The zenith of iron and the transition to mild steel in Great Britain

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ABSTRACT: The production of iron by the puddling process continued after Bessemer invented his process for making mild steel, reaching its zenith in the 1870s, then declined rapidly as mild steel was substituted for iron for rails and then shipbuilding. Data on furnace numbers in the Mineral Statistics are used to estimate output of puddled iron and of mild steel from four processes. The total output of all iron and steel processes rose from 5.44M tons in 1875 to 6.0M tons in 1899, but with significantly lower output in the intervening period. Acid Bessemer steel output was at its highest in 1889. Soon after, Open Hearth steel overtook Bessemer steel in importance. Between 1877 and 1899, the roles of puddled iron and mild steel were reversed, with the former falling from 80% of the total to only 20%.

Introduction

There are three common forms of metallic iron: pig iron, wrought iron and steel. Pig iron, the initial product of smelting iron ore in a blast furnace contains 4-5% carbon, perhaps with silicon replacing some of the carbon, and is a relatively brittle material. Malleable iron (also called wrought iron) is commercially pure iron (though usually not absolutely pure), produced by fining pig iron. 'Wrought iron' is in fact a chemists' and metallurgists' term, covering a number of chemically and metallurgically identical commodities, differing mainly in their shape. The British Customs limited the term 'wrought iron' to finished ironware, made from (unwrought) bar iron and so on: 'viz. axes, adzes, hoes, armour, bits, knives, locks, fowling pieces, muskets, pistols scissors, stirrups and all carpenters and gravers tools, jackwork, clockwork, and all ironmongers' wares perfectly manufactured' (*Statute*, 12 Car. II, c. 4). Steel (strictly carbon steel, as opposed to alloy steel) is intermediate in composition between pig iron and malleable iron. It is split according to its carbon content into high-carbon steel with up to 2% carbon and mild steel with as little as 0.1%. High-carbon steel is a harder material, suitable for the edges of blades, but historically it was more difficult to produce.

The traditional fining process (for making malleable bar iron from pig iron) in hearths, using charcoal as fuel, began to be replaced by new processes using only coal (or coke) in the late 18th century. The process that was ultimately the most successful (and almost universally adopted) was puddling, devised by Henry Cort in 1785. Initial difficulties were only solved by adding a preliminary refining process to make 'finers' metal' (also called 'refined iron'). This breakthrough (which was not patented) probably took place at Merthyr Tydfil in about 1791 (King 2012, 112-6). This was the work of Samuel Homfray, but perhaps suggested by Joseph Firmstone, apparently a step-son of John Guest of Merthyr Tydfil and like him from Broseley in Shropshire (Shill 2008, 47 49; Anon 1830, 3).[1] The result was that charcoal largely disappeared as a fuel in the iron industry in Britain, though small quantities of charcoal iron continued to

be made for some purposes. The supply of charcoal had been a limiting factor in the growth of the British iron industry, whose production grew little between about 1620 and 1780. The new processes released the industry from the stranglehold imposed on it by the speed of growth of the trees from which the charcoal came. This allowed a sudden expansion of production, beginning with the construction of new melting fineries for the potting and stamping process from 1785 (King 2005). This was eclipsed by puddling (King 1996, 9-11; Riden 2001; Evans 1993a, 10-29, 96-100). Various improvements took place in puddling methods in the following period, but failed significantly to increase productivity per man (Gale 1967, 45-53; 71-9). Before the 1850s, steel was a difficult material to produce. High-carbon steel was made for edged tools, springs, and other purposes for which wrought iron or mild steel were not suitable (Barraclough 1984). A number of new methods were tried in the first half of the 19th century, but none seem to have been much adopted. A possible exception to this may be the application of the puddling process to make steel in the 1850s (Barraclough 1984 ii, 94-106; 1990, 29-35).

The status of steel changed greatly after the 1850s, with the development of new processes. These produced a new material, mild steel with up to 0.2-0.3% carbon. This functionally replaced wrought iron, rather than the traditional high-carbon steels, about which little more will be said. The first mild steel was the invention of Henry Bessemer, whose converters blew air through molten pig iron to decarburise it, but his early process could not produce satisfactory steel from pig iron made from phosphoric ores, such as the ironstone found in the Coal Measures. The Bessemer process was followed by the Siemens-Martin Open Hearth process, which used the oxygen in the ore to remove the excess carbon from the pig iron. Basic versions of both processes were later developed, able to work with phosphoric pig iron. Mild steel made by these processes proved to be suitable for most of the processes for which bar iron had hitherto been used (Barraclough 1990). The production of wrought iron gradually declined until the closure of Thomas Walmsley of Bolton in 1976 (Smith and Gale 1987).

The speed with which steel overtook puddled bar iron has not hitherto been adequately documented, partly because most economic history studies either concentrate on iron (Birch 1967, especially 315-86; Hyde 1977, 166-192) or they focus on steel, but only from about 1870 (Burnham and Hoskins 1943; Burn 1940; McCloskey 1973). Most 18th-century statistics focus on bar iron production (King 1996) but from the 1790s the focus shifted to pig iron. This is partly because statistics for 1796 and 1805 were prepared as part of political campaigns against proposed taxes on pig iron or the coal used in making it (Riden and Owen 1995, ix-xxi; Evans 1993b). However, it was perhaps also because statistics on blast furnaces and the pig iron they produced provided a means of measuring the scale of the whole industry, as cast iron goods became a significant part of output. Because of this change in focus there were no national surveys of plant making bar iron between a list of ironworks of the early 1790s (King 2012) and the *Mineral Statistics* from 1860.[2]

This author's estimates of bar iron production after 1790 were derived from data on pig iron production. They differ from estimates for the period before 1790 when his bar iron estimates were largely derived from data on finery-forge plant in existence and on contemporary surveys (King 2005). He ignored the very existence of continued charcoal bar iron production, for example using Lancashire hearths, far into the 19th century, as identified by Hayman (2008). However detailed quantitative information on this sector remains elusive. Notes in the *Mineral Statistics* refer to a few charcoal hearths, but not often enough for estimates to be made. All bar iron estimates based on pig iron output are unsatisfactory, because the proportions of it consumed in the foundry and forge sectors respectively are uncertain. Riden found evidence of a 50/50 split of pig iron between the forge (malleable) and foundry (cast iron) sectors in 1810, moving to 70/30 in about 1830 and remaining at that level subsequently (Riden 1980, 76-7; Hyde 1977, 166-7). Certainly, the demand for wrought iron must have increased substantially from about 1830 with the rise of railways (using rolled wrought iron rails) and the change to building ships of iron instead of timber. Some of the early *Reports* by the British Iron Trade Association (BITA) attempted to estimate consumption in these sectors. This article offers no new solution to these problems: a gap remains in our knowledge of the scale of malleable iron production after 1790.

The data used here come mainly from the *Mineral Statistics* and from the *Annual Statistical Reports* of BITA.[3] The former has data on the number of puddling furnaces in existence from 1860. This is an interesting date, as Bessemer's steel-making process became an effective one in 1859 (Barraclough 1990, 12-15). The *Mineral Statistics* also have data on the installed capacity of Bessemer converters from 1867; on the number of furnaces for Siemens-Martin process from 1876; and on furnaces for the Gilchrist-Thomas (or Basic

Bessemer) and Basic Open Hearth processes almost from their inception. BITA produced national statistics for each steel process from 1879, and in some cases a few years earlier, but for puddled iron only from 1881. Its reports also contain independent data on the numbers of furnaces for each process, which sometimes conflict with the data in the *Mineral Statistics*. Together these offer a means to estimate steel and bar iron production from 1860, rather than starting with the first given in the *BITA Reports*, the source for the figures in the first edition (only) of *Abstract of British Historical Statistics* (Mitchell and Deane 1962, 134-6).

Though the conclusions for the period 1860-80 can only be regarded as tentative, this provides a means of measuring the early stages of the transition from iron to steel. The difficulty is that much of the data concerns the quantity of plant, not its output. The challenge is accordingly to provide an appropriate multiplier to convert the number of furnaces to an estimate of their output. This article seeks to throw light on the period of transition, and to narrow the gap in malleable iron production data by about 20 years. It purposely does not address wider issues, such as any possible entrepreneurial failure, on which see McCloskey (1973) and Wengenroth (1994).

Puddled iron

The established history of puddling is that the process was devised by Henry Cort at Fontley near Portsmouth and the technology was rapidly transferred to Merthyr Tydfil (Mott 1983; Hayes 1990). The introduction of a preliminary refining stage there made this an effective, indeed all-conquering, process (King 2012; Hayes 1990, xii-xvi; Anon 1830, 3). Puddling involved manual stirring ('rabbling') in the furnace and at the end of the process a puddled ball had to be dragged out of it. Human strength is limited, which meant that puddling could only be scaled up by building more and more puddling furnaces. Ironworks with dozens of puddling furnaces were common. Dowlais had 150 furnaces in operation in the 1860s. Albert Hill at Darlington peaked at 205 in 1874. The Consett and Derwent Works averaged nearly 170 between 1874 and 1883. Robert Heath in North Staffordshire had 154 in 1871 and 1874. Various attempts were made at getting around the limitation of human strength by introducing mechanical rabbling. The most successful of these was the Danks furnace (invented in Cincinnati), which had a cylindrical furnace mounted on trunnions. This enabled it to turn on a horizontal axis, so that a churning effect replaced stirring (Danks 1871). Robert Heath's works in North Staffordshire included six of these in 1874. These were more productive than standard furnaces and might be treated as perhaps three ordinary furnaces. Unfortunately, the *Mineral Statistics* do not consistently give the numbers of Danks furnaces, which inevitably adds to the uncertainty in the estimate presented here.

No contemporary data were consistently collected on the production of malleable iron until 1881, but the *Mineral Statistics* give the number of puddling furnaces at each works existing each year from 1860. A few duplicates can be detected, but the data for many works varies slightly from year to year, suggesting that it is based on a real survey of usage. A serious defect is the tendency to include plant that still existed at works that were standing idle. This is probably a minor problem (for estimation purposes) in the 1860s, when the number of furnaces was growing year by year, but becomes a significant issue in the 1870s when a substantial number of works were not in use.

In 1877 J S Jeans, the Secretary of BITA and the compiler of its *Reports*, expressed considerable doubts as to the usefulness of the *Mineral Statistics* data. He provided his tentative estimate of actual output, which he compared to the *Mineral Statistics* furnace numbers, using a multiplier of 600 tons per furnace per year.[4] He found that the latter gave what he regarded as a gross overestimate by factors of up to three. On the other hand, he criticised the furnace number for the 'North of England' (Cleveland to Newcastle) as too low. The North of England Iron Manufacturers' Association had returned 2,010 furnaces to Jeans, whereas Hunt's figure was 1,894 (*BITA 1877*, 36-7). However, these could both be accurate counts, but made at different dates. Jeans' criticism is only appropriate to the period in the mid to late 1870s when puddled iron production was in severe decline, not to its period of growth in the 1860s.

The *Mineral Statistics* puddling furnace numbers actually start in 1859, but only with figures for the South Staffordshire district (which extended slightly beyond the county boundary). From 1860, figures for the rest of England and Wales were provided (Fig 1). The Scottish figures are incomplete for that year, and only start properly in 1861. Those for (south) Lancashire begin in 1864 with 109 puddling furnaces in seven works, suggesting that they were incorrectly omitted in preceding years. This article makes no adjustment for these omissions.

The region with the greatest number of furnaces was South Staffordshire (*Mineral Statistics, passim*). In 1850, this had an estimated potential output of about 9,500 tons per week, but was only making about 6,000 (Shill 2008,

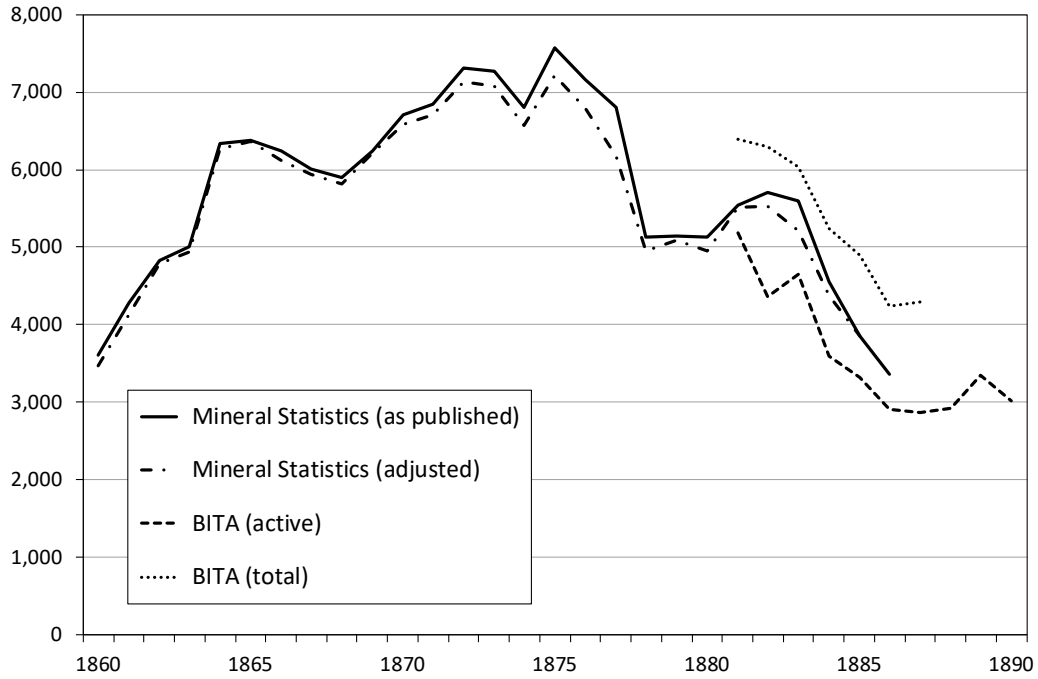

Figure 1: Numbers of puddling furnaces. The adjusted series deducts those furnaces which were recorded as idle or whose owner was insolvent.

94-5). In 1859, there were 1,686 furnaces, slightly more than the 1860 figure of 1,494. The total rose to 2,150 in 1865 and after a drop was again above 2,000 in the early 1870s. The national total passed 6,000 in 1864 and exceeded 7,000 in the early 1870s. It is nevertheless difficult to adjust the number of furnaces in existence to a more realistic number operating. A first step is to eliminate any that are noted as 'silent' or whose owner was in liquidation or bankrupt. The numbers remained high until 1877 (*Mineral Statistics*, *passim*), despite the decline in the exports of railway iron, which had fallen from 945,000 tons in 1873 to 415,000 tons in 1876 (Burn 1840, 5-9), but the precise scale and timing of the downturn in the 1870s can probably never be known.

Griffiths' Guide to the Iron Trade (1873, 268-81) – produced by the editor of a trade newspaper – contains a list of puddling furnaces which seems to be independent of the *Mineral Statistics*. For South Wales, these are markedly similar to the *Mineral Statistics* for 1871, though not identical. In Lancashire, Griffiths recorded a few works that do not appear in the *Mineral Statistics* until 1873, but includes 'silent' works in his totals. These numbers are often slightly higher than those of the *Mineral Statistics*, conceivably due to the inclusion of charcoal forges such as Cookley in north Worcestershire. Being a snapshot for a single year, his figures do not provide a series and have thus not been used for the computations described below.

When BITA began counting puddling furnaces in 1881, its count of active furnaces was significantly lower than that of the *Mineral Statistics* but, with inactive ones included, the BITA total was higher (Fig 1). The *Mineral Statistics* showed a sharp decline in numbers from 1877 to 1878, followed by a modest rise and then a decline until that series stops in 1886. Nevertheless, the use of furnace numbers may underestimate the decline in the industry in the late 1870s. It is impossible to estimate how many owners had reduced their output, for example by stopping their night shift, which would have halved output without any change in the number of furnaces in use.

In the period before 1881, when the *BITA Reports* began giving figures on puddled bar production, the reports give various estimates of this, but most are unsatisfactory. The most useful are figures on the 'North of England' industry, compiled by the Board of Arbitration and Conciliation in the Iron Trade of the North of England. These are limited to four varieties of finished iron: rails, plates, bars and angles. They are first given in the *BITA Report for 1877* with later totals published in subsequent years (Fig 2).[5] These figures differ from those for puddled iron, partly because not all firms were members of the Board (*BITA 1884*, 24-5), and partly because they concern a different commodity: some weight would be lost as scale in finishing the iron. Nevertheless, this provides a useful sample of the iron industry and illustrates a great change in its products, with the collapse in the market for iron rails. By the time that the overall rail market recovered, it had been found that mild steel rails were more durable, so that the market for iron rails did not recover (Burn 1940, 25-30; Wengenroth 1994, 45-50). The rise in plates and angles (mainly for shipbuilding) in the early 1880s proved temporary, due to

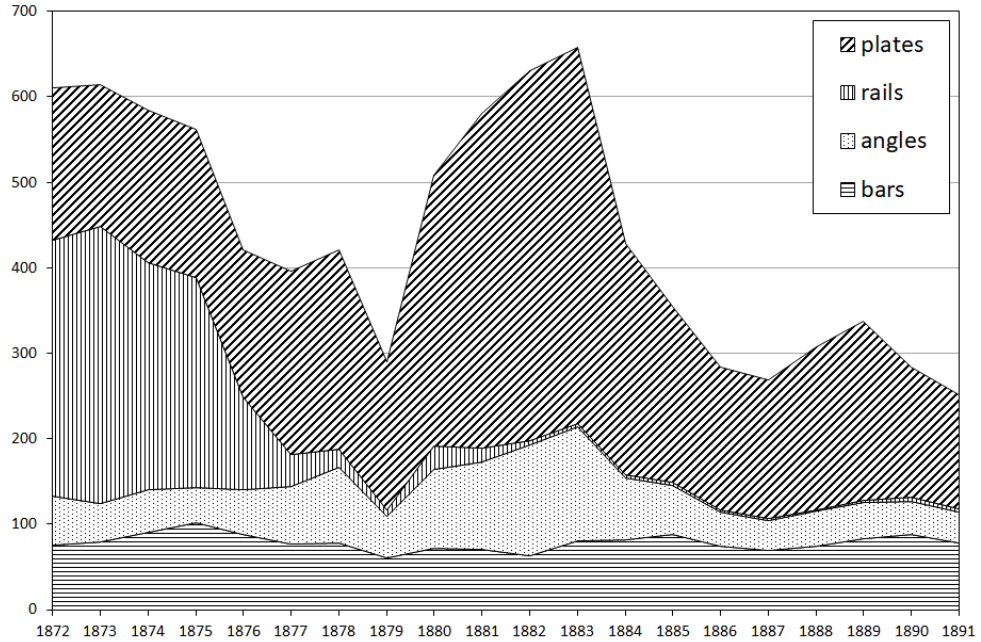

Figure 2: Output of four types of finished iron from the 'North of England', which here means the Cleveland and Newcastle areas (thousands of tons).

the substitution of mild steel, a change that came slightly later than for rails (Fig 3). In 1878 steel ships were only 1% of the tonnage of metal ships completed, but in 1890 the position was reversed and only 3% of the tonnage of new metal ships was iron. The iron tonnage declined suddenly from 933,774 tons in 1883 to 290,429 tons in 1885. These figures relate to registered tonnage, not the amount of metal used, but they clearly indicate the scale and timing of the change. The data are continued in later *BITA Reports*, but only for the total new tonnage. The full data up to 1890 were given by *BITA* (1890, 58).

The most difficult issue is how to estimate output from the numbers of puddling furnaces. As stated, artificial power had not (or hardly) been applied to the process, so the question of the average output of a furnace is one that ought to have a meaningful answer. A survey of published sources (contemporary and modern) does not provide any simple answer. This is complicated further because some sources give figures for finished iron and others for (semi-finished) puddled iron. Bell wrote that 22 cwt as a day's work was doing well. If this refers to a turn (shift) and two turns were worked each day, this comes out at 682 tons per year (Bell 1884, 27). Roberts, who studied the Britton Ferry ironworks near

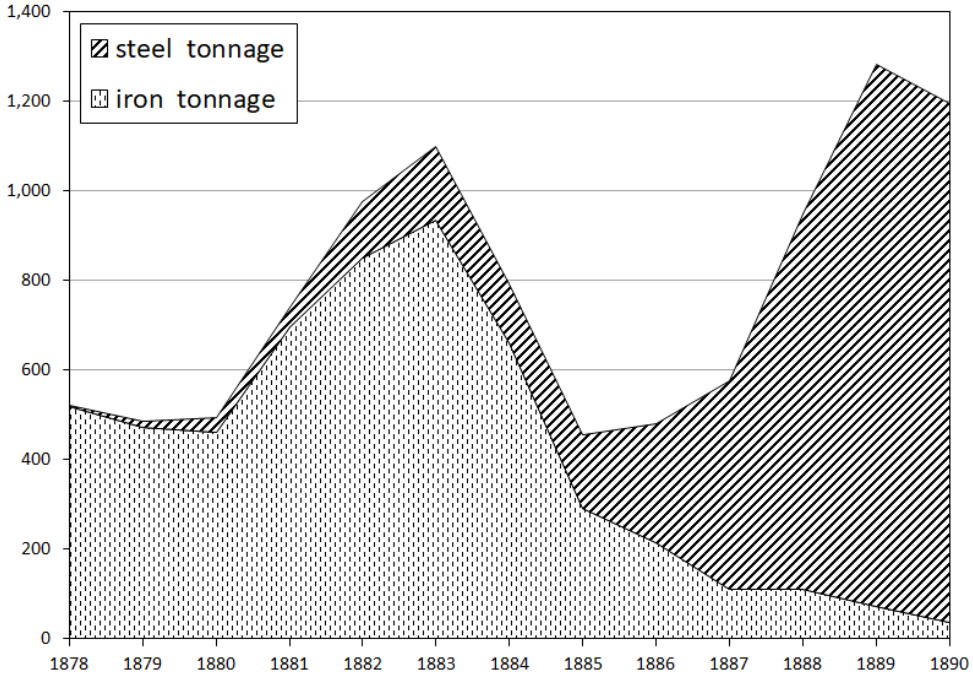

Figure 3: Iron and steel used in shipbuilding. The figures are the registered tonnage of the ships built but probably do not include naval vessels (thousands of tons).

Neath, wrote of 23 cwt per 12 hour shift (perhaps 713 tons per year). However, in another place he pointed out that stoppages for repairs might keep one furnace in twelve out of work (Roberts 1983, 43), reducing this to 628 tons per year. Albert Hill (in Durham) managed 500-600 tons per week from 45 furnaces (Harrison 1979, 129), which comes out at 636 tons per furnace per year. Truran (a South Wales contemporary) reckoned that in favourable conditions 21 tons might be made per week, but suggested an average of 18 tons. This, he said, was above production in some districts, instancing a mere 10 tons in Staffordshire. This he explained by Staffordshire furnaces working shorter hours, about 104 per week, compared to 140 in South Wales. He also noted that output was higher where iron was already molten when charged to the furnace (Truran 1862, 216-7).

One approach that may help in dealing with this complexity is to apply regional averages from the 1880s to the preceding decades. Such averages can be calculated from data in the *BITA Reports* for 1881 to 1890 (excluding the 1881 figure for the Cleveland district which is explicitly for finished, not puddled, iron). Output in subsequent periods tended to be a little higher, either reflecting mechanisation or other changes. The regional averages range from 520 tons per furnace per year in Shropshire to 756 tons in Lancashire. The older-established ironmaking regions (the Midlands and West Yorkshire) all made less than 600 tons, but the outputs in South Wales, Cleveland and Scotland were significantly higher.

Figure 4 and Table 1 shows production estimates, using the adjusted puddling furnace numbers in the *Mineral Statistics* (cf Fig 1) multiplied by the regional average outputs described above, up to 1880 (1881 for Cleveland), together with outputs published in the *BITA Reports* for the subsequent period. Hyde suggests that Richard Cort's estimate of total British production at 1.6M tons in 1855 is plausible, in contrast with two other estimates of the same period (Hyde 1977, 166-7). The output continued to rise during the 1860s and early 1870s, from 2.61M tons in 1861 to peaks of 4.52M tons in 1872 and 4.73M tons in 1875. From there output declined sharply to 3.14M tons in 1878 and continued to fall to a low of 1.61M tons in 1886. It recovered to 2.25M tons in 1889, but then gradually declined to fall below 1M tons in 1901. Finding that South Wales (peaking at 0.89M tons in 1864) and Cleveland (1.45M tons in 1875) were among the productive regions is unsurprising. However, South Staffordshire's dominance, peaking at 1.17M tons in 1865 and 1.19M tons in 1872 is perhaps less so: it was rather less prominent as a pig iron producer (Riden and Owen 1995, lv-lvii). It was evidently using pig iron brought in from Scotland, the North West, and the East Midlands Jurassic Belt, as well as locally-made pig. Cleveland and South Staffordshire maintained their importance until the 1890s, but South Wales's declined by 1880. Despite having blast furnaces, the Jurassic Belt hardly did any puddling.

Bessemer steel

The history of the Bessemer process has been told many times. Bessemer announced his initial success in

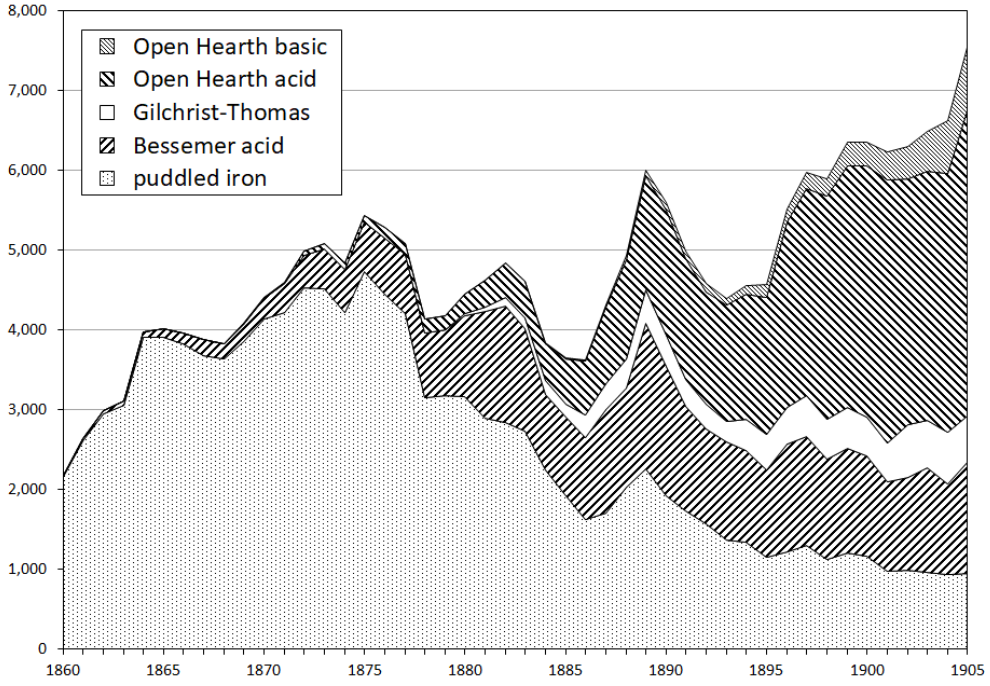

Figure 4: Iron and steel made by all major processes; data from Table 1 (thousands of tons).

Table 1: Production estimates by process (tons).

	Puddled iron	Bessemer acid	Gilchrist-Thomas	Open Hearth acid	Open Hearth basic	Total
1860	2,164,626	7,676				2,172,302
1861	2,610,355	23,184				2,633,540
1862	2,940,333	45,663				2,985,997
1863	3,049,663	54,381				3,104,044
1864	3,901,830	73,190				3,975,019
1865	3,901,374	106,812				4,008,186
1866	3,826,279	138,694				3,964,973
1867	3,681,894	194,376				3,876,270
1868	3,630,075	192,437		0		3,822,512
1869	3,856,517	214,398		8,000		4,078,915
1870	4,141,910	254,783		16,000		4,412,692
1871	4,210,905	366,168		23,200		4,600,273
1872	4,521,961	410,026		51,520		4,983,507
1873	4,514,452	495,000		77,500		5,086,952
1874	4,213,134	539,000		90,500		4,842,634
1875	4,732,576	620,000		88,000		5,440,576
1876	4,452,739	700,000		128,000		5,280,739
1877	4,198,631	750,000	0	137,000		5,085,631
1878	3,146,333	807,487	20	175,500		4,129,340
1879	3,170,138	830,199	3,363	175,000		4,178,699
1880	3,165,938	1,015,352	19,030	251,000		4,451,320
1881	2,894,740	1,333,668	61,931	338,000		4,628,339
1882	2,841,534	1,451,667	112,618	436,000		4,841,819
1883	2,730,504	1,287,665	136,535	455,500	0	4,610,204
1884	2,237,535	953,847	166,829	471,403	3,847	3,833,461
1885	1,911,125	996,065	162,355	572,376	11,542	3,653,463
1886	1,616,701	1,024,521	287,533	682,608	11,542	3,622,905
1887	1,701,312	1,293,269	336,088	949,507	31,597	4,311,773
1888	2,031,473	1,233,068	371,162	1,241,089	51,653	4,928,445
1889	2,253,756	1,826,510	422,211	1,429,169	71,708	6,003,354
1890	1,923,221	1,612,730	402,113	1,564,200	101,287	5,603,551
1891	1,733,902	1,306,229	335,776	1,514,538	100,486	5,090,440
1892	1,560,697	1,202,027	298,783	1,418,830	108,056	4,588,583
1893	1,363,974	1,230,992	262,362	1,456,309	78,645	4,392,282
1894	1,339,062	1,139,611	395,753	1,575,318	104,531	4,554,275
1895	1,148,012	1,093,675	441,550	1,724,737	159,869	4,567,843
1896	1,214,005	1,357,580	458,262	2,317,555	172,287	5,519,689
1897	1,288,159	1,374,339	509,816	2,601,806	208,088	5,982,208
1898	1,115,699	1,255,252	504,134	2,806,600	216,088	5,897,773
1899	1,201,606	1,307,696	517,378	3,030,251	294,688	6,351,619
1900	1,162,765	1,253,903	491,101	3,156,050	293,484	6,357,303
1901	974,385	1,115,955	492,268	3,297,791	351,177	6,231,576
1902	988,278	1,157,380	668,399	3,083,198	406,690	6,303,945
1903	950,393	1,316,915	593,103	3,124,083	510,809	6,495,303
1904	936,228	1,129,224	652,309	3,245,346	662,064	6,625,171
1905	938,558	1,396,233	577,977	3,838,072	795,238	7,546,078

1856 as a process to make wrought iron. His original experiments happened to be conducted on phosphorus-free pig iron, made from haematite ores from Furness. Unfortunately, when he licensed his methods to others, they (using the commoner phosphoric pig iron) found themselves unable to make good iron or steel, and Bessemer ultimately had to refund the licence fees he received. Bessemer perfected his process as one for mild steel, by the addition of his version of R F Mushet's 'triple compound', a cast iron with 5-15% manganese, usually known as *spiegeleisen* or ferro-manganese, which mopped up impurities present. However, this acid Bessemer process was limited to non-phosphoric pig iron (known as Bessemer pig), derived from haematite ores (Barraclough 1984 ii, 113-7; 1990*,* 39-66; Wengenroth 1994, 20 29). An effective process was in use at Sheffield from 1859 that involved a roughly oval vessel, mounted on horizontal trunnions so that it could pivot. It was brought to the horizontal for charging with hot-blast haematite pig iron, then turned to the vertical so that the furnace could be blown through tuyeres in the end that was now at the bottom to decarburise the metal. Finally, the converter was tipped so that the molten contents, now mild steel, could be poured into a ladle and thence into ingot moulds.

Unlike puddling, there was no inherent limitation of the size of the converter. Early ones held three or four tons, but did not differ in principle from those in use a century later, such as the 25-ton converter, used at Workington until 1974 and now preserved at Kelham Island (Sheffield Industrial Museum Trust, LI 1974.001). This meant, for example, that an ingot could be cast large enough for a single rail, giving steel an advantage, compared to puddled iron, despite the higher price (Wengenroth 1994, 34-6). Data on Bessemer furnaces are given in the *Mineral Statistics* from 1868 to 1886. Barraclough reprints other contemporary surveys from 1867, 1871 and 1878, the first two by S Jordan, a French observer, writing in 1871 (Barraclough 1990, 70-4 83-4). Barraclough (1990, 67 and 80 – probably from Warren 1964, 132, 135-9) gives dates for all but two works listed in 1867. The exceptions are Lloyds, Foster and Co of Wednesbury, whose licence was apparently contemporary with that of John Brown and Co of Sheffield – *ie* late 1861 (Lloyd 1975, 256) – and Bessemer Brothers of Greenwich, set up by the inventor for his sons 'in the 1860s when the process had triumphed' (Bessemer 1905, 342); the date seems to be about 1865 (Mills 1998). The earliest source available for each works usually states the number and sizes of furnaces built, but not when additional plant was subsequently added. Where the next available evidence (in 1867) shows more plant, linear interpolation has been applied to fill the gap. This is unsatisfactory, as the increase would not have been linear, but should reflect the trend.

Jordan and the *Mineral Statistics* serve as a check on each other. However, it is often difficult to decide whether a dash in the *Mineral Statistics* means no production or that no return was made to the compiler. The 1867 survey shows the Mersey Iron and Steel Works of Liverpool and the Lancashire Steel Co of Gorton (near Manchester) to have operated in that year, though the *Mineral Statistics* first list them in 1869. In fact they were in operation in 1864 and 1865 respectively (Barraclough 1990, 67 80). The Dronfield Works of Wilson, Cammell and Co appear several times in the *Mineral Statistics* until 1881, but without any capacity, when it is said to have 'removed to Workington'. However, the firm's Derwent Works at Workington first appears in 1885. The works were established in 1873 with four six-ton converters. The removal to Workington refers to the company's purchase of the Derwent Hematite Iron Co in 1882, the transfer taking place in (or from) 1883 (Barraclough 1990, 80; Tweedale 1995, 66 69). The omission of plant at Dronfield is accordingly taken as the result of a lack of data, rather than a lack of production. The London and North Western Railway's works at Crewe had a capacity of six tons until 1881 according to the *Mineral Statistics*, but Jordan, both in 1867 and 1871, describes four 5-ton converters. It is however conceivable that Jordan misremembered which works he was describing, and that the description was of Manchester Railway Steel and Plant Ltd, not the Crewe Works. Charles Cammell and Co had two works, the Cyclops Works at Sheffield and the Yorkshire Works at Penistone. Jordan gives these capacities of 8 and 28 tons respectively in 1867, but 20 tons each in 1871. The *Mineral Statistics* combine them in 1868 as 30 tons, and 40 tons in 1870 and subsequently. In 1867 Jordan also listed Workington Iron Company whose inclusion may be an error as they made Bessemer pig iron but probably not steel (Lancaster and Wattleworth 1977, 39-42); and Thompson and Armstrong of Normanton who appear in no other list and probably did not make steel. This is likely to refer to William Thomson, ironfounder, of the Railway Foundry, Normanton near Leeds, who patented several railway-related inventions in the period.[6] The *Mineral Statistics* show installed capacity at the Barrow Haematite Steel Co was reduced from 108 tons in 1877 to 56 tons in 1878, whereas Jeans' list of 1878 gives the intermediate figure of 96 tons (Barraclough 1990, 84). This may be the result of both surveys being a snapshot of what was happening on a particular date, perhaps the start of the year for Jeans, as opposed to 30 June for the

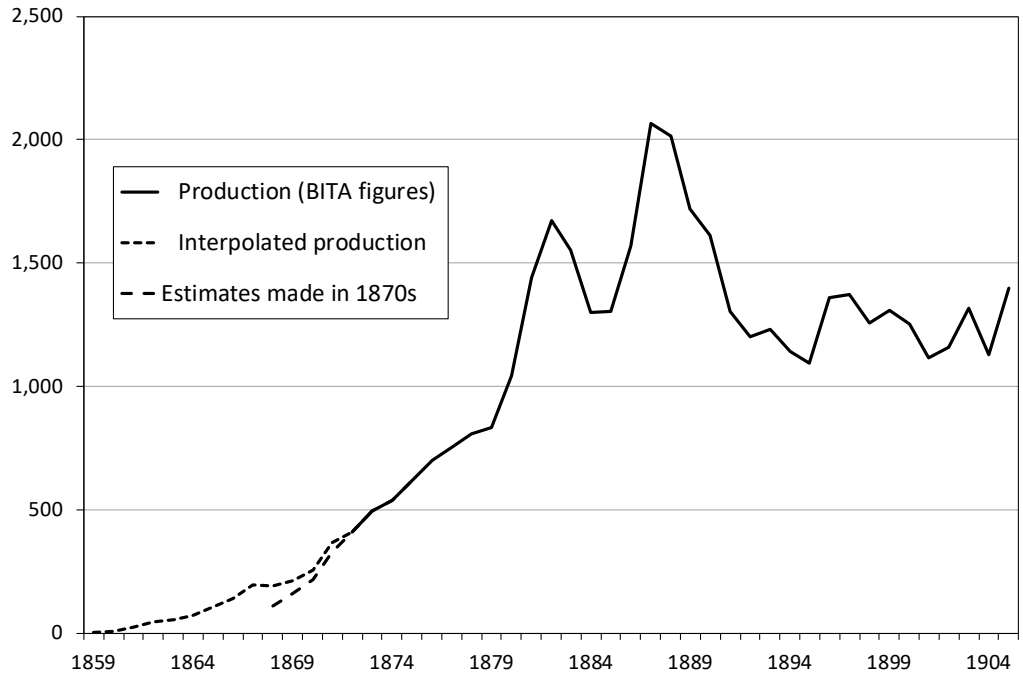

Figure 5: Bessemer steel production (thousands of tons). See text for data sources and calculations.

Mineral Statistics. Jeans omits Lloyds, Foster and Co though they continue to appear in the *Mineral Statistics* until 1880. For estimation (below) where evidence conflicts, the lower installed capacity has been used.

Jordan described the furnaces at Crewe as being blown 12 to 14 times per day, but they needed relining every 90-120 blows ('rounds'). On the basis of an installed capacity of 300 tons, operated 300 days per year and blown 4 times per day, Barraclough estimated output of the order of 350,000 tons per year, a figure that he evidently rounded down (Barraclough 1990, 73). Alfred Krupp in Germany in 1873 managed 18-20 charges per 24 hours, but if half the plant was under repair this is more than Barraclough's estimate (Wengenroth 1994, 78). The *Journal of the Iron and Steel Institute* published figures on output in 1875 for 1868-73, but described those for 1868-71 as estimates (*JISI* 1875, 238; reprinted with later figures in *BITA 1886*, 130). They seem to be the result of a crude back projection of the trend for the subsequent years in a way that would suggest that Bessemer steel production only began in about 1866, which is clearly wrong.

A better estimate (Fig 5) is however possible. Though they are from different sources, there are statistics both on total output of Bessemer steel and on installed capacity. The ratio between these must be related to the number of rounds (cycles of operation) per furnace per year. In the early 1880s, each furnace sometimes managed a ratio of 2,100. In the period 1875-9, the ratio was about 1,325 times; and in 1873 898 times. This reflects improvements, including in the durability of the bottom which had lasted as little as six blows in the 1860s, when only half the plant was actually producing steel at a time (Wengenroth 1994, 52-7). In 1865 three Sheffield firms were said to make 400 tons per week (Warren 1964, 132). If this covers all the plant at four works (including Charles Cammell and Co's at Penistone) which had an installed capacity of about 80 tons in 1867, each furnace was used only 260 times per year, perhaps barely one round per day. However, if it refers to eight four-ton furnaces (excluding Penistone and the two largest furnaces of John Brown and Co, listed in 1867) the ratio would be 650 for each furnace. With a new process some growth in productivity is to be expected. The figures for the 1870s suggest that this was still improving then. Linear interpolation of the ratio, using the fixed points of 1867 and 1873, provides a more credible estimate of the growth of output than the *JISI* figures (Fig 5). This starts with 766 tons in 1859 from Bessemer's first 33-cwt converter at Sheffield. Output increased steadily to 194,000 in 1867, when there was a short pause, followed by an increase to over 410,000 tons in 1872, double the 1867 output. It is possible that this underestimates the growth of the process, but any errors will not make a great difference to the total production of iron and steel as the annual total for steel (during the period of uncertainty) is small compared to the production of puddled iron. Growth continued, accelerating from 1879 to peaks of 1.67M tons in 1882 and 2.06M tons in 1887. With the rise of alternative processes, output fluctuated between 1M and 1.5M tons in the 1890s and beyond.

Siemens-Martin or Open Hearth steel

The Siemens-Martin process was the second process to produce mild steel in bulk. Siemens had already developed his regenerative system, which involved two firebrick chambers: the hot waste gases from an industrial process pass through one, heating the firebricks up; cold air passes through the other chamber, heating the air up, thus pre-heating it before it entered the furnace. Then, the flow was reversed, so that hot waste gas passed through the now cooled chamber and cold air passed through the chamber previously heated. This saved fuel and enabled higher temperatures to be achieved. The Siemens-Martin process applied this regenerative system to steel making. The original process involved melting pig iron in the furnace and then adding puddled steel (or scrap wrought iron or steel). The result was that over five or six hours the whole charge became molten steel. Siemens had an experimental furnace in or near Birmingham operating successfully in 1866. In 1868 he moved to Landore near Swansea, where he built a full-scale steel works. The process was attractive to railway companies because it enabled them to recycle worn out wrought iron rails. Before going to Landore, he had already licensed the process to the Bolton Iron and Steel Company and the Crewe works of the London and North Western Railway (Barraclough 1990, 137-48).

Data exists in the *Mineral Statistics* from 1876 on the number of furnaces (though not their sizes); there were then 84 furnaces. This increased to 127 in 1879, the year in which production totals (in round hundreds of tons) begin to be given. Evidence can be found for the date of most of the early works either from published works or when the company owning it was incorporated. The exceptions are Charles Cammell and Co of Grimethorpe and Manchester Railway Steel and Plant Company Ltd, which also made Bessemer steel; also Spencer and Sons of Newburn near Newcastle, a longstanding unincorporated crucible steel firm. For these, the estimate made here assumes that their first open-hearth furnace was built in 1872.

At least as difficult is the question of how much steel each furnace made. The Landore-Siemens Steel Company was making 75 tons per week by mid-1869 (about 3,800 tons per year) but the number of furnaces is not stated (Erickson 1959, 156). In mid-1874, Landore had 24 furnaces making 1,000 tons per week, nearly 42 tons per week per furnace or nearly 2,200 tons per year each. As most of the furnaces held six tons, the 1869 output may have been that of two furnaces. However, in 1874 each furnace apparently only averaged seven heats per week, when two should have been possible each shift. An average output can also be deduced by comparing the national and regional outputs in the *BITA Reports* with the number of furnaces in the *Mineral Statistics*. In 1880 and 1881 the national averages were 1,960 and 2,223 tons per furnace per year, but the regional averages differ considerably from these figures. The average at Sheffield was always well below this between 1879 and 1886, suggesting that the furnaces there were small or under-employed, while in Scotland and South Wales the averages were usually considerably higher. From 1883 the average per furnace climbed considerably, perhaps as a result of the larger furnaces being built. Jeans (who compiled the *BITA Reports*) estimated production for several previous years (Jeans 1880, 103). Applying the estimated furnace numbers to this, an average per furnace may again be estimated. This varied around 1,500 from 1874 to 1879, but was 1,613 in 1873. On the basis of this figure and the 1874 Landore output, it is suggested that a multiplier of 1,600 may be applied to the pre-1873 furnace numbers. The use of data from two different sources (the *BITA Reports* and *Mineral Statistics*) is not wholly satisfactory, since the data may not have been collected for the same period, but this does mean that production in the earliest years of the process can be estimated, producing figures somewhat lower than would be provided by simple linear interpolation.

The *Mineral Statistics* in the 1880s attribute their regional figures to the representatives of Sir William Siemens and subsequently to 'Mr Frederick Siemens', who presumably derived them from royalty receipts (*Mineral Statistics 1883*, 74; *1886*, 78). These figures are generally identical to those published by BITA. However, for 1885 the *Mineral Statistics* has figures in round hundreds or thousands of tons, so that the precise figures in the *BITA Report* (*1885*, 41) are to be preferred. As the Siemens-Martin patent would have expired by then, the family would no longer be receiving royalties. Production by the process (Fig 4, Table 1) generally increased steadily (with a pause in 1878-9), reaching 1,564,200 tons in 1889 (including the basic version of the process for phosphoric iron) and probably slightly more the next year. This was followed by a brief decline in 1892, before slow growth resumed, followed by more rapid growth from 1895, with total output exceeding 3M tons in 1899 (Table 1).

Basic steelmaking processes

Bessmer's process could only handle low-phosphorus haematite pig iron, which excluded most of the British output. This problem was solved by the Gilchrist-

Thomas process (also called Basic Bessemer). This was similar to the original (acidic) Bessemer process, but dealt with the phosphorus problem of the acidic process, by using 'dead burned' lime, calcined at over 1200°C, with sodium silicate (water glass) as binder. The early experiments were made in South Wales, but were soon transferred to the Eston Works of Bolckow, Vaughan and Co in the Cleveland ironmaking iron district, where the phosphorus problem was particularly acute. There the inventors first produced a lining material made from dolomite with hot tar, boiled long enough to expel any water. They continued the blow in the converter longer than was usual in the acidic Bessemer process. This after-blow provided steel with a negligible phosphorus content (Barraclough 1990, 206-15). Unlike the older process, there is no gap between the start of the process and the start of surviving statistical data. The experiments had been done in a 30-cwt converter, the final patent being applied for in April 1879. A six-ton demonstration vessel was in use the following month (Barraclough 1990, 212-3). A pair of 15-ton converters was built in 1880, another pair in 1881 and a third in 1882 (Barraclough 1990, 219-20). The *Mineral Statistics* describe these as 12-ton converters in 1882 and perhaps as 10-ton converters in 1881. They appear as a separate item in the 1880 statistics but were combined in a higher total for the acid-process converters in 1881 (*Mineral Statistics 1880*, 102n; *1881*, 94-5; *1882*, 78).

J H Darby developed a basic version of the Open Hearth process at Brymbo in Denbighshire from 1884 (Darby 1889). The *Mineral Statistics (1885*, 71) record three open heath furnaces at Brymbo with a capacity of 10 tons each, followed by four furnaces of the Patent Shaft and Axle Co Ltd at Wednesbury (three furnaces with a capacity of eight tons and one five-ton furnace), while the Steel Co of Scotland Ltd has one 3½-ton furnace. The *BITA Report for 1886* lists Brymbo and may include it in its total for 'other districts' but in 1887 includes Brymbo in its total under 'Wales'. The *BITA Reports* from 1885 include in their chapters on Bessemer steel a section on basic steel giving statistics back to 1880, and stating in 1885 that the seven works making basic steel included two with Open Hearth furnaces, a process which is also discussed in the following chapter of each *Report* (*BITA 1885*, 35); and there were still two in 1886 (*BITA 1886*, 40). These works seem to be Brymbo in Denbighshire and Farnley in west Yorkshire, but experiments at the latter probably failed as Farnley is not listed subsequently (*Mineral Statistics 1884-1886)*. The figures are continued in subsequent volumes, but the 1887 volume states that the 1886 and 1887 figures were for 12 months to 30 September and 13 months to 31 October respectively (*BITA 1887*, 27-9). The 1889 volume attributes these figures to 'Mr Gilchrist'. As he and his fellow patent owners had a financial interest, the figures are likely to derive from their accounts of royalty receipts. As long as there were no significant patent infringements, these are the best source for that period (*BITA 1889*, 31-2; *BITA 1890*, 31-2; Barraclough 1990, 220), but the different year-end means that an adjustment must be made for calendar year estimates. It is difficult to know whether these figures are additional to those for the original acid version or included in the total; double counting needs to be avoided. Since the basic figures appear in a section of the Bessemer chapter (not in a separate one), they are probably included in that chapter's total, rather than being additional to it; accordingly, the total needs to be apportioned. That difficulty disappears in 1889 when the *BITA Reports* start giving separate figures for each version of each process. However the *BITA Reports* for 1891 and 1892 have not been found. Possibly none were published, being replaced by a *Bulletin*, the source of data in the *Iron and Coal Trades Review* and the source used here (44 (1892), 329 and 46 (1893), 345 and 426).

For the few years before 1888, there are thus three series of statistics covering four processes (two acidic and two basic). The issue becomes how to split Gilchrist's total for basic steel between the two basic processes, so that they can be deducted from the total for both versions of each process. The key to this is Brymbo, then the only basic steel works in Wales, and one where the capacity of the plant is known from Darby's description (1889) and the *Mineral Statistics*. The 1889 and 1890 statistics suggest an output of 385 tons per ton of installed capacity. This may be applied to the installed capacity for 1884-6, giving an output of about 11,500 tons from Brymbo in 1885 and 1886. There is inadequate data for the next two years, and that gap has to be filled by linear interpolation. Once again, the contribution of the newest process, basic open-hearth, was very modest, so that the inadequacies of the estimation methods adopted are unlikely to have a significant effect on the overall conclusions.

Total output

Figure 4 and Table 1 bring estimates on all processes together. As with many processes, the arrival of mild steel did not immediately sweep all before it. The production of puddled iron continued to grow in the 1860s, reaching peaks of 4.52M and 4.73M tons in 1872 and 1875 respectively. Bessemer steel first passed 5% of the total of iron and steel production in 1870. At its all-time peak in 1875, puddled iron was still 87% of

this total. However the figures show a sharp decline in puddled iron from 1877. That was the year when Jeans criticised the *Mineral Statistics* data on furnace numbers as exaggerated, but his own rival estimate was a rough one and is hardly more credible. The North of England Arbitration Board's data on that area shows a more gradual decline starting in 1875, principally due to a decline in demand for rails. The data on Bessemer steel production in that period comes from contemporary compilations, but the growth in steel production was considerably less than the fall in puddled iron so the overall total declined.

In the 1880s care has to be taken with the data, as to whether figures quoted relate to the acid and basic versions of each steel process together or separately, to avoid double counting. However, in this period the output from all processes together was significantly lower than the zenith of output in early 1870s. This matches with what economic historians used to call the Great Depression, until there was a worse one in the 1930s (Mathias 1983, 360-8). Puddled iron production recovered slightly to a peak of 2.25M tons in 1889, with a total for all processes of 6.00M tons. There was clearly a recession in output in the early 1890s with the total output from all processes falling to only 4.39M tons in 1893. The previous peak was reached in 1899, but this time the level of total production was sustained and continued to rise beyond the end of the period covered by the *BITA Reports* (Burnham and Hoskins 1943, 27, 273-5). In 1899 the proportions of the puddling, Bessemer and Open Hearth processes were respectively 20% (and declining), 30% (and roughly stable) and 50% (and rising). In the 22 years from 1877 to 1899 the roles of puddled iron and mild steel had reversed. Puddled iron had dropped from over 80% of output to 20%, while steel output had risen from under 20% to 80%. On the other hand the growth from a peak for all processes of 5.44M tons in 1875 to 6.00M tons in 1899 is not all that spectacular, particularly as there were intervening periods of much lower output.

Difficulties over shipbuilding data have been outlined above. The compiler of the *BITA Reports* seems to have overcome these by 1888, to obtain statistics on iron and steel shipbuilding in terms of tonnage (not metal used) and these were continued in later reports. The figures up to 1885 came from a paper by B Martell with later ones returned by builders to *Shipping World* (*BITA 1888*, 58 from B Martell's 'Progress of mild steel for shipbuilding', read before the Institution of Naval Architects in 1886; *BITA 1888*, 58). These clearly demonstrate the transition from iron to steel in shipbuilding from 1% of the tonnage being built in steel in 1878 to 97% in 1890 (Fig 4). The advantage of steel was that it was stronger, so Lloyds Register accepted thinner (and thus lighter) steel plates than iron for the same class of ship, thereby increasing its cargo capacity (*BITA 1878*, 64-7; from a paper read before the Institution of Naval Architects in April 1878). As described above, the market for iron rails had collapsed in the 1870s, with the substitution of more durable steel ones. These were two major markets where the demand for puddled iron shrank substantially, replaced by steel. However, the uses of iron and mild steel were too numerous for any complete description of the transition to be feasible.

Conclusion

The need to use estimates for the 1860s and 1870s is unsatisfactory but unavoidable. It is also unsatisfactory to be using data for puddled iron, rather than finished iron, for 26 cwt of pig iron might make 23 cwt of puddled balls and 20 cwt of finished iron. However, the steel data probably refers to steel ingots, which were also not a finished product. In both cases, up to 20% of the weight would be lost subsequently as slag, scale and other waste. It is not simple to relate these figures to those for pig iron, because scrap was added in the Open Hearth process and scale (or haematite) during 'wet' puddling. Furthermore, the production of charcoal iron and of blister, crucible, and other high-carbon steel has been ignored. These were small sectors, so will not greatly change the total.

This paper has sought to throw some light on a period of great change, but uncertainties remain in some of the data that it has used, which can only be resolved by detailed further research into the histories of as many ironworks as possible. It has narrowed the gap in our knowledge of malleable iron and steel output somewhat, but a gap remains from the end (in *c*1790) of the author's series, based on finery forge and other iron plant (King 2005), until 1860. In this period, the best estimates currently available are derived from data on pig iron production, with the estimate that 70% of this was used in the malleable sector, rather than for foundry work. The pig iron data is robust, but the split between foundries and forges depends only on slight evidence. No attempt has been made here to correlate the malleable iron and steel data presented here with pig iron production: such a computation that would need to take account of pig iron exports, which the published statistics (unhelpfully) combined with those for puddled iron (*BITA 1878*, 64-7; from a paper read before the Institution of Naval Architects in April 1878). The rise of the railways, with

their demand for iron rails and other material (Hawke 1970; Vamplew 1969; Riden 1980), is likely to have had an effect on the forge/furnace split, as is the rise of the use of iron in shipbuilding. Considerable further research remains to be undertaken, particularly on the early to mid-19th century.

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Notes

1 Joseph Firmstone's widowed mother married a John Guest at Broseley on 13 October 1774. Joseph's subsequent presence at Merthyr Tydfil suggests the husband was either the Dowlais ironmaster or a close relative. If the husband was indeed the prominent ironmaster, it was his second of subsequernt marriage. The relationship is based on family history research compiled by the author's grandfather W W King, a great grandson of Joseph Firmstone and others, using the normal genealogical sources, particularly the parish registers of Broseley and Merthyr Tydfil.

2 *Mineral Statistics* (produced annually by the Mining Record Office, under the Museum of Practical Geology, 1859-1881; and by the Home Office, 1882-86). Citation is by the year described, not the year of publication. Earlier and later issues do not include relevant data on malleable iron and steel.

3 *BITA*: *Annual Statistical Reports of the British Iron Trade Association* (annually 1877-1905). Citation is by the year described, not the year of publication. The precise title varied slightly from time to time. These volumes are scarce and Mitchell Library, Glasgow has the most complete set. The British Library's set is nearly complete for 1877-90, but the only known copy of the 1881 volume is at the North of England Institute of Mining and Mechanical Engineers, Newcastle. No copy of the volumes for 1891 and 1892 has been traced; possibly none was published. A short-lived replacement, the *BITA Bulletin* is cited in *The Iron and Coal Trades Review* (44, 1892, 329 and 46, 1893, 345 and 426) from where data for 1891-2 are taken. No surviving copy of the *Bulletin* could be found in Britain, though it is possible that Harvard University has a set. For further discussion of this, see Riden and Owen 1995, xxvi-xxvii, note.

4 The units used throughout are imperial tons of 2240 pounds (= 20 cwt), which at 1016 kg are slightly larger than metric tonnes. M tons means 1,000,000 imperial tons.

5 *BITA 1877,* 95-6 and similar figures in subsequent volumes. The whole series to date appears at *BITA 1882*, 21; and is continued at *1883*, 21; *1889*, 22; *1890*, 24. The 1891 figures are from *Iron and Coal Trades Review* 44 (1892), 412.

6 *London Gazette*, 30 March 1866, issue 23092, 2149 (petition on 6 March 1866 for improvements in the manufacture of railway crossings); 3 July 1868, issue 23396, 3753 (petition on 3 July 1868 for improvements in rails and chairs for railways).

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