A Practical Treatise on the Smelting and Smithing of Bloomery Iron

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Abstract

For several years, we have explored many aspects of the process of bloomery smelting. In contrast to most attempted reconstructions of bloomery smelting, our work has focused on the process itself, rather than it's archaeological signatures.

This paper describes a typical smelt of the most efficient smelting regimen we have yet discovered. We will pay particular attention to methods that differ from those of most experimenters, especially in regards to blowing rate, slag management, and the recycling of furnace products. A bloomsmithing experiment is also described, and yields, resources, and labor requirements quantified. We then offer a few observations when our experience differs from what we have read in the literature. Finally, we suggest that these methods, when applied to archaeological reconstructions of ancient bloomeries, may provide some missing answers to the archaeometallurgical community.

Introduction

We have been experimenting with the bloomery process since January of 1998. From the beginning, our primary goal has been to smelt iron of sufficient quantity and quality for the creation of hand-forged artworks, and to explore the process for a deeper understanding of iron as an artistic medium. We have strived to remain open to what the iron itself has to teach us, and to keep scientific knowledge in the background.

Our interest and expertise is in iron and ironworking, not in archaeology or metallurgy. We feel that this devotion to the process and its product, rather than to furnace morphology or slag residue, has led us to uncover an approach to bloomery smelting that has the potential to provide more accurate data for historical and archaeological research than the current predominant models.

Our first 11 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. These early attempts were also hampered by particularly irreducible ores.

We built our second furnace in a modular system. This allows us to explore many different furnace configurations by varying shaft heights and tuyere heights. 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. From this serendipitous beginning, we have evolved a very efficient smelting regimen based on minimal preheating, air flows from 1200-1600 l/min, the recharging of tapped slag, and the recycling of residue from the previous smelt.

Experiments #21-27 have all been run in a very similar manner. This paper will describe smelt #25 as typical of this series. This experiment has the benefit of especially good notes from the smelt, and the bloom is preserved and sectioned as a specimen. We then describe a smithing experiment with a similar bloom from smelt #26, a portion of which was forged to a billet and then to small "currency" bars using manpower for forging and charcoal as fuel.

Smelting

Raw Materials

The ore in this trial was our local "brown ore", a dense goethite of 58 % iron content. It was roasted in a gas flame, and then broken up until the pieces ranged from 2 cm to fines.

The charcoal in this experiment was commercial charcoal composed largely of oak and hickory. We broke it in a fairly cursory manner so that most pieces range from 3 to 8 cm, and sifted out the majority of the fines. In earlier experiments using lower airflows, we found that the fines tended to clog the furnace. This is not a concern at higher blast rates, but sifting out the fines helps keep spark damage to both the local environment and the furnace's operators to a minimum.

Furnace Construction

The furnace is designed in modules to allow the investigation of many furnace types. The shaft height above the tuyere can vary from 12 to 160 cm to recreate anything from a bowl hearth to a high bloomery or stuckofen. The diameter of 35 cm was chosen intuitively, as a manageable size that would not require an onerous amount of raw material to feed, but would provide more working room and larger blooms than our previous 30 cm furnace. We later found this furnace to be similar in size, construction, and concept to that designed by Tholander (Tholander 1987).

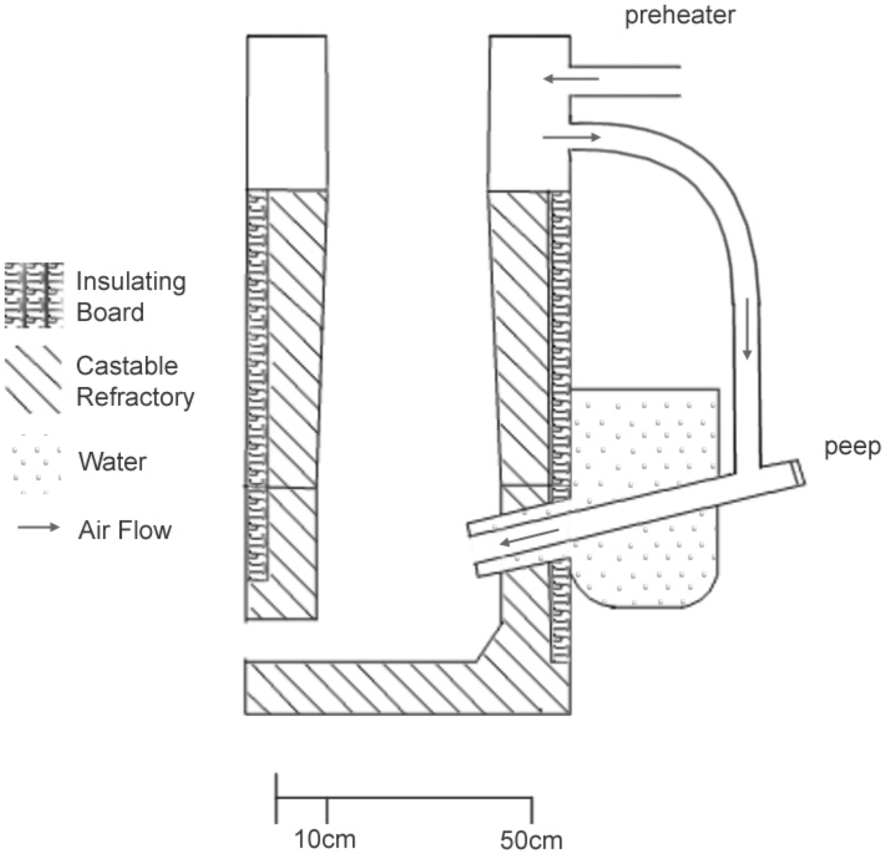

Figure 1 - Furnace cross-section

The furnace as configured in this experiment had a shaft height above the tuyere of 100 cm, with the tuyere 23 cm above the furnace floor. This is roughly analogous to the dimensions of a Roman shaft furnace (Tylecote, Austin and Wraith, 1971, 343). The slag tapping arch, measuring 12 x 15 cm, was located at the base of the furnace, opposite of the tuyere. There was a single probe hole for measuring temperature 40 cm above the tuyere and 10 cm in from the furnace wall.

The furnace is constructed of an outer layer of steel sheet, lined with 5 cm of insulating board, and then with a 7-8 cm thickness of castable refractory as the furnace’s lining. In this experiment, the final 30 cm of shaft height was a hollow steel section that functioned as an air preheater. The preheater provided 100-200 deg C of preheat. (We think the only major effect of this preheating is the conservation of charcoal, but this assumption has yet to be verified experimentally.) Although our earlier smelts utilized ceramic tuyeres, we used a very simple water-cooled tuyere in this experiment.

In general, the details of furnace construction were chosen for durability, practicality, and convenience. With this approach, we are able to concentrate on the smelting process and its variables, rather than on furnace maintenance.

Blowing Apparatus

Our earlier trials used squirrel cage fans as an air supply. This type of fan does not overcome back pressure very well, so we found it difficult to control the blast as the smelt progressed. The back pressure in the furnace mounts as the reduction reactions escalate. The air source we are now using is a vacuum fan, which generates better pressure, and delivers approximately 1600 l/min at full blast through the 5 cm tuyere orifice. Air flow was measured and calculated using a Kestrel 1000 anemometer to measure air speed. This is probably not a terrribly accurate measurement, but serves as an approximation.

Description of Smelt # 25

This experiment took a total of 5 hours and 30 minutes from lighting the fire until the removal of the bloom. We think of the smelt as breaking down into four general phases: **1)** preheating; **2)** charging of ore; **3)** recycling and recharging; and **4)** decarburization and burndown.

Preheating: We kindled a fire, and preheated the furnace with wood strips, utilizing natural draft through the open tap arch. After 30 minutes, we loosely blocked the tap arch, added charcoal, and began a blast of 1275 l/min. Preheating with charcoal continued for another hour, consuming 18.5 k of charcoal.

Charging of ore: After 1 ½ hrs of preheating, we added our first charge consisting of 6.8 kg of charcoal followed by 6.8 kg of ore. At this time the temperature at the probe hole had reached 850º C. Each of the succeeding charges were identical in charcoal and ore weight to the first. Each charge was added as there was room to do so in the top of the furnace, at about 20 minute intervals. By the time of the second charge, the temperature had risen to 980º. The exhaust gases from the furnace did not ignite until just before the third charge. By the time of the third charge, the temperature at the probe hole had fallen to 930º. The blast was then increased to 1500 l/min.

Rationale for air rate and temperature changes

We don’t often bother to measure the temperature at the probe hole, but when we do, we usually expect to record 1000º to 1050º. This measurement is not the major factor in our decision-making. We most often base our temperature and airflow decisions on three other major factors.

The first factor is our view through the “glory hole”, the sight glass that allows us to look through the tuyere into the bloomery’s hot zone. So far, we have been unable to measure our temperature here, so suffice it to say that we want to see a very brilliant white, greatly in excess of forge-welding temperature.

The second factor in our temperature decisions is the condition of the slag bath. We can monitor this by careful probing through the tap arch. The first slag to work its way to the base of the furnace tends to be a frothy, high iron slag that quickly cools to a bowl-shaped insulating layer on the furnace bottom. The pool of slag that fills this bowl is a high iron, free running “tap slag” in which the bloom forms. We want this pool to stay very hot and liquid, and to gradually melt into and enlarge the bowl of solidified slag.

The third decisive factor 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.

Charging of ore cont'd: Shortly after the third charge, the blast was increased to 1625 l/min, and then reduced back to 1500 l/min at charge four. Shortly before the fifth charge, we saw a few sparks of burning iron at the tuyere, and reduced the blast again to 1275 l/min. The blast remained between 1275 and 1500 for the remainder of the smelt.

Recycling and Recharging: The sixth charge consisted of 5.8 kg of "gromps" and magnetic slag recovered from the previous smelt, along with 1 kg of ore to make up a 6.8 kg charge. By "gromps" we mean bits of unconsolidated iron and magnetic material that either failed to adhere to the bloom in the furnace, or were removed from the bloom during its initial cleaning.

The next cycle of the smelt is the tapping and recharging of slag. First we scraped as much of the early semi-solid sponge slag from under the incipient bloom as possible, cooled it, broke it up, and recharged it into the top of the furnace with an equal weight of charcoal. This sponge slag contains reduced iron that never had a chance to adhere to the bloom, as it was the first material through the furnace. Thereafter, liquid slag is tapped from the furnace by poking through the solidified slag at the tap arch. We try not to tap more than four to five kilos of slag at once, in order to keep the incipient bloom covered, and to maintain the heat reservoir of the slag. We cool the tapped slag in water, break it up, and return it to the furnace with an equal amount of charcoal.

We tend to continue this recharging sequence until we detect a change in the quality of the slag that indicates a lessening iron content, such as increasing viscosity or a decrease in the rapidity of freezing. Sooner or later, the slag becomes too difficult to tap, and we proceed to the burndown phase. In this smelt, a total of 14.5 kg of slag was recharged with an equal amount of charcoal, followed by a further 9 kg of charcoal.

Decarburization and Burndown: Finally, we added charge of 5.5 kg of ore and 4.5 kg of charcoal. This final charge of ore has a pronounced decarburizing influence on the bloom. In our usual practice, another 5-10 kg of charcoal would be added for burndown, but this time we did not do so. A little over an hour later, 5 ½ hours after kindling the fire, the furnace burden had burned down enough to allow us to disassemble the furnace and remove the bloom.

Table 1-Smelt #25

Furnace configuration: 100cm shaft height above tuyere, air preheater on, tuyere 23cm above floor
Fuel type: hardwood charcoal
Ore type: goethite - Victoria mine

Time	Char coal	Ore	Slag (Recharged)	Gromp	Air	Temperature (40 cm above tuyere, 10 cm in)	Notes
hh:mm	kg	kg	kg	kg	l/min	Deg C	
0:00							start preheat with wood
0:30	22.7				1275		switch to charcoal, blast on
1:15						850	
1:28	6.8	6.8					Charge #1
1:48	6.8	6.8				980	Charge #2
2:02					1500	935	first liquid slag in front of tuyere
2:08	6.8	6.8					Charge #3
2:28	6.8	6.8			1625	930	Charge #4
2:40	6.8	6.8			1275		Charge #5, furnace now hot enough
2:58	6.8	1		5.8		1045	Gromp charge
3:15	5		5			1025	Recharge #1
3:35	4.5		4.5				Recharge #2
3:49	4.5		5				Recharge #3
3:54	4.5						
4:10	4.5						
4:14	4.5	5.5					decarburizing charge and burn down
4:45							remove preheat section
5:10							remove shaft section, consolidate visible bits onto bloom
5:25					0		remove tuyere, blower off
5:30							remove bloom
totals	91	40.5	14.5	5.8			

The Bloom

Immediately after the bloom's removal from the furnace, we hammered all loosely consolidated material off of it. The bloom thus cleaned was roughly 25 cm in diameter, 12 cm thick, and weighed 14 kilograms. We later sawed the bloom into approximate halves along the vertical plane axial to the tuyere. As can be seen in figure 2, 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 center, the interstices of the sponge iron have been filled by iron particles reducing in situ. The carbon content, judged by hardness and spark test, indicates this bloom to be of a low carbon content, similar to that of modern mild steel. It has a density of roughly 4.5 g/cm^3.

The 14 kg bloom represents a yield of 60% of the iron available in the ore, and required 94 kg of charcoal and 5 hours 30 minutes to produce.

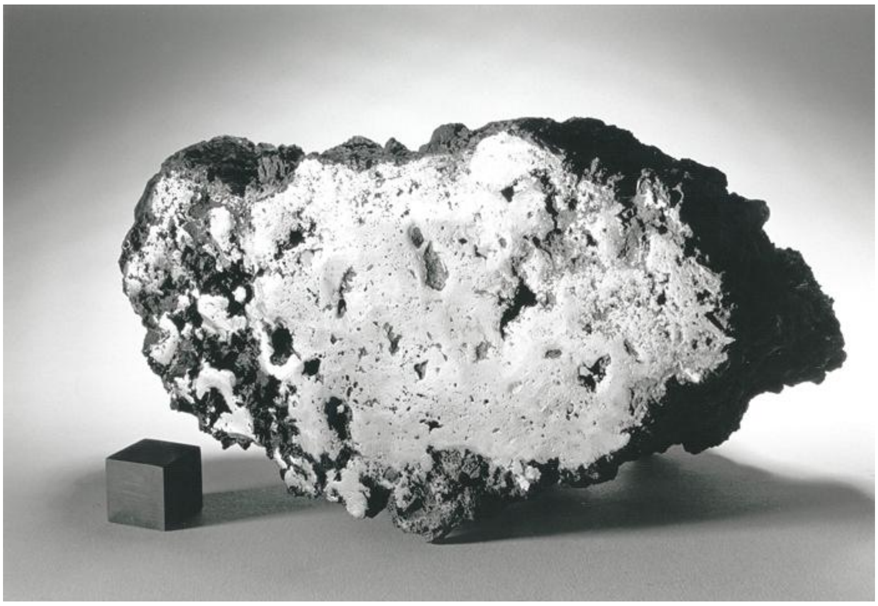

Figure 2 -sectioned bloom with 2.2 cm cube for scale

Table 2

Smelt #25

Input		*Bloom*	
Ore	Available Fe	Weight	Yield
40.5 kg	23.5 kg	14 kg.	60%

Bloom Smithing

In order to quantify the useable iron in a bloom of this type, as well as to supply a comparison to Peter Crew's work with a non-slag tapping furnace, we forged a similar small Llyn Cerrig Bach currency bar. Unlike Crew's experiment all heating was done with charcoal and all forging by manpower alone (Crew,1991).

From Bloom to Billet

The bloom forged in this experiment was the 13.5 kg bloom produced from Smelt #26, which was very similar to the bloom from smelt #25 described above. The entire bloom was first heated in a gas furnace, to replicate the hot bloom removed from the bloomery. It was easily split in two in this single heat, using a splitting maul as a hot cut, driven by sledges. We selected the larger of the two sections, weighing 7.7 k, to forge into a 5 x 5 cm billet similar to roman billets. (Cleere 1985, 48) (Sim 1998, 55)

The half-bloom was heated for forging in a modern cast iron bottom blast blacksmith's hearth with several bricks stacked around it to increase the depth of the hearth. This approach to heating with charcoal was found to be fairly unsatisfactory, as we were unable to bring the entire piece to a welding heat all at once. We also briefly attempted to convert this forge configuration to a side blast, with poor success. All forging at this stage was done as near to a welding heat as possible. The lead smith wielded a 2 kg hand hammer, and the two strikers used 4.5 and 5.5 kg sledges. With a bloom of this type, there is no need for gentle compression before welding and forging. Despite our heating difficulties, in 29 heats we managed to forge the half-bloom to a 5 cm x 5cm x 30 cm billet in 3 hr 40 m (11 man/hours labor). The finished billet weighed 5 kg. This represents 65% of the starting weight of the bloom section, and a yield at this stage of 36% of the iron available from the ore.

Although we use this data in the time and yield analyses below, we feel that this procedure could be greatly improved, and thus made more accurate. Our insufficient 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. Given a more efficient furnace design and a better trained set of hammermen, it is conceivable that these billets could be forged in much less than an hour.

From Billet to Bar

We forged two currency bars of similar dimensions from portions of this billet. The first trial was a continuation of the morning's billet smithing, using the same forge set up and personnel. A roughly cubical section was isolated from the billet by fullering, and then hammered to a flat of approximately 7.5 cm wide by 2 cm thick. A major transverse crack appeared where the billet had been most drastically deformed during the fullering. We welded this crack as best we could, and then folded the flat section in two, and faggot-welded the entire length. We then cut this flat section from the billet and continued to draw out the bar, welding up any cracks as they appeared. We made the mistake, when faggot-welding, of forging the bar to a fairly thin flat cross-section, which slowed the drawing out process considerably. A more efficient forging technique would have been to forge it to a square cross-section that would then be forged to the correct flat stock in the final heats. The latter portion of the work was carried out with a single striker. The final result, after 2 hr 30 m (representing 6.5 man/hours of work), was a socketed currency bar 2.5 x .6 x 50 cm, weighing 623 g. Forging from bloom to billet to this final bar required 73 kg of charcoal.

The following afternoon, Sauder forged another currency bar, utilizing the lessons of the previous day's work. The forge was reconfigured as a shallow side blast forge by filling the firepot with refractory insulation. A more traditional approach to this would have been to create an insulating base of packed cinders (Fitzgibbon 1990). We set our tuyere from the bloomery on the forge table, and stacked up firebricks around it to create a hearth. This hearth set-up functioned much more satisfactorily than either of the previous day's attempts. The side tuyere was not troubled by slag blocking and choking by charcoal dust as the bottom blast had been. Also, by having a shallow, well insulated base, the bottom of the hearth reflected heat to the fire. Somewhat counter to expectation, the hottest zone of the fire was not in front of the tuyere but below it, halfway between the tuyere and this reflective base.

A 3 cm chunk of the 5cm x 5 cm billet, weighing 538 g, was hot cut completely from the bar. All forging was done with a single 2 kg hand hammer. This smaller chunk was easy to bring to a welding heat. Four heats were used to weld from all three directions, bringing the billet chunk to a cube. After a total of 17 heats in 1h 35m, we had a short bar 1.6 cm square and 21 cm long. A further hour of forging and 16 heats produced a socketed currency bar 4.5 mm thick, 2.25 cm wide, and 37.5 cm long, weighing 312 g. This represents 58% of the starting billet weight, and a yield at this stage of 21% of the iron available from the ore. Forging this bar from the billet consumed 20.5 kg of charcoal. Total labor required for this bar was 2h 35 m. This bar was smaller than we intended. If we had started with a 5 cm length of billet, it is reasonable to assume that a 500 g bar could have been forged in 3 hrs.

Spark testing of both currency bars indicated a low overall carbon content. One small zone in the large bar was of a medium carbon content, similar to spring steel, but the rest of both bars were of a low carbon content, between modern mild steel and wrought iron.

Analysis

In the following analyses, we have not included the gromp charge in our yield calculations, as at least as much gromp is produced as is consumed in each smelt. The billet and currency bar weights are extrapolated as if the entire bloom had been worked to these forms. If the entire bloom had been worked to small bars, it would have produced 10 bars of 500g each.

Yield Analysis

Table 3 – Smelting and Smithing Yields for Smelt #26

Input		*Bloom*		*Billet*		*Currency Bars*	
Ore	Avail. Fe					Weight	Yield
40.9 kg	23.7 kg	13.5 kg	57%	8.55 kg	36%	4.95 kg	21%

Fuel Consumption

As with our previous estimate of labor requirements, we used our results based on smithing one section of the bloom from smelt # 26 to estimate the fuel needed to smith the entire bloom .

Table 4

Process	*Charcoal used*
Smelting	94 kg
Billet Smithing	78 kg
Bar Smithing	238 kg
Total fuel for 4.95 kg of bar	410 kg
Fuel consumption/kg of bar	82 kg

Labor Analysis

Table 5

Process	*Time (man hours)*
Mine and roast ore, cut wood, make charcoal (assumed as per Crew 1991)	50
Smelting- assuming a three man team (as per Crew 1991) Smelt #25, 5 hr 30 m duration	16.5
Billet Smithing- extrapolated to full bloom	18.8
Currency Bar Smithing- extrapolated to full bloom at 3 man hours per .5 kg bar	30
Total time to smelt and forge 10 bars .5 kg each	115.3
Total labor/kilo	**23.06 man hours**

It should be noted that 9.76 man-hours/ kilo of the above figure represent the smithing process, which our experiments replicated inefficiently, so further reduction of this figure is likely.

Discussion

The most significantly different aspects of our smelting method, or at least those that can easily be reduced to language, are threefold: air rate, management and manipulation of the slag, and the recycling of furnace products.

Air Rate (the myth of the overblown bloomery).

Early archaeological experimenters in the bloomery process used air rates in the neighborhood of .4 l/min/cm^2 of hearth cross section (Tylecote 1971, 362). This air rate seems to have been arrived at due to fairly theoretical criteria (Tylecote 1971, 348).

It is understandable that later experimenters stayed within this range. Our earlier experiences with blasts of these lower rates indicates that as the blast approaches .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 (Crew 1991, 27) (Harvey 1988, 36). 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. A furnace run on blasts of .4 to .8 l/min/cm^2 will resemble figure 3.

But, if the blast is increased still further, in the neighborhood of 1.2 to1.5 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. A furnace that is run on higher blasts will resemble figure 4.

At these higher blast rates, the bloom does not adhere to the furnace wall, and so is easily removed from the furnace. Our current slag tapping arch is quite small, but if the size of the arch were nearly the size of the interior diameter of the furnace, as is the case in many ancient furnaces, the bloom could easily be removed through it.

At yet higher blasts for prolonged periods, in the neighborhood of 1.6 l/min/cm^2, carbon content again seems to elevate, and incandescent sparks indicate reoxidation.

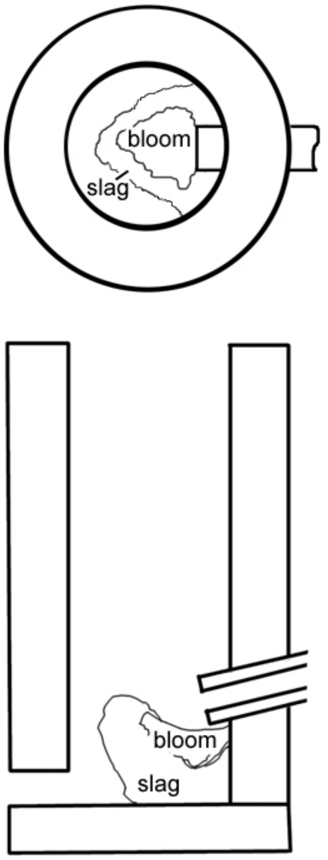

Figure 3

Bloomery run with a blast of .4 - .8 l/min/cm^2

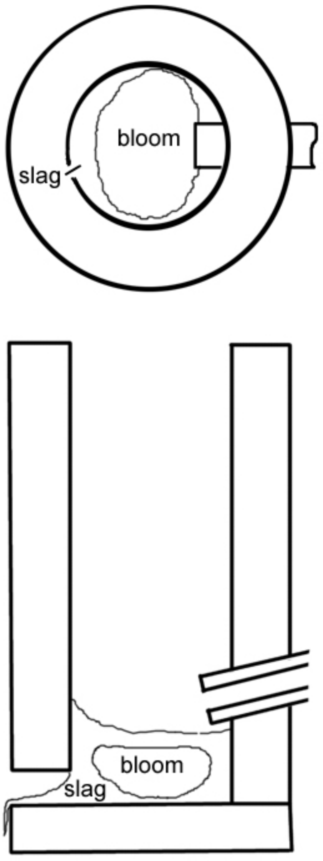

Figure 4

Bloomery run with a blast of 1.2 – 1.5 l/min/cm^2

Slag as a physical, chemical, and thermal resource.

Slag fulfills two **physical** functions in a furnace: protection and transportation. Molten slag coats and protects reduced iron particles from reoxidation. After the bloom begins to form, we also strive to keep it physically covered by molten slag at all times, to protect it from reoxidation.

Slag flow also serves to transport reduced iron particles to the locale of bloom formation. The recharging of the first slag to reach the bottom of the furnace utilizes the transportational function of the slag. Iron particles that did not have a chance to coalesce into a bloom are thus carried back to the active zone of the hearth.

Both protection and transportation require a liquid, free-running slag. The fluidity of the slag is a function both of its chemistry and its temperature. Higher temperatures facilitate slag flow through all parts of the hearth.

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

$$FeO_{\text{in slag}} + C_{\text{in metal}} = Fe + CO_{\text{gas}}$$

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, along with reduction of wustite by direct contact with bits of charcoal, is the real workhorse of bloom formation, and that reduction within the stack merely provides a seed for reduction in the slag bath below. Low temperature, small slag baths, and low fuel:ore ratios only serve to inhibit these hearth level reactions. A small low carbon bloom, composed of loosely accumulated stack-reduced particles, is like an ungerminated seed. This type of bloom accounts for the difficulty reported by many researchers (e.g. Crew, Sim) of consolidating the bloom without breaking it apart. In contrast, our process produces a very dense bloom that is in no way fragile, and may be hammered vigorously from the start.

Finally, the slag performs vital **thermal** functions. The growing slag bath, as well as the incipient bloom itself, provide both a reservoir of heat and a source of radiant energy that keeps the temperature of the furnace from falling with the addition of each fresh charge of ore. This heat reservoir, along with the exothermic nature of the reduction reactions taking place, provides the not-so-gradual increase in furnace temperature in the latter stages of the smelt. This is another reason for restraint in the tapping of slag, which removes heat from the furnace.

The hot, fluid slag also tends to carry heat down to the lower part of the hearth, allowing the hot zone, and the bloom itself, to sink lower in the furnace as the smelt progresses. The hot bloom also tends to melt its way down towards the bottom, leaving room for more bloom formation above (we think we have yet to approach the limits of charge weight or bloom size in this furnace).

The tapping and recharging of slag ensures a constant flow of this physical, chemical, and thermal resource through and around the growing bloom. The use of these slag manipulation techniques is not necessarily limited to slag-tapping furnaces, however. Many of the same goals could be accomplished through the recycling of slags from previous smelts. Also, any pit furnace with a bottom of combustible material, like the grass used by the Haya of Tanzania, and in Scandinavian slag pit furnaces (Schmidt 1997, Mikkelsen 1997), could provide a slow subsidence that ensures a constant flow of fresh slag across the bloom.

The Recycling of Gromps.

We use here the term ‘gromps” to refer to the leftover bits of mixed slag and reduced iron that litter the furnace site after a smelt. Like most experimenters, we initially refrained from the recycling of iron and slag from previous smelts, in hopes of making each smelt an isolated, measurable event. But ancient smiths would have rarely carried out any smelt as an isolated event, and ancient smiths surely recycled all material possible. An accurate reconstruction of an ancient bloomery process should therefore use recycled material.

In our yield analysis above, we have not included recycled material as an input in our calculations. Theoretically, each smelt will produce as much gromp as was put into it. In reality, each smelt produces more gromps than it consumes, as a glance at the ground around our furnace proves.

So why use it if there is no net gain from its use? Because the use of gromps is a variable that significantly alters the process. When we use gromps in our last charge, we get blooms of greater density. We can't posit a mechanism for this effect, only report our empirical observations. This recycling charge seems almost to have a catalytic effect. We perceived no impact on bloom density when we used the gromps as the initial charge, only when added last, before the slag tapping and recharging phase of the smelt.

A few miscellaneous observations:

Preheating: The conventional practice of attempting to bring the furnace to full operating temperature before charging is simply a waste of charcoal. The heat reservoir of molten slag, and the exothermic reduction reactions, are what really bring the furnace to full heat.

Control of carbon content: 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 that 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.

The addition of a late charge of fresh ore also has a pronounced decarburizing effect on the bloom. We stumbled on this technique by accident, but have since found that Evenstad prescribed this final charge (Espelund, 1997, 54). This procedure could apply to any furnace type.

Conclusions and Suggestions

As can be seen from the analyses above, the three interrelated procedural changes of increased air flow, constant monitoring and manipulation of the slag bath, and the recycling of furnace materials lead to very different results in terms of yields and labor requirements than those published by most other experimenters. Most significantly, the labor requirements to produce a kilo of fully smithed iron drop from the 25 man-days suggested by Peter Crew to a mere 23 man-hours in our experiment-- a difference of a full order of magnitude.

Much might be learned if these procedural changes were applied to archaeologically accurate furnace morphologies, and the results compared to the archaeological record. For instance, the larger hot zone of this method could supply the "furnace bottoms" whose absence has frustrated many experimenters. If these experiments produced slags and degrees of furnace vitrification that matched findings from archaeological sites, ideas of the economic input and output of ancient iron sites might have to be revised.

Conversely, if the results of such experiments resemble later sites but not earlier ones, much could be learned as well. For instance, if our process produced results that closely matched the Roman bloomery sites, then we can suppose a change in technology had occurred that would have widespread historical implications. A tenfold improvement in iron output would explain a lot about Roman military might. Such a shift in the archaeological record could also help to more closely date such technological innovations as the use of wooden bellows or water power.

We offer this information in hopes that those with more scientific and archaeological training, not to mention institutional support, may be able to apply what we have learned to experimental archaeology.

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Biographical note

Lee Sauder is a professional artist-blacksmith and sculptor. He began his apprenticeship in 1973 at the tender age of 12, and has supported himself solely by his art since 1981.

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