A question of grey or white: Why Abraham Darby I chose to smelt iron with coke

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ABSTRACT: The tendency for an iron to solidify white or grey on coming out of a blast furnace in the 17th and 18th centuries is reviewed and quantified. It is demonstrated that iron from a charcoal blast furnace could not produce the necessary grey iron in a thin-walled cooking pot cast in a cold mould. Charcoal iron masters therefore had to pour their metal into heated moulds, which obliged them to use the costly loam moulding process. Abraham Darby's great breakthrough was realising that iron made with coke could produce a grey iron pot in a cold mould, which allowed him to use the much cheaper green sand process. His patent tells us he realized this several years before moving to Coalbrookdale. Part of the evidence for this assertion involves identifying castings made with each process. A pot in the Ironbridge Gorge Museum is identified as the oldest known coke-iron casting made in the western world.

Introduction

The development of the industrial revolution could justifiably be ascribed to the inventions of new cheap mass production processes, inevitably powered by coal. Abraham Darby I (1678–1717) is known as the man who pioneered the use of coal in the form of coke (instead of charcoal) for the production of iron in the blast furnace, but less known is that he also simultaneously introduced a new mass production process, that of green sand moulding. He actually invented neither of them, but he put them together in a commercial enterprise of a type which had not been seen before and which became, throughout the 18th century, a significant contributor to the early days of the industrial revolution. Yet nobody has properly grasped exactly why he chose to use coke in the first place.

Certainly the use of coal as a replacement for wood in other industries was proceeding apace at the time on purely economic grounds (Neff 1966, 222) and ironmasters would have liked to have been free of the restrictions and difficulties that ensuring their supply of charcoal presented, but in its early days coke-iron was actually more expensive than charcoal iron (Hyde 1977, 32–36; King 2011, 135–136; Mott 1957, 9). There had therefore to be another driver beyond general economics.

In this paper it will be concluded that Darby knew before he moved to Coalbrookdale in 1708 that he was going to use coke in his furnace, and that he must have fully grasped the technicalities of coke iron, both in its production and in its properties, before he had ever run a blast furnace himself. It is also shown that he identified the sole application for coke iron that at that time represented a commercial proposition. Commentators (rather amazingly in retrospect) have said what remarkable fortune it was that coke iron was so good for the manufacture of the pots that were the subject of his moulding patent (Raistrick 1970, 25; Rehder 1987, 40; Cox 1990, 131). It will be shown here that it was not just good fortune: he knew exactly what he was doing. The same commentators have put this fortuitous application to pot making down to a higher fluidity coming from

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the higher temperature that a coke-fired furnace reached. Fluidity was important, but it was not the only factor; whether the iron would solidify grey or white was much more important.

The difference between the two irons is explained below, as are their different uses, how different degrees of greyness were required to make different castings and how alloy composition affected the issue.

The Patent of 1707

The outline history of Darby's great breakthrough is well known (Raistrick 1970, 17). He was apprenticed as a smith in the Midlands, went to Bristol in 1698 to practice the manufacture of malting machinery and then in 1702 took on the management of the new Bristol Brass Company. Whilst still doing this, he set up an independent iron casting facility and experimented with casting cooking pots, using an air furnace to re-melt iron that he bought from blast furnaces within reach by water. This culminated in the successful filing of his only patent, Number 380, of April 1707 (Raistrick 1970, 22):

> 'Our trusty and well beloved Abraham Darby, of our city of Bristol, smith, hath by his petition humbly represented unto us that by his study and industry and expence he hath found out and brought to perfection, a new way of casting iron bellied pots and other iron bellied ware, in sand only, without loam or clay, by which iron pots, and other ware may be cast fine and with more ease and expedition, and may be afforded cheaper than they can be by the way commonly used, and in regard to their cheapness may be of great advantage to the poore of this our Kingdome, who for the most part use such ware, and in all probability will prevent the merchants of England going to foreign markets for such ware, from whence great quantities are imported, and likewise may in time supply foreign markets with that manufacture of our own dominions and hath humbly prayed us to grant him our Letters Patents for the sole use and benefit of the said Invention for the terme of fourteen years.'

There are three very particular statements in the above:

- I want to make pots
- I can make them much more cheaply than hitherto
- I use sand without clay

Why cooking pots? The implication is quite clear, everybody had to eat, everybody cooked, but the poor could barely afford the means to do so. Making the pots cheaper would mean the creation of an extended market, and not only in the British Isles.

Why were cooking pots expensive? Quite simply, they were the most difficult castings to make in the 17th century. The difficulty was their very thin walls. Thin castings chill the metal very quickly as it comes in. It has to be very fluid and very hot to get to the extremities of the casting without solidifying as a 'cold shut'. Such fluidity issues would have applied to all metals, but with cast iron, there was another difficulty, the issue of grey and white metal which is discussed below.

The thesis presented here is that 17th- and 18th-century charcoal blast furnaces could not practically produce iron with a composition which would solidify grey in a thin (less than 5mm) cold mould. Iron masters therefore had to pour their iron into a mould which had been heated to a high temperature, and there was only one moulding process which could be so heated: a loam mould that contained a lot of clay.

Darby was not going to use clay and therefore not loam moulding and thus he could not heat his moulds. He was therefore going to use an iron which would solidify grey in a cold mould. In fact his moulding process did use a little clay, but not added clay. It used sand as dug out of the ground, with a few percent of a clay-like material already in it, which when moistened would hold together the sand in whatever shape it was squeezed into. This was the green sand process, 'green' because it was not dried and metal was poured in while it was still damp.

It must be admitted that there have been suggestions that he used the dry sand process (Schubert 1957, 268; Mott 1957–58, 80), but this cannot be true. Dry sand has always been a minority technique, used only when extra strength was needed in the moulding sand, particularly when casting steel. Furthermore, dry sand does involve the use of extra clay, together with baking the moulds in large ovens and is accordingly much more expensive than green sand. Schubert and Mott's texts appear to suggest that they did not properly understand the difference between green and dry sand.

Duhamel de Monceau described the sand moulding of a pot (1774, 206–212), including digging up just the right quality of sand near Paris and moulding the pieces without the addition of any further clay and not using any heating at all. To this day, green sand is the universal method for the manufacture of long-run iron castings.

White and grey iron

The topic of the colour of cast or pig iron has been discussed in all general treatises on iron since the second half of the 18th century (among them Karsten 1841, 566–606; Percy 1864, 116–129; Elliott 1988, 1–4). The product of the 17th–18th century blast furnace was a liquid alloy of iron in which was dissolved 2.5–4.5% of carbon, but in which there were also a number of other accidentally-introduced alloying elements. This alloy could solidify into two very different solids. One of them was known as white and the other as grey cast iron.

The iron masters, even in the 17th century, knew this very well without in any way understanding what happened to cause the phenomenon. They coined the terms because it was obvious that the two types of iron were quite different and if a newly broken surface was examined it looked either white or grey. It was not only the appearance that distinguished them though, other features were equally obvious and were acknowledged in writings of the time. The white iron was very hard and it would easily scratch the grey. It could not be cut with the steel tools of the day, nor filed. It was extremely brittle and would fly into many pieces if hit violently with a hammer. If hit gently with a hammer, it would emit a pleasant, continuing ringing tone. When allowed to solidify slowly within an open top mould, it would show a pronounced concave surface (provided the evolution of dissolved gases did not mask it) because it shrank on solidifying. When reheated it melted much more quickly than grey iron and if held just below its melting point for a considerable period, it would soften and become less brittle.

Grey iron on the other hand could be easily cut or machined. Whilst still quite brittle, it was clearly much less so than white iron. When struck gently with a hammer, it made a much more dull and short-lived sound and when allowed to solidify with an open upper surface, that surface would be either flat or even slightly convex, because it did not shrink on solidifying. It took longer to melt and however long it was held at a temperature just below its melting point, it did not become malleable.

Because of its quicker melting, even 19th-century metallurgists thought that white iron melted at a much lower temperature than grey iron but they were wrong, modern measurements put the difference at only a few degrees. Although it liquefied more quickly it did not seem to melt properly. It was rather pasty at first and then became more fluid as the temperature was increased. In contrast, when grey iron did finally melt, it was clearly a proper fluid liquid.

Yet grey and white irons were nominally the same metal. In fact, the two appearances could come from the same melt and could even be found simultaneously in the same iron casting. They could even be found intimately mixed together, when the colour was described as mottled.

The completely different properties of these two materials fitted them for two different principal applications in the three centuries leading up to the 1900s. The properties of a white iron made it very suitable for turning into bar iron while those of grey iron made it the ideal casting material. It was primarily the difference in viscosity between the metals which was critical when it came to fining the iron into bar, whether in the original charcoal hearths or in the coal-fired puddling process. The pasty white iron could be rabbled to expose a large surface area to oxidation, but it was difficult to get oxygen below the surface of a slag-covered, properly liquid, ex-grey iron.

That grey iron was converted only with extra difficulty into bar iron is contrary to an assertion by Schubert (1957, 286) who has caused historical mischief among some non-metallurgists by stating that it was the other way round (*eg* Awty 1996, 18). To see how Schubert was wrong, it is only necessary to look at a table just one page further on from the principal reference that he gave in support of his assertion (Percy 1864, 608–609). On page 610, Percy, reporting the work of Thirria (1840, 285), reproduced a table comparing the costs and charcoal consumptions of bar iron made from white, mottled and grey pig, making it quite plain that such was indeed the order of commercial merit. Schubert's other reference was Karsten, in the first edition of 1816. The second edition of 1827, translated into French by Culmann (Karsten 1830, 253), has a section that deals specifically with the question and makes it quite clear that 'pure white iron deserves the preference, whatever the decarburisation method'.

Modern understanding

By the middle of the 19th century scientists had worked out the reason why the two types of iron existed. It has to do with the manner in which the carbon precipitates from its solution in both the liquid and the solid state as it cools. It is a chemical phenomenon, beautifully illustrating the twin laws of thermodynamics and kinetics. Thermodynamics is the science that tells us what chemical reactions want to happen, based on the study of the lowest energy states into which nature can arrange itself. The lowest energy state is the one that wants to result most, as it were. Whether it is allowed to and how quickly it can arrive there, is a matter for the science of kinetics to decide. Kinetics is about how easily and quickly the atoms and molecules in state 1 can move themselves about in order to rearrange themselves into state 2. Thermodynamics proposes, kinetics disposes.

The state that thermodynamics wants to see is grey iron, but under certain circumstances the kinetics will not allow it, and white iron results. In grey iron, the carbon has to precipitate as elemental graphite, a soft black plate-like material, slippery in a large lump because the chemical bonds align only in two dimensions and platelets slide over one another. If graphite cannot form for lack of time at a high enough temperature, then a higher energy content (and therefore metastable) iron-carbon compound, iron carbide (Fe_3C, also known as cementite) precipitates instead. This is a hard crystalline compound which when spread evenly throughout the metal gives white iron its properties. White iron is pasty when first molten because at the particular carbon composition where it occurs, a solid and a liquid coexist in thermodynamic equilibrium, for which an understanding of the iron carbon phase equilibrium diagram is necessary (Fig 1).

In grey iron, when graphite precipitates, it is a much less dense solid than either the iron matrix or iron carbide and the resulting increase in volume compensates for the natural liquid-to-solid shrinkage of the iron, hence the flat top on open-cast ingots. The graphite also acts as a vibration dampener, which is why a bell made of grey iron does not ring. Graphite is soft and helps to lubricate cutting and machining operations; to this day grey iron is the most easily machined of metals. Grey iron melts like a true liquid because the compositions at which it forms are very close to the eutectic point on the phase diagram where, as it cools, a liquid with one unique composition of iron and carbon solidifies simultaneously into two solids at just one temperature.

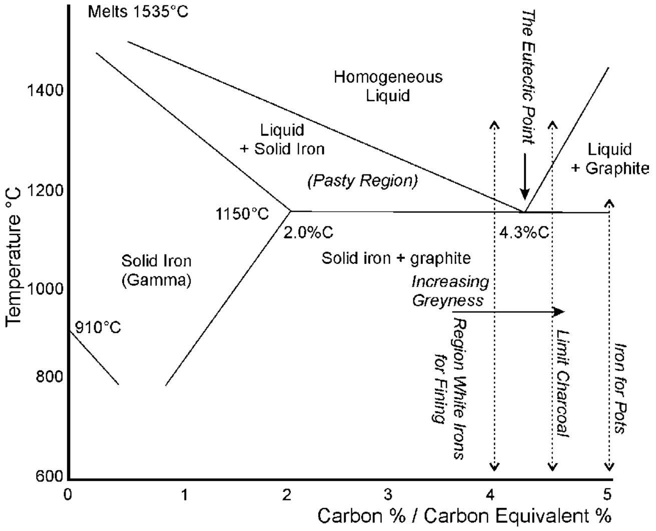

Figure 1: A simplified version of the iron-graphite phase equilibrium diagram. It illustrates which phases exist for any combination of temperature and carbon content. The positions of white irons and grey irons are indicated.

The principal mechanisms in the kinetics of graphite formation are nucleation and then diffusion. An initial micro-concentration of carbon atoms, very often on top of a minute foreign body, is followed by the passage of atoms from the body of the metal to these nucleation points. These mechanisms require time and temperature. Modern practice is to encourage the nucleation of graphite by the use of externally added inoculants (Elliott 1988, 79–85). Without inoculants, before the 20th century, for the iron to achieve its stable, equilibrium, lowest-energy state (that of a mixture of iron and graphite) it needed above all else to be cooled relatively slowly. When cooling a quantity of liquid iron in a mould, the rate-controlling factor was the section thickness of the solid metal which was to result. That is, thin-section castings cooled much more quickly than thick-section ones and were thus more likely to turn out white than thicker ones. But time and temperature (time at temperature) were not the only influences.

The presence of other alloying elements besides carbon interfered with both the thermodynamics and the kinetics and made it more or less difficult for one or other of the two forms of carbon precipitation to happen. The most important of these elements was silicon and this carbon-like metalloid played a very large part in the metallurgy of the industrial revolution. Its presence strongly promoted the formation of graphite and therefore of a grey iron. Phosphorus did the same. Other elements (particularly manganese and sulphur) theoretically made a difference in the opposite direction but in practice phosphorus and silicon were the two chief alloying elements of consequence when it came to the issue of grey or white iron. Neither could be present in great excess because of other problems that they created, but an iron containing 2% silicon and 1% phosphorus was not unusual in a casting in the 18th century in the UK.

Carbon itself also influenced the outcome. The more of it in liquid solution, the greater was the tendency for it to precipitate as graphite as that liquid solidified.

Carbon equivalent

Carbon, silicon and phosphorus come together in an expression which ferrous metallurgists have found useful for many years, the carbon equivalent (CE) which, it turns out, is a useful measure of the tendency of an iron to turn grey. It was empirically obtained when metallurgists noted that silicon and phosphorus dissolved in the iron had much the same effect on the position of the eutectic point. In fact, their presence moves the eutectic point, as well as the solubility line for carbon, one percentage point to the left for every 3% by weight of the combined additions of the two elements. The carbon equivalent therefore became defined as

CE% = carbon% + 1/3silicon% + 1/3phosphorus%

The point of the carbon equivalent is that the eutectic point, 4.3% carbon in a pure iron-carbon alloy, continues to appear at a carbon equivalent of 4.3% when that alloy is modified with silicon or phosphorus.

There is evidence that a relationship exists between the phenomenon that the carbon equivalent originally defined and the influence that the same elements have on graphitisation. The work of Zhukov (as reported by Elliott 1988, 77) particularly supports this, in that he used thermodynamic reasoning to show that the influence of silicon and phosphorus on graphitisation demonstrated the same 3:1 ratio in their effects relative to carbon. A simple test of this may be made using data from the days before modern cast iron technology developed between the two World Wars. In the 19th century the classification of cast irons was entirely based on their degree of greyness. A standard sample, normally a sand-cast pig, was broken and examined and rated, typically as white or mottled, then numbered from 5 to 1 in increasing order of greyness. The picture given of each grade by Wilkie (1857, 45–46) is among the best, but it will be apparent from studying his descriptions of each one that the system was open to a considerable degree of individual interpretation.

Around 1900 many people published chemical analyses of the historical grades of iron (Forsythe 1909, 308; Greenwood and Sexton 1907, 54; Bauermann 1890, 272) and it is possible to calculate the carbon equivalents of such grades to compare them. Table 1 demonstrates that in general the higher the grade (perversely, the lower the number) the higher was the carbon equivalent. The results are for a number of different coke-fired blast furnaces throughout Britain and show that Grade 1 irons tended to have a carbon equivalent approaching 5%, whilst the Grade 4 irons were nearer to 4% and the sole Grade 5, to 3%. There is not a perfect correlation but it would be remarkable if there were, given the haphazardness of the grading system and of the early analysis techniques.

Table 1: Carbon equivalent calculations for cast irons of various grades from a number of British blast furnaces.

Blast Furnace	Grade	C%	Si%	P%	CE %
Eglington	1	3.68	2.84	0.95	4.94
	3	4.03	2.10	0.98	5.06
	4	3.48	1.40	1.00	4.28
Gartsherrie	1	3.35	2.45	0.75	4.42
	3	3.35	2.00	0.75	4.27
	4	3.10	1.65	0.76	3.90
Summerlee	1	4.18	2.85	0.91	5.43
	3	3.76	2.78	0.86	4.97
Merry	1	3.97	3.29	0.96	5.39
	3	3.64	2.87	1.08	4.96
	4	3.90	1.61	0.94	4.75
Carron	1	3.63	2.44	1.09	4.81
	3	3.46	2.16	1.13	4.56
Newport	1	3.40	3.30	1.50	5.00
	3	3.35	2.80	1.46	4.77
	4	3.35	2.50	1.48	4.68
Cleveland	1	3.50	3.30	1.51	5.10
	3	3.45	3.00	1.50	4.95
	foundry iron	3.40	2.50	1.50	4.73
Clarence	1	3.30	2.91	1.50	4.77
	3	3.29	2.70	1.64	4.74
	4	3.20	2.02	1.50	4.37
Skinningrove	1	3.35	3.26	1.71	5.01
	3	3.02	2.95	1.53	4.51
	4	3.16	2.35	1.53	4.45
Crazebrock	1	3.07	1.48	0.43	3.71
	2	3.04	1.27	0.34	3.58
	3	3.12	1.16	0.44	3.65
	4	3.03	0.83	0.31	3.41
	5	2.81	0.57	0.29	3.10
Madeley Wood	2	3.67	1.47	0.46	4.31
	3	3.49	1.29	0.48	4.08

Note: Data from Bauermann 1890, 272.

More meaningfully, several writers published recommended iron compositions for specific casting types, particularly rated by casting thickness. Founders always wanted an iron that would just be grey in the section size being cast, so for each casting type, they used the lowest greyness specification that would still enable them to make a satisfactory grey casting. If the iron had a greater grey tendency than was necessary for a particular section thickness, the resulting structure would be coarse and weak.

Table 2 contains the recommendations of Forsythe (1909,

Table 2: Carbon equivalent calculations for coke-irons of various section sizes.

Section inches	C%	Si%	P%	CE%
0.25	3.50	3.25	1.00	4.92
0.50	3.50	2.75	0.80	4.68
0.75	3.50	2.50	0.75	4.58
1.00	3.50	2.00	0.70	4.40
1.50	3.50	1.75	0.65	4.30
2.00	3.50	1.50	0.60	4.20
2.50	3.50	1.25	0.55	4.10
3.00	3.50	1.00	0.50	4.00

Notes: Data from Forsythe 1909, 312; he omitted carbon content so a value of 3.50% has been assumed. 1 inch = 25.4mm.

312) in terms of carbon, silicon and phosphorus and the resulting calculated carbon equivalents. He gave his recommendations for castings of specific wall thicknesses, irrespective of application. It will be observed that there is excellent fit with the CE hypothesis, with castings of wall thicknesses of less than a quarter of an inch (6mm) requiring a carbon equivalent approaching 5% and his thickest castings at 3 inches (75mm) requiring an iron with a carbon equivalent of 4%.

Moldenke (1917, 177) recommended iron compositions for specific applications, noting only that in many applications, different compositions were required for thinner or thicker castings (Table 3). The table has been ordered by the calculated carbon equivalents but again the picture seems quite clear, the thinnest castings require a carbon equivalent of 5%, thicker ones much less. It is of note that Moldenke included gun iron in his collection. He said that this was the sort of iron that was used to make cannon in the past and had retained the name accordingly. White iron is included because it does have a few casting applications, particularly where wear resistance is required. Note that Moldenke recommends a composition for this which represents a carbon equivalent of only 3%.

Table 3: Compositions (and calculated carbon equivalents) recommended by Moldenke (1917, 177) for coke-iron castings of various types.

Application	C%	Si%	P%	CE%
Light ornamental work	3.75	2.75	1.25	5.08
Thin agricultural	3.75	2.75	0.80	4.93
Decorative hardware	3.75	2.50	0.80	4.85
Light machinery	3.75	2.50	0.70	4.82
Heavy machinery	3.25	1.50	0.50	3.92
Gun iron	3.00	1.00	0.30	3.43
General white iron	2.50	0.75	0.75	3.00

Cast irons from charcoal-fired furnaces

It is possible to demonstrate that there was a limit to the carbon equivalent that, in general, a charcoal furnace was capable of delivering. In 1948, L'Usine des Vennes celebrated the first 400 years of its history. Evrard and Descy (1948, 232) included in their history of this foundry near Liège in Belgium analyses of over 100 castings dating from the 16th–18th centuries, all of them from charcoal-fired blast furnaces in northern Francophone territories. They sorted their castings by section size and discussed their results in terms of sections over 25mm, of 5–25mm and under 5mm. Their results are summarised in Table 4 which shows that the iron masters of those days also varied their compositions to suit their casting thickness. There is an interesting report by Henri Fournel (1839, 1–5) when he showed that a blast furnace supplying the casting trade used over 40% more charcoal per ton of iron on average than an otherwise very similar neighbouring one in the Haute Marne supplying the bar trade. To make a really grey iron might well have taken twice as much charcoal as was required to make a white iron. There were economic as well as technical reasons not to make an iron too grey.

However, it is Evrard and Descy's pots that are of interest here. They were all reported to have a wall thickness of less than 5mm, comparable with pots in the Ironbridge Gorge Museum made by Abraham Darby, and their carbon equivalents are considerably higher than those shown for medium and thick section castings (Table 4). However, Evrard and Descy (1948) were themselves quick to point out that even these compositions were not high enough for the pots to have turned out grey in such a thin section, which accords well with the recommendations in Table 2. They should not have been grey, but when looked at under a microscope, they quite definitely were. Evrard and Descy asked how this could be? They thought, rather unconvincingly, that it might be down to very small levels of zinc, or possibly arsenic.

Table 4: Compositions and calculated carbon equivalents for charcoal-iron castings of different section sizes compared with white charcoal-irons intended for fining.

	C%	Si%	P%	CE%
Moldenke thin sections	3.75	2.75	0.80	4.93
Evrard pots	3.89	0.91	0.86	4.47
Evrard medium section	3.67	0.85	0.93	4.26
Evrard heavy section	3.51	0.60	1.06	4.09
*White charcoal pig for fining	3.57	0.35	0.14	3.74

Notes: Data from Evrard and Descy 1948, 232 and Moldenke 1917, 177. * = values averaged from those given by Bauermann 1890, Greenwood and Sexton 1907 and Percy 1864.

They quite categorically ruled out that the moulds might have been heated, noting that Réaumur had reported that thin pieces were cast by this means, 'but we know that they did not use this inconvenient and costly process'; they did not say how they knew. Cyril Stanley Smith, who provided the technical input for the translation of Réaumur's earlier work, also disbelieved Réaumur's assertion that moulds were heated (Sisco and Smith 1956, 375).

Casting iron into preheated moulds

There appears to be no reference in any work in the English language that moulds needed to be heated in order to make pots before coke-smelted iron came along. However, there are many references to this practice in the francophone literature. Réaumur's assertions (1761–2, 105) are convincing and he was not alone in making them. Similar statements were reproduced in most of the encyclopaedias of the time; for instance in Diderot and d'Alembert (1779, 26):

> '… finally the mould needs to be more or less hot, depending on whether the pieces to be cast are more or less thick'.

Macquer's statement in his earliest dictionary (1767, 517):

> 'A precaution that is absolutely essential to take before casting is properly to heat the moulds to a very high degree … they also need to be hotter or colder depending on the quality of the cast iron that will fill them. Finally the mould must be hotter or colder depending on whether the pieces which are moulded are less or more in thickness.'

is equally included in his later one (Macquer and Jaubert 1773) and also faithfully copied in the *Encyclopédie* of Diderot and d'Alembert (1779, 26).

Réaumur did write about heating dry sand moulds, remarking though that they would have to be encased in iron boxes rather than ones made of wood; perhaps that is what Smith thought to be totally impractical (Sisco and Smith 1956, 375). But when it came to the manufacture of thin castings, particularly pots, he explained the superiority of loam (Réaumur 1761–2, 102):

> '… but the real reason is that loam moulds are much less dense than moulds of sand and they can be heated much more easily'

Duhamel de Monceau, in his article on loam moulding pots in the *Description des Arts et Métiers* (1774, 214) writes:

> '… but it is not possible to heat sand moulds (as one is obliged to heat loam moulds) which causes quick cooling. Besides, and for this reason, there remains more moisture in sand than in the loam, which causes bubbles.'

while Hassenfratz (1812, 264) also contrasts the two mould materials:

> 'loam moulding … takes longer and presents a little more difficulty than moulding in sand … but it produces a much sweeter iron, more easy to work, because the moulds can be easily heated.'

It is clear from these authors that before Darby and coke-smelted iron, the makers of the best, thinnest pots used the loam process only because they had to. Heating a loam mould *per se* was not actually an additional problem, as Duhamel de Monceau (1774) hints. The last stage in the manufacture of a loam mould, irrespective of whether the metal was going to be cast into it hot or cold, involved heating it to red heat. This was partly to render it hard and strong, but also to improve the passage of gases through the wall. Hot molten metal both released and generated gases, which if not removed from the mould through the wall, left a void in the casting or even caused it to explode. Moulds were therefore always made to be permeable. Besides the basic clay/sand mixture, organic material in the form of horse hair, farmyard manure and straw was added to the loam mix before moulding (Sharp 1905, 414). Burning this out left porosity in the mould, but it had to be done near red heat. The result was a finished, very hot mould ready for immediate pouring. Thus all that was necessary to pour iron into a heated mould was to coincide the finish of firing with the onset of pouring, but loam moulding was still overall an expensive process.

Readers following up the foregoing references might be puzzled that in spite of all the recommendations to use loam for making pots, when Duhamel de Monceau (1774) described the (green) sand process, he chose the manufacture of a pot as his example. Certainly thick-walled pots could be made in that way with the greyest iron that a charcoal furnace could muster, but it may very well have been that he was describing what he knew happened in England. Gabriel Jars had visited England in 1765 (cf Duhamel de Monceau 1774) and came back as a great enthusiast for coke in foundry work. He reported verbally before the book about his travels appeared (Jars 1774). His work led directly to the first coke fired blast furnace in France at Le Creusot in 1782.

The implication from the results of Evrard and Descy (1948) is that the maximum practical carbon equivalent that could come out of a charcoal blast furnace, at least in the northern Francophone areas, was only about 4.5%, good enough according to Forsythe to cold-cast something of half an inch (12mm) thickness, but not less. Charcoal furnaces could therefore use green sand to make firebacks and weights etc, without trouble. They could also make cannon, requiring a carbon equivalent of only 3.4% (Table 3), but for that they did actually use loam, probably because it was not deemed economic to make patterns for such large castings, which tended to be required in the early days in small quantities and in many different sizes, and because the shape of a cannon lent itself very easily to the loam moulding process.

How to recognise a loam-moulded pot

For the moulds to have been heated, Evrard and Descy's castings would have to have been made in a loam mould. They did not discuss the moulding technique, but it is easy to show that they were, because these pots still exist and a pot moulded with loam can be readily differentiated from one made with either green or dry sand. Each process leaves its own unique mark on the pot that was made using it.

Loam moulding involved the use of sand with perhaps 25% of clay added to it. The resulting mixture, when suitably wet, could be treated and shaped like the material used to make an earthenware pot. It was most useful for making a casting which was symmetrical about a single axis. The core (the inner shape) and mould for making a cast iron pot were turned on a sort of lathe, whilst being shaped against a cut-out strickle board (Fig 2). The core was shaped with one board and then a slightly bigger one was used to add a weaker mix over the core, the thickness of which would be that of the casting itself. It was in effect the pattern, known in French as the *chemise*. Finally, a thick coating was put on top of that, known as the *manteau* or *chape* (cope in English), together with the added moulded pieces that were to make the feet and ears of the final pot and a sprue cup into which the metal would be poured. Figure 3 demonstrates what happened next. After it all had been dried to a certain extent, a knife was used to cut the outer layer into two parts in a vertical plane. The *chemise* was then broken off and the *manteau* reassembled around the core with extra clay, inevitably involving a slight misalignment. It will be appreciated it is this mismatch that leaves a tell-tale mark on the finished pot.

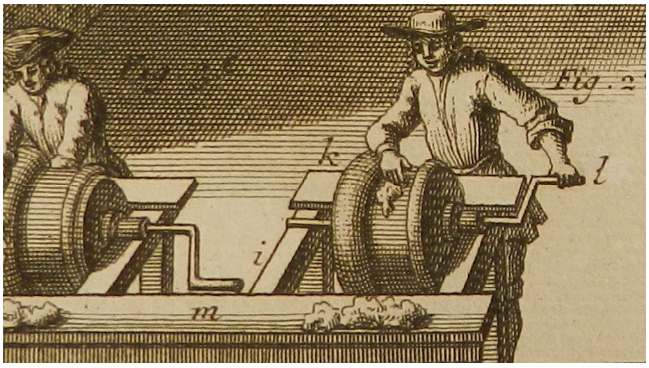

Figure 2: The first stage in making a loam mould: forming the core with a lathe and a shaped board. From Duhamel de Monceau 1774.

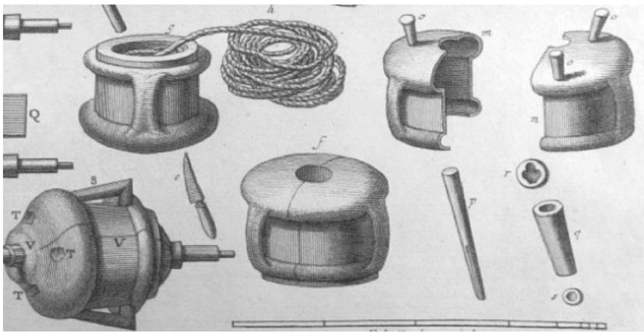

Figure 3: Further stages in making a loam mould: splitting the outer layer to give the characteristic parting line. From Duhamel de Monceau 1774.

Twenty of Evrard and Descy's pots were checked by the author at the Maison de Métallurgie in Liège in March 2014 and three more were observed on display in the Musée de la Vie Wallonne there. All of the castings with a wall thickness of 5mm or less demonstrated the characteristic parting line of a loam-moulded pot (Figs 4 and 5).

Figure 4: An 18th-century loam moulded pot, showing the characteristic parting line. MM Acc Num 38128. 200mm diameter.

Figure 5: Another 18th-century loam moulded pot, showing the characteristic parting line. MM Acc Num 28332. 230mm diameter.

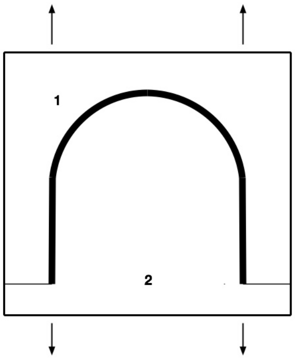

Figure 6: The two parts of a mould for the simplest green sand casting, that of an un-bellied pot.

The evidence that these pots were all loam moulded does not mean that the mould had to have been heated as they could have been manufactured and then allowed to cool down, but the castings would not then have solidified grey, and using cold loam moulds seems extremely unlikely in the light of the sources quoted above.

Green sand moulds

A green sand mould left a very different set of parting lines. Green sand casting used a permanent pattern, which had the plastic-consistency green sand rammed around it within the confines of a moulding box. The main pattern had to be extricated in one piece (although feet and ears were moulded with separate inserts which were removed first) and the design of the mould had to permit this. Different complexities of casting required different complexities of mould. The simplest unbellied pot could be made with a two part mould, providing that there was a small amount of taper in the pattern design to facilitate its withdrawal (Fig 6). Such a pot would exhibit only a single parting line, which would lie around the open rim. In this position it was easy to clean off and so it is not usually visible.

Figure 7: Pot made from a three part mould, with a central horizontal parting line. John Edwards collection. 320mm diameter

A simple single-bellied pot required a three-part mould, although one part, required to make the internal shape, was the core. The outer part of the mould was in two halves, parting at the point of maximum diameter of the pot. A pot cast in this way exhibits a parting line at that point (Fig 7).

The full, re-entrant bellied pot (Fig 8) required a five part mould, comprising a core, a top and bottom and two central pieces which had to slide sideways to permit the removal of the pattern, leaving a very characteristic set of parting lines (Figs 9 and 10). Note in Figure 10 that there is no trace of a line passing underneath the pot, as is found in those pots cast in loam moulds, nor are there any such lines on any of the other pots on display at the Ironbridge Gorge Museum. Also in the Ironbridge Gorge Museum is a fine example of a four-part moulding box made to contain just such a mould (Fig 11).

There is however, one complication that should be borne in mind. Quite often a casting is found that appears to exhibit both sets of parting lines. The pot in Figure 12 bears the name of the Carron Company, which company exclusively used coke in its blast furnaces. The marks of the four part green sand mould are clearly visible, yet there is a faint parting line passing all the way under the pot too. There are two ways in which this feature can arise. The Coalbrookdale pots appear to have been made using a full pattern for the outside shape and a separate split core box for the inside, but apparently moulders sometimes used a single iron pattern that could be split to make both mould and core (Sharp 1905, 379–80). The split could leave a very fine parting line in exactly the place that a loam moulded pot would exhibit it. Secondly, coke foundries apparently often made their first iron patterns with loam moulding (Sharp 1905, 379–80) or indeed simply used earlier loam-moulded pots. The parting line on the original casting would leave a much fainter one on the subsequent green sand ones.

The limitation of charcoal blast furnaces

Why could a charcoal blast furnace not produce a greyer iron? Actually it probably could and under certain circumstances perhaps did, but not consistently and,

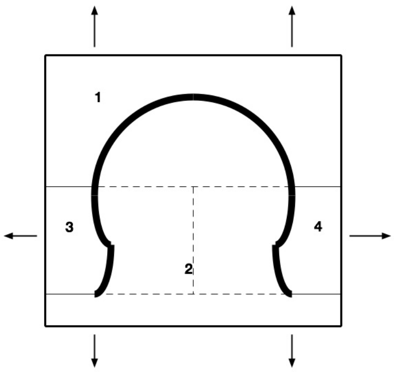

Figure 8: The five parts of a mould for making the true double-bellied pot, showing the positions of the parting lines.

Figure 9: Cast iron pot made using a mould of the type shown in Figure 8. The two upper horizontal lines are decoration but the bottom one is a parting line, as is the vertical line. IGMT Acc Num 1993.5731, 400mm diameter.

Figure 10: The pot shown in Figure 9; note the absence of any loam-type line across its base.

Figure 11: Set of iron moulding boxes for the manufacture of pots like those shown in Figures 9 and 10. IGMT Acc Num 1997.623–5. 300mm diameter.

Figure 12: A spurious, much fainter line across the base of a green sand moulded pot, revealing that the original pattern was made with loam. John Edwards collection. 300mm diameter.

above all, not economically. In areas where an ore was conducive to greyness and the charcoal was of the right quality, many charcoal furnaces naturally produced an iron which was greyer than usual. The most interesting of these areas was Franche Comte, where iron masters developed a special fining process to make wrought iron because they could not easily make a white *gueuse*, the heavy section single cast sow which was the standard output of a French furnace making iron for the forges.

The universally accepted explanation for the greater grey tendency of a coke iron is that such a furnace worked at a higher temperature than a charcoal one and that the iron absorbed more silicon as a result (Rehder 1987, 38; Tylecote 1991, 214). The author explained to the Historical Metallurgy Society's Conference in June 2015 why he believed this to be a significant oversimplification (Williams in prep).

The Darby breakthrough

Making a pot with the loam process, whether the mould was poured hot or not, was clearly time-consuming, demanding of skill, and expensive. With green sand moulding, once a pattern had been made, or adapted from a previous casting, a relatively unskilled workman could produce moulds in large numbers. There was no process waiting time involved; once made the mould could be cast immediately. There is no doubt which process was the cheaper, but it needed an iron that would turn out grey when cast into a cold, thin-walled mould. As is now well understood, what came out of a coke-fired furnace was just such an iron. Clearly, when Abraham Darby petitioned for his patent, he knew it; indeed he may well have known it for many years.

It is clear that by the time Darby was doing his experiments in Bristol a great deal of knowledge about smelting iron with coke had been accumulated and there are several postulated routes by which Darby could have known about it. Many failures were catalogued by Ashton (1963, 10) and also by Dudley (1665, 16–19) amongst others, but at least three attempts before Darby probably had some success, those of Dud Dudley, Thomas Middleton and Shadrach Fox.

Some people have decried Dud Dudley's claims to have smelted iron with coal in the 1620s (Mott 1934, 31, Ashton 1963, 11), but others have supported his claim (King 2002, 43). There is one good reason to believe him following the above. He specifically mentioned that it was grey iron that came from a coke fired furnace (Dudley 1665, 24).

Abraham Darby was born and lived within a few miles of where Dudley had done his first work 60 years before. Both Darby's father and grandfather were also born and lived in the same area, they too were smiths and must have known what had been going on. There is even the possibility that Abraham's paternal grandfather had married Dudley's niece (Higgs 2005). If Higgs is correct, this grandfather's life overlapped with Dudley's for some 66 years, with Darby's for 20 years and his brother-in-law, Edward Parkes, or Parkehouse, was a confidant of Dudley's and mentioned in the Mettallum (Dudley 1665, 6).

There must also have been a considerable amount of experimenting with coke, about which we know nothing. It was extremely easy to do this. Charcoal furnaces often had to shut down for lack of fuel and the temptation to try a substitute at that stage must have been immense. There was no need to spend any extra capital (although a bigger water wheel would have been a help to provide the extra blast). Henry Powle, reporting on iron making in the Forest of Dean (1677, 934) noted in passing that they had tried (several times) to use coke there, but failed to make it work. All the news of the experiments would have got about somehow, gossip must have been as much sought after then as now in the trades. One can imagine a conversation about coke iron that would finish up with: 'Ok, it's alright to make castings with, but it's rubbish for making wrought iron and who just wants to make castings?' Apart from cannon-founding, there were no specialist casting businesses around at the time, and something like 95% of blast furnace output was turned into bar by the forges. But by the 1690s it is clear that considerable knowledge had been built up about making and using coke iron. Somebody was soon going to realize where the commercial opportunity lay. History might have recorded that it was a man called Shadrach Fox, who apparently used it to make ammunition for cannon, including hollow grenado shells (quite pot-like), delivering them to a government agent in Bristol in at least 1693 and 1695 (King 2001–2, 40).

Darby must have known about Fox, who it is now widely accepted smelted iron with coke at Coalbrookdale from the early 1690s until probably the very early 1700s. King (2001-2) has pointed out the connection between Fox and the Governor and Company for the Making of Iron with Pitcoal. Among those involved in this business were Thomas Addison (who patented a coke iron process in 1692 and used coke at Cleator in Cumbria), Sir Clement Clerke and Shadrach Fox's brother Thomas. Whatever the commerciality of Fox's process, he was singularly unlucky; the date of his furnace being inundated with water is given as 'not later than 1703'. He subsequently went to Russia to work for Peter the Great, but died shortly after arriving there. Darby would have experimented with iron from up and down the Severn before settling on Coalbrookdale, or could have known from the moment he first thought of producing iron pots that he was going to use coke iron and that Coalbrookdale was the place to go. It is entirely possible that the men who had worked for Fox were still about and helped him set up.

A 300-year-old pot

There is in the Ironbridge Gorge Museum, a cast iron pot of simple, non-bellied shape, which has cast into it the year 1714, just five years after Darby first smelted iron with coke (Fig 13). This casting was presented by a local householder to the fore-runner of the present museum in the 1950s, with no provenance attached to it. The museum has only ever said that it was probably a Darby pot. We can now say that since there is no vertical parting line visible anywhere on the pot (Fig 14), it was almost certainly made by the green sand method illustrated in Figure 6. It therefore must have been made with coke iron. Furthermore, it cannot be a direct copy of an earlier pot, because with the embossed date, lettering and frieze, it could not have been made with a simple two part mould. There would have to have been sideways moving mould parts, just as for a bellied pot. The original pot was probably made by making a simple unembellished mould as above and once the pattern had been removed, the adornment was added by pushing letters and numbers into the outer part of the mould before closing and pouring.

The implication is therefore that this historic pot is a genuine Abraham Darby I pot and as such, the oldest known coke-iron casting in existence, a surviving monument to the genius of the man who first realized the real worth of coke iron. It deserves to be better known and properly revered.

Conclusions

The tendency of an iron to solidify white or grey on coming out of a blast furnace was of extreme importance in determining what use could be made of it. Blast furnace operators had some control over the matter, but were limited to a large extent by the raw materials that they had to hand. In particular, charcoal blast furnaces found it commercially impossible to obtain iron grey enough to be used to make pots using the most economical available moulding method.

A metallurgical appreciation of the technology involved in the moulding of thin-walled pots before Abraham Darby first used coke demonstrates that, contrary to historical belief, he knew that he was going to use coke iron long before moving to Coalbrookdale and that it was not just good fortune, as previously alleged, that coke iron was perfect for making pots.

We have to rewrite the history that places him as a serendipitous technical innovator and put him in the class of those commercially-minded entrepreneurs who recognize before anybody else that a new technology has a very useful modern application with economic benefits in the marketplace. Darby knew exactly what he was doing and opted for the manufacture of the only products that could at that time be economically made with coke iron. That was the trigger that led to the first true dedicated iron foundry in Britain, other than those making cannon. The manufacture of pots provided the development time and paid for the general overheads that enabled this foundry to become the most significant works of its type in 18th-century Britain, leading with many innovations all along the way.

Figure 13: The oldest known coke-iron casting. It is a genuine Darby casting, made just six years after he first used coke in his furnace. IGMT Acc Num CBD59.74. 265mm diameter.

Figure 14: The underside of the pot in Figure 13 showing the lack of both a vertical parting line and one across the bottom; it could not have been made with loam and thus not with charcoal-iron.

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References

Ashton T S 1963, *Iron and steel in the Industrial Revolution* (Manchester).

Awty B G 1996, ‘Early cast irons and the impact of fuel availability’, *Historical Metallurgy* 30(1), 17–22.

Bauerman H 1890, *Treatise on the metallurgy of iron* (London).

Cox N 1990, ‘Imagination and innovation of an industrial pioneer’, *Industrial Archaeology Review* 12(2), 127–144.

Diderot D and d’Alembert J le R 1779, *Encyclopédie, ou dictionnaire raisonné des sciences, des arts et des métiers*, Vol 15 (Lausanne/ Berne).

Duhamel de Monceau M 1774, ‘Manière de mouler les marmites de fonte de fer’, in J E Bertrand (ed), *Descriptions des arts et métiers*, Vol 15 (Neuchatel), 205–222.

Dudley D 1665, *Mettallum martis* (London).

Elliott R 1988, *Cast iron technology* (London).

Evrard R and Descy A 1948, *Histoire de l’usine des Vennes* (Liège).

Forsythe R 1909, *The blast furnace and the manufacture of pig iron* (New York).

Fournel H 1839, ‘Différence de consummation qui a lieu dans la production de la fonte blanche ou de la fonte grise’, *Recuil de brochures 1828-1838* (Paris), 3–7.

Greenwood W H and Sexton A H 1907, *Iron and steel* (London).

Hassenfratz J-H 1812, *La sidérotechnie, ou l’art de traiter les minerais de fer pour en obtenir de la fonte, du fer ou de l’acier*, Vol 2 (Paris).

Higgs K 2005, ‘Dud Dudley and Abraham Darby, Forging new links’, *The Blackcountryman*, 38(3), 43–53.

Hyde C K 1977, *Technological change and the British iron industry 1700 -1870* (Princeton).

Jars G 1774, *Voyages Métallurgiques* (Lyon).

Karsten C J B 1841, *Handbuch der Eisenhuttenkunde* (Berlin).

Karsten C J B 1830, *Manuel de la métallurgie de fer*, trans F J Culmann (Metz).

King P W 2001–2, ‘Sir Clement Clerke and the adoption of coal in metallurgy’, *Transactions of the Newcomen Society* 73, 3–52.

King P W 2002, ‘Dud Dudley’s contribution to metallurgy’, *Historical Metallurgy* 36(1), 43–53

King P W 2011, ‘The choice of fuel in the 18th century iron industry: The Coalbrookdale accounts reconsidered’, *Economic History Review* 64(1), 132–156.

Macquer P 1767, *Dictionnaire portatif des arts et métiers*, Vol 1 (Paris).

Macquer P and Jaubert P 1773, *Dictionnaire raisonnée universel des arts et métiers*, Vol 2 (Paris).

Moldenke R 1917, *The principles of iron founding* (New York).

Mott R A 1934, ‘Dud Dudley and the early coal-iron industry’, *Transactions of the Newcomen Society* 15, 17–38.

Mott R A 1957, ‘The earliest use of coke in the blast furnace’, *Gas World, Coking Section* 50, 7–18.

Mott R A 1957-8, ‘Abraham Darby (I and II) and the coal iron industry’, *Transactions of the Newcomen Society* 31, 49–93.

Neff J U 1966, *The rise of the British coal industry,* Vol 1 (London).

Percy J 1864, *Metallurgy: Iron and steel* (London).

Powle H 1677, ‘An account of iron-works in the Forest of Dean’, *Philosophical Transactions of the Royal Society* 12, 931–935.

Raistrick A 1970, *Dynasty of iron founders* (Newton Abbott).

Sisco A and Smith C S (trans) 1956, *Réaumur’s memoirs on steel and iron* (Chicago).

Réaumur R-A F de 1762, *Nouvel art d’adoucir le fer fondu …* (Paris).

Rehder J E 1987, ‘The change from charcoal to coke in iron smelting’, *Historical Metallurgy* 21(1), 37–45.

Schubert H R 1957, *History of the British iron and steel industry* (London).

Sharp J 1905, *Modern foundry practice* (London).

Thirria M E 1840, ‘Mémoires sur les perfectionnements et modifications des proceeds employés pour la fabrication du fer obtenu par l’affinage des fonts dans les foyers d’affinerie’, *Annales des Mines* 18, 215–292.

Tylecote R F 1991, ‘Iron in the Industrial Revolution’, in J Day and R F Tylecote (eds), *The Industrial Revolution in metals* (London).

Wilkie G 1857, *The manufacture of iron in Great Britain* (Edinburgh).

Williams R in prep, The production of foundry irons from 18th-century charcoal- and coke-fired blast furnaces.

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