10.2.4 Bloomeries

Real Smelting

So you smelted some iron. Some time between 1000 BC and 1000 AD or even later. It doesn't matter much as far as the basics are concerned. You used a "**bloomery**" type of furnace, essentially a stone lined hole in the ground plus a cylindrical tube made from e.g. clay on top; see all the pictures below and elsewhere. A bellows is attached via a tuyere. Your bloomery is not much different from the shaft furnaces used for making copper.
You did the best you could, trying to follow the working recipe as closely as possible. You and your crew worked for many hours. Some roasted the ore and smashed it into small pieces of suitable size; others built the smelter and the hearth of the forge. During smelting time it's working the bellows, feeding the smelter, fetching the beer, and watching closely if everything goes well. You may tap the slag once in a while through a tap hole or you just let it collect in the bottom pit.

- Now it is time to stop the smelting. How do you do this? You tell the guy at the bellows to stop pumping? Then your smelter stack will be full of burden that got stuck when the fire goes out and everything cools down. That will be no problem if you tear down the whole thing to get at the bloom while it is still hot. It's just wasteful.
  So you stop feeding the smelter but keep blowing air until everything is burned off. Then you use up all material. It's just that the smelting process sort of fizzles out uncontrolled during this turning-down process and you don't know what happens to your bloom. But you might be able to get your bloom out through the top or an opening at the bottom without being forced to tear down your smelter completely.

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Doing it

- Here are some pictures of a smelting experiment. It was re-enacted to investigate the old techniques and also to see what one would dig up years later:

Small Bloomery starting up, dismantled, and bloom

Source: Thomas Birch, Robert Scholger, Georg Walach, Frank Stremke, Brigitte Cech: "Finding the invisible smelt: using experimental archaeology to critically evaluate fieldwork methods applied to bloomery iron production remains", Archaeol Anthropol Sci; Published online 16. Mai 2013.
With friendly permission

- This was a smelting experiment done by archaeometallurgists. That's why we have data and numbers:

  - The ore was limonite, roasted and then crushed and sorted.
  - 15 kg charcoal for preheating.
  - Constant airflow until the *end stages* of the smelt, when it was *increased*.
  - 18 kg ore, 45 kg charcaol; ore to fuel ratio 1 : 2.5.
  - Charge added every 20 min.
  - The slag-rich bloom weighed 9.5 kg

Illustr. Module

Blooms & Bloomeries

- This was high-efficiency smelting. Limonite contains about 50 % iron so at most 9.5 kg iron could be produced. Even if only halve of the bloom consists of iron this is a good result; compare to numbers given here.
  More pictures of blooms and bloomeries can be found in the link.
  - Note that no flux was added. This implies that there was sufficient SiO_2 in the gangue. Slag from smelting iron invariably contains **fayalite** or iron silicate (Fe_2SiO_4), a member of the olivine group that constitute the Earth's most common minerals by volume. SiO_2 or quartz reacts with iron oxides in many ways; the end products being fayalite, **wüstite**, the iron mono-oxide FeO rarely found in nature, some elemental iron (Fe) plus carbon mono and di-oxides. What, exactly, you get depends on conditions; here are a few possibilities for the end result of all interesting reactions:

1.	$3\,Fe_2O + 2\,SiO_2 + 3\,CO$	⇒	$2\,FeO + 2\,Fe_2SiO_4 + 3\,CO_2$
2.	$2\,Fe_2O + SiO_2 + 3\,CO$	⇒	$Fe + FeO + Fe_2SiO_4 + 3\,CO_2$
3.	$4\,Fe_2O + SiO_2 + 9\,CO$	⇒	$5\,Fe + FeO + Fe_2SiO_4 + 9\,CO_2$
4.	$2\,FeO + SiO_2$	⇒	Fe_2SiO_4 + 909 kJ

  - About equal amounts of wüstite and fayalite, i.e. $2\,FeO + 2\,Fe_2SiO_4$ plus a bit of this and that is what we call slag from bloomery iron smelting. It is liquid around 1200 ^oC (2192 ^oF).
    The reactions above have been made "stoichiometric" for certain relations of iron and SiO_2 gangue in ore. Since the fayalite forming process releases a lot of energy, far more than the other processes in the smelter (see the last entry above), it will definitely take place and elemental iron can only be produced if some iron oxide is left over after all the the SiO_2 in the gangue has reacted. The reactions given above (and taken from Vagn Buchwald's book) correspond to the following iron : SiO_2 relations in the ore:

    1. Fe : SiO_2=56 % : 20 %. An inadequate ore that will only produce slag.
    2. Fe : SiO_2=59 % : 16 %. The iron yield is 25 % relative to the iron fed into the smelter-
    3. Fe : SiO_2=64 % : 8.6 %. The iron yield is now a very high 62.5 %.
- This is quite amazing! Change your ore "quality" by a few percent and your smelting results may change dramatically. That's why you paid a lot of attention to your ore. You cleaned it as well as possible, you crushed it and then roasted it. That process can be seen here. Roasting takes place around 500 ^oC (932 ^oF) for several hours and does a number of things:

  1. It removes water. Both the "regular" water and the crystal water in the ore by reactions like $2\,FeOOH \Rightarrow Fe_2O_3 + H_2O$. In other words; it turns Goethite, limonite and bog iron into haematite.
  2. It removes sulfur (S). Many ores contain some pyrite (FeS_2). Roasting releases the sulfur according to $4\,FeS_2 + 11\,O_2 \Rightarrow Fe_2O_3 + 8\,SO_2$. The sulfur dioxide produced is a poisonous gas that escapes and will be noted by its acrid smell. Since sulfur in iron is always bad news, this is quite important.
  3. It makes the ore more crumbly because the iron oxide crystals will fall apart to some extent undergoing all these reactions. This increases the surface to volume ratios substantially and thus makes the solid-state reduction process easier that can only proceed via the surface.
  4. It changes the color of the iron-bearing parts (bright orange if it is pure haematite). That makes picking of good ore pieces now easier. Some unwanted additions like copper may cause discolorations that allow to discard the contaminated pieces.

  So you did a lot of work before you started to actually smelt.
- Anyway, the smelter is is now turned off one way or other and now it is time to get the bloom. That is not a problem as long as the smelter was nothing but a hole in the ground about 30 cm across, lined with a few stones, and a clay tube leading up about 1 m at most. You just tear down the whole thing. You can build a new one in a short time with little cost and effort. The tuyere, the bellows and the connection between both are more critical.
  You could also make make a bigger smelter but then tearing it down and rebuilding gets more expensive. More important: the bloom might be too large to be *wrought* (=old-fashioned word for worked) "by hand". A bloom weighing more then - very roughly - 10 kg needed more bang for compacting than what you and I could deliver with a hammer. The smelter shown above did have an opening for retrieving the bloom (plugged up during operation) but since it was too small, the smelter had to be dismantled. You can try to retrieve the bloom through the top of the stack but it ain't easy either. All in all, iron bloomeries for more than 2000 years tended to be small and were only used once or - after repairs - a few times for good reasons.
  - Metal engineers eventually, like after 1000 AD, found ways to have larger permanent smelters and to get the bloom out without destroying the smelter every time. They also found ways to work those big blooms - with water-wheel driven hammers! But we are still back around 1000 BC and we need to wait for about 2000 year before that is going to happen.
    The best one could do for more than 2000 years was to produce a bloom about 2 to 4 times bigger than what one man could work. The big bloom then was cut into two or maybe four parts while still red hot. Then up to four smiths could work it. Here is a picture showing a cut bloom.

Working your Bloom

- So what, exactly, is a bloom, and how do I work it? As the pictures in the links show, a bloom is a red-hot mass of iron, charcoals, slag, and maybe pieces of smelter lining, weighing a few kilograms. If it is larger than roughly 10 kg, you must divide it. That is easier said then done, especially without modern power tools.
    - You must now **compact** and **refine your bloom**. For that you hit it with a hammer. For starters, you need a hammer with a big head otherwise you just make dents in the red-hot porous mass that is oozing viscous slag. That's why you use a wooden mallet and a stone or the slightly concave surface of a tree trunk as anvil. It's not that wood makes a great hammer head or anvil. But if you ever tried to lift an *iron* hammer the size of the wooden mallet shown below, you appreciate the wooden mallet. Same thing for the tree trunk. It will get burned but keeps the bloom nicely in place.

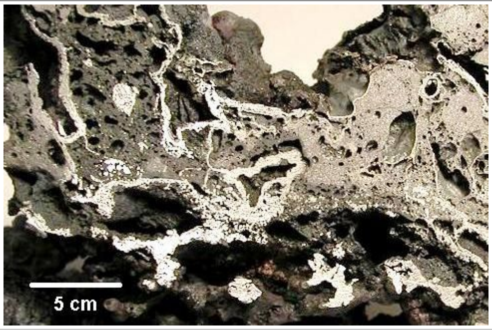
Ready to compact a bloom

Bad bloom from Roman times

Source left

Source right: From the "Hüttenberg" project under the direction of **Brigitte Cech**; photo from Ruth Fillery-Travis; both University College London (UCL). With friendly permission.

- What you want to do is to hammer your bloom into an solid piece of "**wrought" iron**. Wrought because you wrought=worked it, *not* necessarily because it had a very low carbon content. This means that you must remove bits and pieces of foreign matter, squeeze out the still liquid (if viscous) slag, and close the holes and pores in the iron. This is hard work, necessitating a decent supply of beer. While I have never yet hit a bloom with a mallet as shown above, I do have some hands-on experience of hitting things with big wooden (or iron) hammers for prolonged periods of time, and I can testify that it is hard work, producing a magnificent thirst that cannot be quenched with water.
  Hitting a bloom with a wooden mallet will only get you that far, though. At some point the bloom is just too cold to notice your feeble hammer blows. You now transfer it to the hearth of a smithy, heating it up again, and banging it some more. This you do on an anvil (stone in ancient times), using an iron hammer. In between banging you reheat the piece in your hearth. You go for very high temperatures, necessitating a good air supply to you hearth. Very high temperatures in excess of 1000 ^{o}C (1832 ^{o}F) make it not only easier to shape your piece, but re-liquefy still present slag and enable fire-welding of the many seams.
    - Just banging on your bloom randomly will compact it some but you will not achieve optimal results. It takes some experience and cunning to produce a nice bar of iron (or shapes like Celtic double-pyramid bar; see below) from a given bloom. You will, for example, sprinkle some special sand on the mass from time to time, because that helps to hammer or fire weld iron to iron. If you want to close holes, you must join iron surfaces, and this is not possible as long as they are oxidized. Adding a bit of silicate (from quartz sand) will produce liquid fayalite when it reacts with the oxide, the main material in slag, that you now can squeeze out. I'll get to that in more detail in a moment. You also will tend to fold your flattened piece over and weld it together, and you repeating that several times. In other words, you produce what some like to call a piece of "damascene" iron / steel. Well - you don't. All you try to do is to make your piece of iron as uniform as you can, and folding and rewelding a lot does just that. Done professionally we call it "faggoting". Try it with random lumps of brown (chocolate) and white dough. Flatten, fold and "weld" a few times and you have more uniform light-brown stuff.
- Of course, the quality of a bloom matters very much in this. Some blooms are simply too bad for "processing"; and experts can "see" that, it appears, and won't bother to work it. The "bad" bloom *above* was found in Hüttenberg; Austria, one of the places where the the famous "**Ferrum Noricum**" of the Romans was produced between 100 BC - 400 AD. It was found when the smelting place was dug up by Brigitte Cech and others like Thomas Birch. We must assume that it was judged to be unworthy of use by the ancient smiths.
    - Here is a bloom from a modern experiment, it looks rather similar to the "bad" Roman bloom from above.



Bloom from a recent experiment

Source: Besucherbergwerk „Grube Wohlfahrt“

When the smith is done, he has produced a shapely piece of iron. A straight bar, perhaps, or the famous Celtic "**double pyramid" bars** (Spitzbarren) as shown below:

"Double pyramid" iron bars found in my home town in 2009

Typically made from two blooms; the (bad) welding line is visible.

Source: Photographed at the "Special Exhibition Dedicated to the Celts of the First Millennium BC"; Stuttgart, 2012/13

- But no matter how good your bloom and your compacting skills: the iron / steel pieces produced contained slag particles and maybe other inclusions, and their carbon content varied within a piece and between pieces (as we will see in the next chapter). They may or may not contain relevant (varying) concentrations of phosphorous and other stuff, too. Moreover, closing holes in the bloom and folding the workpiece many times produced plenty of weld seams that can be perfect or bad, depending on the skills of the smith and local conditions. The specimen above, for example, show "cracks", probably from bad weld seams.
  This kind of stuff can *never* be a match for inclusion-free homogeneous steel!

The Carbon Content of Your Bloom

Now I can no longer avoid dealing with the crucial question: What did those bloomeries really produce? *Always* wrought iron (=soft iron with very low carbon content) as explicitly and implicitly assumed in most of the older "archeological" papers? And never cast iron?
In the preceding sub-chapter I have already argued at length and rather convincingly (to me) that it is possible to produce low carbon iron in a bloomery but that you just as well could get cast iron or anything in between, i.e. all grades of carbon steel. It now behooves me (love that word) to prove that claim. There are two possible ways to do that:

1. Analyze a lot of old iron and determine the carbon content, in particular for everyday "wrought iron" stuff.
2. Run bloomery experiments just as it was done thousands of years ago and see what you can get.

It is quite nice for me that the number of bloomery experiments done by all kinds of people and thus also by people who don't know a thing about Material Science is sky rocketing! Before the year 2000 or so, only a few smelting experiments were done inside the scientific community, e.g. by Tylecote. Nowadays lots of people with or without a scientific background go out, build a bloomery, drink some beer and smelt some iron. Even high school classes do it for their science projects. I'm not sure if they drink a lot of beer and I don't even want to know how they keep themselves amused otherwise out there in the underbrush.

Illustr. Module

Results of Bloomeries

This is good! The kids and many enthusiasts out there do not know a thing about smelting except what they have heard (or read) from others - just like the old Romans and so on. Many a hobby black smith or metal smelter started with very little background knowledge but became a smelting expert by trial and error, who could raise a bloomery and produce some good iron /steel without problems.
It's a rare moment! We also get to witness the errors in the present wild days of empirically re-inventing bloomery techniques by trial and error! My guess will be that in a few years it is all over. The Internet will provide so many (almost) fail-proof recipes for smelting a bit of iron that will work all the time. Just like in antiquity; it just took a bit longer then for the knowledge to spread.

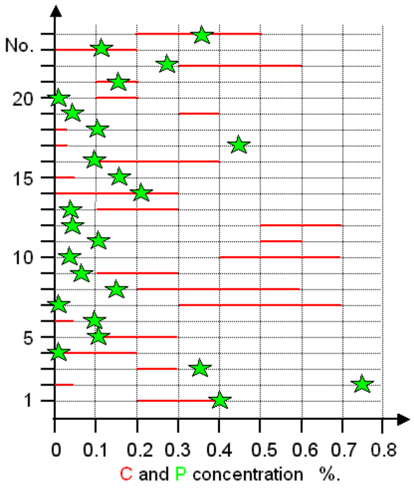
The link above gives some results from randomly selected smelting activities. A clear picture emerges:

- It is perfectly possible to smelt **cast iron**, wrought iron, and anything in between in a simple bloomery.
- It is also possible to smelt no iron, producing only iron-rich ("magnetic") slag.
- Efficiencies (weight of bloom relative to weight of ore) can vary substantially; high efficiencies are possible.
- Changing the carbon content of the bloom by changing parameters "by feeling" doesn't seem to work most of the time.
- Bloom quality can vary a lot, and the carbon content of a bloom can change considerably from top to bottom.
- It does take a fairly large number of smelting experiments done in the time honored trial and error method before you can call yourself an experienced smelter.
- It is possible, however, to develop a smelting technique that produces what you want (i.e. low-carbon iron) most of the time within the possibilties and constraints of your local environment.
- It's not so easy to transfer a technology that works in one place to another one where the ore, charcoal and so on will be somewhat different

Now let's look at the archeological record. Below I give carbon concentrations for some objects as given and discussed in Buchwald's authoritative book.

Iron clamps Parthenon 447 BC			**Roman nails** 40 AD		
	No	[C %]	No	[C %]	
	1	0.395	1	0.019	
	2	0.419	2	0.21	
	3	0.117	3	0.04	
	4	0.104	4	0.07	
	5	0.350			
Left: Iron stub for connecting column drums in-situ in Ephesos **Right: Roman "standard" nail**					

The Greek routinely used iron clamps (always encased in lead) to keep layers of shaped stones together, and stubs as shown between two column drums. This added resistance to shear forces as they might be encountered in an earthquake. The clamps that kept the marble "bricks" of the temples together sure varied a lot with respect to their carbon concentration. None was "wrought iron" in a strict sense (i.e. less than 0,1 % of carbon). That makes sense. You want strong steel to make your temples earthquake-prove. I have my doubts, however, that the Greeks knew much about the properties of their iron / steel.
Nails you typically like to be made from soft and thus very bendable iron. It thus makes sense that the Roman nails are low in carbon. Three of them would even qualify as wrought iron.
Now let's look at some **Celtic swords** from around 350 BC. They all have been investigated in detail by R. Pleiner. Vagn Buchwald was able to re-examine 23 of these swords, including the structure and compositions of the slag inclusions. His results concerning the carbon and phosphorous concentration are shown below in a graphic representation drawn with the data in Buchwald's book. The carbon concentration typically varies between different parts in an unsystematic way and the measured range is shown as red bar. The phosphorous values represents the maximum concentrations found.



Carbon (C) and phosphorous (P) concentrations in Celtic swords from about 500 BC - 250 BC.

Source: Data are from Buchwald's book; p. 116

- There are four *wrought iron* swords, rather useless one should think. But two of them are high in phosphorous and thus also quite hard. The rest represents a mixture of all kinds of carbon concentrations - between swords and in a given sword.

Rehder in his wonderful book raises the same point. Bloomeries produce iron with a wide spectrum of carbon concentrations. He analyzed data for 507 iron artifacts, spanning the time range from 1000 BC to 500 AD, and, after eliminating cast iron ("which was so easily made") arrived at an average carbon concentration of 0.48 % with a range from 0.001 % to 0.9 %. Rehder also reports on an independent work of Schaaber et al. where an average carbon concentration of 0.53 % was found for 484 samples, mostly from late antiquity in central and southern Europe.

- Rehder also makes a point that finished iron objects had experienced a lot of forging that must have lead to some de-carburization. I have discussed at length that carburization during forging is not impossible but unlikely and that not much will happen in any case. De-carburization is far more likely, since most parts of the forged objects will experience oxidizing conditions most of the time - and that's when de-carburization takes place. It also will only affect surface-near parts, but with a lot of folding and fire-welding, the effect might be noticeable throughout the volume.

What's Left

Untold millions of bloomeries must have been used in Europe and the Middle East in the more than 2500 years between 1200 BC and 1500 AD. It shouldn't be too difficult to dig some up. What can we expect to find?

- Not much exiting stuff, actually. Besides a (completely grown over) slag heap you can only expect some burnt looking stones and discolored soil wherever there has been a hole-in-the-ground bloomery. With luck, maybe some pieces of the wall and the tuyere are still in-situ. With extreme luck, you might find an abandoned bloom. Archeometallurgists actually have run bloomeries with all the trimmings (roasting the ore, forging the bloom, ...) for a while. Then they tore down the smelter, cleaned up a bit, and went away.

The smelting place from above after finishing

Source

- After just a few years grass will have grown over the whole affair and nobody will recognize that the place was used for smelting some iron some time ago. After a few thousand years, some topsoil has aggregated and nothing is visible at all - by human eyes. With some special "eyes" provided by your friendly physicist or Materials scientist around the corner that can also "see" (very small) magnetic fields, you will recognize something special there, however.
  When you dig it up, it might look like this:

Remains of a Roman furnace in Hüttenberg, Austria

Source

Not much is left from old bloomeries and forges. Essentially you find some holes in the ground or just depressions with some blackened soil. Maybe a few stones and some slag pieces if you just take in an overview. If that site is from 1000 BC or 1000 AD is not immediately obvious; the remains of smelting places look very much the same, regardless of age.
If you dig and look *closely*, however, you find much more:

1. Slag deposits from the "run-off" slag (Run slag, tap slag, ...) if the furnace was tapped for slag.
2. Furnace bottom slag (furnace bottom cakes) if there was no tapping and the slag collected a the bottom.
3. Hearth slag. That is slag released when the bloom is re-heated in the hearth. It trickles down and leaves a "cake" looking very much like furnace bottom slag.
4. Hammerscale or oxide particles that flew off when the smith banged on the always oxidizd hot iron.
5. Pieces of iron banged off from blooms and the hot iron parts.
6. Discarded "bad" blooms.
7. Hammer and anvil stones.
8. Furnace lining stones.
9. Remainders of flux and ore.
10. "Lost" items like an iron bar or beer bottles from more recent smelting.

No. 5 - 10 are obvious, and I won't discuss them. The first four items, however, warrant a few words (and pictures).

For finding the "run-off" or **production slag**, you may want to look around yourself. Then consider that those hillocks and the large hills you see out there might be huge mounds of slag! We have seen that before in the context of copper smelting. Now we may encounter really big deposits of slag. We definitely do!

- In 1915 - 1943 the modern steel mills on the Island of **Elba** (Portoferraio) or just across in Italy (Populonia, Follonica, Piombino) were fed with iron-rich ancient slag from the general area. Up to *2 million tons* of ancient slag, found in layers 2 m - 8 m thick, were "harvested" with heavy equipment. The slag was produced by bloomeries running there for a long time, the maximum activity was after 450 BC. Ancient slag from bloomeries always contains a lot of iron because iron oxide (=ore) was used as flux. Modern blast furnaces use limestone as flux (producing $CaSiO_4$ instead of $FeSiO_4$) and thus can work with old slag.
  True, the general area (including the Island of Elba) was a metallurgical center in antiquity (sort of an ancient Pittsburg, Sheffield or "Ruhrgebiet") for many hundreds of years - but *2 million tons*? Assuming that one bloomery produces at most 50 kg of slag in one run, this means that *40 million* bloomery runs must have taken place. Assume somewhat smaller numbers, and it still boggles the mind.
  So we could expect that the archeologists dug up a lot of bloomery remains and lots of artifacts related to iron making? Not so! First, the large strip-mining machinery left little behind, and second, the archeologists then did not care all that much about blackened holes in the ground. They cared about the discovery of unrobbed **Etruscan graves** around Populonia from about 900 BC - 420 BC that were hidden (and thus protected) below thick layers of slag.
  The **Etruscians** were about in Italy before and during the rise of the Roman empire and masters of copper / bronze technology. They were also easy going, given to throwing good parties (look at the pictures in those tombs), and not above making fun of their victims:

Etruscantomb ("tumuli") at Popolunia; formerly hidden under slag.
Inset: Embellishment on a chariot. Last thing you might have seen while still alive.

Source: Internet commercials

- In the graves some iron objects were found but few have been analyzed. As far as one can tell, the old Etruscian iron was, as expected, a mix of all kinds of grades.

Furnace bottom slag and **hearth slag** look rather similar. In the first case it is the stuff that collected at the very bottom of the bloomery and couldn't flow out because the tap hole was too high (or because there was no tap hole). In the second case it is the slag that drips down from the bloom when it is re-heated to be forged to its final shape. Forging sqeezes out the slag still in the bloom and possibly adds a bit more because the smith sprinkles silica on the bloom. Some of the stuff clings to the bloom and only flows off during reheating.
Furnace bottom slag and hearth slag thus will be roundish and bowl-shaped on one side.

- Here is a 100 ton furnace slag found in Rochester, USA, in 2013, when the City dug up a parking lot in order to move some electrical lines in preparation for the construction of Rochester’s new marina. It so happens that in 1926 or so, the Quinnesee Iron Mining Co. operated a blast furnace right there, but when they folded and tore down the furnace, they forgot to take the rather weighty furnace bottom slag along.

100 ton (about 220 000 pounds) furnace bottom slag in Rochester, USA.

Source: "Rochester Subway".

- The furnace bottom slag of an ancient bloomery looks about the same, except it is just much smaller.
  Here is a typical hearth slag, cut into two pieces. It has the same basic geometry as a furnace bottom slag because both once filled a round bowl-shaped depression.

Hearth slag .

Source: English Heritage Internet site. With permission.

- There is no lack of ancient slag and analyzing it has become a major activity. Slag, however is always a complex mixture of many ingredients; here is an example. It is therefore not easy to learn a lot about the smelting and forging process from slag analysis alone. However, much progress is being made right now and the analysis of slag will certainly provide major insights into ancient metallurgy in years to come.

Now to ***hammerscale***, the last point of the list above that I will discuss. What is hammerscale? It is the oxide formed on your iron when you put it into the forge fire. You then simply "burn" it. When you bang it with the hammer, the brittle oxide breaks off in small fish-scale like parts. Small iron particles might break off too, becoming oxidized as the fly off, and if your iron still contains some slag, droplets of liquid slag, solidifying as the sail off, will join the rest.
Here is a picture of hammerscale on the anvil:

Hammerscale on an anvil.

Source: Sorry, forgot.

- Hammerscale is essentially Magnetite (Fe_3O_4). Quite a bit is produced during forging and that limits the time you can heat and bang a piece of iron. It gets smaller all the time.
  Hammerscale is a great ore. If you produce enough you can put it right back into your smelter.

Enough! It should have become quite clear that iron and steel was mostly made in small bloomeries for more than 2000 years. The product always contained slag inclusions, and carbon (and other stuff) in all kinds of concentrations. With experience and cunning, the process could be optimized to some extent but the final product could never compete with uniform iron / steel that did not contain slag inclusions, meaning steel that was liquid once.

- It remains to see how Europe and some of the East cultivated bloomers iron / steel technology and how in the far East wootz steel came into being, a steel that was liquid once and thus free of slag inclusions.