

10.5.2 Making Steel up to 1870

A few General Points

In the preceding subchapters I have given you a hell of a lot of details about making *solid* blooms in a bloomery and *liquid* cast iron in a blast furnace. Making *steel* was somehow mixed in with all of that. As far as iron and steel making in bloomeries is concerned, I have essentially covered that. However, I have not yet given you much about how to make **wrought iron** and **steel from cast iron**.

So let's look a bit more focussed on how to make steel, in particular if you start with cast iron. But before I come to that I will deal once more with making steel in a bloomery. And before I do that I need to point out something:

Throughout the ages the average customer wanted wrought iron, not steel!

Wrought iron or mild steel, stuff easy to forge and easy to work with (e.g. by filing, drilling, bending, ...), was what one needed for most everyday products - the last subchapter will give examples. Hard steel was good for (some) weapons and some civilian things, for example coulters (I'll get to that) or piano wires. It is estimated that about 90 % of the iron production was for wrought iron and not steel for most of history up to modern times.

If you were running a bloomery you tried to get a bloom of carbon-lean iron most of the time. Since archeologist mostly reported that they found wrought (or better carbon-lean) iron, and since theoreticians [predicted](#) that bloomeries should produce nothing but wrought iron, there shouldn't have been a problem in making the stuff. The problem for people investigating old objects was rather to explain why there was also quite a bit of steel around, especially if you went back to the very early iron era. The explanation offered for this was simple: a smith carburized the wrought iron in his hearth - even in cases when this made not much sense because he would have been better off with wrought iron.

As we know now: *all of the above is wrong*. Why? Here are the reasons in short:

1. Archeologists actually did *not* find mostly carbon-lean iron. Almost 1000 analyzed iron artifacts from late antiquity to 500 AD contained an average carbon concentration around 0.5 %, as already pointed out [before](#).
2. If later products were indeed carbon-lean it only means that people by then had learned to run their bloomeries in such a way that they did produce at least some wrought iron that could be separated from the steel also produced. That bloomeries actually do not produce wrought iron *only* but anything between wrought iron and hypereutectoid steel has been proved by plenty of [experiments done recently](#).
3. A basic and quite valid theory does indeed predict that *only* wrought iron should be produced inside a bloomery as long as there is still some wüstite (FeO) around (meaning always). The theory is not wrong but just too simple. Bloomeries are far more complex than considered some time ago when the theory was conceived. [Here are details](#).
4. Carburization of a sizeable piece of wrought iron in a hearth cannot work for quite elementary reasons as [explained here](#).

So what do you have to do to get a piece of nice steel with a *defined* carbon concentration of, for example, 0.5 %, 1 % or 1,5 %? From just a bloomery? From cast iron? Or from combining whatever you have? Plenty of good questions. But let's not forget: there is also phosphorous steel. And mixed carbon - phosphorous steel. Plenty of that, actually. And we have ancient crucible steel or wootz / bulad in many variants. Not to forget either: if your steel product should contain x % carbon, you generally must start with a *higher* concentration because forging actually always *de-carburizes* your steel. A little more carbon or quite a bit, depending on what exactly you do with your steel.

What already becomes apparent is that many different kinds or grades of steel emerged after, let's say, 1500. And all these iron / steel kinds had names! Since we have more writings about iron and steel from 1500 and beyond than actual samples, we often don't know what, exactly, a certain name implied. Names of steel might point to the origin, to intended uses or to the method for making. What, for example, is pig iron? Or sarschach steel? Who put the blisters in blister steel? The link leads to a module with a list of expressions and names for iron and steel.

In what follows I cannot go into all the intricacies hinted at above. I will therefore only give a taste treat.

[Advanced Link](#)

Iron / Steel names

Making Steel With Bloomeries

Let's start simple and *only consider pure carbon steels* from a bloomery for starters. If you want steel of some type, you first need to make a [bloom](#). Then you need to separate the steel grade you want from all the other iron / steel that is also contained in the bloom you made. Finally you have to forge your steel pieces into a bar or billet with as few slag inclusions as possible. If you were very good at that, your product might have been relatively uniform steel. Your options for optimizing this process chain are limited:

- Run your bloomery in such a way that plenty of the wished-for steel is produced. Easier said than done but possible within limits.
- Try to make the bloom compact and homogeneous with respect to the desired carbon concentration. That seems to be quite impossible, so:
- Try to make the bloom as compact as possible with a clear distribution of the carbon. You might for example make a bloom with wrought iron inside and steel outside. That [can be done](#) but it [is not easy](#).
- Optimize your ore and (in later times) the flux you added. That is your best option. In particular see to it that your ore contains some manganese oxide (MnO). For reasons not [entirely clear](#) that helps to make steel. Also carefully pre-treat your ore by cleaning, roasting or even weathering it for a few years (maybe dissolving some unwanted impurities in the rain).
- Find ways to recognize and separate the proper steely parts from your bloom.

These recipes do not look very convincing, in particular because they aren't really recipes. It's like proposing to somebody who has the ingredients for making bread to take them but to make cake now. Small wonder that different cooks at different places and times produced different cakes - if they produced cakes at all! And some of the cakes might have looked good but had a weird aftertaste and gave you heartburn - like steel containing some phosphorous.

But once more: what I listed above is about all you can do. The key word then is: experience! On the part of the bloomery masters and the smiths. Ways were needed to judge the quality of some iron / steel, and there must have been a lot of "tricks", some probably lost by now. I'll get to some of that [later](#).

Making Steel From Cast Iron - Basics

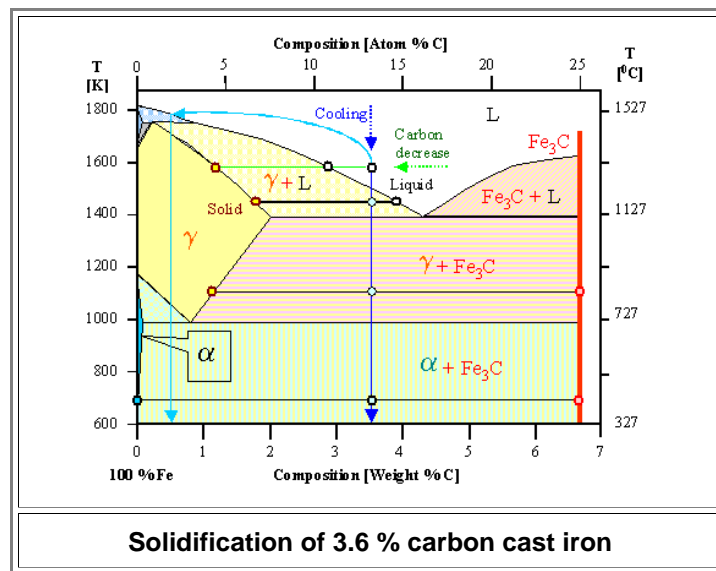
That's how we make steel *right now* and how we made some steel for the last 500 years or so. The [Chinese](#) were at it longer: for the last 2500 years or so.

So let's remember: [Cast iron](#) contains about 2 % - 4 % carbon and usually a bit of this and that. If silicon is among the this and that, you might get *grey* cast iron instead of *white* cast iron and so on. Read up about this [here](#).

Whatever - if you want to make steel you have to take out some of the carbon. In principle this is easy. Just remember how your very remote ancestors got their [copper clean](#). Just melt the stuff again and expose it to oxygen. Everything that likes to oxidize *will* oxidize at the high temperatures needed for melting and either disappears as gas (like carbon), forms slag (like silicon) or what's called **dross**: oxides that swim on top of the liquid metal.

There is no problem for cleaning "dirty" copper this way. Cleaning iron, however, is not so easy. We encounter major problems:

1. As the carbon disappears, the melting point goes up. From a meagre 1140 °C (2084 °F) for [eutectic cast iron](#) (4.3 % carbon) to 1538 °C (2629 °F) for pure iron. You cannot produce that kind of temperature and that means the stuff solidifies *before* it is pure iron.
2. Solidification is inhomogeneous. The solid lumps that form first are austenite with far less carbon than your liquid; see the picture right below.
3. The temperature might be a bit erratic. The oxidation of the carbon to carbon dioxide (CO₂) produces a lot of energy or heat and your temperature might actually go up.
4. You also remove all the good stuff like manganese and silicon.
5. And you remove some of your iron because it oxidizes too. This provides energy and thus raises the temperature even more. You typically lose 25 % of your iron.



- The example shows what happens if 3.6 % carbon cast iron solidifies in three different ways.
 - First, doing nothing but by cooling down, the state point follows the **dark blue** line. As soon as the mix has reached the austenite (γ) - liquid phase field, it decomposes into solid austenite with at most 2 % carbon and a liquid with a corresponding carbon concentration above 3.6 %. As soon as the temperature drops into the austenite and cementite field, we will find lots of cementite and carbon-saturated austenite. Same thing once more when the final ferrite (α) - cementite field is entered.
 - Second, if the carbon concentration is reduced at constant temperature, the state point follows the **green** line. Once more the first solid to form is austenite with just about 1 % carbon.
 - In reality one follows a line like the **bluish** one that first moves to the left, possibly first going up because of the heat generated by forming CO_2 , burning iron and anything else. Eventually it will come down - the blue line gives an idea of what that could look like.

It should become clear that you **cannot** reasonably expect that a solid with a perfectly uniform composition will result. In the first two examples above most of the carbon has to come out while the stuff has solidified, and that depends on relatively slow diffusion. Your best bet for making **wrought iron** is to move left and up as much as you can, taking out the carbon while everything is still in the liquid state. If you want to make steel, you now have two basic options:

1. Remove just as much carbon as is necessary to end up with the concentration you want. But how to do this? How to know when to stop? And how to stop when you know the time has come?
2. Make wrought iron first and then put back some carbon. Complicated but maybe worth the effort because a lot of people made wrought iron, meaning that it was around **and** cheap.

Of course you can also mix the two basic ways. Considering that for most of the time people made steel, they didn't know a thing about carbon, you can be almost sure that strange and overly complex procedures were used. But all that counted was that it worked.

Making Steel by Fining Cast Iron - Examples

Let's look first at making **wrought iron** from pig iron. I will call the product of the blast furnaces from now on **pig iron** because that was its name for many centuries. Again, wrought iron was in far higher demand than steel. One thing is clear: you should liquefy the stuff first. For fining your cast iron to steel, you run a **finery**. A finery, on the outside, is not all that much different from the good old smithy where you worked or **wrought** your old-fashioned bloom. The procedure isn't much different either if viewed from a lofty perspective: heat it and bang it! It's the **details** that make the decisive difference. The hardware is quite different, for example. While in ancient times you heated your bloom in a pit in the ground and banged it on a hard rock, you now run a raised and complex hearth blown with bellows, and you bang with a whole set of hammers (including power hammers) on an anvil or other specially made surfaces. And what you do, exactly, is also different, see below.

It appears that fineries for pig iron were first used in the Sauerland / Siegerland area in Germany, a major iron / steel producing regions until the advent of coke-fed furnaces, when everything moved to coal-rich areas, for example the "Ruhrgebiet" in Germany.

A good way to start is to break up the pig iron into smaller parts, something not too difficult to do with the brittle stuff. What might happen next for making wrought iron I give you in the words of Vagn Buchwald (with my markings), describing the production of "**Osmund iron**", a Swedish commodity traded far and wide from the 14th to the 16th century:

"With hand-blown bellows a helper and the Osmund smith maintained the charcoal fire and moved the pig iron fragments into the *oxidizing* blast. The iron *smelted* at 1150 °C - 1200 ° (2102 °F - 2192 °F) and transformed into small drops that started to burn, i.e. react with oxygen. The reaction was violent and accompanied by significant heat evolution of about 400 kcal per kg of pig iron, all elements of the pig iron participating. Because the pig iron disintegrated into droplets with a large surface, the reaction went *to completion* within minutes and a new *pasty* material, malleable iron with low content of carbon, silicon and manganese was formed. The Osmund smith carefully manipulated the new iron in the hearth so that it sintered into larger lumps, in the end forming a cake or bun of about 4 kg - 7 kg".

Now did they *smelt* or melt their pig iron? If you consider pig iron to be some kind of iron-carbon ore, smelting could be the right word, so I won't criticize Buchwald for using it. But in effect the pig iron was simply melted. *Pasty* material means that you have a two-phase mix. One phase is solid, the other one is liquid. In other words, that's the austenite-liquid mix.

If the reaction really *went to completion*, i.e. if *all* carbon was removed, remains to be seen. That Osmund iron was wrought iron was always just *assumed*. Historians who looked into the Osmund iron production and trade only found a lot of paper, documenting what was going on. What they did not have was a piece of actual Osmund iron. That changed only recently (beginning around 1980), and finally one could analyze the stuff. Here are typical analytical results from Osmund iron, as presented in Buchwald's book:

No.	C	Si	Mn	P	S
Pig iron (typical)					
A	4.1	1.10	1.35	0.028	0.028
B	3.06	0.79	0.32	0.018	0.050
Osmund iron					
1	0.16	0.07	0.03	0.017	0.005
2	0,58	0.04	0.03	0.024	0-005
3	0,34	0.10	0.08	0.012	0.024
4	0.51	0.10	0.06	0.011	0.019
5	0.97	0.03	0.01	0.009	0.007
Composition of pig iron and Osmund iron					

What we have here is *steel* and not wrought iron! Samples 2 and 4 represent good hypoeutectoid steel that could be hardened by quenching, and sample 5 is actually a rather brittle hypereutectoid steel. Either the process was *not* always completed with respect to the carbon or the old iron mongers put some carbon back into their product.

The picture below shows a whole barrel full of Osmund iron. It was found (but not analyzed and recognized for what it was) in 1969 close to Gdansk, Poland, in a shipwreck dating to 1450 -1500. The barrel is now in the Maritime Museum of Gdansk; originally it was labelled "iron ore". That is not quite as idiotic as it appears since most of the original iron pieces had meanwhile oxidized to stuff resembling ore. However, some iron survived and was found to be hypereutectoid steel with about 1 % carbon. So, contrary to "public opinion" in historically minded circles, Osmund iron was *not* exclusively "sehr weiches und zähes, gut schmiedbares Eisen" = very soft and tough iron, good to forge (German Wikipedia) but also steel.



Maybe the guys doing the production just couldn't control the process very well and involuntarily produced a whole spectrum of carbon concentrations? Maybe they knew how to make made various steel grades deliberately ? By method 1 or 2 from above? Were different products offered and traded? I don't know. But I'm sure we will find out in the fullness of time



A barrel full of Osmund *steel*

[Source](#) Buchwald's book, i.e. from around 1980

Similar fining processes were run elsewhere and elsewhere, for example in the Walloon area (Belgium). Letting the pig iron melt drop-by-drop was essential. A small drop could heat up enormously by the heat released from all the oxidations taking place, and the large surface-to-volume ratio made it possible to get the oxides out. Note that the resultant carbon-lean iron could not be kept liquid anymore so the resulting particles needed to be compounded once more by sintering and compacted by banging! By fining pig iron you essentially formed a bloom! But this was now a rather uniform and relatively slag-free bloom.

Fining pig iron was not easy. A source as late as 1775 points out that "[fining iron is the most difficult operation in metallurgy](#)", for example.

There were some other ways to get the carbon out. I give you just one example as a taste treat: the "**Kärntner Löscharbeit**" (Carinthian extinction or quenching work):

Sprinkle some water on your pool of molten pig iron (be careful!) so the surface layer solidifies. Since the surface region was exposed to oxygen it might have had a lower carbon concentration than the bulk. The austenite forming first allows only less than 2 % carbon, anyway. Remove the resulting thin solid and carbon-lean plate. Repeat the process and you get a whole collection of thin steel plates called "Blattel" (leaflet), about 6 mm to 1 cm thick and with around 1.5 % - 2 % carbon. Stack them and heat the batch in an oxidizing atmosphere for a while and you get wrought iron. Once more, the large surface to volume ratio of thin sheets helps enormously in this.

Eventually - 18th century and beyond - a lot of wrought iron was made from pig iron in one way or another. All methods depended on getting the carbon out by oxidation in air and on the surface. Wrought iron was in large demand, [see above](#), and a sizeable industry revolved around making it.

Steel was also in demand. You didn't need all that much in quantity, but you needed the quality. Many products simply needed steel; if made with wrought iron their quality was poor or not acceptable. So being able to make steel from pig iron was crucial and important for competing nations. Everybody could make wrought iron, not to mention that you could just buy it. But not everybody could make good steel and process it. If you had the better steel, you had a commercial and military advantage.

Until about 1870 steel was made from pig iron with the two totally different basic technologies given above. Now we will give them names:

1. "**Cementation**" = putting carbon into the *wrought* iron that was made first from *pig* iron.
2. "**Puddling**" = making steel by taking some but not all carbon out of *pig* iron.

There were many variants per basic technology and some precursor in older times but I won't go into this; suffice it to mention the basics.

Let's look at **cementation** first. The name is a bit [unfortunate](#) and has come to mean, in modern terms, solid-state processes where the material to be processed is immersed into (powdered) solids, followed by heating the ensemble. And yes - cementation does mean *carburization of wrought iron!* But didn't I [stress repeatedly](#) that this couldn't be done?

No, I didn't!

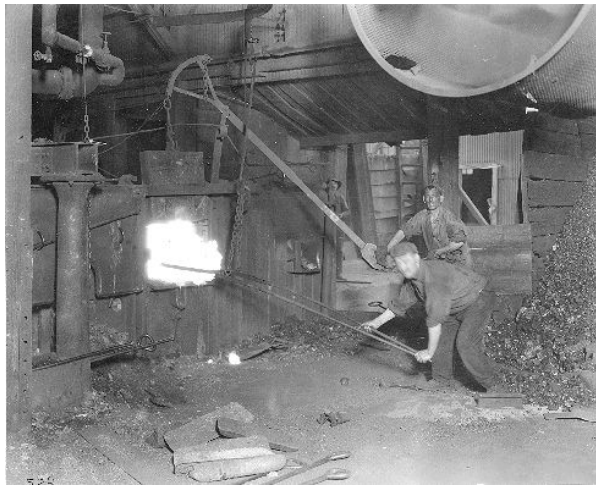
I *did* stress repeatedly that a smith couldn't carburize sizeable pieces of iron in his hearth! An industrialist, however, can carburize sizeable pieces of iron by completely immersing them in carbon dust (plus some magical ingredients) contained in a cementation box, followed by cooking the whole thing at high temperatures for *days* in a kind of kiln.

The process was described in a treatise published in Prague in 1574. Then it was re-invented by Johann Nussbaum of Magdeburg, who began operations at Nuremberg (with partners) in 1601, says Wikipedia. Cementation on a large scale started in the early 17th century in Germany and then spread; in particular to England - but not to France for some reasons I don't know of.

The heating lasted for a week or more. The temperature was certainly high but I couldn't find any numbers (not surprising considering that nobody could measure temperatures this high). The surface of the finished steel product often shows "blisters", supposedly related to the gases CO and CO₂ that were produced in the mix but couldn't get out completely. Personally, I'm pretty sure that the blisters were rather related to hydrogen that quite likely was also produced - but I won't bore you with details. Just believe me. Anyway, here is the reason why cementation steel was also known as [blister steel](#).

Henry Cort from England is usually credited with inventing **puddling**; his patent is from 1784. Puddling essentially means that you stir a pool or "puddle" of molten pig iron with a kind of paddle, getting oxygen in and carbon out. The stirred region gets carbon leaner, its melting point goes up, austenite starts to solidify since the temperature was around 1300 °C (2372 °F) at most.

Eventually the iron "comes to nature", and forms a pasty lump of austenite plus liquid that you can extract and let cool off. In *principle* it proceeds exactly as shown for the old Chinese [here](#).



Puddling - extracting the product

"A puddler and his helper remove a 150-pound, near molten ball of wrought (? Nah, It's steel) iron from a puddling furnace at Youngstown Sheet & Tube's Campbell Works in the 1920s."

[Large picture](#)

Source: Jarret Ruminski's Internet blog.

In practice, however, the Western puddling was far more sophisticated. It was suitable for mass production because it did not depend on charcoal but used regular coal or coke in a [reverberatory furnace](#). Note that once again a kind of bloom was produced that needed to be forged in order to make it compact and homogeneous.

Puddle steel was the best steel for its time. It was almost slag-free and halfway uniform. The Eiffel Tower (1887) and the original framework of the Statue of Liberty (around 1885) were made from puddle steel, for example. But it also had a lot of drawbacks. The quality varied from lot to lot; it depended on the skill of the people doing the puddling and forging. It was labor intensive, needed a lot of room and fuel, and thus could not be cheap. There is no economy of scale. If you needed more steel, you couldn't get it by making a *bigger* puddle furnace but only by making *more*.

Being a "puddler" wasn't a fun job either. However, you didn't have to do it for a very long time since you tended to die young. In more enlightened times this was seen as a bit wasteful.

Puddle steel thus was not really good enough for making large amounts of reliable things like all the steel implements needed for railroads or elevator cables. With time and cunning, however, one could make remarkable *expensive* objects like very good swords.

It's time for a [revolution](#). But before I get to that, I need to look at a few more processes important before 1870.

Making Steel in Other Ways 1. The Brescian Process

You have carbon-rich cast iron and carbon-free wrought iron. It is not a very far-fetched idea to combine the two in some ratio that results in a desired carbon concentration. Not too far-fetched, that is, if you *know* about the carbon and so on. Back in 1500 people were not really sure if cast iron was essentially the same stuff as their good old bloomery iron. Moreover, they were still confused by [Aristotle](#) and might have believed that steel is particularly pure iron. The idea of mixing the two then is not so obvious, it is actually a bit outlandish.

It was done in the area around Brescia in Northern Italy, and [Biringuccio](#) gives it some room in his [1540 opus](#). Brescian steel actually enjoyed some fame in the 14th - 17th century. The process was secret, of course, and is still shrouded in some mystery.

The only question now is: how to do this? Just dunking a piece of wrought iron into liquid cast iron will produce something like what's shown below, as a modern smith just found out:



Wrought iron imperfectly coated with cast iron as obtained by "dunking"

Source: Scott A. Roush in the Bladesmith Forum; Internet

It's not unlike dunking a banana into liquid chocolate. You now have a chocolate coated banana but the banana part of the composite is pretty much the same as before.

Well, you have to immerse your wrought iron for quite some time into the molten cast iron if you want it to turn into steel. The old North Italians dunked their 15 kg blooms for four to six hours, indeed, at a temperature probably around 1200 °C - 1250 °C (2192 °F - 2282 °F) writes [Biringuccio](#). The wrought iron will not melt at this kind of temperature and the cast iron simply acts as a nice uniform source of carbon that can diffuse into the carbon-lean wrought iron. An ideal situation for basic diffusion down a concentration gradients - from high to low carbon concentrations - as expressed in [Fick's famous diffusion laws](#).

For the temperatures and times given carbon atoms can cover a distance in the order of 5 mm. An iron bar 10 mm thick then could get carburized rather completely up to the saturation limit of the austenite present at these temperatures. This would be about 1,5 %; just look at the phase diagram above. Thicker pieces would have the 1,5 % carbon on their outside and a decreasing carbon concentration with depth, approaching low values after about 5 mm. Cutting these pieces into smaller ones and repeating the process would produce homogeneous steel. Alternatively, forging with some folding or piling could also result in good pieces of steel with an halfway uniform "good" carbon content around 0.7 %.

The Brescian process never caught on outside Northern Italy. It is easy to see why. Not only do you need to know a lot of tricks, you also need money! It is an expensive process, not to mention that it is a dangerous (and secret) process. Immersing into, cooking in, and retrieving heavy iron pieces out of a large vat of liquid iron was hot and unhealthy work, prone to accidents causing major injuries.

Making Steel in Other Ways 2. Cast Steel from Crucibles

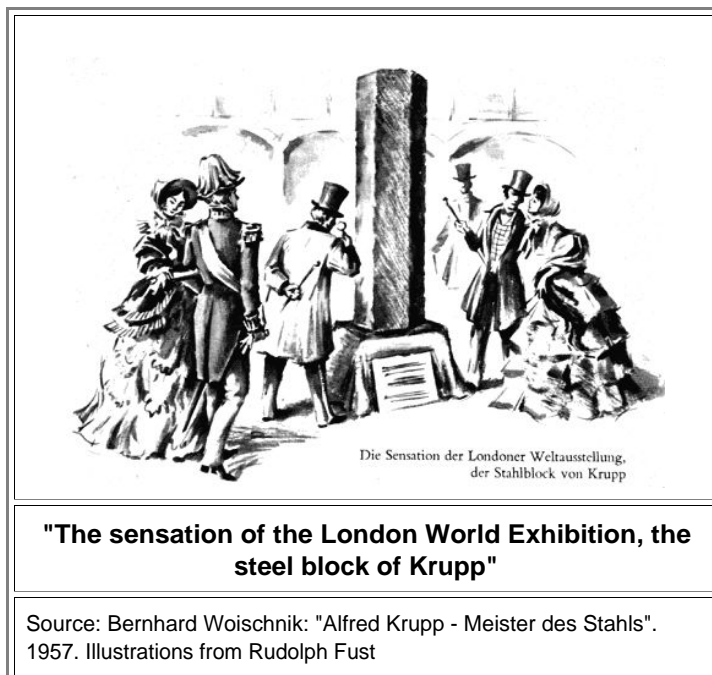
Blister and puddle steel was not very uniform and might still have contained some slag. Small but demanding objects like the springs of clocks needed to be rather hard and very uniform, and the steel available was problematic. It was **Benjamin Huntsman** (1704 - 1776) who finally hit upon the obvious: Melt the stuff, skim off the liquid slag and the solid dross, add, maybe, a bit of this and that, and cast the remaining homogeneous steel into moulds.

● Sounds easy, is difficult. First, you need to contain your liquid metal in a crucible, and that crucible must be able to take the heat - around 1500 °C (2732 °F) at the least. The same is true for the linings of your [fireplace](#), [kiln](#), [reverberatory furnace](#) or whatever else you had in mind. So Huntsman applied himself first to making suitable ceramics and pottery, and finally succeeded - around 1740 - to produce crucible steel.

Of course, crucible steel had been produced in the East already for at least 1500 years by then; I gave you two [long modules](#) on this. But this wootz or bulad, as we call it now, was ultra-high carbon steel not good for many applications, and it was only made in small ingots.

Huntsman used larger crucibles and produced normal steel - the best there was in his time and the time after.

● The local yokels didn't like that, of course, because it threatened their business model. Huntsman had to export all the steel he made to France at first. Making crucible steel was also rather complicated. You had to make the crucibles from special stuff, re-line your furnaces a lot, use a lot of coke to get it real hot, and so on. Eventually and gradually, however, crucible steel *plus* casting caught on. It was the German **Alfred Krupp** (1812 - 1887) who perfected it. In the London world exhibition in 1851 he caused a sensation with his cast 2150 kg steel piece



● The raw steel used was puddle steel. The achievement was logistics, as we would call it today: making sure that one kind of steel was molten in 86 crucibles and then transported to and cast into the mould at exactly the right time. More important than the making of a giant steel block, however, was that Krupp could make axles and wheels for railway cars that did not break erratically all the time - and cannons that could shoot faster, farther, more often and with far more power than the competition.

But now I'm reaching the time of the steel revolution around 1870, and this I will cover in the next module. Before I do this, however, I like to ask a deceptively simple question:

How Good Was Old Iron?

How good was old wrought iron or steel? Good question. But how could we find an answer? Pretty much only by destroying an old specimen. You can carefully bend an old sword a bit without destroying it but that only gives you a lower limit of some property. You can state: it is at least as good as ... (some number) .. as far as bending is concerned, but no more than that.

Looking at the microstructure would reveal a lot. This is destructive, of course but only for a small area. That's good but you only get the microstructure from a small area either. Can you really extrapolate from an area at best as big as a rice grain on the properties of a whole sword or cooking pot? Not to mention that the microstructure does you tell a lot, indeed - but not everything.

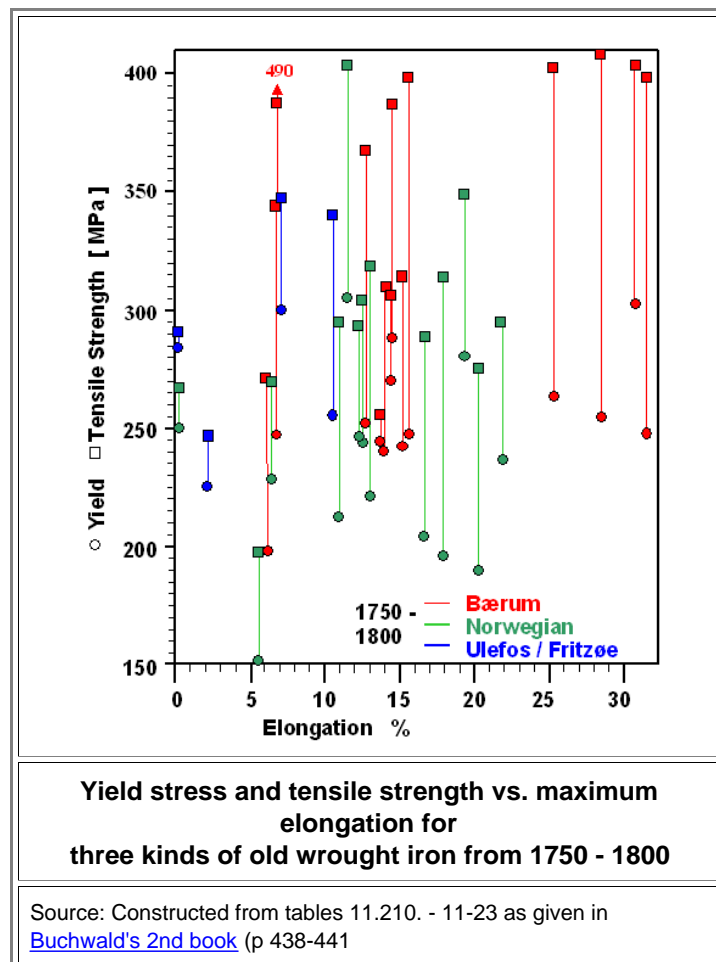
Then there is the phosphorous issue. All the way [up there](#) I stated that we will look only at "ideal" carbon steel. Real iron and steel, however, contained other elements, too. Most important was sulfur (S) and phosphorous (P), causing [red](#) and [cold](#) shortness, respectively. Sulfur was only bad but the problem could be kept under control. Phosphorous was bad most of the time but it could also also be good - up to a point. It [hardened](#) carbon-lean wrought iron to some extent but would not allow quench-hardening by martensite formation. It might have made steel more corrosion resistant, witness the ancient [iron pillar in Dehli](#). Ancient smiths are reported to have liked phosphorous iron since it was easy to forge, something the modern smith [Lee Sauder rediscovered](#). But then your steel might become brittle and break all of a sudden when it got cold.

Pretty much all iron and steel before, let's say, 1800, could contain some phosphorous. If it was there, it tended to be distributed unevenly because all the solid-state processes employed to establish a certain carbon concentration and to make that concentration uniform, did not much influence the distribution of phosphorous. Phosphorous, like all elements besides carbon and nitrogen, diffuses rather slowly and thus tends to stay wherever it was after the final solidification.

Inhomogeneous phosphorous concentrations thus go a long way to account for the large spread in properties of otherwise standardized iron and steel. The problem was eventually recognized in the 18th century. For example, a "Bergskollegio" in Stockholm, Sweden, **banned the use of phosphorous-rich iron ore** from certain mines for making iron and steel. In fact, the revolution in steel making around 1870 tied to names like Bessemer, Siemens, Martin and Thomas, encountered a lot of problems related to phosphorous. Overcoming these problems was the real beginning of the age of steel.

With all these complications in mind, I ask once more: How good was *real* old steel? I should be clear by now that a satisfying answer could only result from mechanical testing of large pieces, in particular by performing [tensile tests](#).

Vagn Buchwald actually succeeded in getting a bunch of old (nominally) wrought iron specimens that could be pulled apart. Here are some of his results:



The wrought iron came from girders taken out of old churches. The pertinent data are:

- **Bærum:** Iron made in the Bærum iron works and used in churches in Hatting and Barrit.
- **Norwegian:** Norwegian iron of unclear make used in the churches St. Petri, Copenhagen and in Stouby.
- **Ulefos / Fritzøe:** Iron made Ulefos / Fritzøe and used in churches in Odder and Jørlunde

Not to make too fine a point: This is shitty stuff! There are tremendous fluctuations and some specimen were perfectly brittle. And no! The Scandinavian folks were not just behind the rest, quite the opposite. They were typically at the forefront of iron and steel technology.

- Vagn Buchwald does not give the impurity concentration data of the specimen but notes that "good" wrought iron should have a yield stress of 160 MPa, a tensile strength of 280 MPa, and a maximum elongation of 36 %. Phosphorous and slag inclusions go a long way in explaining the bad results. Some of the fracture surfaces evidently showed the typical shininess of phosphor-ferrite grains and slag inclusions were evident on microstructure investigations. Some sample also showed cold shortness.
Could the average *steel* be better than this run-of-the-mill wrought iron? Yes, because people might have picked the wrought iron for making it with some care and put more labor and cunning into the forging. However, it could not have been routinely excellent given the problems with the starting material.
I'm not aware of any tensile test results from much older bloomery iron or steel but it is unlikely that they would be much better.

▸ Buchwald has investigated more samples than shown here with similar results. We might take then this as typical for cheap and bulky structural iron. But is it typical for fine steel swords?
Probably not. We can safely assume that more cunning and care was put into making fine objects. But we cannot avoid one major conclusion: Only the very best swords, forged with utmost cunning and a large dose of luck, could live up to the potential of the basic composition of the steel used. Most, however, must have been inferior. In other words: A modern 0,7 % carbon steel object will outperform pretty much all old objects with that kind of composition.

- Don't believe for a second that I'm trying to put the old iron masters and smiths down for making shitty objects here. The reverse is true. Given the problems they faced, it is simply marvellous what they could make when they really applied themselves. They wrought unbelievably good and fancy stuff - but no miracles.