Practical Bloomery Smelting

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ABSTRACT

The art and technique of bloomery smelting, man's original method for winning metallic iron from its ore, has been largely lost in recent centuries. Many reconstructions of this technique have been attempted by archaeologists in the last 30 years. These experimental smelts have tended to be rather disappointing in terms of the production of usable iron; nonetheless, many conclusions have been drawn from this work.

The main goal of our work with bloomery smelting is the production of iron for the creation of forged sculpture. Our focus on producing a usable product has led us to a somewhat different view of the technology from what has been published in the archaeological literature.

In this paper, we will briefly summarize our work through the spring of 2000, which has been published elsewhere. We'll then report our recent findings from the 2000-2001 smelting season, describing 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 other experimenters, especially in regards to blowing rate, slag management, and the recycling of furnace products. Finally, we'll point toward areas of upcoming research.

INTRODUCTION

Summary of early work

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.

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.

With experiments #21-27 , conducted during the spring of 2000, we achieved an efficiency and quality of iron that we feel are more consistent with ancient practice than other published experiments [1]. The smelting season of 2001 has led to further refinements of technique, especially in regards to the control of slag chemistry, and the use of recycled materials from the previous smelt. What follows is a brief description of a particularly successful smelt, experiment # 32, which illustrates well these recent refinements of technique.

EXPERIMENT

Apparatus

The bloomery is a simple shaft furnace constructed of refractory materials. Our furnace is designed in modules to allow the investigation of many furnace types. Each module consists of an outer ring of steel sheet that acts as a form for the interior of castable refractory. The furnace as configured in this experiment had a shaft height above the tuyere of 100 cm, with an interior diameter of 35 cm. This is roughly analogous to the dimensions of a Roman shaft furnace [2]. A simple water-cooled tuyere projected 5 cm into the interior, 23 cm above the furnace floor. Opposite this tuyere, at the base of the furnace, is an removable access door, 24 cm high and the width of the furnace interior. This access door is in turn pierced by a small 12 cm x 15 cm slag tapping arch.

The final 30 cm of shaft height was provided by a hollow steel section that functions as an air preheater. The blast source for the smelt was a vacuum fan that delivers approximately 1600 l/min at full blast through the 5 cm tuyere orifice.

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.

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**.** In addition to the raw ore, we also charged significant amounts of iron-bearing materials from earlier smelts. The sixth charge consisted largely of “gromps” (here defined as bits of bloom and other magnetic material retrieved from the previous smelt), and hammer scale retrieved from the working of the previous bloom.

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.

Description of smelt # 32

This experiment took a total of 6 hours and 10 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)** recharging of slag; 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 40 minutes, we loosely blocked the tap arch, added charcoal, and began a blast of 1275 l/min. Preheating with charcoal continued for another 30 minutes. The entire preheat consumed approximately 18 kg of charcoal.

Charging of ore: After preheating, we added our first charge consisting of 6.8 kg of charcoal followed by 6.8 kg of ore. The second, third, and fourth 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 20-25 minute intervals. Between charges three and four, we increased the blast to 1500 l/min. By raising the temperature at this time of incipient bloom formation, we enlarged the isotherms in the furnace. Our intent here was to encourage the initial formation of the bloom lower in the furnace, leaving room above to grow a larger bloom before it began to block the tuyere.

For the fifth charge, the amount of ore was doubled. Half of the ore was laid on the edge of the furnace, and raked in gradually. By this point, the furnace contains a large mass of hot molten material that's able to absorb the extra influx of cold material without a precipitous drop in temperature.

The sixth charge consisted of 4.1 kg of gromps and 2.7 kg of raw ore to make up a 6.8 kg charge.

Recharging of slag: 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 roughly 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. After cooling the tapped slag in water, broke it up into small bits, and returned it to the furnace with a roughly equal amount of charcoal.

After the first recharging, we mixed in increasing amounts of hammer scale. Hammer scale has a high iron content largely in the form of wustite and magnetite. The addition of the hammer scale helps to maintain the slag in a fluid, iron-rich condition. In our earlier work, we concluded the smelt when the increasing viscosity of the slag, due to its lowering iron content, made it difficult to continue. With the additions of hammer scale, we can basically continue the smelt as long as the supply of hammer scale (or our patience) holds out.

In this smelt, a total of 22 kg of slag was recharged, along with 27 kg of charcoal and 4.8 kg of hammer scale.

Decarburization and burndown: Often, at the end of a smelt, we add an additional charge of fresh ore to decarburize the bloom [1]. In this instance, since the additions of hammer scale had kept the slag quite fluid (thus iron-rich) throughout the smelt, we felt it unnecessary to add this decarburizing charge. 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.

Table I. Smelt #32

Date: 3/17/01
Furnace configuration: 41" shaft height above tuyere, air preheater on, tuyere 7" above floor
Fuel type: hardwood charcoal
Ore type: goethite - Victoria Mine
Other additions: gromps, hammerscale

Time	Charcoal	Ore	Slag (recharged)	Gromps	Hammer scale	Air	Notes
hh:mm	kg	kg	kg	kg	kg	l/min	
8:50						850	Start preheat with wood, blast on.
9:30	18					1275	Switch to charcoal.
10:00	6.8	6.8					Charge #1
10:25	6.8	6.8					Charge #2
10:50	6.8	6.8					Charge #3
11:05						1500	Hoping to initiate bloom formation lower in the furnace.
11:10	6.8	6.8					Charge #4
11:30	6.8	6.8					Charge #5
		6.8					6.8 kg of additional ore laid on edge of furnace, and added gradually-plenty of heat, no need of extra fuel.
11:50	6.8	2.7		4.1			Charge #6
12:00						1625	Slag in tuyere. Cleared under bloom, slag flowed to furnace floor.
12:10							Tapped slag.
12:20	5.5		4.5				Recharge #1
12:40	2.7		2.7		.63		Recharge #2
12:50	3.6		3.6		.63	1500	Recharge #3
1:05	4.5		5.5		.63		Recharge #4
1:30	4.5		1.8		1.6		Recharge #5
1:50	6.4		4		1.3		Recharge #6
	4.5						Burndown. Gromp scraped off furnace wall from above.
3:00							Bloom removed through tap arch.
totals	90.5	43.5	22	4	4.8		

RESULTS OF SMELT #32

The bloom from this smelt weighed 18.2 kilos. It was roughly kidney shaped, slightly concave on the top surface, and measured 30.5 x 25.5 x 12.7 cm. This bloom was 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. Spark testing indicated a low carbon content. This 18.2 kg bloom represents 58% of the estimated iron available from the ore, gromp, and hammer scale.

We also recovered 6.8 kg of gromps from the smelt, including two small bloomlets that were large enough to be forged into small sculptures. If yield is calculated using this additional iron, we recovered 77% of the available iron.

The entire smelt, from kindling the fire to bloom removal, lasted 6 hr 10 min, and consumed a total of 90.5 kg of charcoal.

DISCUSSION

Our smelting method differs from most other reported bloomery experiments in three significant ways.(1) We use a much greater air blast. (2) We vigorously manage and manipulate our slag, and (3) we recycle all our iron rich furnace products. We'll elucidate these procedural differences below, and then offer a few comparisons of our results to those of earlier experimenters.

1) 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 [3]. This air rate seems to have been arrived at due to fairly theoretical criteria [4].

It is understandable that later experimenters have 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 [5,6]. 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 1.

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 2.

At these higher blast rates, the bloom does not adhere to the furnace wall, and so is easily removed from the furnace.

At yet higher blast rates for prolonged periods, in the neighborhood of 1.6 l/min/ cm^2, carbon content of the bloom again tends to elevate.

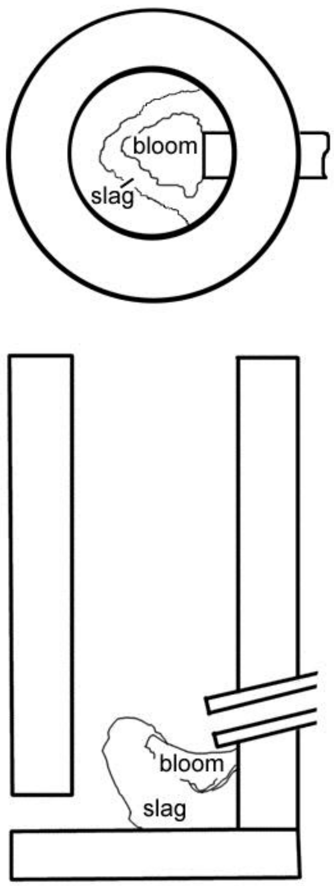

Figure 1.

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

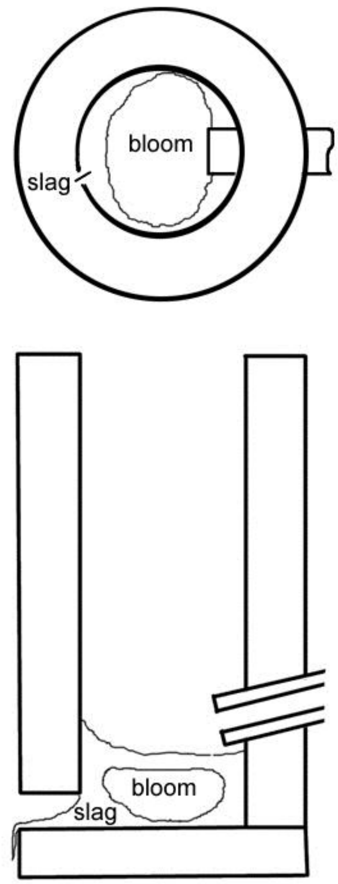

Figure 2.

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

<u>2) Slag as a physical, chemical, and thermal resource</u>

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. In this smelt, our constant additions of hammer scale when recharging slag ensured a continually elevated iron content in the slag. This high wustite content creates a free-running slag. Higher temperatures also 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 [7] as

$$FeO_{\text{in slag}} + C_{\text{in metal}} = Fe + CO_{\text{gas}} \qquad (1)$$

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 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.

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 [8][9], could provide a slow subsidence that ensures a constant flow of fresh slag across the bloom.

3) The recycling of furnace products

Our last charge in most smelts consists largely of “gromps”, the term we use to refer to magnetic material recovered from the previous 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 those smiths surely recycled all material possible. An accurate reconstruction of an ancient bloomery process should therefore use recycled material.

We have also found that the use of gromps significantly alters the quality of our final product. When we use gromps in our last charge, we get blooms of greater density. We have 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. Our recent work has led us to a greater understanding of this effect by running very similar smelts with and without gromp charges.

The bloom as formed along the isotherms in the furnace tends to have a concave upper face, that is sloped towards the tuyere. This can create the problem of slag draining very rapidly in a torrent below the tuyere, leaving no time for the hearth level reactions described above to take place. Since the gromps, largely consisting of metallic iron, have a high melting point, they survive intact to create a sort of strainer for this slag drain below the tuyere, creating a denser bloom with a flatter top.

The recycling of hammer scale recovered from the forging of the previous bloom is not only a ready source of iron, but also provides a very effective tool for managing the composition of the slag, as explained above.

CONCLUSIONS AND COMPARISONS

The three interrelated procedures of increased air flow, constant monitoring and manipulation of the slag bath, and the recycling of furnace materials lead to different results in terms of yields and labor requirements than those published by most other experimenters.

Of the bloom smelting experiments of which we are aware, the most directly comparable to ours are the seminal work of Tylecote, Austin and Wraith, and the thorough but less penetrable work of Erik Tholander[10]. Both of these experiments used furnaces similar in size and construction to ours, and mechanical air supply. Our yields in terms of percentage of iron recovered from the ore, and iron produced per unit of fuel, do not differ significantly from those previous experiments. But our yield of iron from our labor, and from a given furnace size, is greatly increased.

In table II below, we compare the yields from smelt #32, described above, to some of the more successful smelts of previous experimenters.

TABLE II. Yield comparison with other research.

Researcher	**Bloom wt.**	**% Fe recovered**	**Kg fuel /kg bloom**	**Kg bloom/m^2 furnace section**	**Kg bloom/hr**
Tylecote et. al. #21	6.4 kg	78%	7:1	91 kg/m^2	.71 kg/hr
Tholander #6	3.7 kg	58%	4:1	30 kg/m^2	.77 kg/hr
Crew #28	2.2 kg	49%	11:1	45 kg/m^2	.2 kg/hr
Sauder & Williams #32	18.2 kg	58%	5:1	189 kg/m^2	2.9 kg/hr

These figures compare only raw blooms, as that is the only data available for the experiments compared above. How much of the bloom was usable iron? To our knowledge, only Peter Crew [5], David Sim [11] and ourselves [1] have examined the question.

The results we are achieving should be attainable in many historically accurate furnace reconstructions, using these techniques. A single set of large wooden bellows should be able to deliver the amount of air required. We base this on calculations on the tempo and bellows size of smiths who use bellows every day[12]. Rehder estimates that a single man can deliver up to 3600 l/min of air indefinitely [13]. The slag management technique we describe can be applied to many bloomery morphologies. And obviously, the recycling of materials could be practiced in any furnace.

We think that the first goal of any investigator in experimental archaeology should be to match the results of the ancient craftsman. Until this is at least approximated, all conclusions based on an experiment are highly suspect.

Upcoming research

The main focus of our work will be to continue to make iron as well as we can, and see what we learn from it.

But we also hope to achieve a few more specific experimental objects in the coming year. Plans include some smelts with man powered bellows, to verify that air rates of 1200 to 1500 l/min are achievable manually. We also hope to be able to apply our experience to other types of ore, including bog ore and hematite. We also plan to more thoroughly compare smelts utilizing slag –tapping to those that do not. We have also been researching the clays of our region, in hopes carrying our smelting technique a more traditional furnace reconstruction, of a type still to be determined.

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