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AN INVESTIATION INTO THE TECHNOLOGICAL PROCESS USED TO PRODUCE DAVID HARTLEY'S FIRE-PLATING

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Summary

5 samples of thin sheet-iron, used to prevent the spread of fire in late C18th buildings, were examined by metallography and scanning electron microscope (SEM) based inclusion analysis. All samples were found to be uniformly low in carbon, although one contained a significant amount of phosphorus. Low levels of sulphur suggested the preferential use of charcoal-smelted iron.

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ANCIENT MONUMENTS LABORATORY REPORT SERIES

An Investigation into the Technological Processes used to Produce David Hartley's Fire-Plating.

Thomas Finney and David Starley

Introduction

As part of the Ancient Monuments Laboratory's 'Historical Ironworking' project analysis was carried out into the technological background of David Hartley's architectural fireproofing system. This involved both metallography and chemical analysis, as well as some research into the literature on the methods of production of the period.

David Hartley and his Invention

David Hartley was a man of varied talents. Born in 1732, the son of David Hartley (senior) the noted philosopher, he was educated at Corpus Christi College, Oxford and was awarded a BA there on the 14th of March 1750. In 1774 he was elected to parliament for Hull, his first term ending in 1780. From 1782-84 he served a second term for the same constituency. During this time Hartley became known as an opponent of the African slave trade, and the war with America. He was a close friend of Benjamin Franklin, and was appointed by the government to act as its plenipotentiary in Paris where, on the 3rd September 1783, he and Franklin drew up the treaty of Paris ending the war between Great Britain and the United States of North America. Within the House of Commons he had a somewhat mixed reputation. He was known to be hard working and talented, but was also known for his incredibly long and boring speeches, so much so that went he rose to speak the house would empty as if the dinner bell had rung.[1]

Hartley was also an inventor and in 1773 he patented a method for "securing buildings and ships against fire" in which he described his system as protecting against fire;

> "By the application of plates of metal and wire, varnished or unvarnished to the several parts of buildings and ships, so as to prevent the access of fire and the current of air, securing the several joists by doubling in, overlapping, soldering, rivetting, or any other manner fastening said plates of metal in, to and about the several parts of buildings and ships, as the case may require[2]".

The literature suggests that either copper or iron could be used, although no surviving examples of the former are known. In practice the system Hartley actually marketed consisted of thin sheets that were nailed to the joists of a building to form a membrane over the entire floor, the floorboards were then nailed over this sheeting, sealing them in position. The effect of this, Hartley hoped, was twofold. Firstly to slow the spread of fire itself, and to keep it contained within one particular area of a building, and secondly to stop the flow in air between floors, so as to starve a fire of oxygen.

It would seem that Hartley was successful in the marketing of his product; he was voted £2500 by parliament to continue his experiment on fireproofing, to which end he built a fireproof house on Putney Green. The fact that his system was still around twenty years after it was patented to be tested by the Association of Architects must be testament to is continuing use.[3]

Origin of Samples

For this study four samples of fireplate were investigated. Obtaining samples proved to be difficult as, although the system was probably used in hundreds of buildings, there is little knowledge of its existence and much of it is probably still hidden beneath the floorboards of eighteenth century properties. Samples were obtained from the Historic Dockyards Portsmouth, Norbury Park near Dorking, Quarry Bank Mill at Styal in Cheshire and 9 Bedford Square, London. The last sample was obtained from the English Heritage Architectural Study centre.

The use of Hartley's fireplate at Portsmouth Dockyard was documented in Royal Naval records. Their use was suggested to the Navy by Hartley in late 1781, or possibly early 1782 and later installed in number 9 and 10 Stores in the yard. Not only were the floors clad, but also wooden pillars were sheathed with fireplate.[4] The sample analysed was collected from the underside of the first floor of Storehouse 9.

Norbury Park was built by William Locke in the 1790s. Locke was a noted connoisseur and patron of new and clever ideas, and the inclusion of the fireplating system in his house can be seen as a result of this.[5]

Bedford Square was part of the estate of the Duke of Bedford and several of the houses within it were fireproofed by Hartley's method despite the increase in cost, estimated at 2-3% of the total cost of the building[6]. The house this sample was removed from dates from 1780. The Duke of Bedford also paid for a pamphlet to be published, detailing the results of Hartley's fireproofing experiments.[7]

The fireplate from Quarry Bank Mill comes from the mill's weaving shed constructed in 1796.[8] There is no documentary evidence to identify the plate as Hartley's fire-plate and it may be a later addition, though as the design is similar it comes from the same tradition, if not the same origin. Hartley's patent would have still been in force at the time of the building's construction. A similar plated ceiling has been identified at Boars Head Mill, Derbyshire[9].

Technological Processes

A series of technological processes were required to produce the thin iron sheet required for the fireplates. This section briefly reviews the literature on the techniques and methods available at the time.

The Blast Furnace

In the third quarter of the eighteenth century iron was smelted from iron ore in both charcoal and coke fired furnaces. The product of such a furnace was cast iron, typically containing about 4% carbon.

The use of coke as a fuel for iron smelting was introduced by Abraham Darby I. He first successfully smelted with coke in 1709 and it was being used commercially mid way through the eighteenth century. By the 1770s the ratio of coke to charcoal was about one to one and at end of the eighteenth century 90 % of all iron smelted in Britain used coke as a fuel.[10] Charcoal remained in use in areas such as the Forest of Dean, Scotland and to some extent South Wales. There is some suggestion that charcoal-smelted iron was preferred as the raw material for producing the thinly rolled iron sheet for use by the tin-plate industry as it was more malleable.[11]

Charcoal iron and coke iron can be distinguished by the levels of sulphur present within the iron. Coke contains much higher levels of sulphur than charcoal, and this difference is reflected in the concentration of sulphur within the iron.

The Finery

To produce the thin iron sheet that Hartley's fireplate used, the hard, inflexible cast iron from the furnace has to be converted into more malleable 'wrought iron' suitable for rolling. This was done by the burning off of the carbon, and other elements present within the metal, in the finery hearth. The finery consisted of an open hearth in which cast iron pigs were re-melted in a charcoal-fuelled fire blown by water-powered bellows. During melting a number of elements present in the metal were released. The carbon was oxidised by the blast of the bellows to CO and CO_2 and passed off with the furnace gases. Other elements such as silica, manganese and phosphorus combined with the slag in the base of the hearth. As the carbon content decreased, the iron became increasingly solid, entrapping slag within its structure. On removal from the hearth the iron was forged under a water powered hammer to a bar or rod. During this much slag was squeezed out, though some always remained within the iron.[12]

A problem with the fining process was that sulphur was not removed from the iron. High sulphur levels within iron makes it mechanically brittle. If coal or coke was used as the fuel in the finery hearth sulphur from the fuel would pass into the iron, increasing its brittleness. This was first overcome by John Wood in 1761 by the 'stamping and potting' method[13]. Cast iron pigs were fined using coal as a fuel giving a high sulphur, nearly malleable iron. This iron was then heated in crucibles in a reverberatory furnace with a flux which completed the conversion to wrought iron, and removed the sulphur. This led, in 1784, to the patenting of the puddling method by Henry Cort, in which the whole conversion was performed in a reverberatory furnace, the iron not coming into contact with the fuel at all.[14]

The Rolling Mill

It is suggested that the rolling of wrought iron bars into thin iron sheet for the tin-plate industry was first achieved in the late seventeenth century. In 1697 an Edward Lhwyd reported that at an iron works in Pontypool:

> "they cut common iron bars into pieces of about two foot long, and heating them glowing hot, placed them between these rollers, not across, but their ends lying the same way as the ends of the rollers. The rollers (moved with water) draw out these bars into such thin plates, that their breadth, which was about four inches, becomes their length, being extended to about 4 foot, and what was the length of the bars is now the breadth of the plates. With these plates Hanbury makes Furnaces, Pots, Kettles, Saucepans, etc. These he can afford at a very cheap rate (about a third of what is usual).[15]"

The basics of this technique would have been unchanged in the late eighteenth century. It is probable that the process used to roll plates as thin as the ones used by Hartley was pack rolling. This involved stacking a number of thick plates and rolling them, increasing the number stacked as the plates got thinner with each consecutive roll, ending up with sixteen plates stacked together going through the rollers. This method has the advantage of not requiring a particularly high precision on the rollers, and prevented heat loss from the metal.

Analytical Procedures

Metallurgical examination and Microhardness testing

Samples were mounted in thermosetting phenolic resin so as to allow two sections parallel to the two edges of the sheet, to be examined. The samples were ground using abrasive papers then polished with one micron diamond paste, in the standard metallurgical manner. Some difficulty was encountered removing small scratches from the surface of the samples due to the presence of hard slag/corrosion products within a soft iron matrix, and some scratching was not removed.

Examination was carried out using a reflected light microscope, samples were examined both unetched and after etching in Nital (nitric acid in alcohol). An estimation of the total percentage of inclusions in the sample was made. These inclusions were first supposed to be slag, but at a higher magnification, most were identified as corrosion by the roughness of their edges (plate 1). In all samples these corrosion/slag inclusions were present in long 'stringers' running parallel to one edge of the sample (plate 2). These 'stringers' of slag would have been elongated when the metal was rolled, whilst the corrosion occurred later, during the life of the material. This rolling was carried out at a relatively high temperature, with the slag was in semi-liquid form as the 'stringers' were not fragmented, as would be expected with low temperature or cold rolling.

When etched the samples all proved to be a very pure iron, no carbon containing phases were present, only ferrite grains (plate 3). Some of these grains showed elongation along the line of rolling, particularly in the sample from Norbury Park. Grain size was measured using a ASTM graticule (see table 1). Laminations of tinning were identified along both edges of the Bedford Square sample (plate 4).

Microhardness was determined using a Shimadzu microhardness tester, giving hardness values on the Vickers scale (H_v). Harnesses were taken from sound metal areas at five random points within each sample, and a mean microhardness was calculated. (see table 1)

Each sample's thickness was measured using a micrometer. A number of measurements were taken, and a range of thickness is quoted on table 1.

Chemical micro-analysis

Chemical analysis of the metal, and inclusions was carried out with an energy dispersive X-ray analyser (EDX) attached to a scanning electron microscope (SEM). Samples were polished to a flat surface, but not coated in carbon as the samples were sufficiently conductive to allow analysis to be performed.

Two types of analysis was carried out, bulk analysis of clean (i.e. inclusion free) metal areas from each sample, and analysis of five slag inclusions from each sample. All analysis was carried out at a voltage of 25kV and a current of 1.5nA.

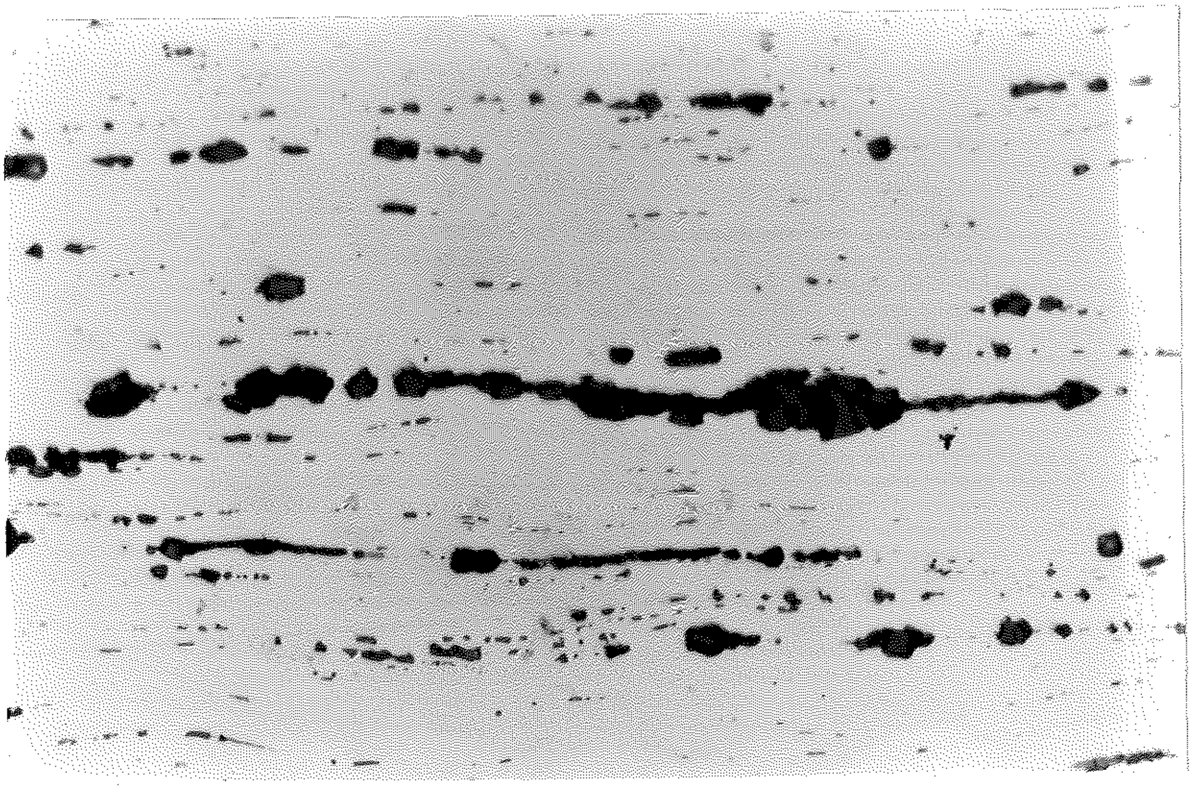

Plate 1: Corrosion areas in fireplate. Unetched, 500x magnification, Quarry Bank Mill, Styal.

Plate 2: 'Stringers' produced by rolling. Etched, 250x magnification, Bedford Square.

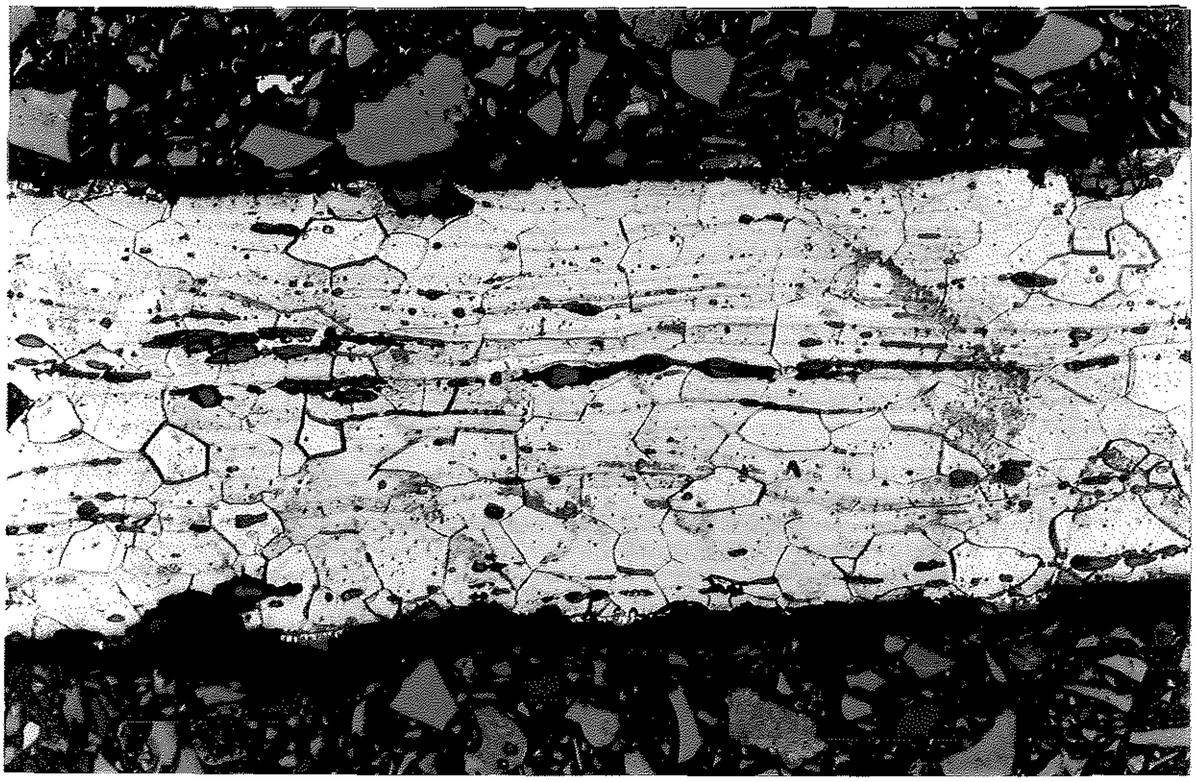

Plate 3: Ferrite grains. Etched, 250x magnification, Norbury Park.

Plate 4: Tinning (bright zone centre of image; mounting resin above, iron below). Etched, 500x magnification, Bedford Square.

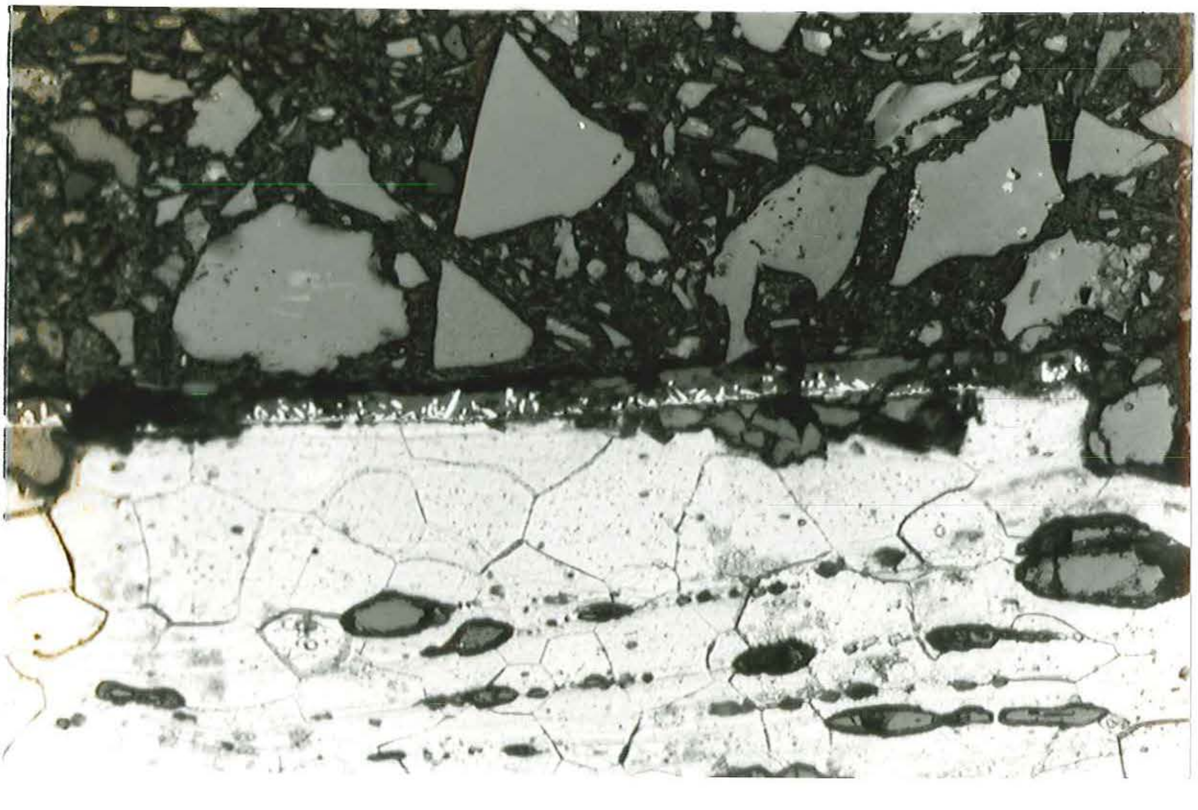

Table 1: Metallographic, microhardness and slag inclusion composition data for fireplates (n.d. = not detected) (see p9 for notes)

sample	provenance	date	grain size (ASTM)	% inclusions	sheet thickness (mm)	Hv	Inclusion size (µm)	% Na_2O	% Al_2O_3	% SiO_2	% P_2O_5	% S	% K_2O	% Cl	% CaO	% TiO_2	% MnO	% FeO	% NiO
960003	Quarry Bank	1796?	5	3	0.45-0.55	187.2	10x2	0.17	1.10	11.21	0.50	n.d.	0.15	n.d.	0.17	0.38	5.67	80.48	0.41
960003							10x10	0.18	0.56	12.69	5.90	0.47	0.09	n.d.	0.10	0.26	4.26	75.56	n.d.
960003							6x6	0.30	0.89	13.77	6.39	0.45	n.d.	n.d.	0.16	0.35	5.74	71.97	0.22
960003							10x2	0.33	0.77	11.15	5.62	n.d.	0.05	n.d.	0.08	0.16	4.12	77.67	n.d.
960003							10x6	0.21	2.19	24.37	0.17	0.38	0.31	n.d.	0.38	0.85	12.68	58.72	n.d.
mean								0.24	1.10	14.64	3.72			n.d.	0.18	0.40	6.49	72.88	
960004	Portsmouth	1782	4	10	0.30-0.45	190.7	16x6	0.48	0.49	12.54	1.67	n.d.	0.28	n.d.	2.05	0.12	0.57	82.31	n.d.
960004							12x8	0.44	0.59	16.65	2.23	n.d.	0.20	n.d.	1.99	0.04	0.53	77.54	0.31
960004							10x8	0.40	0.22	4.15	8.08	n.d.	0.04	n.d.	1.20	n.d.	n.d.	86.04	0.30
960004							6x4	0.26	0.15	4.47	9.83	n.d.	0.02	n.d.	0.45	n.d.	1.37	83.38	0.30
960004							16x5	0.34	0.28	12.92	5.93	n.d.	0.07	n.d.	0.52	0.04	0.14	79.78	0.35
mean								0.38	0.35	10.15	5.55	n.d.	0.12	n.d.	1.24		0.52	81.81	
960002	Bedford Sq.	1780	6	5	0.30-0.35	179.6	10x5	0.57	0.37	15.96	5.77	n.d.	0.23	n.d.	0.63	n.d.	0.40	76.55	0.31
960002							10x5	0.51	0.39	8.41	6.41	0.12	0.19	n.d.	0.87	0.04	0.21	83.23	0.32
960002							6x4	0.15	0.09	10.06	0.28	n.d.	n.d.	n.d.	0.08	0.05	n.d.	89.07	0.30
960002							15x6	*0.02*	*0.10*	*0.30*	*7.02*	*0.24*	*n.d.*	*n.d.*	*n.d.*	*n.d.*	*n.d.*	*91.86*	*0.35*
960002							8x8	0.21	0.22	10.58	1.37	0.12	0.05	n.d.	0.29	n.d.	n.d.	86.99	0.32
mean								0.29	0.23	9.06	4.17	0.11		n.d.		n.d.		85.54	0.32
950012	Norbury Park	1790s	5	2	0.30-0.45	195.4	12x6	0.27	1.00	6.54	16.61	0.30	0.10	n.d.	0.34	0.07	1.14	73.64	0.33
950012							18x6	0.30	0.38	4.62	8.39	0.23	0.09	n.d.	0.15	0.05	0.75	85.12	0.30
950012							8x8	0.41	0.26	5.87	10.82	n.d.	0.03	n.d.	0.28	0.08	0.62	81.66	0.31
950012							12x6	0.55	0.33	8.07	12.40	n.d.	0.10	n.d.	0.22	n.d.	0.61	77.98	0.29
950012							9x7	0.35	1.41	7.29	16.17	n.d.	0.91	n.d.	3.64	n.d.	0.87	70.20	0.24
mean								0.38	0.68	6.48	12.88		0.25	n.d.	0.93	n.d.	0.80	77.72	0.29

Bulk analysis of metal areas

Although EDX analysis systems are not sufficiently sensitive to accurately quantify the low levels of most elements within the metallic iron, the technique was adequate to identify levels of phosphorus and sulphur which would be expected (>0.1wt%) if the iron were to be classified as phosphoric or had been smelted/ fined with coke. A long preset time of 500 seconds was used to improve the limits of detection. Few elements were detected above the minimum levels of detection suggested by the software. Significant data within Table 2 are the 0.11wt% phosphorus in sample 950012 and the uniformly low sulphur contents (a piece of modern tin-plate gave a mean value of 0.11wt% S).

Table 2: Bulk analysis of clean iron areas by SEM EDX (each sample single analysis).

Sample	**percent of element present**							
	Si	P	S	Cl	Ti	Mn	Fe	Ni
950012	0.04	0.11	n.d.	0.04	n.d.	n.d.	99.25	0.50
960002	0.04	0.06	n.d.	n.d.	0.01	n.d.	99.39	0.44
960003	0.05	0.07	n.d.	0.03	n.d.	n.d.	99.45	0.36
960004	0.07	0.03	0.01	0.06	0.01	n.d.	99.33	0.42

n.d. = not detected.

Chemical analysis of slag inclusions by SEM EDX

Analysis of slag inclusions proved difficult for a number of reasons. All of the large inclusions visible under the microscope had become surrounded by large amounts of corrosion, so much so that it was impossible to find any uncontaminated areas for analysis. These large inclusions analysed as almost pure iron oxide. Very small slag inclusions which had not been affected by corrosion were identified by their appearance when the sample was viewed in back-scattered electron (bse) mode. Corrosion inclusions also had rough jagged edges, slag inclusions were more regular and blocky in appearance. All slag inclusions were less then 20 x 20 microns in dimension, forcing analysis to be carried out at over 10k magnification. Due to their small size it is quite possible that the electron beam partially penetrated through the slag into the iron, giving falsely high iron levels. However un-normalised results were encouragingly consistent, with most totals within 10% of 100%.

Table 1 shows the results of the slag analysis. Data has been normalised and for those compounds normally present as oxides, weight percentages were calculated using the following stoichiometry: Na_2O, Al_2O_3, SiO_2, P_2O_5, K_2O, CaO, TiO_2, MnO, FeO and NiO. The preset count time was 50 seconds. Means have only bean calculated where all five analysis of a sample detected the particular element. The analysis in italics from sample 960002 seems to be, from its very low silica level, more corrosion then slag.

Discussion

The analysis of the slag inclusions show that the iron was not produced by the bloomery process. Bloomery slag typically has a fayalitic composition of around 60:40 iron oxide (wustite) to silica, the fireplate iron had much lower levels, 6-15wt% silica. The iron therefore must have originally been produced in a blast furnace, and the inclusions derive from some form of subsequent refining process. All samples were hot rolled, shown by the way the inclusions are strung out and not broken up.

Analysis of the metal and slag inclusions of the Norbury Park sample showed that it had significantly higher level of phosphorus than the other samples. Phosphorus, originating from the ore, has the effect of increasing the hardness of the metal, and the effect is perhaps reflected by the Norbury Park sample having the highest microhardness value. However, the phosphorus level was not high enough to show increased grain size, and phosphorus 'ghosting' was not visible under the microscope.

Chemical analysis of the inclusions and metal showed that all samples are low in sulphur, suggesting that charcoal was used for fuel in both the smelting and fining processes. Documentary evidence suggests that charcoal iron was preferred for the production of thin iron plate. It has been put forward that in South Wales, an area rich in coal deposits, charcoal smelting survived for this reason.[16] However, without having any analyses of known charcoal fined iron for comparison this distinction between coke and charcoal smelting cannot be definitely made.

It has been suggested that fining and puddling slags differ in their levels of alkali (potash and soda)[17]. Slag from the finery, which was in contact with the fuel, would be expected to have absorbed significant levels of alkalis from fuel ash. By contrast the reverberatory furnace, used in the puddling process, kept the fuel separate from the slag and little contribution from the fuel ash would be expected.

The puddling process was not patented until 1784, so historically, the samples that are securely dated to the early 1780s are unlikely to have been produced by this method, even if some features of the method slightly preceded the patent. However, the late eighteenth century was a period of great advances in this particular field; as has been noted above the 'stamping and potting' method, a kind of half way house between fining and puddling, had been in use since the 1760s. This method first partly refined the metal in a coal finery hearth and then granulated and heated it in oxidising conditions in a reverberatory furnace[18]. No published analyses have been linked to this process. However, if as recorded, alkali fluxes were added to remove the sulphur, then both sulphur and these fluxes presumably formed part of any slag present at the time of solidification. Iron from the stamping and potting method would therefore be expected to contain slag inclusions with high levels of both sulphur and alkalis.

Analysis of the inclusions in the fireplate samples revealed very low concentrations of alkali fuel ash (potash and soda). This is inconsistent with individual published finery slag compositions, and suggested compositional ranges for the finery process[19]. Neither does the composition match that predicted for the stamping and potting process. The restricted range of elements present is much closer to that expected for the puddling process, however this is in conflict with the dating evidence of the objects and the documented history of iron puddling.

It is possible that the few finery slag analyses published to date, have given an over-narrow impression of the range of compositions which might be expected. More bulk slag from securely contexted archaeological excavation needs to be investigated. One sample, from Wortley Top Forge near Sheffield, recently investigated at the Ancient Monuments Laboratory gave an analysis much more in line with the fireplate inclusion data.

Table 3: Bulk analysis of finery slag from Wortley Top Forge (wt%)

Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	S	K_2O	CaO	TiO_2	MnO	FeO
0.6	n.d.	1.1	13.2	2.8	0.1	n.d.	0.9	0.4	2.8	79.3

Conclusions

It remains unclear what refining process was used to produce this iron. Little work has been done in identifying the technologies used in iron production of this period from the artefacts themselves. It is hoped that future work to carried out under the Ancient Monuments Laboratory's 'Historical Ironwork' project may help to shed light on this area.

It is probable, from the low level of sulphur in the metal and slag, that the iron was not smelted using coke as a fuel. However, this is not definite as it has not been possible to compare our results with samples of known technological origin, and any sulphur introduced by a coke fuel could have been removed later by an unidentified process.

What can be said about the fireplates is the they were produced from iron smelted in a blast furnace then refined and hot rolled. The iron contained no carbon, which was probably desirable as in this form iron is at its most malleable. This would aid rolling of the sheets, and the fitting of the fireplate into the building, which involved bending and nailing.

The Norbury Park sample, with high phosphorous levels, is distinctive from the other samples. Phosphorous originates from the ore, so this may indicate that this sample has a different origin from the others[20].

It has been noted that the fireplates may be connected with the tin-plate industry. The Bedford Square sample had tinned surfaces, and this would act to inhibit corrosion. It is possible that the sheets were bought, tinned or un-tinned from tin-plate manufactures. As sheet was already being made by these companies it would seem logical for Hartley to tap this ready source.

Analysis of the fireplates was problematic due to penetration of corrosion through their thin section. This resulted in analysis being carried out on very small slag inclusions, which is not ideal. It is unlikely that any further analysis of material of this kind will help in answering the questions this study has brought up.

Acknowledgements

We would like to thank Frank Kelsall for first bringing in a sample of fireplate, and providing the results of his personal research on the subject. We would also like to thank Josselin Hill of Quarry Bank Mill, Mark Meatcher of Portsmouth Naval Base Property Trust, and Treve Rosoman of English Heritage for providing samples.

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18. See note 12.

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20. Frank Kelsall notes that a list of David Hartley's papers compiled by the Berkshire Record Office suggests that plates were made at several places in south Wales, the south-west and Yorkshire including Pontypool, Bristol and Cleobury Mortimer. The papers have now been withdrawn from public access.