The refining process, part 1: a review of its origins and development

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ABSTRACT: Refining was adopted early in 1791 as an initial step for the conversion of coke-smelted cast iron into wrought iron, following the failure of Cort's puddling process to produce good iron directly from grey coke pig. Refining entailed remelting the grey iron under strongly oxidising conditions to produce a white cast iron, known as finers metal, as feedstock for puddling. This paper presents a critical review of the history of this process in bulk ironmaking in Britain, its context amongst 18th-century conversion techniques, the circumstances of its adoption and its purpose, and its development in the light of new archaeometallurgical analyses from excavation of the 1830s-1870s refinery building of the Ynysfach Ironworks, Merthyr Tydfil. Dephosphorisation may have been a major function of refining and it is argued that preventing the reversion of phosphorus from slag to iron was the major reason for the necessity for multi-stage conversion techniques in the 18th and early 19th centuries.

Introduction

Excavations undertaken by the Glamorgan-Gwent Archaeological Trust in 2011 in advance of development at The College Merthyr Tydfil (to be published in full elsewhere) revealed part of the Ynysfach Ironworks, built between 1801 and 1804 to supplement the iron smelting capacity at Cyfarthfa. Amongst various elements of the works uncovered, a refinery building was uncovered, the first phase of which was built in *c*1836. The origins and chemical function of refining are obscure and much current understanding is based on descriptions of mid-19th-century forms of the process (Overman 1851; Phillips 1852; Truran 1855; Percy 1864). This paper reviews the earlier 18th-century processes, the developments at Cyfarthfa in the 1780s and discusses the rich contemporary record of refining, including the many non-English language accounts (de Bonnard 1804-5; Svedenstierna 1804 (translated as Dellow 1973); O'Reilly 1805; Hasenftaz 1812; Dufrénoy and Élie De Beaumont 1827; Coste and Perdonnet 1830; Dufrénoy *et al* 1837), better to understand the context and significance of the Ynysfach refinery.

There have been many previous studies (*eg* Birch 1967, 30-41; Hyde, 1974; Mott 1983; Hayman 2003; 2004; King 2011; 2015) of the 18th-century development of processes to convert coke-smelted pig to bar iron, but they have often been hampered by over-reliance on the broadly-worded patents and technological terms with changing meanings.

The processes were complicated and multi-stage (Fig 1), often using air furnaces and clay pots to protect the iron from contaminants (particularly sulphur) and to provide a flux. Cort's puddling process (patented 1784 and closely related to his 1783 patent for rolling iron in grooved rollers) promised a simpler, single-step solution, that would both be efficient of time and fuel, but also offered the ironmasters a means to break the perceived stranglehold on forges by the artisans of the 'old forge dynasties' (Evans and Rydén 2007, 260). Initial trials went well, but it soon became apparent that puddling produced poor iron from coke-pig. One of the early licensees of Cort's processes was Richard Crawshay of Cyfarthfa Ironworks, Merthyr Tydfil, in 1787. His adoption of puddling was beset by quality issues, but a

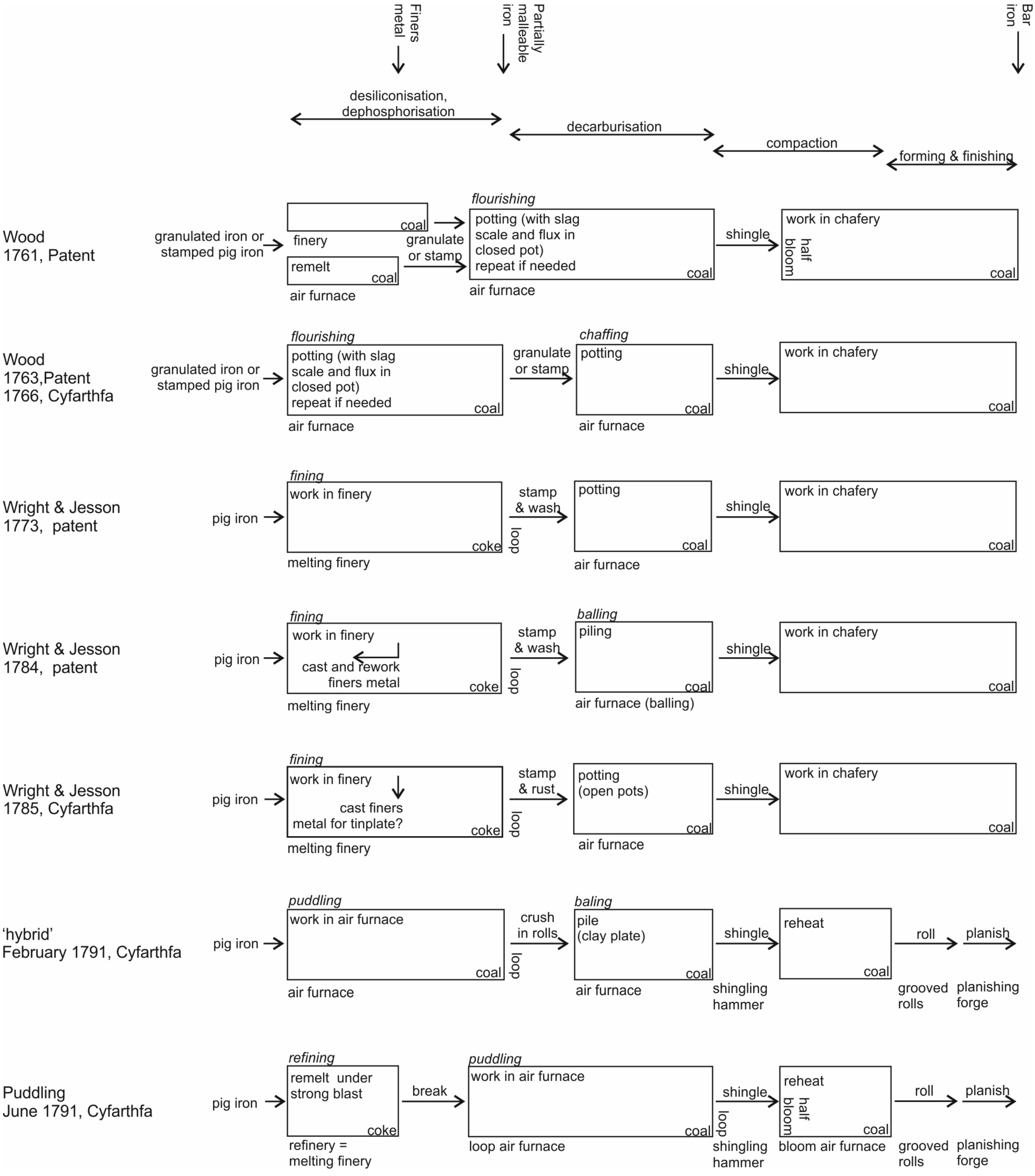

Figure 1: Schematic explanation of the process flow for the named major conversion techniques for coke pig of the 18th century, as discussed in the text. Where appropriate, each box covers a process which is described; its name is above the box, the plant below it, the product/semi-product vertically to the right and the fuel lower right inside the box.

breakthrough appears to have been made early in 1791, after much experimentation, with the addition of a refining stage. Refining involved remelting the pig under an oxidising blast, before tapping and quenching the iron to form a thin sheet of white cast iron, finers metal, that could be decarburised successfully in the puddling furnace. The subsequent success of puddling allowed a meteoric expansion of the iron industry: S Wales smelted 12,000 tons of iron in 1788, 34,000 in 1796 and over 78,000 tons in 1805 (Evans and Rydén 2007, 271-72).

Refineries largely became redundant in bulk ironmaking with the introduction of the puddling variant known as 'pig boiling' from the 1830s onwards, but survived at Cyfarthfa until its closure for conversion to steelmaking in 1879; elsewhere, some persisted in use into the 20th century (Lowmoor Co 1906).

Early in the 19th century, refineries were also adopted as part of the 'South Wales Method' for converting coke smelted iron for the tinplate industry (Percy 1864, 581–91), possibly, at least in part, because of technological expertise transferred into the industry from Cyfarthfa by Watkin George. The source of blackplate before this date had been almost entirely charcoal smelted iron. The use of refining within the tinplate industry became redundant as iron was replaced by steel from the 1870s onwards. The development of refining within the tinplate industry is not discussed in detail in this article.

Conversion before puddling

Rising demand for bar iron during the 18th century drove the development of techniques for the conversion of coke-smelted pig (dominantly grey cast iron), a requirement that proved more difficult than the conversion of charcoal-smelted pig in a finery forge had been.

Conversion requires the oxidation of several elements that are reduced into the metal during smelting in a blast furnace: principally silicon, phosphorus and carbon. Coke smelted iron contains more silicon than charcoal iron, because of the more siliceous nature of the smelting system when using silica-rich coke, rather than low-silica charcoal. Phosphorus will be enhanced in many of pig irons produced from coal measures ironstone – a natural choice of ore when smelting using coke. Both silicon and phosphorus have a strong influence on the system, with the eutectic composition at 4.3% carbon equivalent (CE; where CE = carbon% + 1/3 silicon% + 1/3 phosphorus%).

Williams (2015) argued that the easier introduction of oxygen, by rabbling, into a pasty melted white iron rather than a 'fully fluid' melted grey iron, was the reason behind the relative ease of conversion of white cast iron compared with grey. However, the actual crystalline form, whether grey or white, of the iron before being melted, is not really the determinant of the physical state of the iron at just below its liquidus, but rather the composition of the iron with respect to the eutectic composition at 4.3% carbon equivalent (CE; where CE = carbon% + 1/3silicon% + 1/3phosphorus%). The problem with iron smelted with coke from coal measures ironstones was that both silicon and phosphorus would tend to be in elevated concentrations, producing pig iron with a very high CE, well above the eutectic composition. The desire to use coal as fuel during conversion added to the problems, for it provided an extra source of potential contaminants, particularly sulphur.

Between 1720 and 1790 a variety of processes were tried, many drawn from the pool of technologies employed in the recycling of iron (Hayman 2004), in developments both practical and impractical, punctuated by the issuing of patents (*eg* King 2015). Most bar iron was, however, produced from charcoal pig until well after the middle of the 18th century.

There were three main approaches:
- the manipulation of molten iron under oxidising conditions within an open hearth (building on the existing charcoal finery),
- use of a reverberatory furnace with the iron held inside ceramic pots, typically with fluxes including slag, scale and kelp lye (building on the potting process for recycling),
- similar manipulation, but within a reverberatory (air) furnace, usually on a bed of sand (building on the balling furnace).

None could effect conversion to good quality bar iron on its own and therefore various multi-stage techniques emerged.

Finery processes

The existing Walloon finery techniques that were employed to convert charcoal-smelted pig iron were inadequate for most coke-smelted pig. The Coalbrookdale works produced some bar iron from low-phosphorus coke-smelted pig using charcoal fineries, from as early as 1720 (Flinn 1961-62, 69) and Charles Wood observed a coke-fuelled finery for producing wrought iron for stampers in Coalbrookdale in 1754 (Gross 2001, 223), but, in general, single-stage finery processes proved inadequate. Even multi-step finery processes generally failed to convert coke-smelted pig, unless the process entailed the use of 'cleaner' (but more expensive) charcoal hearths.

Two patents for hearth-based processes (to John Roebuck in 1763 and to John Cockshutt in 1771) are often quoted, but influenced the mainstream conversion of iron very little. That to Roebuck (No 780) was for a two-stage process, first melting the pig iron in a bellows-blown, coal-fuelled finery, where it was worked to 'bring it to nature', and then breaking the iron and heating it again in a bellows-blown 'hollow pit coal fire' until reduced to a 'loop'. Cockshutt's patent (No 988) was for a process involving first heating pig almost to the 'point of melting' in a coke- or coal-fired hearth and then fining the iron in a charcoal finery. Percy (1864) saw in the structural details of the finery presented in the patent (a finery formed of metal plates, open on two or more sides, with multiple tuyères) aspects employed in the later refinery.

Stampering

The dominant conversion techniques of the second half of the 18th century were varieties of 'potting and stamping' or 'stampering' (Hyde 1974). Stampering processes involved multiple steps, typically starting with conversion of the raw pig to either a near-malleable form (known as bringing the iron to nature) or to finers metal (a desiliconised cast iron), either in an air furnace in pots (typical of the earlier versions of the technique patented by John and Charles Wood) or in a finery (in later versions patented by John Wright and Richard Jesson). This semi-product was then broken up (stamped) and the fragments placed in clay pots (or on ceramic or stone plates), which were then heated in an air furnace until the fragments fused (piling, chaffing or balling). The resultant ball would then be shingled under a hammer to bar iron.

The Woods' technique (covered by two patents: No 759 of 18 May 1761 to John Wood and No 794 of 26 November 1763 to John Wood and Charles Wood) had origins in Charles Wood's recycling process, described by Angerstein in 1754 (Berg and Berg 2001, 388). The 1761 patent included variants of the first part of the process (known as flourishing), depending on the raw materials and the desired quality of the product, including bringing the cast iron to a near-malleable state in a 'common finery' with coal, melting the cast iron in an air furnace and then granulating it, or casting the iron into thin plates for stamping. The second part of the process was for the flourished iron to be heated with slag, scale and flux in closed pots in an air furnace to make the iron malleable. If the raw iron was brittle, or the coal particularly sulphurous, then malleable iron could also be added to the pots . The 1763 patent differed in that the material was prepared by stamping or granulation, then flourished in closed pots with fluxes (including lee of kelp) in an air furnace, then stamped again (repeating the flourishing if necessary) before a reprocessing in sealed pots in the air furnace (known as chaffing), and finally working to bar under the hammer as before.

Charles Wood's diary (Gross 2001, 11 April 1766 to September 1766 and 11 April 1767 to May 1767) described the implementation of his process at Cyfarthfa Ironworks for Anthony Bacon. At the Lower Works he built a 'flourishing house' with a granulating cistern and air furnaces for flourishing, a forge with shingling furnaces, facilities for making the pots, a mixing room, and waterwheels powering two stamps, a chafery, two hammers and a clay mill. It was proposed that the blast furnace would produce 18 tons of iron per week, unusually supplying granulated metal (formed by tapping the furnace into water; Gross 2001, 145; Mushet 1840, 12) to four flourishing furnaces and two shingling furnaces, all using coal or coke (30 August 1766; Gross 2001, 137). The ease with which one of the flourishing furnaces was reconfigured for casting furnace components (Gross 2001, 189), suggests it had been built for tapping metal, which the location of the granulating cistern in the flourishing house, rather than the stamping house (Gross 2001, 182), would appear to confirm. A description of Cyfarthfa process was given in a letter of 1770 (Birch 1967, 31):

> 'They let the metal run from the furnace into water to granulate it, and what is not small enough is pounded under stampers … it is granulated to be made malleable with raw coal, For this purpose a number of crucibles or pots about 6 inches deep and a foot wide are prepared, these vessels are filled with small iron … the pots are put in an oven or reverberatory furnace, and when the metal begins to run, break. The breaking of the pots is the signal to take it out … it is now cooled and granulated, and the operation repeated a second time when it is taken to the hammer'.

A second variant (patent No 1054 of 1773, to John Wright and Richard Jesson) entailed heating cast iron with scale and slag in a bellows-blown finery using coal or coke. The malleable product was beaten to plates under a stamp, and the plates themselves broken by a second stamp. The fragments were washed and heated in closed pots in a reverberatory furnace before shingling. A revised patent (No 1396 of 1784) described piling the flattened cakes and reheating them without the use of pots. Insight into the implementation may be gained from detailed contemporary descriptions by visitors to works, including by Marchant de la Houlière of West Bromwich works (1775; Mott 1983, 12), Charles Blagden and Henry Cavendish of Willey (1785; MacCormmach 2014, 246) and the La Rochefoucauld brothers of Coalbrookdale (1785; Scarfe 1995, 98). The plant for the two stages of this process correspond to the 'melting finery' and 'balling furnace' of the forge list of *c*1790 (King 2011). Both the patents and the descriptions of the process by travellers, demonstrate that the semi-product of a melting finery was not a molten cast iron, but solid and malleable.

Blagden and Cavendish also described Cyfarthfa forge in 1785 (MacCormmach 2014, 240), by which date Cyfarthfa, too, was operating the Wright and Jesson process, rather than the Woods':

> 'The pigs are first melted down in a hearth and stirred till they become a lump, as in the charcoal works; they are then put under the hammer hot, and reduced to flat plates in general about ½ an inch thick, of an irregular shape, and rough cracked irregular edges. These plates are then broken under a hammer into pretty large lumps, which are laid in a heap, and kept moist by water dropping upon them. We found them blackish on the outside, with spots of rust, and at the fractures of a granulated texture bright light colours, but also in places much rusted. The small stuff that was collected in the hearth, they washed with water, and then laid it by separate. Afterwards the broke lumps are put into cylindrical pots, made of refractory clay near a foot deep, with a certain proportion of the washed small stuff, which served as a flux. There is no other addition, and the surface is not covered. The heat is not urged for the metal to melt, but so that the different pieces may be welded together, which happens by their sinking down into a sort of mass, and contract so as to leave the sides of the pot, which usually cracks and is easily separated, This mass is then formed into a half-bloom, a bloom, &c as in the common forges.'

The intermediate rusting stage followed by washing or scouring, also used in the preparation of iron rod for wire drawing, is usually interpreted as a desulphurizing process. Blagden and Cavendish compared the 'hearth' of the first stage with those of the charcoal fineries of Pentyrch Ironworks and Melingriffith Forge they had just visited, confirming that an open finery hearth, not an air furnace, was used, support for which also comes from a letter from John Cooke of Doncaster to Henry Cort on 21 December 1788 (Mott 1983, 56):

> 'I am informed that, at Cyfarthfa, one Forge is employed in your method, the other in the Shropshire mode of Fineries with Coak and Stamping and Balling as it is there called and that they cannot decide on the advantage of one over the other.'

King (2011, 110) identified the 'melting finery', which appears on late 18th-century lists of plant, as that for the first stage of the Wright and Jesson process, which normally produced a malleable semi-product for stamping (see above). However, there is evidence that their use commonly differed in practice from that outlined in the patent. Cyfarthfa sold 2 tons of 'finers metal' to Melingriffith Forge in 1783-4 (Evans 2001, 420), suggesting that the fineries could produce cast finers metal as well as the malleable product described in 1785. A letter from James Cockshutt to William Cort in 1812 (King 2011, 115) also indicated that finers sometimes repeatedly 'ran-out' iron from the melting finery as a part of the finery process.

Manipulative air furnace process

The oxidation reactions of the finery may also be achieved in a reverberatory furnace. Manipulation was a feature of early attempts to use such furnaces for smelting (Flinn 1961-62) as well for the recycling of scrap iron in a reverberatory furnace known as 'buzzing' (Hayman 2004, 117).

Patent No 815 (1766) to Thomas and George Cranage was thin on detail, but the process as described by Chisholm in 1768 (Mott 1983; Hayman 2004) was two-stage, with both stages in air furnaces: first, using a mixture of pig and scrap on a sand bottom, until 'run together irregular masses; and become less fusible', followed by a second stronger heating, when it was 'continually moved and turned'. Charles Wood (Gross 2001, 72-73) commented that the Cranage process was similar to one patented by Roger Woodhouse (for Thomas Tomkins) in 1724 (Flinn 1961-62; King 2015). The Cranage process does not appear to have been a commercial success.

Peter Onions took out a patent in September 1783 (No 1370) for a single-stage process in an air furnace with a short stack and supplementary forced draught. The furnace could be fed, optionally, by pre-melted metal and an opening allowed the furnace to draw fresh, cold, air onto the iron (Percy 1864, 637-39; Mott 1983, 13-15). The idea and practice were clearly very similar to those of Cort (despite the protestations of Cort's biographer, Mott 1983). Onions failed, however, to produce good iron in trials at Dowlais and in Shropshire. Following his move to Pentyrch, Onions fared better and Crawshay favourably compared Onions' blooms with Cockshutt's from Cyfarthfa (Evans 1990, 29, 35), even suggesting variations to the technique at Cyfarthfa based on Onions' process (22 May 1788, 30 May 1788; Evans 1990, 16, 17). King (2011, 115) speculated that Onions may have contributed to solving the problems with puddling, but alternatively, however, Pentyrch Ironworks was able to exploit the Lesser Garth haematite (low phosphorus) ores, making Onions' task much simpler.

Henry Cort's 1784 puddling process was ideally a single-stage process although the patent, No 1420, actually allowed for multi-stage variants. It involved the manipulation of iron, including pig, scrap cast iron, recycled process waste and fragments of wrought iron (Cort's own use was mainly for the recycling of scrap), melted in a reverberatory furnace with a sand floor and tall chimney. The half blooms produced were to be rolled using the grooved rollers of Cort's earlier patent (No 1351, 1783).

The introduction of puddling and refining

Following award of his patents, Cort ran demonstrations in late 1784 with a variety of pig irons (Mott 1983, 47-50; Anderson and Jones 2012, 704-11, 787-92, 866-73, 883-84). Samples of iron produced at the demonstrations were often cold-short (as described by James Watt, 6 June 1784; Anderson and Jones 2012, 710):

> 'The kind of iron you describe is known here by the emphatic name of rotten tough/ I have long known that almost any cold short Iron may be brought to \ that/ state, by rolling it very hot, or by drawing it across the anvil so as to spin the Crystals into threads; & by certain mechanical processes good Iron may be rendered Cold Short, nevertheless in neither of the cases the quality of the Iron is altered   The good Iron continues strong and the Cold Short is very weak. I look on Mr. Corts Iron as a Cold Short whose crystals are spun out by the rolling, and which is mixt with a large quantity of half metalled earth. It is tender to the file and soft to the hammer, rusts very readily, and ought never to be used where it is subjected to any strains as it is very weak, therefore unfit for Engine work Ship work etc but good for nails, because easily wrought, but there are nailers complain that it wastes more than the com^{n} cold short, I suppose because not so well freed from its cinder. Good Iron is hard under the hammer & stubborn to the chisel & file, breaks white, generally granulated, but the very best is fibrous & white like silver – I find I am getting into a dissertation on Iron, which I must shorten.'

The implication is that although the typical appearance of cold-short iron (in phosphoric iron with a low carbon content, the segregation of phosphorus to grain boundaries favours intergranular fracture, seen as large shiny crystal facets on a fracture; Wanhill *et al* 2007) was masked by the microstructural modification produced by rolling, cold-shortness manifested itself in final forged products.

Despite these issues specifically occurring in 'Mr Homfrays Welch Pig' puddled at a trial in Wednesbury (26 November 1784; Anderson & Jones 2012, 790-91, 869), Richard Crawshay become a licensee of Cort's process just three months after taking the lease of the Cyfarthfa works (1 May 1787). Following apparently satisfactory trials in June 1787, James Cockshutt (manager at Cyfarthfa) proposed building eight 'Corts' furnaces (to become the 'New' or 'Upper Forge') on the Boring Mill stream in September 1787 (Birch 1967, 40). Cort sent workers to Cyfarthfa to build the furnaces and to train staff. Initially, output went to Rotherhithe and elsewhere for rolling, but by March 1788 (Evans 1990, 10) Crawshay requested construction to start on the rolling plant, which became operational in autumn 1789.

Stampering continued (in the Lower Works) in parallel with the new process (the list of *c*1790, shows Cyfarthfa with 2 coke blast furnaces, 3 melting refineries,3 balling furnaces, 1 rolling mill and 8 Cort's furnaces; King 2011). Crawshay's letterbook of the period was peppered with complaints about quality (Evans 1990, 4, 6, 7, 14, 16, 25, 29, 30, 35, 40, 41, 42, 49, 54, 71) and by September 1790 Crawshay wrote (Evans 1990, 77) 'I fear we must give up puddling at last'. On 12 October Crawshay instructed Cockshutt to set up two new fineries in the Lower Works to increase the make of stamped metal (Evans 1990, 78) and on 14 October Crawshay reported to Wilkinson that puddling was suspended (Evans 1990, 79).

If puddling was proving problematic, the use of rolling found favour, not just for the production of bars, but as an alternative to stamping, and on 26 November 1790, Crawshay told Cockshutt to exchange the stamps in the lower works for rolls (Evans 1990, 84). Their use was described in Crawshay's letters, firstly to Count de Reden on 10 February 1791 (GwRO D2/162 f96):

> 'The term pudled is that we make in Air Furnaces instead of Fineries and lately we have much improved the method of crushing the Metal between Rollers, instead of drawing it immediately into a Bloom from the Air Furnace - 'tis true we increase the process & consume more Metal & Coals but the improved quality fully compensates for it …. Crushing with Rollers instead of Stamping will be generally practiced – they are more effective as to Speed & equality, every particle being crushed alike'

and in another a few weeks later to Baron Demidov (3 March 1791; Evans 1990, 95-96):

> 'we make use of Air Furnaces instead of Finerys, when the Metal is bro.^{t} into nature, instead of Hammers, we put it between a pair of Rolls, & crush it like a paste about ¾ in thick – then we break it into small pieces, pile up 60 to 80 lbs w.^{t} on a Cake of baked Clay, heat 20 of those piles at a time in an.^{R} Air Furnace, then shingle them under a Hammer of 1200 lbs w.^{t} fixed in

an Iron helve of 2 tons w.[t] The blooms thus finished is again heated in an Air Furnace & bro.[t] into a very handsome Bar by Groov'd Rollers … to make 'em straight & handsome, we planish 'em under a lighter Hammer'.

Although such complex combinations are not familiar in the light of the subsequent development of puddling, Cort's patent had described three ways in which the iron 'loops' from the puddling furnace might be treated:

- stamp the loop into plates, and reheat in another air furnace either with or without pots
- reheat the loops to welding heat in an air furnace and then shingle under a hammer to half blooms or slabs and pass to a chafery for working
- reheat as above, shingle to a size suitable for passing through the grooved rollers

What Cyfarthfa had implemented in late 1790, and was using to good effect in early 1791, was to crush the iron after puddling with rolls and then to ball (or pile) it in the manner of the second part of the Wright and Jesson stampering process, the air furnaces being used instead of melting fineries and rolls instead of stamps.

In the letter of 3 March 1791 quoted above, Crawshay also said he had made 'a simple discovery in the make of this usefull Metal', but would not elaborate. Crawshay's letter to Samuel Homfray (14 April 1791; Evans 1990, 98) also gave no details, but expressed delight with the improvement in the quality and appearance of the iron, but advised against taking out a patent, instead saying 'let us get into the habit of making as much & quietly as we can'.

Cockshutt reported details of the process operating on 14 June 1791: the pig iron was converted to finers metal, which fed the puddling furnaces ('loop air furnaces'). The loops were shingled under a hammer before reheating in the 'bloom air furnace' for rolling in grooved rollers, after which the bars were planished in the double forge. (Evans 1990, 107; GwRO D2/162 f104). The use of finers metal as feed for the puddling furnace had removed the need for crushing and piling after puddling; the loop could now be consolidated by shingling immediately. This, at last, was the implementation of puddling that would spread through British ironmaking so quickly. Although conventionally this is described as the introduction of an intermediate refining process before puddling, it is better interpreted as a switch from using puddling as a replacement of the first stage of the two-stage conversion process, to using it as a replacement for the second stage.

The 'New Fineries' (*ie* refineries) account in the Cyfarthfa ledger (GRO DCY-1, f104) shows expenditure for construction from May to June 1791 (with some further expenditure in October to December of the same year) and they were probably in use by June. The 'Stampt iron' account (GRO DCY-1 f452) showed around 800 tons of accounted for in the first half of 1791, but only the sale of old stock in the second half; there were no transactions on the 'Stampt iron' account for 1792 and it does not appear after 1793.

With the technical issues solved, Crawshay's complaints turned to a lack of productivity, which he addressed by dissolving the Cyfarthfa partnership (22 September 1791) and taking direct control; by 29 December 1791 (Evans 1990, 123) he was able to tell William Reynolds that he had 'at last overcome the Evils of pudling'.

The origin of refining

The circumstances surrounding the adoption of refining have remained obscure. King (2011, 115) discussed evidence linking the development to Penydarren Ironworks, and since that publication, further evidence has been recognised (King pers comm 2014) in an obituary to Joseph Firmstone in the *Staffordshire Advertiser* of 30 January 1830:

'Mr F. conceiving an idea by melting the pig before it was puddled would deprive it of some of its impurities, and thereby refine it, suggested the idea to Mr Samuel Homfray, who with his usual quickness instantly put it into practice, by merely melting pig iron in the finery (such as was then used for making a malleable iron), and running it out on a floor without any mould, grey as it was – (hence the names of running-out fire and refinery). This iron was puddled and the quality of the wrought iron was found much improved by it; and this was the first cause of iron being refined and led to the present much improved process.'

Firmstone is not known from industrial records when living in Merthyr Tydfil through the 1780s but parish records show he was still there on 11 June 1790 when two of his children were baptised; his next child was born on 29 November 1791 after his move to Staffordshire. It is therefore possible he was in Merthyr Tydfil at period of the developments in winter 1790/91.

The Homfray family had been involved with the trials of puddling from 1784, but Samuel Homfray became more directly involved through Crawshay (who bought much of the product of the Homfrays' Penydarren Ironworks in its early years). Cort won Homfray over to puddling after he was able successfully to puddle pig from a batch that he had observed fail to make usable iron by stamping at Penydarren in 1787 (Mott 1983, 54-55). Homfray appears to have experimented with puddling in early 1789 (Mott 1983, 55). Puddling furnaces were not reported at Penydarren in the *c*1790 list of works (King 2011), but by September 1790 puddling was in operation at Penydarren (Evans 1990). Following the improvements made early in 1791 by Crawshay and Homfray, apparently in concert (letter of 14 April 1791; Evans 1990, 98), output increased and Penydarren blooms (most likely puddled) worth £5084 13s 11d appeared in the Cyfarthfa accounts for June to August 1791 (GRO DCY-1 f17).

As detailed above, finers metal had been an intermediate material in the stampering processes, either explicitly as the semi-product from the first stage of Wood's 1761 patent or, transiently, in the occasional practice of finers to run-out metal before returning it to the finery during the first step of Wright and Jesson's process. In the former case, the metal was cast from a coal-fuelled air furnace and in the latter a coke-fuelled finery hearth. There is good evidence for the practice of running-out in the manufacture of blackplate in the early 19th century, and the evidence from the Melingriffith accounts cited above, may extend the documented use of finers metal for blackplate back into the 1780s. Finers metal would, therefore, have been well-known to the iron workers of the day, and must surely have presented itself as a potential solution to the problems of puddling. It seems possible that a desire to see Cort's patent implemented as a simple, single-stage process, plus the additional costs of using finers metal, may have been more of a barrier to the adoption of refining than any lack of recognition of possible solutions. As Hayman (2004) remarked, the 'importance of collective knowledge has been underestimated'; so perhaps the search for an individual instigator of refining is misplaced? Mott (1983, 69) has claimed that Cort himself was aware of the possibility in January 1789, when he produced calculations for Crawshay for using both finers metal and grey pig as feedstock for puddling, but it had been more expensive. The documents to which Mott was apparently referring (Weale MSS MS371-3, 202-203) are a subsequent compilation; part of the costings are given a date of 7 January 1789 (a comparison of costs at Cyfarthfa and Wilsontown Ironworks), and part allow, apparently, for pig to be prepared by refining before Cort's process. It is far from clear, however, that all the costings date from January 1789, and it is possible the costs with refined iron were derived from a later estimate.

The development of the refinery

The early refineries could produce either liquid or solid semi-product and were therefore not likely to have evolved far, if at all, from the melting finery as is indicated by a letter from Crawshay to Admiral Keith Stewart of 29 June 1791 (Evans 1990, 106):

> 'I don't think Shotting the Metal will do. 'twill fall to the bottom of the Finery before it receives the blast & will be difficult to raise into either a Loop or Fluid Metal – however it will be try'd & you shall hear the result'.

The morphology of the refinery was not recorded in detail until Rees' description of 1811, which still differed little, even then, from an 18th-century charcoal finery. The first published description of refining was written by de Bonnard (1804-5, 265-68) following his visit to Britain in 1803 travelling in the company of Svedenstierna (Dellow 1973, 52-53), whose description is similar:

> 'The method generally used today, is to submit the cast iron to a second melting in a hearth named a finery, quite similar to our refinery fires, but larger, and fuelled with coke. For this purpose, after the pig iron has been broken in pieces of 50-60 pounds, one or more of these pieces is placed on the coke, with which the hearth is filled, above the bellows blast. The material melts, and falls into the crucible, passing the tuyère where the wind continually burns almost all the carbon that it contains and where the slag cover then prevents it from being in contact with the fuel that could provide it again. New pieces of pig-iron are successively added over the coals, as the first melts, the crucible fills with metal, the supernatant dross is driven by the blast of the tuyères and flows naturally over the edges of the hearth.
>
> 'Every two hours or even more often, a hole that is at the bottom of the plate which forms the anterior wall of the furnace is opened, and the melt flows through channels that were prepared in the sand to receive it, and it moulds itself into pigs that are larger than those formed at the blast furnaces. They make two at each casting. This pig is called fine metal. Workers know they must make a white cast iron, by giving the pigs a broad and thin shape, and they sprinkle them with plenty of water to render their fracture as white as possible by sudden chilling.'

O'Reilly (1805) republished Bonnard's account with a gloss incorporating his own observations from a visit to Britain, probably also in 1803, and Hasenfratz (1812, 86-88) provided a description based largely on those by Bonnard and O'Reilly, but adding some production figures.

Rees (1811) provided the earliest comprehensive description of a refinery in English, which bears many similarities with Bonnard's, but marked differences to later descriptions:

> '… the first step in the process of decarbonization, according to the more common mode of operating, is to expose the iron in a furnace, called by some a refinery, but by others, to distinguish it from one hereafter to be described, as a run-out furnace. It consists of a vessel open at the top, embedded in stone or brick work, about two foot three inches long, two feet wide, and ten inches deep. This is generally, in part, constructed of cast iron; and when so made, has an outer case about two or three inches distant from the inner one, which is constantly supplied with a stream of cold water to prevent the apparatus from melting. The iron to be decarbonized is placed in this receptacle, and kept in a continual state of fusion for three of four hours by the aid of a coke fire, which is heaped to a considerable height above the level of the vessel, and extended proportionally on the hearth that surrounds it. The size of the hearth is mostly about three yards in length, from two to three wide, but is completely covered by the funnel of the overhanging chimney. Bellows of considerable size are employed to carry on the process; and the current of air which issues from them is directed immediately on the surface of the iron by one or more tuyères. These tuyères are double, like the case, and continually cooled by the application of the same means, When the decarbonisation is completed, the metal is let out of an opening in the side, which has to be kept close during the operation by a stopping of sand. It flows into a groove about 18 inches wide, and six or seven feet long, constructed of stone in the floor that surrounds the furnace.'

Rees also described other methods of conversion, including a variant of stampering employing an initial charcoal finery, which he stated was properly called a refinery as opposed to the run-out furnace that preceded puddling, but that these were 'species of furnace precisely similar'. Scrivenor (1841, 115) described the same process entailing refining in a charcoal-fuelled refinery, stamping, balling on a round stone and working in the chafery and also mentioned 'running-out' as an integral part of the work of the refinery. His description is reminiscent of a blend of 18th-century descriptions of charcoal forges with Wright and Jesson's process. Somewhat similarly, Percy (1864, 625) quoted S B Rogers on the origins of the refinery:

> ' "... The invention was a modification of the old charcoal running-out fires, in which the pigs were (a few at a time) melted, run out, and when set, thrown up on the fire again and remelted, two, three, and occasionally four times over, according to the quality of the pig-iron. This was, I think, done at Beaufort with coke, In Mr Latham's time." (About 1810.)'

It is likely Rees, Rogers and Scrivenor were referring to the use of running-out fires in the manufacture of blackplate. Since Rogers appears to mention the first decade of the 19th century and there is no other evidence for 18th-century charcoal running-out fires, it is likely that this process was an intermediate step in the introduction of coke pig into the tinplate industry, and was derived from, or shared a common ancestry with, rather than being the ancestor of, the refinery of bulk iron making. Percy (quoting E Rogers; 1864, 590) attributed the development of the South Wales Process (Percy 1864, 583-90) for fining coke pig for blackplate to Watkin George (formerly of Cyfarthfa Ironworks) at Pontypool Ironworks in about 1807, which suggests that he may have transferred the technology of the coke refinery from bulk ironmaking into the tinplate industry. This process used 'melting fineries' (an interesting application of this old name to a coke refinery) to produce liquid cast iron, which was run directly into the second stage, the charcoal fineries, from which the malleable iron was taken to be hammered into a slab, which was then broken into smaller pieces (stamped) and then finished by piling on an iron 'staff' in a coke-fuelled 'hollow fire'.

Rees (1814, plate 2 to accompany the text of Rees, 1811) illustrated a charcoal finery with a water cooled tuyère, but added that the side plates were also water cooled in the run-out furnace. His illustration of a finery hearth is comparable to Angerstein's of 1754 (Berg and Berg 2001, fig 154a), except that the latter does not have a water-cooled tuyère. The melting fineries observed by Blagden and Cavendish at Willey and at Bradley Furnace Forges in 1785 (MacCormmach 2014, 244) already possessed a water-cooled plate in the base, so the more advanced water blocks and water cooled tuyères of 1811 can probably be viewed as evolution, rather than revolution.

Thus in the two decades up until 1811, the coke refinery was probably morphologically similar to the coke-fuelled melting finery (itself little evolved from the charcoal finery), possessing a brick-built hearth with a cast iron 'crucible' (sometimes with water-cooling) set to one side, below multiple water-cooled tuyères and with a run-out floor of sand or stone, on which the iron would be quenched by water sprayed or poured onto it.

In contrast, by the mid-1820s, the refinery had taken on the essentials of its developed form, with a fully water-cooled, large rectangular hearth, a chimney supported on cast iron columns, tuyères commonly on more than one side of the hearth and, most significantly, an iron run-out trough (*eg* Dufréynot and Beaufort 1827, 467-69, 494-99 and plate 14, figs 10-14).

Numerous descriptions over the following four decades provide a history of the 'developed' refinery (Encyclopaedia Britannica 1824, plate 89; Pelouze 1827-8, 212-16; Coste and Perdonnet 1830, 101-33, plate 6; Herbert 1836, 764-66; Dufrénoy *et al* 1839, 14-37, plate 1) although some were not original and therefore not indicative of contemporary practice (Ure 1839, 1840 and 1843 and Phillips 1852, 278-82 were largely direct translations of Dufrénoy and Beaumont 1827). They are not directly significant for the understanding of its origin but provide background to the investigated residues of *c*1850-1878 from Ynysfach Ironworks (Young and Hart forthcoming). The early descriptions of iron running-out troughs gave the length as 10 feet (*eg* Dufrénoy and Beaufort 1827; Coste and Perdonnet 1830; Dufrénoy *et al* 1839 plate 1, figs 1 and 2; Ure 1843; Overman 1851). Later descriptions illustrate and describe longer troughs (20 feet Herbert 1836; 20 feet Rogers 1836; 15-20 feet Dufrénoy *et al* 1839; 30 feet Truran 1855, 1863 and 1865). The first mention of a water-filled cistern below the trough was by Herbert (1836; presumably but not certainly of brick) and they were later described by Overman (1851) Truran (1855, 1863, 1865) and Percy (1864). Truran (1855) described cast iron cisterns as 'now coming into general use'. The surviving iron cistern at Ynysfach Ironworks, in a bay constructed *c*1850, was 7.39m (24 feet 3 inches) in length (Young and Hart forthcoming).

Contemporary understanding of refining

Early interpretations generally inferred a decarburising role, for instance those of de Bonnard (1804-5, 265-68) and Dufrénoy and Élie de Beaumont (1827, 496-97), who also provided the first description of refinery slags:

> 'The slags are black, a bit metallic, often fibrous and crystalline, but much less so than those from the previous operations. These slags are produced only by those that are contained within the iron subjected to this operation, and the slagging of those earths which are components of coal. Sometimes, when the pig iron is of poor quality, there is a slight addition of limestone.'

They sent a sample for analysis by Pierre Berthier (Professor of Assaying and the chief of the laboratory at the École des Mines in Paris), on which their commentary was decades in advance of British authors:

> 'A slag coming from a refinery in the Dudley area has been analysed by M. Berthier, with the following result:

Silica	27.6%
Protoxide of iron	61.2%
Alumina	4%
Phosphoric acid	7.2%
	100%

> It will be observed that the slag is very analogous in composition with slag ordinary forges, but that they have most remarkably the existence of phosphoric acid in considerable proportion, a property which had been doubted by some people, including Mr. Jefstroem of Fahlun. This analysis shows how useful, especially for the treatment of phosphatic ore, as are generally those of the coalfields, is this operation which completes the smelting.'

Early British accounts of the refinery make no reference to phosphorus but, bedevilled by confusion over the relative carbon contents of grey and white cast iron, describe a decarburising role. For instance Rees (1811) wrote:

> 'The total quantity of carbon which the iron contains is not estimated at more than 1/25th; and yet the approach of it to the pure state, or, in technical language, to the state of bar or wrought-iron, after this operation, is very inconsiderable.'

Truran (1855, 128) provided a rather similar view:

> '… hence, in refining, the object in view is not so much to deprive the iron of the cinder alloy, except in cases where this is of a prejudicial quality, as to decarbonate the iron. If depriving it of the alloy was the object of refining, as is commonly supposed, the grey varieties having the least amount would be refined with facility instead of difficulty'.

Others authors, including Phillips (1852) and Rogers (1858, Ch 18) also identified desiliconisation as important, with an understanding that oxidation of silicon (and other elements) contributed to slag formation. Philips also lacked an understanding of phosphorus, but made an explicit connection with iron being cold-short (1852, 279):

> 'It is generally known that the lean carbonates abounding largely in silica produce finished iron of a cold-short character. The addition of lime in moderate quantities appears to neutralize this tendency, and the resulting iron is comparatively free from the opposite extreme – red short.'

Percy (1864) described removal of both silicon and sulphur in the refinery, but clearly believed decarburisation was the main purpose and expressed surprise at the unexpectedly high carbon content of finers metal (626). Truran (1865, 203-04) discussed at length problems with the mass balance of the refining process, but similarly referred mainly to removal of silicon.

Bell (1884, 351) provided the first 'modern' chemical description of refining and recognised the role of dephosphorisation:

> 'Mr Edward Williams informs me that the use of the "sand bottom" had been generally abandoned before he was old enough to remember much of its peculiarities. His impression is that it did its work badly; because it was necessary to avoid the accumulation of fluid cinder, rich in the oxide of iron, which in puddling, as in refining, is the agent which effects the removal of phosphorus, could not fail to damage the quality of the product. To some extent I apprehend this evil would be counteracted by previously passing the pig iron through the refinery, and by the time required in puddling "a heat" which occupied three hours.'

Discussion

The high phosphorus content of the Ynysfach residues (Young and Hart forthcoming) suggests that although desiliconisation has been suggested as the main role of the refinery, dephosphorisation may have been equally, if not more, important – just as suggested by Dufrénoy and Élie de Beaumont (1827, 496-97). This is supported by the implication of phosphorus in some of the problems (as revealed by accounts of Cort's trials and demonstrations of puddling in the 1780s) that the introduction of refining was later to solve.

Thermodynamics predicts that sequential oxidation of silicon, phosphorus and carbon would occur during conversion. Descriptions of puddling in Cort's patent (No 1420, p3) mention a prolonged stage in which the molten iron was quiet, followed by a period in which 'ebullion, effervescence, or such like intestine motion takes place, during the continuance of which a bluish flame or vapour is emitted'. These stages may, with caution, be interpreted in the light a chemical description of the later puddling variant, 'pig boiling'. For Flemings and Ragone (2009), this involves three stages: clearing (including desiliconisation and dephosphorisation), low boil (decarburisation) and high boil (decarburisation and solidification of iron). They described how stirring the furnace contents during the clearing stage of 'pig boiling' (likely to have been broadly equivalent to the quiet initial stage in dry puddling), allowed the iron to be in contact with the oxidising slag (initially produced by oxidation of the surface of the iron charge), promoting oxidation of silicon, manganese and phosphorus by the iron oxide in the slag. Only once this process had occurred, did carbon begin to be oxidised, with the carbon monoxide produced burning with a blue flame (the second stage in dry puddling). They state that care had to be taken, through careful control of the atmosphere and by slag removal, to prevent reversion of the phosphorus into the iron as the temperature rose after this point and as the iron oxide content of the slag reduced. The slag within the early 'dry' puddling furnaces would have been acidic (stemming largely from the reaction of oxidised iron and sand bed of the furnace, together with silica from desiliconisation); there would have been extremely little calcium present. This would mean the slag at was not a strong dephosphorising agent, nor would it have bound the phosphate well – so would have been particularly prone to reversion.

The advent of 'pig boiling' produced a system in which rabbling alone worked the slag-iron interface to permit transfer of oxygen (Williams 2015). The introduction of iron oxides below the charge aided the oxygenation of the slag, with the rapid reaction producing sufficient carbon monoxide to stir the liquid, thus permitting the conversion of very fluid grey iron melts.

The process of dephosphorisation has been studied intensively for modern steelmaking systems (*eg* Monaghan *et al* 1998), but not for slags with fayalitic composition, as present in refining and puddling. Several factors would, however, have enhanced their dephosphorising capabilities, including a high activity of FeO, a relatively low temperature and an increased basicity; the dephosphorising and phosphate-holding properties of slags are strongly influenced by the presence of calcium and sodium. Examples of the use of lime in refineries were provided by Dufrénoy and Élie de Beaumont (1827, 496), Philips (1852, 279) and Truran (1865, 201); Percy (1864, 626) quoted an example of brine soaked coke being employed for refining the best cable iron. The analysis of the residues from Ynysfach suggested neither of these additions had been made there.

The hybrid process operating at Cyfarthfa over the winter of 1790-91 added a piling stage after fining in an air furnace, with the loop then crushed 'like a paste' (Evans 1990, 95), before being submitted to a 'potting' process. This indicates that the puddling was not achieving full decarburisation and that a break in the process was used so that the process could be completed in the new chemical environment provided by fresh slag production. This hybrid process had switched the role of the air furnace from being primarily decarburising (as in Cort's original usage) to mainly desiliconising and dephosphorising. A similar break in process was a feature of all the 18th-century conversion techniques (Fig 1).

The subsequent modification of the Cyfarthfa workflow to incorporate a refining stage before puddling instead (the breakthrough of early 1791), allowed Cort's process to return to its intended role for decarburising, with the refining stage having already achieved much of the desiliconisation and dephosphorisation. If the problems with Cort's dry puddling process had been solved by adding a refining stage, then the issues must have been either with the clearing stage and/or with subsequent phosphorus reversion; the adoption of a multi-stage process, in which carburisation was undertaken on finers metal separated from the slagged residues of the refinery, yet again, strongly suggests that phosphorus reversion had been a problem.

After the first implicit mention of a new process in February 1791, excitement filled Crawshay's letters and by June the process seems to have fully adopted with a new refinery building at least partially constructed. Whether the initial experiments with refining had been conducted at Cyfarthfa or at Penydarren is unknown; both works were operating potting and stamping with coke fineries (melting fineries) which would run-out finers metal on occasion (and even produce finers metal for sale). The claim that the process was proposed to Samuel Homfray by Joseph Firmstone is plausible but remains entirely anecdotal. The claim that the charcoal running-out fire was a precursor to the refinery is very unlikely; the charcoal running-out fire may rather have been derived from the refinery for the conversion of coke-pig for the tinplate industry, and was later replaced by the use of a coke refinery as the initial stage of the South Wales Process (Percy 1864, 581).

Contemporary accounts document the development of the refinery from the typical finery of the late 18th century into its familiar form by the mid-19th century. Early refineries cast the finers metal onto sand or into a stone channel, as had previously been undertaken explicitly in Wood's variant of the potting and stamping process and in practice in Wright and Jesson's later variant. In Wood's process, the division between the flourishing and the potting stages corresponded, chemically, approximately with the division between refining and puddling. In Wright and Jesson's process, the fining stage was prolonged to include some of the decarburisation stage too. All the various multi-stage conversion processes for coke pig employed in Britain in the 18th century entailed slag-iron separation after dephosphorization, thereby preventing the problems of phosphorus reversion into the iron during decarburisation. These same issues threatened the adoption and development of puddling, until refining provided a solution by the prior removal of much silicon and phosphorus before the puddling stage.

Cyfarthfa Ironworks (including the Ynysfach works) provides a particular narrative for the development of conversion, from the well-documented implementation of Charles Wood's process in the late 1760s, the use of the Wright and Jesson process in the mid-1780s, the early licensing and experimentation with puddling in the 1780s under Crawshay leading to the abandonment of puddling in 1790 but its successful implementation in 1791, the early 19th-century visits to Cyfarthfa of Bonnard, Svedenstierna, Rees and O'Reilly, and the new archaeological evidence for the 1830s-1870s.

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Glossary

Note: The terminology employed in late descriptions (*eg* those by Percy, Phillips and Truran) is frequently different from that employed during the late 18th century. Terminology also frequently differed between works, and even differed between the Crawshay letters and the Cyfarthfa accounts. Only a brief treatment of the use of each term is possible here.

air furnace: a reverberatory furnace (variants were employed for balling, puddling, melting iron for foundry work etc).

balling: a process in which iron was heated in a reverberatory furnace so that smaller pieces could be aggregated into a larger lump or ball. Balling appears to have been used initially to describe this use in recycling, but later use expanded this to include similar processes during the conversion process, in particular for the second stage of the Wright and Jesson process of stampering, so that stampering was sometimes known as 'stamping and balling'. See also piling, chaffing.

blackplate: the plate iron produced specifically for the production of tinplate.

bloom: in the late 18th/early 19th centuries sometimes employed for the raw iron mass produced during puddling, but this was also known as a loop, in which case the term bloom was reserved for a compacted billet ready for rolling. The precise meaning of the terms bloom and half-bloom is often unclear.

bloom air furnace: a reverberatory furnace employed for reheating blooms (or half-blooms) prior to rolling.

chafery: a shallow open hearth for the reheating of impure iron, during its working under a hammer to remove slag, and to produce the elongate slag microstructure of bar iron. Typically employed as the second hearth in the two-stage Walloon process, when iron produced in the finery was worked. Later employed to describe a hearth similarly used to reheat the iron produced during stampering.

chaffing: another word for balling or piling.

coke pig: pig iron produced from the smelting of iron with coke as the fuel in the blast furnace (in distinction to charcoal pig produced from a charcoal-fuelled blast furnace).

cold-short: metal that is brittle when cold. The usual cause of cold-short iron was an elevated phosphorus content (in distinction to hot-short iron, that is brittle at high temperatures and which is usually caused by elevated sulphur).

conversion: the process of turning cast iron into wrought iron.

dry puddling: a variety of puddling employing a sand bed to the hearth, as originally employed by Cort. The sand bed was later replaced by an iron bottom, an invention attributed Samuel Baldwin of Nantyglo in 1818. Baldwin fettled his iron bottom with various fluxes including haematite, predating the introduction of what is commonly called wet puddling or pig boiling.

finers metal: a form of white cast iron produced rapid cooling of thin flows of iron tapped from refinery or melting finery.

finery: a shallow open hearth for the decarburisation of pig iron under a strong oxidising blast. Typically employed as the first part of the two-stage (finery and chafery) Walloon process used for the production of wrought iron from charcoal pig. The term common finery was used to describe fineries producing solid iron (as in the Walloon process), as opposed to the later melting fineries, which could produce a molten product.

grey cast iron: cast iron in which much or all of the carbon is present as graphite, rather than combined with iron as cementite. Silicon is a graphite stabiliser and so promotes the formation of grey cast iron.

grey pig: pig iron comprising dominantly grey cast iron.

half-bloom: a compacted billet produced from the compaction of a bloom from a finery.

loop: commonly used for the raw iron mass produced in a puddling furnace. This mass could then be shingled into a half-bloom. Sometimes used synonymously with bloom.

loop air furnace: a term sometimes used for the puddling furnace.

pig boiling: a variety of puddling in which oxygen was introduced to the reaction from a furnace lining (fettling) of haematite iron ore and roasted slag, as well as introducing scrap iron and scale to the charge. The vigorous evolution of gas made the molten charge appear to boil. The process involving the addition of scrap is commonly attributed to Joseph Hall in the 1820s, who also patented the use of 'bull dog', roasted puddling slag, in 1839. Also known as wet puddling.

piling: the compaction of small pieces of iron into a larger mass. See also balling.

planishing: a process for finishing bar iron with a hammer to produce straight bars with flat, smooth surfaces.

puddling: a family of processes in which cast iron was decarburised, desiliconised and dephosporised by agitation in a reverberatory furnace as part of a process for production of wrought iron (and later mild steel). Variants include dry puddling, wet puddling and pig boiling.

rabbling: the process of (usually manual) agitation of the metal in a pudding furnace.

running-out fire/hearth: a finery in which the product is a molten metal that is tapped out of the hearth. Although sometimes employed as a general synonym for a refinery, the term was particularly applied to the refineries employed in the Welsh Process for blackplate manufacture (not to be confused with the running-in hearth, a variant of the refinery employed in many works, but not Cyfarthfa, in which molten iron was fed straight from the blast furnace, rather than using solid pig).

shingling: the process of compaction of the loop/bloom to a billet (half-bloom).

shotting: the production of cast iron in tiny particles by casting into water. Granulation.

stampering: a family of conversion processes commonly referred to as 'potting and stamping'.

white cast iron: cast iron in which the carbon is combined with iron as cementite, rather than existing as graphite.

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