Making Steel in the "Aristotle Furnace"

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Introduction

The early presence of steel is usually explained as direct production from the bloomery, or long cementation in a hearth, or later, by crucible steelmaking. There is another simple, almost obvious way to increase the carbon content and decrease the slag content of bloom iron, that we like to refer to as the “Aristotle” method.

My friend Skip Williams has designed an elegant little furnace for this process, which I demonstrated at the conference. After a brief description of the building and running of the furnace, I’ll give a little background on how we stumbled onto this idea, and then summarise the variables we have identified that influence the carbon content of the resulting steel. And then, of course, pose a few questions.

Experiment description

Furnace Construction

After several days of very hard work on the bloomery experiments, and some not insignificant celebrating afterwards, I was not really intending to do anything for the Friday morning experimental session. But I was encouraged by Steve Mankowski to build and run an Aristotle furnace. Steve had earlier had several discussions with folks who were interested in this process, and more compellingly, with several folks who didn’t believe it possible. Since this whole process is so simple, quick, and straightforward, I agreed, and we set to work.

I had not built or run one of these furnaces in a year and a half, and I was dusting off my memory as we went, so all dimensions and procedures recounted here are very approximate. I built the furnace with clay leftover from the bloomery construction. In form, it is basically a tiny shaft furnace, about 10cm in diameter, and perhaps 20cm in height. This was formed quickly around a tin can Steve scrounged up somewhere. A steeply angled blowhole (about 45°) entered the furnace shaft about 6cm above the furnace's clay floor. The blowhole was made with a pencil, so was about 1cm in diameter.

A clay air chamber was built onto the side of the furnace shaft. This air chamber functions solely as an adapter to connect the air supply to the blowhole, though a movable lid on the chamber can function as a dump valve for additional control of airflow. In cutting the blowhole, this arrangement also allowed me to cut through the back wall of this air chamber as well, to provide a peephole into the hot zone (Figure 1).

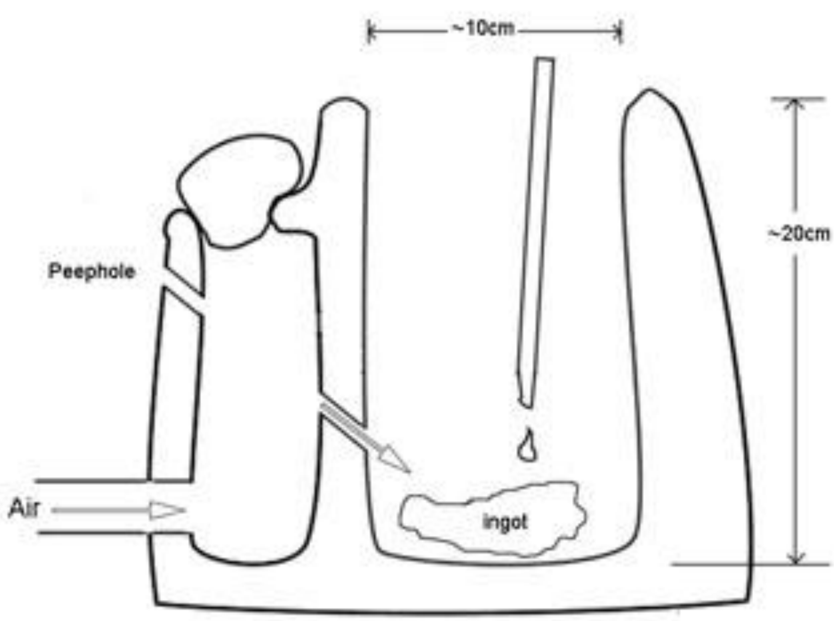

Figure 1. Cross-sectional sketch drawing of the Aristotle furnace

I built this furnace on a wooden stump. Given that I built the furnace floor a bit thinner than I should have, we burnt into that stump rather quickly. A nice fat layer of clay on the top of the stump would have been a good idea.

I built a small fire of kindling wood around the furnace to dry it, which literally took longer than constructing the furnace did. The construction and drying of the furnace probably took a little over an hour. Meanwhile Steve went to the blacksmith shop and scrounged some cold rolled, low carbon bar stock to convert. Shel Browder and Hector Cole forged up some of the previous day's bloom into small bars for the same purpose. The air was supplied by the same vacuum fan used in the bloomery experiments, but in this case turned way down.

Experiments

We selected out a small pile of finer charcoal to feed this furnace, so that the lumps varied from 1 to 2cm in the largest dimension. We lit the fire in the shaft, and slowly brought up the blast until we judged it was hot enough, and consuming the charcoal at the proper rate. Again, I was just winging it here, but a look back out our old notes suggests that a nice workable rate of charcoal consumption is about 100g per minute.

The feed stock for the first run was 675g of round mild steel bar, which was probably around 8mm in diameter, and cut to convenient lengths of about 25cm. Once the furnace was good and hot right to the top, I used tongs to drop the first rod vertically into the furnace, directly in front of the blast hole, about two-thirds of the way towards the back wall. I simply allowed the bar to drop of its own weight as the end of it melted off, and added a new bar as the end of the previous bar reached the top of the charcoal, in order to keep a continuous supply of iron at hearth level. Steve kept the furnace topped off with charcoal at all times.

The bars melted slowly at first, but more quickly and steadily as the puddle grew in the base of the furnace. The last rod disappeared below the charcoal perhaps 20 minutes after we charged the first bar. We added one last handful of charcoal, and allowed the charcoal to burn down about halfway before we cut the blast, scooped the rest of the hot charcoal out, and then pried the ingot from the bottom of the furnace. The entire process, from turning on the blast to removing the ingot, took 30 minutes.

While the ingot was still hot, I hammered it a bit, just to get an idea of what we had made; if we had added too much carbon, it would crumble pretty immediately. It felt hard and "ringy", so I guessed we had succeeded reasonably in making steel; this seemed to be confirmed by spark-testing with a hand-held grinder that was on site. When removed from the furnace, the shape of the ingot was generally plano-convex, which I flattened to a disc shape by the light forging. The resulting ingot was 10cm in diameter, 1.5cm thick, and weighed 392g.

After a few minutes we refilled the furnace with charcoal and repeated the process with the bloom iron bars. There was less of this material, perhaps 500g, but otherwise both the process and result were quite similar to the first ingot. These ingots are now in the possession of Janet Lang and Don Wagner, so more complete analytical results of these particular ingots may follow in the future.

Discussion

Background

I can almost hear the entirely reasonable objection to this process, from the view of an archaeometallurgist: that we just made the whole thing up. Of course we did, that's what artists and craftsmen do! But ideas don't come from nowhere. So I think a little background on how we came across this method might illuminate our sneaking suspicion that there is a whole chunk of ancient steelmaking technology that's been almost entirely overlooked.

Way back in 2003, Skip Williams and I agreed to try to make a sheet of armour plate from steel made directly in a bloomery, for a television program Alan Williams was working on. This was perhaps unwise, as there were pretty severe time constraints on the job, but I figured it wouldn't be too difficult, since all our early struggles with the bloomery process had been to reduce the bloom's carbon content. The goal was a 60x60cm plate, 2.5mm thick, with a carbon content of about 0.8%. We had no difficulty in producing a steel bloom, but the problem lay in forging this down to thin plate without decarburizing it. If the included slag in the bloom was low enough in iron to not decarburize the metal during forging, the metal would not weld up well enough to forge into a thin plate (regardless of the welding flux used). If the included slag was high enough in iron to allow good welding, it rapidly decarburized the metal. After weeks of work, we were smack up against the deadline and looming failure. After one last smelt, our desperation play was to drop a previously folded and forged billet into the hot bloomery, and leave it overnight in hot charcoal to see how much carbon it would absorb by cementation. We dropped the billet onto the top of the full furnace, with the blast on, with the intention of cutting the blast when the billet got down to the hot zone. But due to the distractions of beer and conversation at the end of a long day of smelting, by the time we looked into the furnace again, the billet was right in front of the tuyère, melting and burning! We killed the blast, hoping there was enough left of the billet to suffice, and let it cook overnight.

When we disassembled the furnace in the morning, we found the remains of the billet, which had not picked up any carbon. But below the tuyère we found a small "bloom" of high carbon steel, with very little included slag. This piece did hold its carbon during the initial forging (but was far too small to forge a breastplate with). Though our deadline for Alan was past, we repeated this experiment several times, simply charging chunks of wrought or bloom iron through the furnace as if we were charging ore, and each time got a 'bloom' of steel. This caused Skip to remember an odd passage from Aristotle's Meteorologica:

> Wrought iron indeed will melt and grow soft, and then solidify again. And this is the way in which steel is made. For the dross sinks to the bottom and is removed from below, and by repeated subjection to this treatment the metal is purified and steel produced. They do not repeat the process often, however, because of the great wastage and loss of weight in the iron that is purified. But the better the quality of the iron the smaller the amount of impurity.
> (Lee 1952, 325)

This passage is in a section dealing explicitly with melting and solidification. To judge from the commentary in Lee's (1952) translation, scholars' confusion about this passage has been largely attributed to confusion on Aristotle's part. But now, in light of our accidental melting of iron, this passage suddenly made sense as written. According to Aristotle's mental framework, steel was iron that had been purified by repeated passages through the fire. According to our current framework, the steel was iron that had absorbed carbon by repeated passages through the fire. Regardless of the abstract framework, the resulting chunk of steel is still a chunk of steel! Soon after this we also came across Ole Evenstad's description of steelmaking in a hearth, which seems to be another widely known and widely ignored reference to this phenomenon. (Evenstad 1968, 65; Wagner 1990, 114–5).

Some time later, Evelyne Godfrey asked me to make a set of bloom iron samples for the calibration of neutron imaging and analysis techniques. Up to this time, I had used either a gas forge or coal-fired bottom blast forge for almost all of my bloom forging, but for this purpose, she needed the iron to be forged entirely with charcoal. I set up a side-blast trench forge built of clay, and proceeded to work a half-bloom into a billet, fold and weld it three times, and draw it down to 1cm x 2.5cm bar. I want to emphasize that this was only the second time that I had forged a bloom to artefact entirely with charcoal, and the first time that I had done so in a side-blast trench forge. So it might not surprise you that on occasion, during this long bout of forge-welding, I may have overheated my bar a time or two, as I tried to get accustomed to the set-up and the fuel. The next morning, as I set up to start another day's work, I cleaned out the bottom of the hearth. "Oh look", I thought, "one of those plano-convex hearth bottoms I'm always reading about." I smacked it with a hammer to break it, to examine the slag. You see where I'm going with this. It didn't break. It was a little bloomlet of high-carbon steel. So on the very first time I forged bloom iron extensively in a traditional forge, I accidentally made a piece of steel.

Skip became particularly intrigued with all of this, and began experimenting with this phenomenon on a smaller scale than our trials with the large bloomery. Although his original intent in reducing the scale of the operation was to make the individual experiments cheap, quick, and easy, the furnace he eventually developed actually turned out to be very practical as well, producing about the amount of steel required for a knife or two, or for the steeling of several edges on larger tools. In the spring of 2009 a group of friends gathered at my workshop for a more extensive campaign of experiments with these little furnaces to see if we could get a better understanding of how and why this works. Over the course of a week we ran more than 30 trials in many different furnace configurations. These experiments produced the entire range of products from low carbon iron to molten cast iron, so we were able to identify some of the variables that influence the carbon content of the resulting metal.

Variables

One difficulty with using a furnace this small is that it is almost too responsive; it's a bit like driving a sports car when you're used to driving a truck. Or even a sports car with really poor wheel alignment. This makes repetition of experiments, with only one variable changing at a time, even more difficult than in a large furnace. Though it is hard to control carbon content very exactly, it almost always works to some degree, so the experimental campaign relies as much on observation of whatever happened as it does on controlling variables. In the practical realm of the smith, this variation is just fine, even an advantage, and the ingots can just be sorted and chosen for their intended use.

In the 2009 experimental series, two variables that emerged as important influences on final carbon content were the angle of the blowhole, and the height of the blowhole above the hearth floor. Steeper blowhole angles produced higher carbon contents, though lower, and even flat, angles could still produce steel. Shallower hearths produced lower carbon contents, deeper hearths produced higher carbon contents. These two are actually somewhat related, as regardless of the material the floor is built of, a steeper blowhole will tend to burn down into the floor.

There are some other variables that might be more or less important, but that we have not yet managed to pin down very exactly. They include the shape and size of the feedstock, the burn rate/temperature, and the residence time and temperature during after the final metal charge. At first glance, these might seem like simple questions to answer, but when you realize that the shape and size of the feedstock size has a direct and immediate effect on the temperature of the furnace, you can see how things get a bit complex. But again, a reminder: in the practical realm, exact control of these variables is of limited importance. Build a fire, melt some bar iron, and you get some steel. That’s all a smith really needs to know to make a useful tool; the rest is just satisfying curiosity.

Mechanism of carbon uptake

My understanding of how this process works is rather dim, really; I only know that it works. I can say definitively that it is capable of producing the entire range of metal from almost carbon-free to white cast iron. The iron may begin to pick up carbon immediately upon melting in front of the blast, or after the initial melting while sitting in the hearth, or only after the ingot reaches a mass, temperature, and sufficient carbon content that the metal becomes at least partly molten, at which point the carbon absorption really speeds up. Perhaps all three are at play.

In one series of experiments, we interrupted the process at different stages of the melt. These experiments suggest that the carbon is being picked up throughout the process, but the most significant carbon increase is at the very end. We are currently at work on the metallography of these experiments, which is clearing up the mechanism of the carbon uptake, and we hope we can present these results before too long.

In addition, we have of late been working with this technique in a larger scale, in a more open hearth such as that described in Evenstad (1968), which is opening up more interesting avenues to explore.

Questions, Questions, Questions

The question of when and where such a steel-making technique might have been used in the past is, of course, way beyond my expertise. But as my recounting of our own discovery of this process makes clear, it is so simple that it seems inevitable that it would occur often and early. Since it can occur in a simple blacksmith's hearth, or in a shaft furnace, the employment of such a technique would seem mighty easy to overlook in archaeological contexts, of either bloomery or smithing sites, as it would only leave behind a scattering of low-iron slags or bits of high-carbon iron fragments. For instance, this process offers an alternate explanation of the suite of artefacts from Saxon *Hamwic*. (Mack *et al* 2000).

Can the use of this technique be detected in implements and artefacts? Can it be distinguished from direct production of the bloomery? Can it be distinguished from crucible steel? As only one example, could such a process provide an alternative to the proposed use of Asian crucible steel the famed Ulfberht swords? (Williams 2009). Only a sustained campaign of experiment and analysis could give us answers here.

Even the presence of similar small furnaces to the one Skip arrived at independently is not out of the question. When Jake Keen, Michael McCarthy, and I travelled to Burkina Faso in 2008, we demonstrated this same furnace at a music, dance, and iron-smelting festival. Joacim Zalle, of a family of smelter/smiths from the village of Saye, told us that they do almost exactly the same thing. Vincent Serneels, who was translating during this conversation, did not believe Joacim really understood the distinction of converting iron to steel, but Joacim is not a man whose understanding I would consider it wise to underestimate. We later saw a photo from his village of a furnace pretty much indistinguishable from the one described above. Later in that trip, we visited a massive and beautiful bloomery site about 40km southwest of the town of Kaya. In one section of this site was a field of hundreds of small fist-sized furnace bottoms that looked suspiciously familiar.

On a more general note, perhaps this process raises some questions about the ways we think of steelmaking. A common paradigm seems to be that steel can be created by adding carbon to iron in the solid state, or removing carbon from (cast) iron in the liquid state (Craddock 1995, 237). Here, we are adding carbon to iron in a liquid state, or at least a locally liquid state.

It seems to me that the ‘Aristotle’ process can thus provide us with a ‘missing link’ among steelmaking technologies. It would seem a natural precursor to the development of crucible steel. It can also provide an explanation for the presence of small finds of cast iron, and potentially be considered as a source of cast iron for such known technologies as co-fusion, or Biringuccio’s ‘Brescian’ process (Smith and Gnudi 1990, 69–70). If nothing else, the ease and simplicity of the ‘Aristotle’ process provides a useful context for thinking about other steelmaking technologies.

Nonetheless, I think there's lots of work to be done here, both experimental and analytical. The experimental part isn't difficult or expensive, either, so I hope many of you will try it, and help provide some answers to all these questions.

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References

Lee H D P (trans. and ed.) 1952, *Aristotle Meteorologica* (London).

Smith C S and Gnudi M T (trans. and ed.) 1990, *The Pirotechnia of Vannoccio Biringuccio: the classic sixteenth-century treatise on metals and metallurgy* (New York).

Craddock P 1995, *Early Mining and Metal Production* (Cambridge).

Evenstad O 1968, 'A treatise on iron ore as found in the bogs and swamps of Norway and the process of turning it into iron and steel (1782)', *Bulletin of the Historical Metallurgy Group* 2, 61–65.

Mack I, McDonnell G, Murphy S, Andrews P, and Wardley K 2000, 'Liquid steel in Anglo-Saxon England', *Historical Metallurgy* 34, 87–96.

Wagner D 1990, 'Ancient carburisation of iron to steel: a comment', *Archaeomaterials* 4.1, 111–117.

Williams A 2009, 'A Metallurgical Study of some Viking Swords', *Gladius* 29, 121-184.

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