10.4. Crucible Steel

10.4.1 The Making of Crucible Steel in Antiquity

Debunking the Myth of "Wootz"

Before I start on "wootz" I want to be very clear on how I see this rather confused topic:

- There never has been a *secret* about the making of crucible (or "wootz") steel, and there isn't one now. Recipes for making crucible steel were well-known throughout the ages, and they were just as sensible or strange as recipes for making bloomery iron or other things.
- There are *many ways* for making crucible steel. If the crucible process worked properly, the steel produced was fully liquid, and it didn't matter much exactly how you made it. If the process did not work well and the steel was only partially molten, i.e. a mixture of liquid cast iron and solid austenite, the product was not good steel.
- Besides differences in the (always large) carbon concentration, the *concentration of impurities* might also be different - just like for bloomery steel. This might lead to differences in properties for comparable carbon concentrations, for example the susceptibility to cold shortness or the ability to form a good "watered silk" or "water" pattern.
- Crucible steel that has been liquid once is relatively homogeneous and slag-free - in contrast to bloomery steel. That is where crucible steel is "*better*" than bloomery steel.
- Crucible steel is *always* high carbon if not ultra-high carbon steel (***UHCS***). This is generally not so good. However, mixtures that would, for example, have produced 0.8 % carbon steel, a steel optimal for many applications, would *not melt* at the temperatures available. Crucible steel thus is a compromise. It is very hard but also very brittle and almost useless in its "as made" state.
- Some products like surgical knifes, files or punches (but typically not swords) are best made from high-carbon steel. In this case crucible steel was fine. It closed the gap between low and medium carbon bloomery steel and too-much-carbon cast iron. There was no other easy way to cover the 1 % - 2 % carbon range.
- Special processing, including very special forging techniques, allowed to make products like swords from crucible steel that were very hard *throughout* but not completely brittle. Like any *homogeneous* hard steel, they could be bend a lot before plastic deformation or fracture occurred, in contrast to not-so hard *and* slag inclusion containing bloomery steel swords. Slag inclusions simply trigger early fracture.
- Some crucible steels could be induced to precipitate their carbon *inhomogeneously*. The cementite formed was not distributed evenly but arranged in such a way that a visible pattern could be produced at the surface. These steel blades with a "**watered silk**" pattern or "water" pattern for short, were highly priced in the Arabic cultures but not necessarily better than featureless blades. There were in fact not as good as blades made from homogeneous steel.
- The term "wootz" is rather meaningless in all of this. It is supposed to be some *special kind* of crucible steel but nobody knows what, exactly, makes it special relative to "non-wootz" crucible steels. One might reserve the term for those crucible steels that can produce a "water" pattern. The problem with this is that nobody can sort given crucible steel ingots into "wootz" and "not wootz" before all the forging takes place. There are just no clear criteria.
- Crucible steel was made in India and in large parts of Asia since at least 500 AD, possibly much earlier, up to the end of the 19th century - but not in the "West" (and China). That is not so much because "the West" didn't know the secrets of making crucible steel; it didn't want to make it.

If you are dreaming of wielding that wootz super-sword one day, enabling you to beat the competition, kill the dragons and win the heart and more of all those damsels out there - sorry for letting you down. My advice is to go see a shrink about the possible meanings of those dreams.

Now let's see what one can find out about crucible *steel*. The swords made from crucible steel will be dealt with in some detail in the next chapter.

What is Crucible Steel?

Can you produce iron in a crucible? Well - why not? Take a crucible, fill it with a mixture of (powdered) iron ore and charcoal, and heat it up. There is something like a direct reduction process between iron oxide and carbon that produces iron and carbon monoxide. I have described that process in some more detail in a science module. If something is possible, chances are that somebody did it. So did our *remote* ancestors make iron and steel in a crucible?

No - they didn't! It's not as simple as it sounds. There are a few catches:

- Even if some iron is produced: as long as it doesn't melt, you cannot expect to find a bloom or a solid piece of iron in your crucible after cooling down. How are those iron particles all over the place supposed to get together and form a bloom? You might produce slag that could help forming a bloom but trickling down in a powder is difficult. If you use big lumps of ore and charcoal not much reaction is possible because of the strongly reduced contact area.

- Melting the iron might help - but that requires very high temperatures in excess of 1500 ^oC (2732 ^oF), not easily attained in antiquity.
- If you could produce temperatures that high, you needed a crucible that could survive this temperature while not reacting with its contents. Another tough assignment to meet in antiquity!
- If you could do all this, chances were that you started a run-away reaction, exploding your crucible.

Maybe in the 19th century iron was produced in a crucible; there are some vague reports about that [4]. Whatever there might have been - direct reduction in a crucible was and is of no importance. When we talk about crucible steel we do not talk about making it by direct reduction. We make it by dissolving carbon in old-fashioned bloomery iron / mild steel by turning everything liquid.

I'm starting a touchy business here and want to be very clear. Whenever I use the assignation " crucible steel" in what follows, I mean:

Crucible steel = high-carbon steel made by enriching low-carbon iron / steel with carbon in a crucible in the liquid state

Why is crucible steel a touchy business? There are multiple reasons. Here is the list:

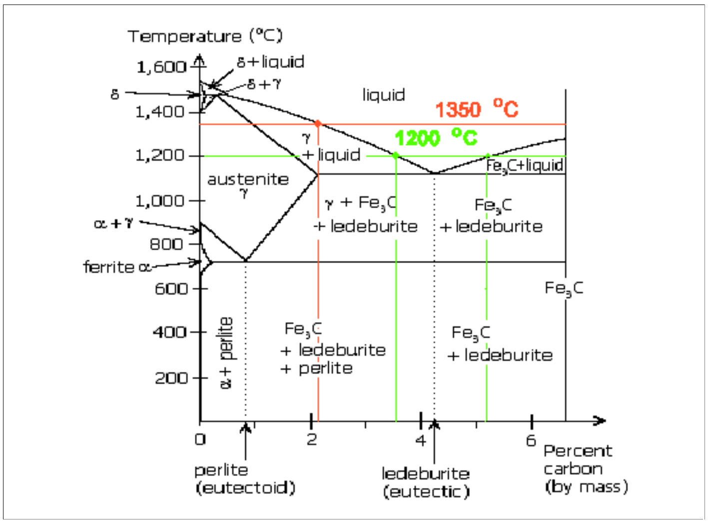
- Crucible steel is almost a synonym for "iron / steel of the East". Many regions / cultures / nationalities compete for the honor of having been the inventor of this "superior" steel.
- The early history of crucible steel is not all that clear, nor are the details of the particular technology that was used in certain places and times. That does not prevent a lot of people from having strong opinions and emotions about that.
- Extremely good swords have been made from crucible steel. They were far better than their Western counterparts! Or they weren't. Strong emotions about this topic are ignited as soon as the magic word "*wootz* " is mentioned.
- Some crucible steel lends itself for making blades with a pattern often described as "watered silk" pattern, "water" pattern or "true damascus" pattern. These *patterned blades* are (wrongly) believed to be the best blades ever made. I like to call it a "water" pattern not only because this is a standard expression for this but also because the girl friend of my son, when she saw a wootz blade for the first time in her life, spontaneously called it a "pattern like flowing water".
- It is hotly debated what kind of factors need to come together to produce coarse cementite particles that are non-randomly distributed in a way that forms the "water" pattern. Lots of emotions again - but the final word isn't yet in.
- Many (wrongly) believe that the technology for making crucible steel and the rather special forging techniques for making patterned blades was lost centuries ago, and that the "secret" for making "super" steel will remain lost forever.
- Indian crucible steel has been known in the "West" for quite some time without anybody paying much attention. It became "famous" late in the late 18th and then 19th century, when Western intellectuals "discovered" the wonders of the Orient, and not, as many believe, during or after the crusades.
- Western guys (including scientists) created considerable confusion around the "secret" of wootz steel. To some extent this was deliberate for all kinds of non-scientific reasons (like money). Mostly, however, the confusion was not so much about the secrets of wootz steel but about the secrets of steel in general.

In what follows I will look into crucible steel in a scientific, detached, objective and unemotional way. You must believe me or I will rave and scream, haunt you in your dreams, curse you and your descendants, send you unpleasant deceases like kneasles or smallcocks, and inform the IRS that you have hidden accounts.

Let's start by assuming that you, personally, have a furnace that can go up to 1350 ^oC (2462 ^oF), and a crucible that can take the heat. You have build and run a bloomery just for the fun of it - just like Claes Vahlberg and his buddies - and now you have some normal bloomery steel or wrought iron at your disposal. In other words, you have an inhomogeneous mass of iron with an average carbon concentration of around 0.3 %, slag inclusions, and possibly some phosphorous. This is now your starting material for making crucible steel.
Two thousand years ago some of our ancestors could muster about the same equipment and materials. But you, in contrast to your ancestors, also know all about the science and engineering of steel! You decide to use this knowledge for turning your bloomery iron into good steel.
It is absolutely clear to you that you must *melt* the stuff. This is the *only* way to release all the entrapped slag and homogenize the carbon concentration plus whatever else is in the iron. You might also purify the molten iron a bit, along the lines used for copper purification or for making steel out of cast iron.

Unfortunately your furnace is not hot enough to melt your stuff. What will you do?

- You look a the [iron-carbon phase diagram](), of course. It will tell you what kinds of liquid you might be able to get at the highest temperature your furnace can produce. Just look:



Making and Melting High-Carbon Steel

- Obviously, you have to have at least about 2.1 % carbon in your steel if it is to melt at 1350 ^{o}C (2462 ^{o}F). If you could only produce 1200 ^{o}C (2192 ^{o}F), the steel needs something between about 3.5 % - 5.2 % carbon - and it wouldn't be steel anymore but cast iron. If you want only about 1 % carbon (not shown), you must go well above 1400 ^{o}C (1673 ^{o}F).
  Now you know what you have to do. You need to supply just the right amount of carbon to raise the level from the average carbon concentration in your bloom (about 0.3 %) to at least the required minimum of 2.1 %. It's easy enough to figure out how much carbon that will be per kg of bloom iron. So you take your (pieces of the) bloom, put them into your crucible, add the proper amount of carbon, cover it with a lid (with a hole so gases can escape), and put the filled crucible in your furnace. Run it up to the maximum temperature, keep it there for the time it takes to have a few beers with the boys, then let it cool down.
  What you will find is a steel **ingot** snug in the bottom part, covered with a bit of slag. The slag comes from the slag still contained in the bloom, and because you might dissolve some of your crucible material. At high temperatures the slag will liquefy and sit on top of the far denser *liquid* steel, protecting it to some extent.

Now to your questions. The first, quite obviously, is:

1. Why should the *bloomery iron* liquefy? After all, *its* melting temperature is never reached.
   Well - liquefaction occurs for the same reason that the ice in your driveway liquefies to water if you sprinkle salt on it at temperatures *below* the freezing point of pure water but *above* the [freezing point of salt-saturated water](). A little salt then diffuses into the solid ice, lowering its melting point, and small parts will eventually turn liquid. This can happen already on a nanometer scale so not much diffusion or time is needed for the process. The liquid dissolves the salt rapidly and at the solid-liquid boundary the salt keeps diffusing into the solid, turning it liquid. The boundary area increases and the process accelerates. If you supply enough salt, all ice will eventually turn into liquid salt-enriched water.
   Same thing with iron and carbon. It might take a while, but a few hours to a day should be enough for a crucible charge of at best a few kilograms.
2. What should one use as a *source of carbon*?
   Pure carbon = powdered charcoal, would be the obvious answer. Obvious, yes - but not what (most of) your ancestors did. The evidence points rather to the use of organic stuff like tree leaves or pomegranate peelings. Whatever it is, during heating up all organic stuff will [pyrolyze]() to carbon and gases that escape - provided you make sure that no oxygen is around! That's one of reasons why you put a lid on your crucible (with a small hole to allow the escape of gases produced inside), and why it makes sense to put the crucible in the *reducing* part of your furnace fire. All organic waste then is a source of carbon (and possibly a few other key elements).
   The use of organic waste instead of charcoal now certainly triggers the third question:
3.

3. Why? *Why plant matter* and not charcoals?
   The answer is simple. I don't know. I can guess, however. Read on and you will find out what my guesses are.
4. The second-to-last question is also clear: Is there *anything else* besides bloomery iron and plant matter that you like to put into your crucible?
   The answer, as expected, is: it depends. If you have a little manganese-bearing stuff handy, it might be helpful. A bit of glass or something to that effect might help in slag formation, especially if your bloomery iron is rather on the slag-lean side.
5. A last question comes to mind: Are there any other ways to make crucible steel?
   Yes there are - but not that many! You might, for example, mix wrought iron and cast iron in a relation that produces the proper carbon concentration. You might use cast iron and *take out* some of the surplus carbon in there by adding something oxidizing stuff like quicklime or even iron ore. Or you might use cast iron .... However, there was no cast iron in most places before, roughly, 1500 AD (with the exception of China).

Modern scientists and smiths have made crucible steel as described above; I will get to that in due time. Here I only want to impress on you that *making* crucible steel involves neither a secret nor is some magic required. It is rather straight forward. Precise recipes for the process have been published by several authors from 400 AD onward.
There are a few documents that were written before 400 AD and allude to iron / steel in ways that could mean crucible steel from India. Maybe, but probably not. More important than a few very vague early writings that may or may not allude to crucible steel are the *large amounts* of early writings, in particular in India, that never mention crucible steel. We are justified in concluding that if crucible steel existed before 300 AD or so, it was of no importance.

Special Module **Early Writings**

So let's assume that (Indian) crucible steel appeared "on the market" around **300 AD**. The first surviving good recipe for making it dates to about 380 AD. It was written by one *Zosimos* (ca. 350 AD - ca. 420 AD), a kind of early alchemist in Alexandria. Refer to the special module for details
The problem we have with *ancient* crucible steel from around 300 AD to 1700 AD is *not* to figure out how it was made but:

- Figuring out from dug-up remains what, exactly, was going on *when and where*. This is not so easy because not too many *ancient* places have been found, and not much is left there anyway.
- Figuring out if some ancient (rusty) object was made from *crucible steel or bloomery steel*. Not too difficult if you can destroy the piece - the rare exception. Quite difficult if you mustn't touch it - the normal case.
- Figuring out how *Eastern* ancient smiths were able to work with the brittle high-carbon stuff in such a way that high-quality products resulted.
- Figuring out how *some* Eastern ancient smiths could produce blades with a "damascene" or "water" pattern from some crucible steel, and what, exactly, made that steel different from crucible steel that did *not* allow pattern formation.
- Getting some solid data about the *quality* of crucible steel blades in comparison to other blades of the same time period - and in comparison to blades made from modern steel.
- Just for human interest, we might also want to know why the "West" never adopted the technology considering that the information was available.

How good is (good) crucible steel? It is certainly better in one respect than run-of-the-mill bloomery steel. Since good crucible steel was once molten, it is homogeneous on a macroscopic scale and free of slag or other inclusion. That makes automatically for far better fracture toughness properties. That is the bright side of crucible steel.
As always there is also a dark side: Ancient crucible steel is *always* high-carbon steel and thus rather hard but perfectly brittle, just like cast iron. In contrast to cast iron, however, it could be forged - with special skills, love, and tender care. That allowed to make useful objects like razor blades, surgical instruments, or files. For those products extreme hardness is good (e.g. for making very sharp edges that stayed sharp) and the still large degree of brittleness is tolerable because these objects were not exposed to high-energy impacts like swords.
One also could make crucible-steel swords with very hard and sharp blades that could be bend without fracturing to some large degree. Thise swords, however, were still rather brittle since the grains were encased in cementite as shown here, and possibly cold-short since crucible steel like any early steel often contained phosphorous with all the concomitant problems. But then there are also what I will call "wootz" swords, showing a water pattern on theire surfaces. This pattern is due to "spheroidized" cementite, made in rather tricky ways (just wait), that gives some ductility to the steel.

Looking into these points in some detail will be a substantial amount of work. Let's start with the *when and where* .

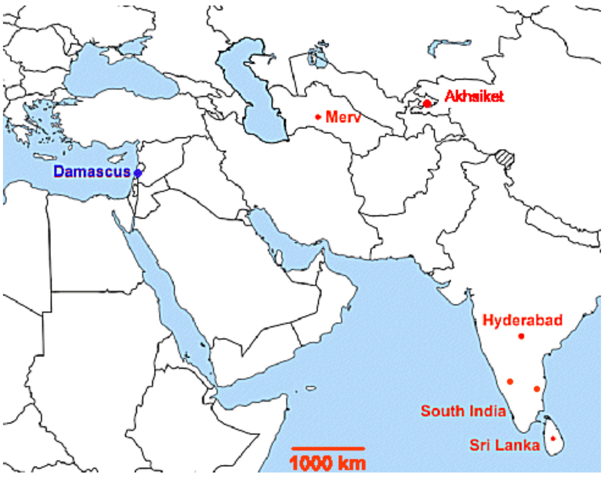
Extremely Short History of *Early* Crucible Steel

What do we know about the *early* history of crucible steel? We have essentially three sources we can exploit:

1. The remains from ancient places where crucible steel was made. This needs finding these places, digging up some artifacts, *and* figuring out what those artifacts can tell us about the making of crucible steel.
2. Very old objects, in particular swords and armor, that have been made from crucible steel. We need to analyze these objects and conclude from the results to the making of the crucible steel *and* the way the steel was forged into the object.
3. Whatever ancient authors wrote about crucible steel.

Nothing here is straight forward. Ancient crucible steel workshops or "factories" do not leave much behind that can be easily recognized after thousand-plus years, just like bloomeries. What you find needs to be analyzed and interpreted, and interpretations might be ambiguous or simply wrong. Very old swords of any kind are usually not available for close (and thus destructive) analysis. In the rare cases where this was possible, the results of an analysis do not tell you exactly how that sword was made. As far as written accounts go, we know already that we shouldn't expect too much from this module.
Let's start with the evidence from dug-up crucible steel work shops.

There is one thing we know for sure about **crucible steel work shops**: we haven't yet discovered most of them. Until about 20 years ago, the only known early places for crucible steel were in Sri Lanka and South India. **Anna Feuerbach** (plus many others), put the Merv area in present Turkmenistan on the "crucible steel" map, in particular in her (unpublished but available) PhD thesis work (2002 Univ London) and in later publications [1)]. Meanwhile we also have Akhsiket in Uzbekistan [2)] and a few places in (South) India [3)].
However, the crucible steel workshops in Central Asia that were dug up and investigated by an international team date to the early Islamic period, i.e. the late 9th - early 10th century AD. That is, maybe, still "early" but not very early. Anna Feuerbach, however, has reasons to believe that crucible steel technology in Central Asia goes back at least 500 more years.
The map below shows the known early places (plus Damascus) and makes clear that there is definitely a lot of room for more finds.



Known Places where Crucible Steel was made in early times

I emphasize "*early places* " here because crucible steel has been made for a long time - from at least 300 AD up to the 19th century in India and Central Asia. Of course we know a lot more about *later places* than about the more interesting early places.
Contrariwise, there is presently no *evidence* at all that crucible steel has been made in Damascus / Syria or, more generally, in what one might call the "Arabic" countries, not to mention the "West" at large. There are a few written hints that some crucible steel was made in Syria and Egypt but nothing has been found yet. On the other hand we know for sure that "India" exported crucible steel on a large scale to the Arabic / Muslim countries for 1000 years or more.
Once more, this doesn't mean that the "Arabs" didn't know how to make crucible steel (or bloomery iron / steel). It just was easier and cheaper to import the stuff - considering that the Arabian peninsula, Egypt, and so on had neither much iron ore nor much wood for charcoal on their territories. India, in contrast, had plenty of both. In North Germany we do import our wine even so we know how to make (and drink) it.

If one digs up an old crucible steel work shop one tends to find parts of used crucibles, remains of furnaces, and a bit of slag. The very few iron / steel objects left over only exist as rust or small "prills" embedded in the slag or sticking to crucible shards. To the best of my knowledge, no good *ancient* "wootz cake" or "pulad egg" (I'll get to that) has ever been found so far. Dating the finds is difficult, and interpreting what they mean not always easy. For example many crucibles dating to 300 BC - 300 AD have been found in Kodumanal in India. These crucibles may or may not have been used for making crucible steel. You also need crucibles for the much older techniques of melting and casting copper, bronze and gold. Crucible remains from other (Indian) places definitely have been used for making steel (they might, for example, be encrusted with steel prills) but no dating was possible.
In other words, we are a far cry from knowing who, where and when made the *first* crucible steel. We do know, however, that whoever did it, had to be able to run a bloomery *and* to make some pretty good ceramics, far more heat resistant than the normal pottery of those days. In addition they needed a furnace or kiln that could produce very high temperatures for many hours in a reducing environment. Moreover, without a good knowledge of forging technologies, crucible steel would have been of little value.

- All things considered, crucible steel could have been made as early as 500 BC or so - it's just not likely. If so - and personally I'm not convinced of that - it either was a small-scale operation or we have not yet found major centers. What we need to bear in mind is that almost anything that is known or assumed to be known about crucible steel and the swords made from it comes from around 300 AD or later, much later in fact. We simply do no know much about *very early* (= before 300 AD) crucible steel making at present. There are good reasons to believe that there might not have no been any. To quote **Bennet Bronson** , whose 1986 paper [4] in my opinion still sets the standards:

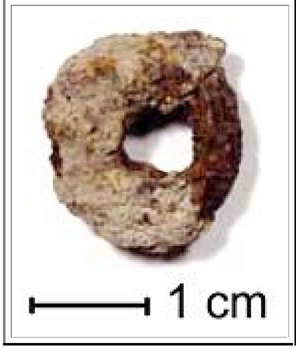
Special Module
Late Writings

> **"We have no indications that crucibles were used in steel making before the late first millennium AD, and we have no real reason to think that they were used in India as early as that"**

- The famous iron pillar from around 400 AD, by the way, was made from bloomery iron. That was the only way since the high-carbon crucible steel cannot be hammer welded, it is said.
  What we do know about crucible steel and most of the mythology surrounding it and those "true damascene swords" comes from its "*late*" history (after 1700 AD, say). The special module gives a short account of the late (and very confused) history of crucible steel.

No let's look at *old artifacts*. For old steel artifacts, in particular swords, a detailed metallographic analysis can give clear indications if the object was made from bloomery or crucible steel. Crucible steel is free of slag, inclusions of which are always found in bloomery steel. Early crucible steel should always be hypereutectoid high-carbon steel, and thus contains a lot of cementite in one form or other. The concentration of carbon and other elements is rather uniform throughout the material, in contrast to bloomery steel.

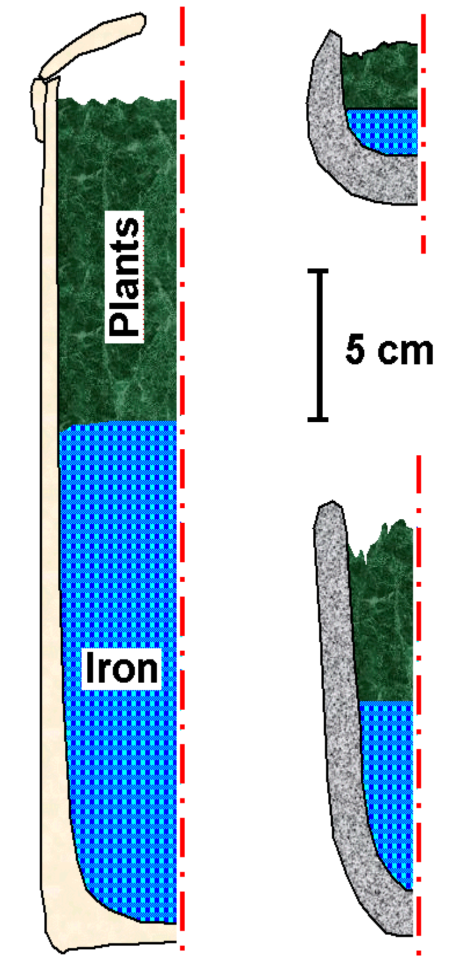
- Anna Feuerbach has analyzed a number of old blades and reported the results in her 2002 PhD thesis and in a paper from 2005 [1]. She found a few blades that have been made from crucible steel: "One of these blades (from 3rd–4th century A.D. burials in the Russian Northern Caucasus) has aligned spheroidal cementite, the metallographic feature that produces the visible pattern. *This is the earliest known crucible Damascus blade*". If we assume that Anna is right, crucible steel and the forging technology going with it must have existed at least as early as 300 AD; a date we are familiar with by now.
- More recently, **Sharada Srinivasan**, an Indian authority on crucible steel, reported on metallographic investigation of a (heavily corroded) ring (see picture) form the South Indian site of Kadebakele, securely dated to to 800 BC – 440 BC. It is: "one of the earliest known examples of pearlitic or higher carbon steel found anywhere in the world. The structure is not inconsistent with that found in the crucible fragment from Mel-siruvalur, which is confirmed to be from high carbon crucible steel production" [3].
  That is certainly true but the structure is not inconsistent with high-carbon bloomery steel either, something that ancient smiths could turn into small things like rings on occasion. Other iron artifacts from the same place and time were definitely bloomery iron, says Sharada.



- As far as *early* authors go, I already mentioned that above. There are no definite statements from the time before the Alexandrian historian Zosimos wrote a detailed description of crucible steel production during the 3rd century AD. He stated that it was being used in India and Persia. This would date crucible steel making to at least 300 AD once more. Just to give a taste of what else is around: Alexander the Great reportedly received some special "white" steel from Indian rulers in 326 BC. This could have been crucible steel, putting the date of its first making *before* 350 BC or so - but this is just guessing. More to that in this module.
- What emerges once more is that the making of crucible steel *might* go back to about 500 BC but that there is no incontrovertible evidence for that. We know that bloomeries could produce cast iron and thus also high carbon steel. Mrs. Srinivasan's ring thus might have been made from a high-carbon steel piece that was produced in a bloomery. Whatever. If people actually made crucible steel before about 300 AD is doubtful, and even it they did we can simply ignore it at present for lack of data.
  While the basic technique for making crucible steel never changed, we can be sure that the technology developed and that late processes were far more advanced and better controlled than the early ones. We do know this, actually. Many Westerners have seen crucible steel being made in India between 1795 and 1900. Some wrote about that and we still have about 20 written eyewitness accounts, some from people with a scientific training or a deep knowledge about iron and steel. Look at the "Late History" module for some more details
  - The "West", however, never caught on, and never made crucible steel of its own (with the exception of the Russians in the first half of the 19th century). Benjamin Huntsman; if you wonder about that statement, just melted steel in crucibles in the 18th century; he didn't add carbon.
    This is a puzzle of sorts. Overfunded spy organizations like the CIA or NSA are rather recent inventions but it is nevertheless not likely that nobody was able to steal the secret recipes, in particular because they weren't all that secret to start with. Plenty of written recipes were open to all that could read since 300 AD and certain ways for getting a working recipe would have worked just as well then, as getting big sports events to Qatar now, for example.
    As always, it might have been plain old stupidity or religious / social bias (same thing anyway) that kept crucible steel making out of Western Europe. That attitude keeps equal rights for females out of many countries at present, for example. But, maybe, the real reason was that Western steel and Western swords were just as good as their Eastern crucible-steel counterparts. The Crusaders, after all, fought their way deep into the lands of crucible steel swords late in the 11th century and most of the 12th century with their bloomery steel swords, while the other side never quite made it into Northern Europe - and they sure tried for many centuries!

Some Points about Making Crucible Steel

- **First** of all you need a crucible that can take the heat, at least 1350 °C (2462 °F) and higher is better! You can't make it from "regular" clay because your crucible then would start to melt around 1200 °C (2192 °F). So use "special" clay and strengthen it with roughly equal amounts of (silicon dioxide rich) rice chaff. Or find some other way, e.g. by using "China clay" or stuff containing a lot of aluminum oxide.
  Different cultures at different times found different solutions. The Sri Lanka / Indian crucibles, for example are quite black whereas the Central Asia stuff is rather on the white side - like modern porcelain.
  I don't want to belittle crucible technology. It is absolutely crucial to the development of metallurgy, and much could be said about it. It's just just not crucial to the topics here. If you can make one that can take the heat, you can make crucible steel. If you can't, forget it. The schematic drawing shows what old crucibles looked like in almost natural size.



Crucibles. Left, the larger but thin-walled Central Asia kind; right the smaller and older Indian variety

Source: Redrawn from Rehrer's paper [2)]

- **Second**, you need a furnace that can produce *at least* 1350 ^{o}C (2462 ^{o}F). You can easily get that kind of temperature close to the tuyere of a well-constructed and vigorously blown bloomery but here you need to heat a crucible inside a kind of kiln. That is not so easy to do.
  In Merv some remains of kilns from around 900 AD have been found. They were rather advanced constructions, certainly outperforming their counterparts from 500 BC or 100 AD. Several crucibles were put in a bed of charcoal inside a domed kiln and a lot of air was blown in from below.
  - But nothing helps. If you want to make crucible steel with at most 2 % carbon, possibly a bit less, you must keep up a temperature of at least 1350 ^{o}C for hours and within a not too small area. One might speculate what you might get at lower temperatures, where you find yourself inside the "γ + liquid" phase field. There you have a mixture of carbon-lean solid austenite and a carbon-rich liquid. This probably has happened a lot, and than you get "bad" crucible steel that is rather inhomogeneous.
- **Third**, you need some bloomery iron and a source of carbon. For the latter you might use those magic plants the shaman recommended or just about any organic waste. Some plants might work better than others because they might supply a bit more of "good" trace elements but we do not know much about that. The decisive point is to add just the *right* amount of organic matter. Since even you, the modern crucible steel maker, do not know the precise amount of carbon contained in your bloomery iron and also not exactly how much carbon will remain from the plants after pyrolyzing (some of the carbon will escape as CO_2 or CO), this is simply a matter of trial and error, culminating eventually in a working recipe.
  Your iron needs to be crushed into suitable lumps. Note that for an "ideal" crucible steel process, you may want to have your iron more or less as dust or powder - but that is not something easily done with ancient technology.
  For added value, you might also want to add a bit of "flux". It should be the right kind and the right amount, of course. Some manganese containing stuff would be good since a bit of manganese in your steel is always beneficial.
  Then you might consider how to stack the stuff inside your crucible. Iron - flux - leaves? The other way around? Several layers in succession? There is no obvious good reason why this should matter but it is an issue with modern crucible steel makers.
  Now put a lid on and maybe secure it by smearing some clay around the rim. Or seal your crucible in some other way. You need to do this for the reason mentioned above and for simply keeping stuff from falling in. You might want to put a

small hole in the lid, though, because gases will develop with your particular mixture for almost sure. You should allow them to escape lest they blow up your crucible.

So why organic matter and not charcoal? My guess is that the decomposition of the organic stuff at high temperatures releases hydrogen (H_2) and carbon monoxide (CO) among other stuff, gases that will not only prevent the oxidation of the iron but remove the oxides already there. The carbon produced by pyrolysis of leaves etc. will also be a fine dust that can more easily coat the iron and penetrate it than lumps of charcoal. The ash produced might help in slag formation.
But that's only a guess. There are reports that in more modern times charcoal was actually used as a source of carbon. If done *just right* there shouldn't be a problem.

All you need to do next is to stew your charge for a while - several hours, maybe a day or two, and then let it cool down. You have two options for that:

1. Cool down quickly, including taking the crucible out of the kiln and using some violent cooling procedure.
2. Cool it down slowly.

It appears that the early Indian crucible steel makers preferred the first possibility, and the later Central Asia people the second. I'm not aware of solid evidence for that, however.

Backbone Link

Easy Segregation

This is a rather important issue since the cooling speed determines the general microstructure obtained at room temperature, including in particular the amount of macro and microsegregation of whatever impurities are contained in the iron. If a "water" pattern can be formed in swords forged from the steel, and what it will look like, is possibly determined by this structure.
I will come back to this in detail, meanwhile it would be a good idea for you to read up on those topics a bit.
Go ahead, Give it a try. Don't drink beer. Have your girl friend support you if necessary.

Science Link

Segregation Science

Sorry about that but it's good to have you back.
Now you can remove your crucible steel from the crucible (which you have to destroy in the process). You will have produced either

- a **wootz cake** if you feel attached to the modern English tradition, or
- a **bulad egg** if you use the more ancient names for naming the ingot

"Cake" or "egg" refer to the shapes of your ingot, determined mostly by the shape of the crucible bottom. Since we have neither old wootz cakes nor bulad eggs, these names do not tell us a thing about the (average) properties of "raw" ancient crucible steel.

The somewhat unusual identifier "**wootz** " was and still is the commonly accepted name for crucible steel in the West. Lengthy papers have been written about its origin. "Wootz", writes Sharada Srinivasan in 2009 [3)], "is thought to be a European corruption of the south Indian Telegu/Kannada word for steel, *ukku*". Ukku may derive from the related Tamil word *uruku*, meaning to make molten. It could also be related to *ekku*, the old Tamil word for sharpness/ sharp spear. And so on.
As far as I'm concerned one needs to imbibe a lot of beer before one is able to pronounce "ukku" like "wootz". Maybe the British just didn't want to be outdone by the French in the art of mispronouncing foreign words.

Pulad, Fuladh, Bulat, Bolat and so on simply is the (much older) term for "wootz" in most "non-Western" countries. It is also the word used by the old writers like Al-Kindi and Al-Biruni Maybe it relates to the Persian word "pulad" = steel. Or to some other words in some other languages.

While I'm at it: **Damascene** or damask, one of the many names for blades with a "water" pattern, could mean coming from the city *Damascus*, the capital of present Syria, that a smith named "*Damasqui*" has made the sword, or from the Arabic word *damas* = water.

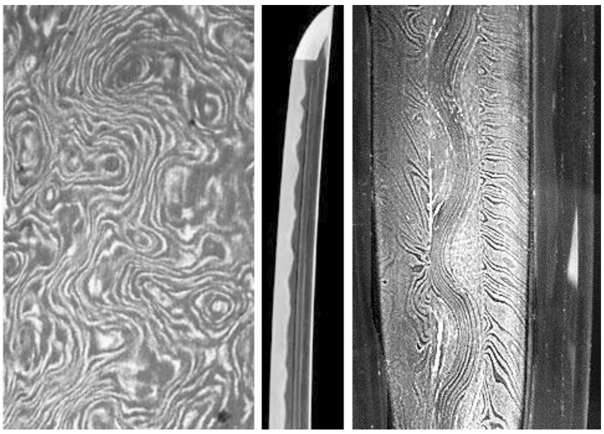
The point is that both words are a bit ambiguous. They do not always mean just "crucible steel". The term "wootz sword", for example, denotes *only* a sword with a visible "water" or "damask" pattern. While *all* "water -patterned" swords were made from a wootz cake or bulad egg, there are crucible-steel swords *without* that pattern.
And now we finally can ask the most difficult question in the context of crucible steel:

What, exactly, is the difference between wootz cakes / pulad eggs that can or cannot produce a "water" pattern on a blade?

That is *the* question. It is a tricky question because an ancient blade with a water pattern unambiguously proves that its maker could manipulate his wootz / pulad in a way that produced the pattern. One might speculate if somebody somewhere and sometime was able to produce a "water"-patterned blade from a steel that was *not* a crucible steel? The answer seems to be no - as long as we do not look at modern 20th century steels. I will get back to this topic in a somewhat different context later.
Blades *without* a water pattern, however, do not prove anything directly. There could be several reasons for the lack of a well developed "water" pattern:

1. The blade did show a pattern but somebody polished it, *erasing* all traces of the original pattern. Museum people like to do this.
2. The wootz / pulad would have allowed to produce a pattern but the *smith chose* to forge the blade in such a way that no pattern could develop. While the "water pattern" was highly priced in some cultures, others (including, for example, on occasion the Indians who made the steel) liked their blades shiny even after etching.
3. The wootz / pulad would have allowed to produce a pattern but the *smith didn't know* how to forge it in such a way that the pattern could develop.
4. The blade is from wootz / pulad steel and actually does show a pattern - it is just *too fine* to be seen by the "naked" eye.
5. The wootz / pulad does *not* allow to produce a pattern, no matter how it is forged. This happens "automatically" if we have a "low-carbon" crucible steel - but I'm not sure if such a thing ever existed. We look at high carbon wootz / pulad here.

Let's make clear what I mean with "water" pattern. It means a special kind of a layered distribution of cementite particles in the steel because, after some etching, a *nice* pattern visible to the naked eye is produced. If, by contrast, the unavoidable cementite particles are distributed uniformly, there is no nice pattern; at best the blade looks slightly mottled. I will go into this in far more detail in the next chapter.
Just to make sure we understand each other, here is a picture illustrating a few quick points about **patterns on a blade**:



Three blades with a pattern. The contrast is strongly enhanced.

- The left part shows the "water" pattern of parts of a "wootz" blade. People gave it many names and I don't care how *you* like to call it - true damascene, perhaps. Important is only that the pattern results from an *inhomogeneous distribution of cementite particles*. You do not see the individual cementite particles but their arrangement in the fuzzy white bands.
  On the right is the center of a (modern) *pattern-welded* blade. *Two kinds of steel* are involved here. One that appears bright after etching, and one that appears dark.
  The center shows a Japanese blade with a distinct "hamum". The blade actually consists of at least two kinds of steel but you see only one. The pattern is due to a *different microstructure* of one kind of steel. The bright parts are mostly martensite whereas the darker parts are bainite / pearlite.
  I do not show a fourth variety; bands of pearlite grains separated by ferrite grains. This is observed in modern steels (with a microscope) and Anna Feuerbach mentions it in her thesis as a possible "wootz" pattern. I have yet to see this in an old steel, so there is no picture.

Finally we are at the heart of all the excitement and emotions about "wootz" steel and blades. The tough questions to address now are:

- Does it need something *special* so that some wootz cakes / bulad eggs allow to produce a nuce water pattern? If yes, what exactly is it?
- Alternatively: is the pattern produced by a special way of forging? Could a cunning smith persuade *any* high-carbon steel to produce a pattern?
- Is a blade with a nice water pattern always better than one without it? If yes - why?

- I'm talking more and more about sword blades now. Since this is the topic of the next and final chapter, I will stop right here and go on with a quick look at modern ways to reproduce crucible steel and use it for blades.

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4) Bennet Bronson: The making and selling of wootz, a crucible streel of India", Archeomaterials, Vol1, No. 1 (1986) p. 13 - 51.