Lee Sauder and Skip Williams Smelt Iron

Introduction

Lee Sauder is a fun-loving beer-drinking blacksmith who, and I'm guessing this, was born around 1961 in Virginia, USA. Together with "Skip" Williams III he made and ran iron bloomeries since 1998. Their "interest and expertise was in iron and ironworking, not in archaeology or metallurgy", to quote these guys..
Lee Sauder is actually an artist who specialized in making artwork from bloomery iron. I do not know much about Skip Williams, and whenever I refer to Lee Sauder in what follows I mean both of them in case of doubt.

Those two guys more or less single-handedly figured out far more about the art of making iron or steel in a bloomery than all the other amateurs who enjoy to run a smelter on occasion. What's more, it looks to me that they also figured out more than all those *experts* who do experimental archeometallurgy.
When I wrote this part of the hyperscript, I read a lot of papers and books about bloomeries but a number of my questions weren't addressed at all in all these learned papers. I also found a lot of statements that, from a theoretical point of view, were doubtful or just plain wrong. Lee agrees for practical reasons: "As I became more successful in my own attempts at smelting, I found that much of what I read about bloomery smelting in these academic publications, though often brilliant, was also often inaccurate, misleading, or just plain wrong." [4]. It was a pleasant surprise for me that Sauder and Williams offered answers to those questions based on results that came straight from experiments and from their forays into the science of iron smelting.
Mind you, I'm not saying that they got everything right and that no more questions are left (they are not claiming that anyway). I'm just saying that without experiments and "hands-on" knowledge of blacksmiths and other artisans we will not get to the core of the matter. Merely thinking about scientific questions that do have a definite answer (in contrast to many other question, e.g.: "which one of these two dresses should I wear tonight?") will usually not get you there; witness Aristotle and early archeologists .

Lee Sauder

Source: Lee's homepage (http://www.leesauder.com/)

For starters, I give you a few quotes plus comments:

Our first 11 *smelting* trials provided us with valuable experience but produced *only the most pitiable examples of blooms*. These early blooms, besides being fist-sized at best, all had elevated carbon contents that made most of them unforgeable. We attempted to deal with these problems by reducing both the fuel:ore ratio, and lowering the airflow and temperature, with disappointing results.
Pretty much everybody has made this experience, it seems.

We added a final 4.5 kg of charcoal to the furnace, and burnt it down to near the level of the bloom. We removed the access door, and wrestled the bloom from the furnace. We then proceeded with all our ritual observances, in which hammers and *beer* figure prominently.

The secret for being successful. I always knew that <u>beer is important</u> in metallurgy

Our earlier experiences with blasts of these lower rates indicates that as the blast approaches 0.6 l/min · cm^2 , the carbon content of the bloom *increases* , and the slag near the bloom turns to a drab green low iron slag. Others have noted this phenomenon. Further increases above this blast rate produce copious incandescent sparks at the tuyere, indicating the reoxidation by the blast of any iron which has reduced in the stack above, as well as burning of the incipient bloom which adheres to the wall just below the tuyere.

But, if the blast is *increased still further*, in the neighborhood of 1.2 to 1.5 l/min · cm^2, conditions in the furnace again change drastically. The hot zone of the furnace enlarges to encompass most of the hearth's cross section. The furnace burden will burn down much more evenly across the furnace, rather than in a narrow cone that funnels all material directly in front of the tuyere. Iron particles that have reduced in the stack do not have to pass directly in front of the tuyere on their way to the slag bath below, and those that do are protected by the more copious molten slag above the tuyere level. As the hot zone is also expanded downwards, the bloom forms much lower in the furnace, and is thus much more easily protected by the molten slag bath. [1]

The first hint that upon increasing the airflow (and thus the temperature) the carbon content first goes up, then comes down before it goes up again. In other words: If you want to make wrought iron, you must substantially increase the temperature - but not too much. This goes straight against the common "feeling".

These early blooms, besides being fist-sized at best, all had *elevated carbon contents that made most of them unforgeable*.

We learn about "forgeability", an extremely important property that can't be measured in the lab but only assessed by an experienced blacksmith.

Our first truly satisfactory *bloom* resulted from an attempt to make *cast iron* by increasing shaft height, fuel:ore ratio and, perhaps most significantly, air flow.

Another clear indication that going by feeling or "theory" without much experience might get you far - but not necessarily in the direction envisioned.

The third decisive factor (in running a bloomery) is *intuition*. Some of our decisions might look like whim to an observer, but we have come to know what the furnace looks, sounds, smells and feels like when it's making iron.

That's *after* you developed a "feeling" for your baby. I know of people in charge of highly complex High-Tech machinery who listen to their "baby" to assess its present mood.

The bloom is very dense, with little 'spongy' character except at the periphery. Blooms such as this one do not appear to be simply an agglomeration of particles that have *fallen from above*. Rather it appears that in the oldest section of the bloom, in its centre, the interstices of the sponge iron have been filled by iron particles reducing in situ.

A first hint that the production of iron may not be exclusively in the reduction zone high up in the stack but right "on top" of the bloom.

Our lack of experience in forging with charcoal slowed the entire process, and our difficulty in attaining a welding heat left cracks that had to be rewelded in subsequent smithing. Also, modern strikers are trained more for precision than power, since modern smiths have power hammers for heavy work. A striking team trained in heavy forging, such as the anvil or anchor smiths of more recent centuries, would be vastly more efficient.

It needs far more cunning for forging a piece of iron with a hammer that we couch potatoes could ever have imagined! Even experienced modern blacksmiths may not yet be up to all the tricks of the trade. See [4] for more details on that.

Slag fulfills two physical functions in a furnace: protection and transportation. Molten slag coats and protects reduced iron particles from re-oxidation. After the bloom begins to form, we also try to keep it physically covered by molten slag at all times, to protect it from re-oxidation. Slag flow also serves to transport reduced iron particles to the locale of bloom formation.

I couldn't agree more - but in 2002 this was news.

The production of high carbon *steel* in a bloomery is often presented as a special accomplishment of a particular technology. In our experience it is difficult *not* to produce high carbon steel in a bloomery, and the *challenge* is, rather, to create a soft, *low carbon iron*. We find the most important technique for the control of carbon content is ensuring a constant flow of high-iron slag across the bloom. [2]

Wonderful! Exactly what <u>I was writing</u> before I found this paper.

Finally, we added charge of 5.5kg of ore and 4.5kg of charcoal. This final charge of ore has a pronounced *decarburizing* influence on the bloom. In our usual practice, another 5–10kg of charcoal would be added for burndown, but this time we did not do so. A little over an hour later, 51/2 hours after kindling the fire, the furnace burden had burned down enough to allow us to disassemble the furnace and remove the bloom.

Here I beg to differ. You cannot get carbon out of a massive piece of iron by doing something to the surface any better than you can get it in. Even at 1200 ºC (2192 ºF) for one hour you affect less than 1 mm of depth at best. Sauder also fails to explain how he knows that the bloom would contain more carbon without that measure.

High-iron slag also serves two chemical functions: reduction and decarburization. These two functions are often simultaneous: wustite in the slag is reduced by carbon in any iron with elevated carbon content, decarburizing the metal even as it produces more. This mechanism was perhaps described most clearly and succinctly by Espelund (1997, 54) as

FeO(in slag) + C(in metal) = Fe + CO(gas).

Note that the product of this reaction is not only more iron but also more reducing agent. We think the lovely chain reaction thus initiated is the real workhorse of bloom formation, and that reduction within the stack merely provides a seed for reduction in the slag bath below. Reduction of wustite by direct contact with bits of charcoal that survive to hearth level also contributes to bloom formation. Admittedly, we are unable to quantify or directly observe these reactions; remember that these are artisans' working hypotheses. [2]

This is different. Assuming that the bloom is enveloped in liquid slag at all times and grows because small irons particles enveloped in slag rain down and fuse, de-carburization as a continous process could take place as described. In fact, the decarburization properties of wüstite are well-known and have been taken as the (theoretical) reason that bloomeries could *only* produce wrought iron.

Enough! I will now give you Lee Sauder's most recent paper [5] in (almost) full length and with a few *inserts* and comments (violet background) of mine.

Lee Sauder: Update on the "Practical Treatise"

Winter 2010-2011

Introduction and General Stuff

In general, our *more recent* work has tended to go forward by going backward, utilizing more traditional furnace materials and construction. We did all our early work in a rather large furnace built of steel and modern refractory, with a water-cooled tuyere, and often with preheated blast. I think this may have led some to discount the applicability of our ideas to ancient smelting practice. But I still stand by all those ideas, and any changes and recantations that may follow are driven by my greater understanding of the working qualities of the bloom iron, rather than the use of more traditional materials.

Our current work tends to use a smaller clay furnace, with a copper tuyere, and occasionally using bellows for air supply. This is not just the result of curiosity or an urge for authenticity, but practicality as well. Clay has the tremendous advantages of being inexpensive, easily alterable, and almost endlessly recyclable and reusable. Compared to modern refractories, clay's combination of insulative, reflective, and emissive qualities also seem much more suited to the bloomery furnace. All of which I suppose should have been self-evident, since the technology evolved in clay furnaces! But we're all a bit susceptible to the hubris of modern man's technical prowess, aren't we? Most importantly, the use of clay has allowed us to easily and cheaply explore many different furnace designs.

The size of the furnaces have shrunk, with the usual goal of producing a bloom of 8 to 12 kilos. This simply reflects a retreat from the usual Yankee madness of "bigger is better". An 8-12 kilo bloom is just more pleasant to work on than a 20 kilo one.

The early furnaces were designed to be dismantled to **remove the bloom**, or to have the bloom removed through the top. Once we began using clay, though, we quickly converted to removing the bloom through the bottom of the furnace, by digging away enough below the tap arch to allow the bloom to be pried free.

Our use of the copper tuyere was first inspired by descriptions of its use in the Catalan furnace. We have stuck with it as it is extremely durable, convenient, and safe (the water-cooled tuyere caused our worst injury to date, knock on wood). They key to it's durability is its conductivity. It simply needs to be long enough that the cooling effect of the air blast can keep the temperature of the tip from rising to an orange heat.

Though most of my own smelts continue to use a vacuum blower for an air source, I have successfully used hand-powered bellows on occasion. All of Shel and Steve's smelts at Colonial Williamsburg have relied on bellows, and all their successful smelts have been conducted along the lines of the experiments described above.

I'm a trained scientist and I'm sure that Lee Sauder's experiments have a direct bearing on the antique techniques. There are a few questions here and there, and some details might be open to discussion, but the general picture is clear enough. Whatever he could do, some ancient guys could have done.

In the discussion section of our '02 HMS paper, we argued for a different view on three aspects of bloom smelting: 1) air rate, 2) slag management, and 3) the recycling of furnace products. In the early days of our bloom smelting, our goals tended to focus on the *yield* of the smelt. In the years since, our focus has shifted towards the *quality* of the resulting metal. This is a much more delicate, difficult, and complicated realm, and that has altered my view a bit on some of those issues.

- ### 1) Air rate:
  In the '02 paper[1], Skip and I proposed an air rate of 1.2 to 1.5 liters/min · cm^2 of furnace area. This may be excessively quantitative and specific, but I still maintain that if you're not getting the results you desire, blow harder.

  Over the years Skip and I have helped a number of frustrated people get their first good bloom, and find that people commonly fail for one or more of three reasons:

  1. they're not blowing hard and hot enough,
  2. they're using bad ore, or
  3. they're stopping the smelt too soon (i.e. not charging enough total ore).

Another aspect of air rate we addressed in '02, that was perhaps overlooked by being poorly expressed, is that *low air rates tend to produce a high carbon product, and high air rates tend to produce low carbon product*. Many people still think of this the other way around, but my experience has shown this time and again. There are, of course, many other factors that affect carbon content, which I'll address briefly below.

That is a key sentence. It goes right against conventional "wisdom" but I do believe that Sauder is right here. It's the slag production and liquefaction that is decisive.

Since reasonably accurate measurement of air rate is a slippery business, we realized some time ago that it's more sensible to measure the rate of charcoal consumption, since this is really a much easier, direct and more accurate measure of the air entering the furnace. As noted above, we usually do this as a time needed to burn a 2 kg charcoal charge (or actually, at home, a 4 lb. charge). As I dig back in my notes from several very different furnace types, the optimum rate of charcoal consumption works out to a range of from 0.3 to 0.4 grams of fuel/minute · cm^2 of furnace area. I am struck by the fact that the optimum rates we've come up with in each furnace, for high quality blooms, seem to all work out very closely to *0.35g/min · cm^2*.

2) Slag as a physical, chemical, and thermal resource:
Ah, now we're getting down to the nitty-gritty! I still stand by our assertions in the '02 paper, but we have learned so much more here.
I see *slag chemistry as the key to the working qualities of the metal*, both directly and indirectly. Directly, in that if you end up with an iron-depleted slag in your bloom, you have a metal that *welds poorly and fractures easily*, and is in general, just difficult to work. Indirectly, in that the chemistry of the slag bath during all stages of the smelt is the key to the bloom's carbon content.
In short, I don't think it's too bald a statement to say that low-iron slag = bad metal, and high-iron slag = good metal.
We judge the iron content of the slag by observing its behavior upon tapping, and by examining its fracture. We strive for a free-running slag that on freezing, piles up on itself nicely. On fracture, we want to see a grey metallic sheen we refer to as "wustitey", and a certain shape of fracture surface I don't believe I could describe meaningfully.
I often see comments in the literature equating very high iron content in archaeological slags with inefficiency on the smelter's part. Rather, from my point of view, a very high iron content in the slag would point to mastery of the process. 3) Recycling gromps: Ok, time to recant.

The remarks to the relation between slag properties and forgeability are important. Only a blacksmith could find that out.

3) Recycling gromps:
Ok, time to recant. I have found that the recycling of gromps (*'gromps' = bits of unconsolidated iron and magnetic material that either failed to adhere to the bloom in the furnace, or was removed from the bloom during its initial cleaning*) has a deleterious effect on metal quality, so I have largely abandoned the practice.
In several smelts I have made entire blooms largely of gromp, to make a second (or even third) bloom in a hot furnace. These gromps were charged, or even placed directly in the hearth, with fresh ore to make a nice iron-rich slag bath. Though these blooms were dense and lovely to look at, they invariably have resulted in a nasty and recalcitrant metal.
Though there may be a good method of reprocessing this metal, simply adding it to the ore charge of a bloomery smelt is probably not it.

On Quality Control
I have a long way to go to be able to claim any mastery here, but I may as well take this opportunity to share some things we've found so far. It seems to me that the working quality of my blooms is largely determined by the control of three (interrelated) factors: slag chemistry, carbon content, and *phosphorus* content.

Slag chemistry:
I've covered this pretty well above, but in addition to the iron content of the slag, there are also things we definitely want to avoid getting into the slag.
Too much *alumina*, from melting furnace wall, can cause a slag that makes for *poor welding* . To avoid this, we try to build our furnaces with thin walls to shed enough heat to keep the clay from melting and slagging much, especially trying to keep it thin in the hot zone around the tuyere.
The addition of too much *calcium*, added in an attempt either to increase yield or to control phosphorus, also seems to cause *welding problems*. I think I perceive trouble from this even if the slag viscosity during the smelt seemed fine, and the carbon content of the bloom has stayed low.

It occurs to me that we scientists know far too little about fire welding iron (or other metals). I don't even know if other metals can be fire or hammer welded at all. We do know that you should sprinkle some SiO_2 sand on the hot oxidized iron surfaces to be welded so that liquid fayalite can form that is squeezed out, leaving "naked" iron surfaces behind. I have not read anything about the influence of whatever else is in the iron (including the unavoidable slag inclusions) on its weldability. Of course, the relation between slag and weldability invoked by Lee Sauder is indirect but certainly real.

- **Carbon control:**

Some of the more important factors we've identified as affecting carbon content are air rate, slag chemistry, fuel:ore ratio, tuyere angle, type of ore.

Air rate and slag chemistry we've covered above.

The effect of fuel:ore ratio is pretty straightforward and widely understood. Our general charging practice stays pretty close to a 1:1 ratio, and we'll push it as heavy on the ore as we can, especially during the latter stages of the smelt. We're rarely able to get much higher than 4 fuel to 5 ore without knocking down the heat in the furnace.

Steeper tuyere angles promote higher carbon contents. Tuyere angle has a lot to do with the shape of the bloom, and the depth at which it forms, both of which affect carbon content. The best angle varies with each furnace, but generally seems to hover in the area of 15° to 22°.

That the tuyere angle is important and that 15° is a good value is a known fact; it is discussed in Rehder's book in some depth, for example. But Lee gives experimental evidence and that is important.

My experience with *ores* beyond my usual limonite are limited. But it seems that *very rich ores really want to make steel*. I also suspect ore of a very *regular size*, such as magnetite sand ore hematite sandblasting grit, *tends to make steel*. I think a variety of sizes in the charge helps ensure adequate slag formation, since the different sizes travel through the stack at different rates, some reducing in the stack more than others.

I could think up many reasons why success in smelting iron depends on the kind and quality of the ore used. What's needed are experimental results.

- **Phosphorous control:**

It took Skip and I a long time to realize what a significant factor the phosphorus content of our ore is. And it's taken us even longer to start to get some degree of control over it by any procedural means beyond ore selection. Since we have basically no access to any modern, professional analysis, we have been judging our phosphorus content by working properties and a bit of hillbilly metallography. We are still very much in the midst of working through this, but here's what we think so far. Much of this work has been through collaborative effort with our "smeltfest" crew.

Once again, the air rate/temperature/ tempo of the smelt seems to have a large effect. Too slow a tempo produces a higher carbon, or worse, a carbon/phosphorus combination that doesn't want to work up easily. Too high an air rate/tempo seems to raise the P content of the metal enough to cause *cold-shortness*. So a medium tempo seems best. Not adagio, not presto, but andante.

In terms of manipulating P content through slag chemistry, addition of calcium seems to be a poor choice, for the reasons mentioned above. Addition of *manganese* ore to the mix shows more promise in this regard. Don't ask me why, but manganese seems to make a pretty radical improvement in metal quality.

Another thing I'd like to note is that *from a smithing perspective, phosphoric iron is a really good thing.* It makes for an iron that is dense and tough but *forges beautifully*. Some of the highest phosphorus blooms forge so beautifully it's hard to believe there could be anything wrong with them when they're cold!

In this 2010 paper Sauder addresses phosphorous (and manganese) for the first time as far as I know. Once more, giving the influence of phosphorous on forgeability is important and helps to understand the large issue "ancient phosphorous iron".

We know. that manganese in the iron tends to make for better iron. The problem is how to get it in there. Just adding some manganese ore to the burden might help in producing "better" slag but does not necessarily get some manganese into the iron. The reason for this is that manganese oxide needs rather high temperatures for reduction. The famous "Ferrum Noricum", while made with manganese-rich ore, does not contain appreciable manganese concentrations, for example. Sauder and Williams may have succeeded in getting some manganese into their iron because they run a high-temperature process.

That phosphorous iron "forges beautifully" has been known in historical times. Vagn Buchwald in his second book reports that "the smiths usually praised this kind of iron" (p. 278)

- **The Goldilocks principle:**

All the foregoing points to a consistent theme. The key to making quality iron seems to be a matter of finding balance. Not too hot, not to cold. Not too fast, not too slow. Not too much, not too little. Just Right.

A related observation is that success in smelting is built of careful attention to small incremental steps. It's easy for two or three small overlooked details to compound into a big problem. So it pays to attend to every aspect of the job as carefully and thoroughly as possible.

This requires plenty of time. Work up your ore, charcoal, and repair clay in advance, make any tools you need, and generally give yourself the time and space to pay attention.

This really emphasizes the importance of a long, sustained working practice applied to any attempt to understand early ironmaking technologies. Short and scattered experimental campaigns, with a different furnace and different ore every time, can cause more confusion than enlightenment, if they don't find and explore that sweet spot every furnace has.

I couldn't agree more.

Forge it now!

One extremely simple (and therefore easily overlooked) key to producing good iron is to *forge it immediately*, fresh and hot from the bloomery.

No matter how long you try to reheat a cold bloom in a hearth, it will never be as nice and hot through and through as it was when it came out of the furnace. And all that long slow time that you try to get a thorough heat on a cold raw bloom, you are altering its slag chemistry. So the metal you get from starting with a cold bloom will not be the same as metal starting from a hot one.

Even a simple compaction and splitting of the bloom really helps reduce the time and fuel needed to reheat.

Once more: No amount of heavy thinking can replace the hands-on experience!

New questions and directions

Well, there's enough of these to last several lifetimes, aren't there?

Part of what I've found so fascinating about working with bloom iron over the years is its unpredictability and irregularity. Lots of the sculpture I've made from it has been about exploring its failures and funkiness. But as I come to understand it better, I'm becoming most excited about the possibilities of really good bloom iron. I can see the potential to produce iron that is superior to currently available industrial steels for artistic forging.

A few of the directions that seem particularly fruitful at the moment:

Phosphorus:

We've still got lots to do here, not just in getting some control over the metal's phosphorus content, but how best to exploit P iron's characteristics: its forgeability, its hardness, its corrosion resistance.

Manganese:

As I mentioned above, addition of manganese ore to our charge has a pretty dramatic effect on the resulting iron. So much so, that this is the only thing I've ever considered keeping as a trade secret. But I'm just not that kind of guy.

I assume this is a matter of slag chemistry only, but I have no idea what's really going on here.

Tapping regime:

Immediately after the conference, I had the opportunity to help begin an excavation of a medieval bloomery site that Jake Keen located. Most of the bloomery slag I've seen in my life was made by me. Here I had a week to ponder the slag produced by someone with real mastery of the craft. I was struck by its density, the size of the slag flows, and the *incredible consistency of it* from one piece to the next.

Though for years I have been trying to ensure a constant flow of high iron slag across the bloom, this medieval slag seemed to be telling me that I was being to timid in this regard. On returning home, I tried to smelt to reproduce the slag I saw by tapping heavily and constantly, and continuing with fresh ore charges rather than recycling slag. *This smelt produced one of the most remarkable blooms yet, in terms of iron quality*. As of this writing, I only have been able to do one smelt along these lines, but you can be sure there's more to follow.

Remelting:

To date, we have mostly refined our bloom iron by means of folding and welding. I am currently very curious about the possibility of refining the iron by remelting, not to produce steel but to make soft iron. This is described explicitly by Evenstad (Evenstad,1968), and more obliquely by others. Are we overlooking an entire step in the ironmaking process?

I guess it's time to quit writing and go find out.

(Thanks to):Gerry McDonnell, Roger Doonan, and Hector Cole. And very special thanks to my brother Jake Keen for being Jake Keen.

There is still a lot to do. I hope Lee Sauder keeps up his excellent work.

References: Evenstad, Ole, Journal of the Historical Metallurgy Society,25(,1968).

Lee Sauder and Skip Williams Melt Iron and Make Steel

A long way back I wrote: Before about 1850 wrought iron couldn't be melted. Maybe I (and many others) are wrong. Sauder and Williams not that long ago build a tiny furnace (just a bit larger than a regular tin can), run it on fine charcoal and (presumably) plenty of air (easily supplied by bellows used for regular bloomeries) and proceeded to melt some wrought iron / mild steel in it. The solidifed stuff scraped off from the bottom later proved to be good, hard *steel*!

"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". [3]

The guys have a "sneaking suspicion that there is a whole chunk of ancient steelmaking technology that's been almost entirely overlooked."

Aristotle furnace

Source: "Hloh" , Apr 21 2013, on some Internet forum.

The sneaky suspicion is further fueled by a quote from Aristotle:
"*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*."

I made a lot of fun about Aristotle's wrong believe that steel is particularly pure iron, as evident form the quote above. However, maybe Aristotle was right just once when he refers to the *melting* of iron in order to make *steel*?

Did the ancients on occasion melt their iron when they made steel? It is far to early to make any pronouncements but it is definitely something to watch out for when digging up old artifacts.

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1) W. H. Lee Sauder and Henry G. Williams III: "Practical Bloomery Smelting", A paper from 2001 for the Materials Research Society.

2) Lee Sauder and Skip Williams: "A practical treatise on the smelting and smithing of bloomery iron"; Historical Metallurgy 36(2) 2002 p. 122–131

3) Lee Sauder: "Making Steel in the 'Aristotle Furnace'", Lee's homepage (http://www.leesauder.com/.

4) Lee Sauder: "A Journey into Medieval Ironmaking", Lee's homepage (http://www.leesauder.com/

5) Lee Sauder: Update on the 'Practical Treatise'" Winter 2010-2011; Lee's homepage (http://www.leesauder.com/