategies were introduced to recover these residues. Thus some hammerscale was recovered from 76/70 and analysed by McDonnell (1986, 188-193). Both flake and spheroidal hammerscale was recovered, indicative of the full range of iron smithing activity, the spheroidal hammerscale being generated during fire welding (McDonnell 1986, 146; Dungworth and Wilkes 2007).

Table 7.3.3 compares the Wharram slag assemblage with other sites, but all show marked differences. Four of the sites (Mucking, West Heslerton, Yarnton and Flixborough) display high or very high percentages of hearth bottoms compared to smithing slag lumps. This will be a function both of the archaeological site/deposits and researcher preference. Hearth bottoms are more likely to get widely dispersed from the smithy (e.g. through use for post packing), hence the large area excavations such as West Heslerton and Mucking will recover more of them, as opposed to the smaller fragments of smithing slag. There is also variability in researcher's typology: does a partly formed hearth bottom count as smithing slag or a hearth bottom? The closest comparison is with the medieval site of Burton Dassett (McDonnell 1992a), which was also the excavation of a smithy building and its associated slag dump.

Two samples of hearth bottom were analysed as part of the original research (McDonnell 1986, 158-162; McDonnell 2000, 156-157). The Wharram slag sections displayed a mineral texture of silicate laths with fine iron oxide dendrites in a glassy matrix that was more usually observed in iron smelting slag. Daoust (2007) undertook further analysis of the Wharram Percy assemblage to explore composition relationships between smithing slag and weld lines which, supported by Chabot's (2007) analysis, provides an exceptional insight into macro-slag and metal inclusion composition relationships.

The archaeometallurgical analysis of the slag showed that both the hearth bottoms and the smithing slag lumps have similar compositions with two broad compositional groups emerging (Table 7.3.5). This data set represents the largest analysis of a British assemblage of smithing debris. Previous studies have concentrated on hearth bottom analyses (e.g. McDonnell 1986, 150-87). Neither the mechanisms nor the reasons for the formation of hearth bottoms and smithing slag lumps are fully understood (McDonnell 1991, Serneels and Perret 2003). Two key questions are considered: whether the formation of the slag is deliberate or an accidental by product of the process, and hence, whether the slag composition was controlled. The consistency of composition implies a high level of control. As smithing slag is regarded as a 'waste product' it can be argued that its composition would not be controlled, but would vary depending on many factors such as the type of smithing activity.

These analyses suggest that the composition was controlled irrespective of operation, or that the slag could tolerate changing operating conditions. Another significant fact is the overall low free iron oxide content. Free iron oxide refers to crystals of iron oxide in the slag mineral matrix. Since silica readily reacts with iron oxide, it will consume the iron oxide, but in a smithing operation it may be expected that excess iron oxide is generated in the form of hammerscale, thus it would be expected that smithing slag would be iron oxide rich. The Wharram smiths have been careful to control the slag composition ensuring that the hammerscale iron oxide was compensated by the addition of silica rich minerals.

The Wharram hearth bottoms were originally examined in 1986 (McDonnell 1986 158-161, McDonnell 2000). Since that date it has been noted on other sites (e.g. West Heslerton: Cowgill and McDonnell forthcoming) that some small hearth bottoms display particular characteristics. These include high density/fluidity and commonly occur as quarters of hearth bottoms, suggesting fracturing during cooling. These have been interpreted as possible evidence for steel making. Although the iron slag assemblage was not re-examined in full in the recent study, these features were not noted in the original examination. Daoust's selection at random of some hearth bottom examples did not encounter any such examples. Thus this particular hearth bottom type appears to be absent from the Wharram assemblage.

The smithy finds summary

A list of all the finds from the smithy areas, Sites 59 and 76, is shown in Tables 7.3.7-9. Table 7.3.7 lists the domestic artefacts and is characterised by a high number of bone combs; while Table 7.3.8 lists seven artefacts associated with non-ferrous metalworking, indicating that little copper alloy working was carried out in the smithy. Although two mould fragments are present there are no crucibles; and given the high level of preservation of hearth lining, crucibles would unquestionably have survived on the site. There were 48 iron artefacts (Table 7.3.9), other than nails, found in the smithy areas (Sites 59 and 76). The majority of these are either agricultural or structural. There was also a selection of dress fittings, such as pins and strap ends. Beyond these, knives were most abundant. The bars and slag were used to support the presence of the smithy and are not found in other contexts. The ferrous assemblage is characterised by a wide range of artefact types; of particular interest are the artefacts classified as dress fittings which includes the sword guard.

The Products of the Wharram Smithy

Introduction

More than 400 pieces of iron were recovered from the entire South Manor Area (Goodall 2000, 132). These included tools for crafts and agriculture, building ironwork, nails, decorative ironwork like pins and buckles, fittings for horses and swords as well as iron knives. To understand and investigate alloy use and smithing techniques in Middle Saxon Wharram Percy metallographic analysis was carried out on both knives and nails. Knives in the Middle Saxon period were an essential everyday tool and may have been used for many purposes throughout the day, from eating to craft-working (Arnold 1997, 39). They are a common artefact type recovered from both settlements and cemetery sites. Knives also range in size, shape and function and therefore are very suitable for archaeometallurgical analysis (Blakelock 2006, McDonnell 1992b). There have been a number of studies of knives from both Anglo-Saxon cemeteries and settlements, therefore there is a significant corpus of data available for comparison (Blakelock & McDonnell 2007). Ten out of a total of twelve knives dating to the Middle Saxon period from the South Manor Area excavations were selected for analysis. To complement the study of the knives, seven nails were selected for analysis to examine the metallurgy of utilitarian ironwork. This comparison offers an opportunity to contrast the edged tool technology with lower skill ironwork. Both data sets can be compared to the data from the stock bars.

The Archaeometallurgical Analyses of the Knives

During excavations of the South Manor Area, 44 knives were recovered, twelve of them from Middle Saxon deposits. Out of these, four were found associated with the Middle Saxon smithy (WP 134, 442, 472 and 502).

For the purpose of this study a new typology based on knife form was created. This was to allow for easier comparison with other Anglo-Saxon sites that have used one of three different typologies: Evison's (Evison 1987, 113-117), Ottaway's (Ottaway 1992) or McDonnell's (McDonnell *et al.* 1991). The new typology (Fig. 7.3.3) is based purely on the shape of the back of the knife, which is unlikely to change during use. The ten knives selected were sectioned and prepared as indicated in Appendix 1; they were examined using optical and electron microscopy and micro-hardness testing. The manufacturing typology used (Fig. 7.3.4) was based on a simplified version of Tylecote and Gilmour's typology of six different methods of manufacturing knives (Blakelock & McDonnell 2007; Tylecote & Gilmour 1986, 2-7).

The angle-back knife appears to have been the preferred knife type in the 7th to 8th centuries at Wharram Percy (Table 7.3.10). When compared to other knives examined from the Anglo-Saxon period, this seems unusual since the curved-backed knives seem to be the preferred type at both the settlements and cemeteries (Table 7.3.10). This could be due to the small number of knives that were found, those from the South Manor Area not being representative of the whole settlement. The majority of the knives from Wharram Percy had a tang to blade interface which was distinct on both sides. A similar pattern occurs at *Hamwic*, Fishergate and Coppergate (McDonnell *et al.* 1991; Ottaway 1992; Rogers 1993). All the tangs from Wharram Percy taper away from the shoulder which would have been necessary to allow the handle to be fixed to the tang (Ottaway 1992, 582).

Previous analysis of knives from both settlement and cemetery contexts has revealed significant trends (Blakelock & McDonnell 2007). There was a preferential use of manufacturing type 2, butt-welded knives in urban and rural settlements (Blakelock &

McDonnell 2007; Blakelock 2006). In total 79% of all knives examined from Early Medieval settlements in England have been classified as of type 2 manufacture – although some knives classified as type 0 (plain ferritic iron) and 3 (piled iron) may have originally had a steel cutting edges, which have been subsequently lost due to wear. The smiths in the settlements were making economical use of the high quality steel which would have been time consuming and expensive to make.

The results from the metallographic analysis of ten knives are shown in Table 7.3.11 and demonstrate that the smiths utilised the full range of iron alloys available in Middle Saxon England. Seven of the knives were of type 2 manufacture but only one of these (WP159) had a heat treated cutting edge to maximise the potential of the steeled edge. Five of the other six type 2 butt-welded knives all had circa 0.8% carbon, suitable for quenching and tempering; but two of them were worn and found in the smithy, and could have been discarded as scrap. Hence they could have been normalised (i.e. heated) to remove the hardness of the cutting edge. The three knives not of manufacturing type 2 were less distinct in their typology: two (WP134 and 307) were type 0 and the remaining knife consisted of piled iron (type 3). The knife backs were manufactured from a range of alloys: composite iron (six knives), phosphoric iron (two knives) and ferrite (one knife).

Metallographic analysis revealed that while eight of the ten knives analysed were fairly typical of Early Medieval knives found elsewhere in Britain and on the continent, two were unusual. The first, knife WP159, is a typical scarf-welded type 2 knife, but within the heat treated steel cutting edge there were multiple bands of white, similar to white weld lines seen in other knives (Pl. 7.3.4). Chemical analysis of these bands revealed two types: the first was enriched in arsenic and nickel while the other type of band located near to the tip was high in phosphorus with some copper, and showed signs of ghosting. This surface enrichment could have been formed deliberately by ‘phosphiding’ (adding a phosphate mixture such as bone-ash or charcoal with sand, and then heating it under reducing conditions: Tylecote 1986, 192-193). Knife WP278 was the second unusual knife, as analysis showed that it was a fairly well constructed type 2 scarf-welded knife, but at the very tip of the cutting edge a piece of low carbon steel (up to 0.2% carbon) had been welded on (Pl. 7.3.5). It is unknown why the softer iron had been welded on to the steel as it would have made more sense to sharpen the knife instead, although the x-radiograph revealed that this knife was badly worn in areas.

During the Early Medieval period different iron alloys were being used and the highest level of smithing was achieved (Blakelock & McDonnell 2007; McDonnell 1989). However, the knives from Middle Saxon Wharram Percy were not particularly high quality: although they utilised the full range of iron alloys, and utilised type 2 manufacture, only one of the ten knives had evidence of heat treatment, which is demonstrated by the lower overall average hardness compared to other sites (Table 7.3.12). The domination of the type 2 manufacture is in accordance with the data from other sites, but the poor quality of the steel edges cannot easily be explained. The steel in most of the un-treated type 2 knives was of sufficient quality to be hardened, but either the blades had never been hardened or they had reached the end of their lives and were heat treated to remove the hardness in preparation of re-cycling.

The Archaeometallurgical Analyses of the Nails

Nails are often over looked because of their basic utilitarian uses and the quantities found. However, they are useful in the study of Saxon smithing techniques due to their simple nature and ease of creation. A total of 833 nails were recovered from the South Manor Area excavations (Watts 2000, 140-47). They ranged in types from horseshoe to joinery nails. The largest quantity of unused nails from Wharram Percy was found at the smithy, which strongly suggests they were produced there.

Seven nails, of various types and usage (Table 7.3.13), were sampled and underwent optical analysis and micro hardness testing, with elemental composition analysis obtained by SEM-EDS. A summary of the results can be found in Table 7.3.14. The composition and construction of the nails falls into three different categories, phosphoric, ferritic and a combination of phosphoric iron, ferritic and steel. The majority of nails are composed of phosphoric iron, an alloy which is both harder than ferrite and more corrosion resistant. The composite nails appear heterogeneous and have a banded structure of the different alloys present. There were no significant differences in the construction of the different types of nails: they all appear to be constructed from one piece of thin bar with no evidence of welding (Pl. 7.3.6). There is no evidence of heavy cold working, or shock in the microstructure of the nails.

The simple manufacture of the nails and the similarities of their alloys to the bars suggest that they were made from similar stock iron. It is very likely that the unused nails found in the smithy, very similar to the phosphoric iron bars, were constructed there.

Use and re-use

The function of an object can often be determined based on its shape and size. For example, the shape and size of the knife especially that of the cutting edge and knife tip would most likely determine its function. The handle length and materials used may also have affected the function (Cowgill *et al.* 1987, 51). Historic illustrations such as manuscripts and sculpture can also provide clues as to how objects were used in everyday life (Cowgill *et al.* 1987, 57). In other cases the artefacts themselves may provide the evidence for how they were used – for example if a nail is still joining two pieces of wood together.

Whether an iron object was heavily used in antiquity can be determined by looking for evidence of wear, damage and repair. For example, as knives are used the cutting edge will begin to wear down and blunt, so they are often re-sharpened, and this process can result in distortion of the original shape of the cutting edge (Fig. 7.3.5). Ottaway has suggested that the way a knife was manufactured will affect how quickly the knife will be worn and how it will distort when sharpened, and this can also apply to other objects (Ottaway 1992, 598-599). The cutting edges of five out of the ten knives analysed were heavily worn with another four showing some evidence of wear. Only one knife, WP159, showed no evidence for wear, and this is the only heat-treated blade with a hard quenched and tempered cutting edge. This suggests that heat treatment affects the amount of wear, as knives with harder cutting edges are less prone to wear.

When a knife has been completely worn down and become unusable there is an alternative option to recycling or discard: the object could be repaired by adding more metal. This would be difficult for some iron objects but has been noted in a few of the knives from Wharram Percy and Coppergate, York (McDonnell 1992b). The metallurgical analysis revealed the presence of second weld lines in at least three of the knives from Wharram Percy (WP237, WP278 and WP308). These factors suggest that the knives were continuously used, re-sharpened and repaired until they were no longer usable (for example if they had lost their steel cutting edge: knives WP134 and WP308).

Other rarer microstructures can also reveal information about the use of an artefact, such as Neumann Bands which are induced by shock. These have been identified in the Iron Age cart tyres from Ferrybridge (Swiss & McDonnell 2007), Roman knives from Carlisle (Swiss 2000, 18-23) and an anvil from Coppergate, York (Ottaway 1992, 512-514). Recent research by the Archaeometallurgy Research Group has demonstrated that Neumann bands only form in very pure iron and that very low concentrations of alloying elements, phosphorus and carbon, inhibit their formation (Marufi 2007). Hence their absence in the Wharram assemblage reflects the metal composition rather than usage.

It is possible that Early Medieval blacksmiths would have re-used metals when the opportunity arose, as they still do today (Woodward 1985). It may have been particularly important in low status rural societies and those that were some distance from centres of iron production. It has been suggested that the piling effect seen in some iron is due to iron being recycled, although a more likely explanation for the piled structures seen in many iron knives is that it resulted accidentally when the heterogeneous bloom was worked, by bending and forging, into a bar (Tylecote 1986, 145). This piling effect can be seen in the three composite iron bars from the smithy, which have been interpreted as bar derived from the smelting operation, and not as a result of the welding together of scraps of bar. An underlying reason for taking this position is that when heating and welding takes place there will be a high loss of metal due to oxidation of the surface of the iron to form scale. It is therefore highly inefficient and prone to the law of rapidly diminishing returns to attempt to form small bars from smaller fragments. Thus a bar is drawn down from larger to smaller, rather than forging together pieces to make a larger one.

Discussion and Conclusions

Discussion

The discussion will summarise the ironworking landscape models, consider the archaeometallurgical evidence for ironworking at Wharram and then draw some overall conclusions relating to Wharram and to ironworking studies in general.

The ironworking industry was a skilled craft that relied on the successful exploitation of natural resources, the manipulation of high temperature processes, and the application of artistic craft skills.

Three models have been advanced to understand the functioning of the ironworking landscape of a rural settlement belonging to any period. The first envisages an overall self-sufficient iron economy in which the bulk of the iron is smelted within the settlement holdings, for example at Bestwall (Slater and McDonnell 2005), where the smelting was carried out in the field system and the smithing within the settlement. This can be paralleled with sites on the Continent, for example Heeten in Holland, dating from the 2nd to 5th centuries AD (Joosten *et. al.* 1998). The smelted blooms were refined, smithed to bar and forged into artefacts. For complete self-sufficiency the four alloy types must be produced: ferritic iron, phosphoric iron, steel and composite iron.

The second model postulates an iron economy with no primary production and reliant wholly on the importation of trade iron. The third model argues for no significant production of artefacts, the settlement being reliant on importation of artefacts, with some low level smithing, as in the repair or production of simple artefacts on a small scale. The models are not exclusive, and it is easy to envisage a combination of any of the models, for example a predominance of self-sufficiency (Model 1) with some importation of specific artefacts (Model 3).

The study of the metalworking debris from all recent excavations at Wharram reveals no evidence for iron smelting. The local geology which is Cretaceous chalk with alluvial deposits in the valley bottoms, most significantly at the Wolds edge, precludes major iron ore deposits. Tylecote and Clough (1983) demonstrated that iron pyrite nodules collected in the field in the South Downs had the sulphur content weathered out leaving a viable ore. There is evidence of prehistoric iron smelting in and around the Wolds at North Cave (McDonnell 1988) and at Welham Bridge (Halkon and Millett 1999 75-95). There is therefore the potential for some iron smelting near Wharram, but probably not on a significant scale.

The concentration of iron smithing debris on Sites 59 and 76, as well as the probability of substantial slag deposits in the unexcavated area at the intersection of Site 44 and Site 76 suggests a slag dump. It includes hearth bottoms, smithing slag lumps and hearth lining. The presence of a high proportion of hearth lining indicates that the source of the material that constituted the dump was close by. There are very few examples of complete excavations of a smithy tenement, the best example being the medieval one Burton Dassett in Warwickshire (Mills and McDonnell 1992; McDonnell 1992b). In this case the smithy dump was located at the end of the tenement, not adjacent to the smithy building. In an ethnographic case study in Sri Lanka observed by one of us (GMcD), the slag from the smithy hearth was dumped in the smithy but then removed on a weekly basis, for use around the village, fields and roads as hardcore. There is no evidence from either Wharram or any other site to determine the physical relationship between smithy and dump.

The phase distribution analysis of the stratigraphy of the slag show that it was generated in Phases 2 (early Middle Saxon) and 3 (Middle Saxon), and then spread in phases 4 (Late Saxon) and 5 (Medieval). The slag is concentrated at the west end of Site 76, and therefore the smithy was probably to the west as it was not revealed in the earlier excavations of Site 44 to the east. In the original publication it was suggested that some features were potentially identified as original smithy flooring (e.g. Context 59/55: Stamper and Croft 2000, 32-34). These features probably represent snapshots of the deposits that survive as small lenses or in depressions (Figs 13 and 14). This would suggest that there was intense activity in this area and that the smithy building is further to the west, perhaps Building A and/or it suggested predecessor, Building B (Chapter 7.1 above). Alternatively (or as well), it is possible that the line of postholes and features just to the south of the later of the two main east-west ditches (59/52), features 59/103, 59/105, 59/107, and the group further to the south (76/104, 76/106 76/108 etc) represent a late phase of the smithy building, with the surviving lense 59/55 representing the eroded entrance filled with smithy flooring debris.

The archaeometallurgical analysis of the slag showed that both the hearth bottoms and the smithing slag lumps have similar compositions although two broad compositional groups emerged. The consistency of composition implies a high level of control in the smithing slag composition, in particular limiting the amount of free iron oxide. The Wharram smiths have been careful to control the slag composition ensuring that the hammerscale iron oxide was compensated by the addition of silica rich minerals. The Wharram analyses can be compared to data from other Saxon sites (Table 7.3.15).

The archaeometallurgical analysis of the stock iron used in the smithy, the nails and the knives indicate that the smiths were utilizing a range of specific iron alloys. The bars and nails are comparable, with the dominant alloy being composite iron, a heterogeneous iron comprising ferritic/phosphoric/low carbon steel. The bars include examples of single alloys indicative of different iron production centres. The analyses of the inclusions in the bars offer a number of opportunities. The theory being tested in the inclusion study related to inclusions introduced into the metal during stages in the fabrication of the bars, smelting, refining, smithing. The data appears to be more complex; however there are clear differences in slag inclusion between the single alloy bars, which indicate several production centres as sources of the iron.

The analyses of the knives shows that the manufacturing type 2, butt-welded blade was the commonest type (seven out of ten knives), which accords with data from other contemporary sites such as Fishergate (Table 7.3.12). However only one of the knives had been heat treated to exploit the steel to its maximum quality. The other six type 2 butt-welded knives had normalised steel edges, but had the potential to have been heat treated. The lack of heat treatment may be explained in part by the two type 2 knives that were recovered from the smithy and may therefore have been returned for re-edging or as scrap material. However it must be concluded that the knives from Wharram are characterised by the lack of heat treatment. This is unlikely to be due to lack of skill as the consistency of slag composition, the exploitation of different alloys all point to sophisticated smithing knowledge.

One interpretation is that the knives were originally manufactured to a high standard, as evidenced by the quality of the welds and the presence of white weld lines, but that subsequent use and mistreatment had resulted in poorer quality edges. There is evidence at Wharram for re-edging in knife WP278 which had a low carbon strip welded to a quality type 2 knife. The overall quality of the Wharram knives is poor compared to the evidence from contemporary sites such as Flixborough, Anglian York and *Hamwic* (Table 7.3.16). Three knives displayed ‘white weld lines’, which are due to enrichment in Arsenic (Castagnino 2007) and are indicative of high quality steel welding. Analysis of the slag inclusions in the weld lines of two knives clearly demonstrated that archaeometallurgists need to review the definition of a weld line; in one case, analysis showed compositional relationship to the bulk analyses of the smithing slag, which would tentatively suggest manufacture of the knife at Wharram.

Conclusions

The archaeological and archaeometallurgical evidence of ironworking at Wharram from all excavations shows a general background scatter of slag on many sites with a clear focus of iron smithing in the South Manor Area. There is no clear evidence for iron smelting in Anglo-Saxon Wharram despite some possible fragments of tapped iron smelting slag. This slag, on the evidence of its free running tapped morphology, is most likely to be of Romano-British date.

Detailed analysis of the South Manor Area data identified possible locations for a smithy building with its associated slag dump. A model can now be constructed of the Anglo-Saxon smithy. The smith imported bar iron to manufacture artefacts. It is probable that finished artefacts were also brought on to the site. The smith had access to all iron alloys available to the Anglo-Saxon smith, namely ferritic iron, phosphoric iron, steel and composite bars. The analysis of the slag inclusions strongly suggests that the iron came from a number of different smelting centres, but whether these were on the Wolds, on the Jurassic Ridge of North Lincolnshire or even further a field in North or West Yorkshire cannot be determined. The smith most likely undertook the full range of smithing techniques from simple forging to fire welding. There is a high degree of consistency of smithing techniques as indicated by the consistency of the two slag compositions. The expectation was that smithing slag compositions would vary, depending on operator and operation. However within the restrictions of the analysis the compositions indicate a high level of control. What the differences represent is unclear: they may be chronological, as the smithy perhaps operated for several centuries. The presence of two copper alloy mould fragments indicates some minor level of non-ferrous working. There is no evidence to support the smith manufacturing organic components of edged tools, e.g. bone or wooden blade handles.

The analysis of the knives demonstrates that the type 2 butt-welded method of applying the steel blade was in use in common with the practices of the day as evidenced by knife analyses from other sites (Blakelock and McDonnell 2007). The expectation was that the type 2 knives would be high quality with quenched and tempered steel cutting edges. However only one knife had such an edge, the remainder, although well manufactured in terms of alloy selection and welding, were not heat treated. Two possible interpretations are suggested, firstly that the six without evidence of heat treatment were manufactured at Wharram, and that the heat treated knife was an import. The second possibility is that the knives were originally of high quality with quenched and tempered steel cutting edges, giving optimum hardness and toughness, but that in the final stages of their life-cycle these knives were re-heated and cooled slowly, resulting in poorer quality cutting edges of low hardness.

The evidence of the smithy, through its associated finds, its stock iron and its slag composition suggest a high level of smithing expertise. However the quality of the knives suggest otherwise, perhaps even implying a lack of skill. This paradox can only be resolved through further, similar studies. Future studies must overcome the traditional post-excavation practice of taking the evidence of a highly skilled craft (even at a basic smithing level), and disseminating it to separate specialists, making the task of a holistic study of a smithy more difficult. This has been achieved to some extent with this new study of the Wharram smithy. It is essential that detailed archaeometallurgical investigations of all stages of the process are incorporated in such studies.

Appendices

Methodology

The bars, knives and nails were selected using a variety of criteria. The first was that they dated to the Middle Saxon period but the state of preservation was also particularly important. X-radiographs were used to determine the extent of any corrosion and the amount of remaining metal, and therefore the sampling location. Existing radiographs were used initially and when needed new x-radiographs were taken using a HP Cabinet x-ray System (Faxitron series) at a 120kV for 3, 6, 12, 24 minutes with a working distance of 25cm using lead screens. All x-radiographs were scanned into a computer by using an Agfa FS50B scanner along with RADView Workstation software with a pixel pitch of 50 microns in a high quality scan mode .

The assemblage of smithing slag recovered from the smithy was sorted into two groups; smithing slag lumps and hearth bottoms. In total twenty smithing slag lumps and ten hearth bottoms were randomly selected from the South Manor assemblage.

Prior to sampling all iron artefacts and smithing slag were recorded through the use of descriptions, sketches and photographs. The artefacts were be sampled by removing a section or two half sections of metal. A sample of metal in the bars and nails was normally removed from one end, using a Microslice diamond wafering blade. In some cases in addition to the normal cross-section, a longitudinal section was also removed. Sections from the knives were taken using a jewellers piercing saw, across the cutting edge of the blade and the back, where possible two half sections were staggered to preserve the overall knife shape. To avoid the effects of surface corrosion samples were removed from the centre of each smithing slag lump and hearth bottom. All samples were then mounted in Buehler VariDur 200 cold-setting resin and ground and polished to a one micron diamond finish.

The samples were examined using a Nikon Optiphot Reflected Light microscope, and images captured using a digital camera with Fire-I imaging software. The microstructures present in each bar, knife and nail were noted. The grain sizes were recorded using an ASTM grain size standard at 100x magnification. A Vickers hardness test was also carried out on these sections. A load of 200g was used for 15 seconds.

The composition of the metal and slag inclusions in the artefacts and the smithing slag was determined using a Fei Quanta 400 scanning electron microscope (SEM) with an Oxford Instruments INCAx-Sight energy dispersive x-ray system (EDS). This was calibrated using a cobalt reference standard, which is used as a reference standard. Spectra were collected at 0-20keV. The spectra were then quantified using the Oxford Instruments SEMQuant software system. The data was gathered for 50 live seconds for the bars and nails, 150 live seconds for the knives and 100 live seconds for the slag inclusions allowing for a ‘dead-time’ of up to 40%. To allow for the heterogeneous nature of the metal in the bars, knives and nails an average of three or four analyses were carried out in each area of interest. Prior to slag inclusion analysis the bars and two knives (159 and 502) were carbon coated. At least 60 inclusions in each area of interest were analysed and the backscatter detector was used to determine the different phases present in the inclusions. The smithing slag was also carbon coated prior to analysis. Due to the heterogeneous nature of the slag at least 4 bulk areas roughly 270µm by 270µm were analysed.

List of terms:

Bellows – A device for delivering pressurized air into a furnace or hearth

Billet – The compacted bloom after primary smithing removing excess slag

Bloom – The porous mass of iron and slag that results from the smelting process

Cast iron – Iron alloy containing 2-4% Carbon

Composite alloy – Any combination of multiple iron alloys

Dendrites – Are tree shaped structures in the iron microstructure that has been slow cooled and contains some alloying element

Ferritic iron – Iron containing no alloying elements

Flux – A substance that facilitates welding by preventing oxidation and promoting fusion

Forge – Also known as a hearth used by a smithy for heating metals

Gangue – Impurities other than the metal in ore

Hammerscale – The bits of metal and slag that come off metal during smithing

Hearth Bottoms – The remains of the bottom of the forge

Heat treatment – A method of using heat the alter the physical and chemical properties of the iron. Heat treatments include annealing, tempering and quenching.

Indirect process – The process of smelting where the ore is heated till molten and the slag floats to the top and can be skimmed off

Neumann bands – A mechanical deformation twin in ferrite

Pattern-welding – Forming a blade with several pieces of metal of differing compositions forge welded together and manipulated to form a pattern

Phosphoric iron – Iron alloy containing 0.15-1% phosphorus

Piling – The combination of several bands of iron fused together through working

Primary Smithing - The reducing of the bloom into billets and bars

Secondary smithing – The process of smithing bars into completed objects

Slag inclusions – The impurities that remain in the iron after smithing

Smelting – The process of using j=high temperatures to reduce the iron oxides to the metallic state and forming slag from the remaining unwanted material

Smelting Slag – The highly silicate unwanted material that melts away from the iron bloom during smelting

Smithing Slag – The impurities removed from the metal during the smithing process

Steel – Iron alloy that contains 0.1-1.9% Carbon

Stock iron – The iron bars or billets used by the smith in creating completed objects

Tuyere – The ceramic lined openings in the furnace used to let in air from the bellows

Weld-line – A line in the microstructure that is the result of using heat to join two pieces of metal

Bibliography

Andrews, P. 1997. *Excavations at Hamwic. Vol.2, Excavations at Six Dials*. CBA research report 109. York: Council for British Archaeology.

Anstee, J. W. & Biek L. 1961. A Study of Pattern-Welding. *Medieval Archaeology.* 5, 71-93.

Arnold, C. J. 1997. *An archaeology of the early Anglo-Saxon kingdoms* (2nd edn). London: Routledge.

Blakelock, E. & McDonnell, G. 2007. A Review of the Metallographic Analysis of Early Medieval Knives. *Historical Metallurgy* 41: 40-56.

Blakelock, E. S. 2006. *Analysis of knives from the Middle Saxon Rural Settlement of Wharram Percy, Yorkshire*. Unpublished Undergraduate Dissertation: The University of Bradford.

Blakelock, E. S. 2007. *Slag Inclusions and the Quest for Provenance: Slag and Slag Inclusions from Iron Smelting Experiments and their Application in Slag Inclusion Analyses of Artefacts from Tell Hammeh, Jordan and Tel Beth-Shemesh, Israel*. Unpublished Masters Dissertation: Institute of Archaeology, University College of London.

Boyle, A. J. 1995. *Two Oxfordshire Anglo-Saxon Cemeteries: Berinsfield and Didcot.* Thames Valley landscapes monograph; 8. Oxford: Oxford University Committee for Archaeology.

Buchwald, V. F. 2005. *Iron and Steel in Ancient Times*. Historisk-filosofiske Skrifter. Copenhagen: Det Kongelige Danske Videnskabernes Selskab.

Buchwald, V. F. & Wivel, H. 1998. Slag analysis as a method for the characterization and provenancing of ancient iron objects. *Materials Characterization* 40:73-96.

Castagnino, V. 2007. *An investigation of the white weld line phenomenon.* University of Bradford: Unpublished MSc Dissertation.

Chabot, N. 2007. *Modeling of inclusions in forged iron artefacts*. University of Bradford: Unpublished MSc Dissertation.

Clark, A. and Gaunt G.D. 2000 Stone Objects in Stamper, P. & R. A. Croft. *The South Manor area*. 155-166. York: York University Archaeological Publications 10. 101-117.

Clarke 1979 *Iron and Man in Prehistoric Sweden* Jerkontoret Stockholm

Cowgill, J. and McDonnell G. forthcoming The slags and other metal-working debris in Powesland, D Excavations at West Heslerton.

Cowgill, J., Neergaard, M. D. & Griffiths, N. 1987. *Knives and scabbards*. Medieval finds from excavations in London 1. London: H.M.S.O.

Crew 1991 The Experimental production of prehistoric bar iron *Journal of the Historical Metallurgy Society* 25(1): 21-36.

Daoust, A. B. 2007. *The nature and composition of blacksmithing residues and their connection to weld-line slag inclusions*. University of Bradford: Unpublished Masters Dissertation.

Dudley, H.E. 1949 Early Days in North-West Lincolnshire

Dungworth, D. & Wilkes, R. 2007. *An investigation of hammerscale*. Portsmouth: Research Department Report 26/2007.

Evison, V. I. 1987. *Dover: the Buckland Anglo-Saxon cemetery*. London: Historic Buildings and Monuments Commission for England, Archaeological Report No.3.

Evison, V. I. 1988. *An Anglo-Saxon cemetery at Alton, Hampshire*. Winchester: Hampshire Field Club and Archaeological Society.

Faull, M. L. & Moorhouse, S. A. 1981. *West Yorkshire: an archaeological survey to A.D. 1500: Vol 3*. Wakefield: West Yorkshire Metropolitan County Council.

Green, C. S., Davies, S. M. & Ellison, A. 1987. *Excavations at Poundbury, Dorchester, Dorset, 1966-1982 Vol.1. The settlements*. Dorset Natural History and Archaeological Society monograph series; no.7. Dorchester: Dorset Natural History and Archaeological Society.

Goodall, I.H. 2000 Iron Objects. In Stamper, P. & R. A. Croft. *The South Manor area*. 132-139. York: York University Archaeological Publications 10.

Hamerow, H. 2002. *Early medieval settlements: the archaeology of rural communities in North-West Europe, 400-900*. Oxford: Oxford University Press.

Halkon, P. E. & Millet, M 1999. *Rural settlement and industry: studies in the Iron Age and Roman archaeology of lowland East Yorkshire*. Yorkshire Archaeological Society, Roman Antiquities Section.

Halkon P and Millett, M 1999 Rural settlement and industry: Studies in the Iron Age and Roman archaeology of Lowland east Yorkshire East Riding Archaeological Society, Yorkshire Archaeological report 4

Haslam, J., Biek, L. & Tylecote, R. F. 1980. A Middle Saxon Iron Smelting Site at Ramsbury, Wiltshire. *Medieval Archaeology* 24:1-68.

Hedges, R. E. M. & Salter, C. J. 1979. Source determination of iron currency bars through analysis of the slag inclusions. *Archaeometry* 21:161-175.

Hey, G. 2004. *Yarnton: Saxon and Medieval settlement and landscape*. Oxford: Oxford Archaeological Unit.

Joosten, I. 2004. *Technology of Early Historical Iron Production in the Netherlands*. Geoarchaeological and Bioarchaeological Studies. Amsterdam: Institute for Geo- and Bioarchaeology, Vrije Universiteit.

Joosten, I., Jansen, J.B.H. & Kars, H. 1998. Geochemistry and the past: estimation of the outputs of a Germanic production site in the Netherlands. *Journal of Geochemical Exploration* 62: 129-137.

Loveluck, C. P. 1998. A high-status Anglo-Saxon settlement at Flixborough, Lincolnshire. *Antiquity* 72:146-161.

Mack, I., McDonnell, G., Murphy, S., Andrews, P. & Wardley, K. 2000. Liquid steel in Anglo-Saxon England. *Historical Metallurgy* 34:87-96.

Maddin, R. 1987. The Early Blacksmith. In Scott, B. G., Cleere, H. and Tylecote, R. F. (eds) *The crafts of the blacksmith : essays presented to R.F. Tylecote at the 1984 symposium of the UISPP Comitâe pour la Sidâerurgie ancienne.* 7-17. Belfast: UISPP Comitâe pour la Sidâerurgie ancienne, in conjunction with Ulster Museum.

Malim, T., Hines, J. & Duhig, C. 1998. *The Anglo-Saxon cemetery at Edix Hill (Barrington A), Cambridgeshire : excavations 1989-1991 and a summary catalogue of material from 19th century interventions*. CBA research report; 112. York: Council for British Archaeology.

Marufi, I. 2007. *An investigation into the occurrence of Neumann bands in archaeological iron.* University of Bradford: Unpublished MSc Dissertation.

McDonnell, G. 1986. *The classification of early ironworking slags*. Unpublished PhD: University of Aston.

McDonnell, G. 1987a. The study of Early Iron Smelting Residues. In Scott, B. G., Cleere, H. and Tylecote, R. F. (eds) *The crafts of the blacksmith : essays presented to R.F. Tylecote at the 1984 symposium of the UISPP Comitâe pour la Sidâerurgie ancienne.* 47-52. Belfast: UISPP Comitâe pour la Sidâerurgie ancienne.

McDonnell, G. 1987b. *The ironworking residues from Cherry Willingham, Lincolnshire*. London: AML Laboratory Report 92/87.

McDonnell, G. 1987c. *Analysis of Eight Iron Knives and Four Other Tools from Hamwih, Southampton*. Ancient Monuments Laboratory report 137/87. London: Ancient Monuments Laboratory report 137/87.

McDonnell, G. 1987d. *Metallurgical Analysis of Six Iron Knives from Hamwih, Southampton*. Ancient Monuments Laboratory report 93/87. London: Ancient Monuments Laboratory report 93/87.

McDonnell, G. 1988. *The ironworking residues from Romsey, Hampshire*. London: AML Laboratory Report 72/88.

McDonnell, G. 1988. *The ironworking slags from North Cave, North Humberside* London:: Ancient Monuments Laboratory report 91/88.

McDonnell, G. 1989. Iron and its alloys in the fifth to eleventh centuries AD in England. *World Archaeology* 20:373-381.

McDonnell, G. 1991. A model for the formation of smithing slags. *Materialy Archeologiczne* 26:23-26.

McDonnell, G. 1992a. The identification and analysis of the slags from Burton Dassett, Warwickshire. London: Ancient Monuments Laboratory report 46/92.

McDonnell, G. 1992b. Metallography of the Coppergate knives. In P. Ottaway (ed.) *Anglo-Scandinavian ironwork from 16-22 Coppergate*: 591-599. London: York Archaeological Trust.

McDonnell, G. 1993. The examination of the slags and residues from Mucking, Essex. London: Ancient Monuments Laboratory report 4/93.

McDonnell, G. 2000. The Ironworking Evidence. In Stamper, P. & R. A. Croft. *The South Manor area*. 155-166. York: York University Archaeological Publications 10.

McDonnell, G., Fell, V. & Andrews, P. 1991. *The Typology of Saxon Knives from Hamwih*. London: Ancient Monuments Laboratory report 96/91.

Mills, A. & McDonnell, J.G. 1992. *The identification and analysis of the hammerscale from Burton Dassett, Warwickshire.* London: Ancient Monuments Laboratory report 1992/47.

Ottaway, P. 1992. *Anglo-Scandinavian ironwork from 16-22 Coppergate*. The archaeology of York; 17/6. London: York Archaeological Trust.

Peirce, I. G. 2002. *Swords of the Viking age*. Woodbridge: Boydell.

Pleiner, R. 2000. *Iron in archaeology: the European bloomery smelters*. Archaeologický Ústav Avĕr

Pleiner, R. 2006. *Iron in archaeology: Early European Blacksmiths*. Archaeologický Ústav Avĕr

Powell, A., Baumann, J. & Vernon, R. 2005. Experimental charcoal burn at Dalby Forest, North Yorkshire. *CBA Yorkshire Forum*. 7-10.

Rahtz, P., Hirst, S. M. & Wright, S. M. 2000. *Cannington cemetery: excavations 1962-3 of prehistoric, Roman, post-Roman, and later features at Cannington Park Quarry, near Bridgwater, Somerset*. London: Society for the Promotion of Roman Studies.

Rogers, N. S. H. 1993. *Anglian and other finds from 46-54 Fishergate*. The archaeology of York; 17/9. London: York Archaeological Trust by the Council for British Archaeology.

Samuels, L. E. 1999. *Light microscopy of carbon steels*. Ohio: ASM.

Scott, D. A. 1991. *Metallography and microstructure of ancient and historic metals*. United States: The J. Paul Getty Trust.

Serneels, V. & Perret, S. 2003. Quantification of Smithing Activities based on the Investigation of Slag and Other Material Remains. In *Proceedings of the International Conference Archaeometallurgy in Europe*: 469-479. Milano: Associazione Italiana di Metallurgia.

Sherlock, S. J. & Welch, M. G. 1992. *An Anglo-Saxon cemetery at Norton, Cleveland*. CBA research report; 82. London: Council for British Archaeology.

Sim, D. & Ridge, I. 1998. *Beyond the bloom: bloom refining and iron artifact production in the Roman world*. Oxford: Archaeopress.

Slater R and McDonnell G 2002 Bestwall Quarry Slag Assemblage. Unpublished report for Bestwall Aggregates Levy Project English Heritage

Stamper, P. & Croft, R. A. 2000. *The South Manor area*. York: York University Archaeological Publications 10.

Starley, D. 1996. *A technological study of knives and spearheads from the excavations at Mucking, Essex*. Ancient Monuments Laboratory report 37/96. Portsmouth: Ancient Monuments Laboratory report 37/96.

Starley, D. 1999. *The analysis of Middle Saxon ironwork and ironworking debris from Flixborough, Humberside*. Portsmouth: Ancient Monuments Laboratory Report 35/99.

Swiss, A.J. 2000. *The metallographic analysis of selected Roman ferrous edged tools from Castle Street Carlisle.* University of Bradford: Unpublished MSc Dissertation.

Swiss, A. J. & McDonnell, J. G. 2003. Evidence and interpretation of cold working in ferritic iron: Proceedings of the International Conference on Archaeometallurgy in Europe Vol 1.

Swiss, A.J. and McDonnell 2007 Metallurgical analysis of the iron tyres from the chariot burial in Brown, F., Howard-Davis, C., Brennand, M., Boyle, A., Evans, T., O'Connor, S., Spence, A., Heawood, R. and Lupton, A. *The Archaeology of the A1 (M) Darrington to Dishforth DBFO Road Scheme* Lancaster Imprints, Oxford Archaeology North Lancaster. 463-498

Tebbutt, C. 1982. A Middle-Saxon iron smelting site at Millbrook, Ashdown Forest, Sussex. *Sussex Archaeological Collections* 120: 19-35.

Timby, J. R. & Bartlett, A. 1996. *The Anglo-Saxon cemetery at Empingham II, Rutland: excavations carried out between 1974 and 1975*. Oxbow monograph; 70. Oxford: Oxbow.

Tylecote, R. F. 1986. *The prehistory of metallurgy in the British Isles*. London: Institute of Metals.

Tylecote, R. F. 1987. A report on the metallurgical analyses of the knives from Poundbury. In S. P. Green (ed.) *Excavations at Poundbury, Dorchester, Dorset 1966-1982 - Volume 1 the Settlements*: microfiche 2: C10-C12. Dorset: Dorset Natural History and Archaeological Society.

Tylecote, R. F. 1990. Scientific examination and analysis of iron objects. In M. Biddle (ed.) *Object and economy in medieval Winchester*: 140-154. Oxford: Oxford University Press.

Tylecote, R.F. & Clough, R.E. 1983. Recent Bog-iron Ore Analysis and the Smelting of Pyrite Nodules. *Journal Offa*. 40. 115-118.

Tylecote, R. F. & Gilmour, B. J. J. 1986. *The metallography of early ferrous edge tools and edged weapons*. Bar; 155. Oxford: B.A.R.

West, S. 1985. *West Stow: the Anglo-Saxon village Vol.1, Text.* East Anglian Archaeology report 24. Ipswich: Suffolk County Council.

Wheeler, J. 2004. Secrets of the sooty stack, *Planet Earth*, Winter Volume 10-11.

Woodward, D. 1985. Swords into ploughs - recycling in pre industrial England. *Economic History Review* 38:175-191.