adventures in experimental smelting

Iron the Old-fashioned Way

BY ELIZABETH G. HAMILTON

It was a perfect October day to play with fire. The sun shone brightly on the barnyard of the Peters Valley Craft Center in New Jersey as five teams hovered cautiously over waist-high furnaces streaming fire above and dribbling molten rock below. White-hot, hissing, and barely contained by a fragile skin of clay, the furnace fire used air, heat, and magic to transmute charcoal and reddish lumps of mineral iron ore and give birth—we hoped—to a solid chunk of gray, malleable metal. As part of an all-day workshop organized by artisan blacksmiths and metal sculptors, we were smelting iron with a process resembling those used during the 1st millennia BC and AD.

For over 2,000 years, iron was won from its ore by bloomery smelting—a small-scale process that produces a heavy lump, or bloom, of mixed iron and mineral waste rather than the liquid iron generated in modern blast furnaces. Like many old technologies, bloomery smelting was a technique passed from generation to generation through apprenticeship and practice. Although some forms of bloomery smelting survived in North America until the 19th century, much of the knowledge about the process is lost to us today. But slowly, patiently, and with painstaking experimentation artisan and hobby blacksmiths, professional farriers, and sculptors who work with iron are recovering this ancient knowledge—and helping archaeologists to understand ancient technology.

This particular workshop was organized and led by four men. Lee Sauder, a blacksmith and

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Although none of our leaders suggested it, every workshop furnace was embellished with some form of decoration.

In front of a demonstration furnace Lee Sauder (cowboy hat) and Michael McCarthy (knit cap) explain some of the physics of smelting to workshop participants.

metal sculptor from Virginia, and his smelting partner Skip Williams have been smelting since 1998. Why did they start playing around with this little-known and obsolete process?

"Kill what you eat," says Sauder. "Anyone who eats meat, you should kill once to find out what you are partaking of." Before Sauder started producing his own iron, all of his sculpture and artisan work had been done with industrially made iron with predictable properties. But after reading about traditional African bloomery smelting, he wanted to create his own raw material to really know what he was working with. His first attempt with Williams, however, was a dismal failure.

"Once we found out how difficult it was, it became a challenge," says Williams.

After considerable trial and error, Williams and Sauder managed to produce some usable iron and this new material's sculptural possibilities fascinated Sauder. "It's like working with an organic material," he explains, "something harvested from the earth." Looking at a crack in the half-forged piece of iron before him, he notes, "You can't fix that; you can only work around it. It's made the decision."

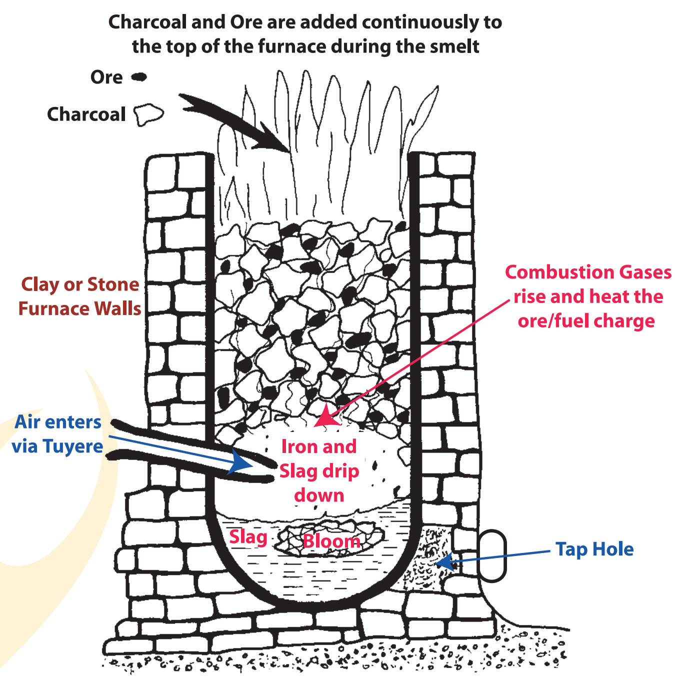
Michael McCarthy, the head blacksmith and metal sculptor at the Farmers' Museum in Cooperstown, New York, and a fellow workshop organizer agrees. "This stuff," says McCarthy, "it's an equal partner in the work."

The final workshop organizer, however, had a different motivation. In 2001, Darrell Markewitz, an artisan blacksmith, was asked by the curators of the L'Anse aux Meadows museum in Newfoundland, Canada, to reproduce the iron smelting and smithing techniques used by the Vikings there around AD 1000. But working with what the archaeologists said had happened, his attempt was a complete failure—clearly the archaeologists had gotten it wrong. This sparked his interest and he soon joined Sauder, Williams, and McCarthy to form an experimental group. "I'm interested in how the finished forms relate to the material culture of the Viking Age," remarks Markewitz. "They had a much different relationship to metal objects than we do."

SMELTING IRON IS NOT EASY

Although it is so taken for granted it is almost invisible, iron is the foundation of our civilization's technology. For nearly 3,000 years, iron has been the preferred material for all kinds of tools and equipment. Abundant and easily worked, welded, and cast when hot, it is capable of almost infinite gradations of hardness, tensile strength, and corrosion resistance.

Yet despite its ubiquity, producing iron from ore—a mixture of metal, silica, and other minerals—has never been easy. For instance, while good evidence indicates that copper smelting and the production of tin-copper alloys (bronze) was invented independently in several parts of the Old and New Worlds, it is still not clear where iron smelting first appeared. All we know is that occasional small artifacts of both naturally occurring meteoritic iron and smelted iron appear at sites in Southwest Asia (Anatolia and Mesopotamia) and Northeast Africa (Egypt) during the 3rd millennium BC and that documentary evidence from the Late Bronze Age (*ca.* 1250 BC)



This generalized low-shaft furnace shows how hot gases rise and preheat the ore/charcoal charge. Oxidation takes place where the hot air and charge meet. During the smelt, the slag can be tapped to drain out, but to remove the bloom the furnace wall must be broken (adapted from p. 29 of William Rostoker and Bennet Bronson. *Pre-industrial Iron: Its Technology and Ethnology*. Philadelphia, PA: Archaeomaterials, 1990).

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describes the deliberate production of iron by the Hittites of northern Anatolia (modern Turkey) and a trade in iron between sites in Assyria (northern Mesopotamia) and Egypt. Later, during the 1st millennium BC, iron smelting seems to have spread east from these areas to India and China and west to Europe and North Africa. Although some archaeologists would dispute this, no convincing evidence yet exists to indicate that iron smelting was invented independently outside of the Middle East.

So what is so difficult about smelting iron? The ideal temperature for smelting iron is between 1100°C and 1400°C—much higher than required to smelt any other metal known in antiquity (e.g. copper can be smelted at temperatures below its melting point of 1083°C). While these temperatures will not melt iron—which melts at 1540°C—they *will* melt the non-metallic minerals (especially silica) found in iron ore, allowing them to drip away in the form of slag from the solid iron in a furnace.

During the smelting process, the furnace is heated by burning charcoal, a fuel which generates an internal furnace atmosphere rich in carbon monoxide that produces two side effects. First, the carbon monoxide helps facilitate the smelting process by providing molecules to which the oxygen found in the iron ore can bond and escape as a gas into the atmosphere, leaving behind the solid iron. Second, carbon left behind during the smelt diffuses into the iron (in a process called carburization) and affects the nature of the resulting metal. For example, the more carbon contained in the iron, the lower its melting temperature and the harder and more brittle it will be. Depending on many variables, such as the ratio of charcoal to ore and the rate of air entering the furnace, bloomery furnaces can actually produce different types of iron, such as cast iron (over 2% carbon), steel (between 0.2% and 2% carbon), wrought iron (less than 0.2% C), or an unworkable mixed lump of all three.

At the end of a successful smelt, the furnace should produce a bloom—a mass of slag, iron, and unsmelted ore—that looks like a giant black sponge, but this does not always happen. If the original ore quality was too poor, or the fuel ratios, temperatures, slag composition, or carbon dioxide-to-carbon monoxide ratio were wrong, the end result might not be a single bloom but, rather, numerous unconsolidated chunks of iron dissolved uselessly in slag. And even if a good bloom is created, this is not the end. To produce useable metal, the bloom must be hammered while at a yellow heat to squeeze out the slag and consolidate the iron—hence the legendary blacksmith muscles! And this hammering can be very difficult or even impossible if the proportion of carburized iron (cast iron or steel) is too high. In short, compared to copper smelting, iron production requires richer ores, larger fuel supplies, closer controls over furnace air supplies and composition, and a great deal more post-smelting work before anything that even looks like a metal is produced.

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To help insulate our furnace, the author (left) helped smear a concoction of insulated clay over it.

PREPARING THE SMELT

Our smelting team consisted of four workshop participants, plus Skip Williams as our leader. The first step was making the furnace. In antiquity most furnaces had a superstructure of thick clay with a hole at the top for pouring in ore and charcoal. Instead of building our own furnace out of clay, we used a two-foot tall rectangular ceramic chimney flue whose size, if not shape, generally matched the dimensions of small Roman period smelting furnaces, to serve as our furnace. Using a hole saw with carbide bits and considerable care, we punched two holes in the flue—a tap hole at the base to allow molten slag to run out and another hole farther up the flue to accommodate the *tuyere*, pronounced "twee-er." This cylindrical tube (ours was hammered copper, but most in antiquity were ceramic) would allow us to pump air into the furnace to feed the fire.

The flues are pretty good insulators, but tend to crack when heated for a long time. To fix this, we mixed sieved clay with cellulose insulation and water and then smeared an inch-thick layer of this insulated clay all over the flue. Next, we wrapped chicken wire tightly around the furnace and smeared more clay over the wire until it was almost completely covered. We then arranged four concrete slabs on the ground, leaving a hole in the middle of them in which to place fine charcoal. This served as a plinth upon which we put our furnace. To dry our furnace, we dropped in thin sticks of wood and burned them for about an hour until the furnace's exterior looked like it had psoriasis. During this time, we also prepared the raw materials for the smelt.

Smelting starts with ore, and as iron is one of the most common elements on earth, many different kinds of iron ore are available, such as hematite, limonite, goethite, magnetite, and bog iron ore. The goethite ore we used was originally mined in Virginia in 1827 by a mining company that had gone bankrupt. Because its land reverted to the state and eventually

Before smelting can begin, the ore needs to be broken up into fragments about the size of half a pea.

to the state park system, the mined ore was left in piles on the surface, free for the taking for those who had permits from the park system.

Before the workshop, the organizers had roasted the ore-stones in a wood fire in order to drive off any water and increase the friability of the rocks. While our furnaces dried, our job was to break down these ore-stones using hammers or heavy weights. The goal was half-pea-sized fragments. Each team needed about 65 pounds of ore for its smelt, a tedious and back-breaking amount of pounding.

At the same time, we also had to break up 200 pounds of charcoal into walnut-sized bits using soft mallets and graduated screens. Although we used commercially made charcoal during the workshop (not briquettes!), the organizers often use charcoal they themselves have made. Smashing the charcoal, while satisfying, was profoundly filthy, and I have no idea how my teammates' faces stayed so clean when I looked like a raccoon.

FROM THE FIERY FURNACE

Finally, with our furnaces hot from the preheating fire at the bottom, we were ready to smelt. We stuck the tuyere in the side hole, turned on the electric blower that would supply a constant stream of air to fuel the burn, and fed the furnace from above with charcoal.

I had to ask the obvious question: How could a smelt with air supply powered by an electric motor possibly compare to early smelts that used bellows? Skip Williams had an answer. Depending on the design, non-electric bellows are perfectly capable of supplying a steady, strong supply of air. To test this, all four workshop organizers had conducted many smelts with various types of hand-powered bellows. Depending on the

experimental archaeology

The workshop organizers have been doing a form of experimental archaeology—the study, through the control of relevant variables in an artificial system, of the processes whereby material objects, ranging from sites and buildings to artifacts and bodies, are produced, used, discarded, and allowed to decay, with the aim of generating analogies to be used in archaeological interpretation. Experimental archaeology includes "living history" museums designed for public education, the making and use of stone and metal replica tools, the creation of buildings using authentic techniques and materials in order to understand labor requirements and material constraints, and the deliberate creation of structures that are subsequently destroyed or allowed to decay to discover their archaeological imprint. The core of the approach, however, is that something in the archaeological record—an artifact, a manufacturing process, a site—is replicated.

While many hobbyists have tried to reproduce specific artifacts such as arrowheads, to be useful for archaeological interpretation, the experiment (like experiments in any science) must follow certain rules. First, the question must be made explicit. Next, the experimenter needs to know all the variables that would affect the process, and then control as many independent variables as possible in order to see the effect of changes in the dependent variables.

To make iron, such variables as ore type, charcoal type and quantity, furnace shape and material, air flow rate, and the smelt time need to be controlled and standardized. The experiment needs to be performed repeatedly under the same conditions, and other experiments should alter important variables. The results should be quantified and analyzed, and the experimenter must realize that just because the process makes a product like one found on an archaeological site, it does not mean that this process was the one used in the past. All the experimenter is really doing is eliminating alternate possibilities.

Sauder, Williams, Markewitz, and McCarthy's work is experimental archaeology because they are trying to determine the operational principles of an archaeologically known process—bloomery smelting. Except for Markewitz's work in Ontario, they are not trying to fit their results to a particular archaeological location or culture, but rather are isolating principles and practices that can be used in interpreting bloomery smelting remains in any part of the world. They are trying to recreate not only the scientific knowledge of the many ways bloomery smelting can be done, but also to recapture the unquantifiable, non-verbal know-how of the process.

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With the air blower on, the furnace roars into action. Here, Darrell Markewitz demonstrates how to smooth out the top of the ore-charcoal charge.

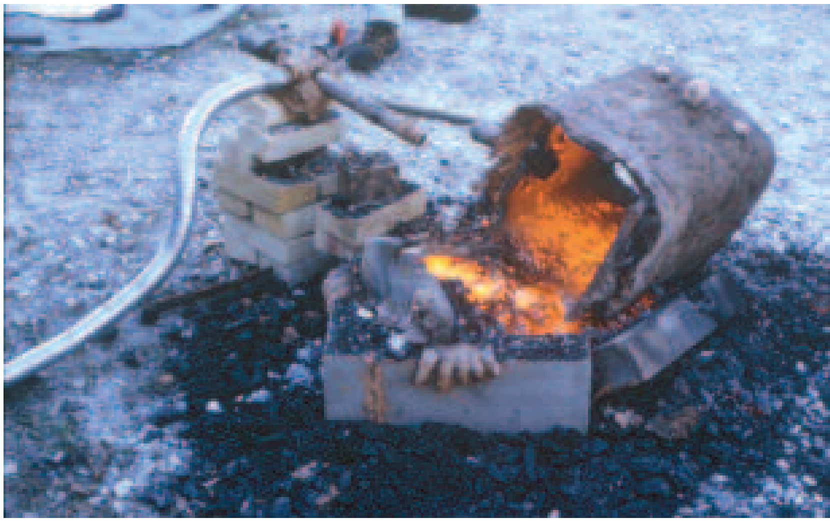
bellows design, the hand-powered bellows have produced air flows broadly comparable to the motorized blowers. As a result, using motorized blowers was a good way to save labor while not affecting the resulting smelt. Through trial and error, they learned that the right air flow in this furnace setup is when 12 kg of charcoal are consumed per hour.

After the charcoal had burned for about an hour to preheat the furnace, it was time to add the ore. We began with a ritual of sympathetic magic, dropping hot peppers into the furnace. We then dribbled ore on top of the burning charcoal using small long-handled shovels. As the furnace consumed the ore and charcoal and the internal mass settled, we added more ore and charcoal. This was done with careful timing, using a ratio of two pounds of ore to four pounds of charcoal every ten minutes, increasing to equal measures of ore and charcoal as the furnace built up heat. If the rate of air entering the furnace was right, the time it took to burn the ore-charcoal charge would remain constant and the smelt would proceed as it should. This went on for about five hours, until we had used all our ore.

Periodically, Skip would nudge open the brick blocking the tap hole and assess the slag coming out. Midway through our smelt, a slow, thick slag began leaking out of the bottom of the furnace. When it solidified, it was very light and cindery—a bad sign. Good slag runs thin and easily, and when it solidifies, it is heavy and iron-rich and is therefore often dumped back into the furnace for further smelting.

What should we do? Was the smelt ruined? Skip wondered unhappily if we should start over, an idea that appealed to no one. After consulting with the other organizers, he decided to continue the smelt and see if the process healed itself. Much to our relief, it did.

After we had emptied our ore container, we let the furnace burn down for an hour, all the while examining the roaring white-yellow-hot interior, where dripping slag and metal could be seen through the unplugged tuyere. Using a long steel rod, we poked the mass inside through the tap hole. Yes! We had a solid, massive bloom.



Slag and charcoal surround the furnace, toppled over so the bloom can be removed.

We carry the bloom to a hollowed log and split the bloom using an axe pounded by sledgehammers. To preserve its temper, the axe must be quenched frequently while it splits the still-hot bloom.

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Sliced open, the iron in our bloom is easy to see, as are the air holes that a blacksmith will have to hammer closed.

By this time, night was falling, and the glow of the furnaces in the dark was spectacular. To remove the blooms, the furnaces had to be tipped over by brave people and the yellow-hot bloom hauled out with tongs. We then hurriedly carried the bloom with the tongs over to an upright log that had a slight hollow at the top. While one person held the bloom steady, another team member knocked off loose “mother” fragments of slag and waste. Next, to split the bloom, one person balanced an axe on the hot mass and two other team members used mauls to pound the axe until the bloom split into parts small enough to be forged in a smithy.

When these fragments cooled, a spark test would indicate the carbon content and thus the workability of our bloom. This is done by holding the iron against a rotating grinder or sharpening wheel until sparks fly off. If the sparks are like fireworks with little explosions of mini-sparks at the end of the main spark, then the iron’s carbon content is relatively high and it will be harder to work. The ideal result of a spark test is a low carbon content, indicated by sparks that form a straight line. In the end, our spark test was clear—our bloom’s carbon content was variable and would require considerable work to forge.

Even after its bloom has been removed, the furnace and its contents remain hot.

APPROXIMATING ANTIQUITY

Our smelting operation was designed by the workshop organizers to be a cheap and (above all) reliable producer of iron in a workshop setting. In their own smelting experiments, however, the four organizers have altered many variables to test the effects of variations in smelting structures and processes. For example, they have experimented with clay-and-straw furnace walls rather than ceramic flues, and have changed the angle of the tuyere, the rate of air flow, the height of the furnace, the temperature at which it burns, and the time taken to smelt iron, all to find out what makes a good smelt and produces a good slag.

Most importantly, however, they compare their results—the quality of the bloom, the appearance and weight of the slag, the physical remains of the furnace—with material excavated by archaeologists. By and large their aim is to elucidate the processes used by ancient and medieval smelters, more so than the recent bloomery smelters of 18th and 19th century North America. Although they do look at archaeological reports about iron smelting sites to determine how ancient smelters made iron, their own experience shows that archaeologists are often wrong when they suggest how iron smelting was done in the past. As Michael McCarthy notes, “archaeologists tend to jump to conclusions.”

In terms of experimental archaeology, Skip Williams identifies two veins iron smelting research can follow, each with many variables to explore. The first involves the accurate reconstruction of ancient furnaces using archaeological remains as a guide. This is the research most clearly associated with archaeologists working from the archaeological record toward conjectural reconstructions that are then ‘tested’ during experimental smelts. The second approach—the one followed by the workshop organizers—involves learning in practical terms the mechanics of how to smelt. For example, if you do not know how to smelt (what works and what does not), then it is unlikely that your reconstruction of an ancient furnace is going to be correct and capable of producing useable iron. Rather than focusing initially on reconstructing ancient furnaces, they try to understand the process of smelting. It is a simple premise, according to McCarthy: “If you’re not reproducing the product [i.e. useable iron], you’re not reproducing the process [of ancient smelting].”

As Lee Sauder explains, “We can’t say that [the way we smelt in our experiments] is the way they did it, but if you don’t get

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Left, during the workshop, Darrell Markewitz also constructed a replica Viking-style furnace with walls of clay and straw. After its use, its remains are not very impressive and would leave little behind for archaeologists to find, especially after some years in a cold climate.

Right, in a nearby smithy, one end of a piece of our bloom was forged into an iron shaft.

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iron [in your experiment], we can certainly say this *isn't* the way they did it." So the key for them is to understand how to make useable iron and then to experiment from there using archaeologically relevant materials and evidence to better approximate ancient smelting.

"We haven't discovered *the* way [to make iron], we've discovered *a* way," says Darrell Markewitz.

"You learn the physics of how these small-scale furnaces work physically, and then subtract more and more of the modern elements to try and recreate the ancient process," adds Sauder. There are many ways to smelt iron, but the closer their results get to the material found at a particular time and place, the more likely it is that at least some ancient and medieval smelters used a process like theirs.

Markewitz, in particular, pays close attention to the physical remains of the furnace and slag scatters that his smelts leave behind. In Ontario, his group has built Viking-style furnaces with walls of clay, straw, and charcoal or sand. After conducting their smelts, they leave these furnaces to decay so that they can see what will be left to be discovered in the archaeological record. It turns out that the answer is not much. In the latitudes where the Vikings lived, the yearly freeze-thaw cycle is not kind to furnaces and destroys them in only a few years. This suggests that smelting may have been conducted at many Viking sites in the past with little physical evidence surviving to indicate it.

Severally and together, Lee Sauder, Skip Williams, Darrell Markewitz, and Michael McCarthy have conducted well over two hundred smelts. Their work has left them with a profound respect for the knowledge of pre-industrial craftspeople. Because there is a lot more to learn, they foresee more smelting in the future. They are the only group in North America giving open workshops, which provides them with an opportunity to get together, experiment, and disseminate their knowledge to a larger group.

"We get blacksmiths, metallurgists, and archaeologists," says Markewitz. "Everyone contributes, and we always end up learning from our students."

As for the students? We all took home a piece of our bloom, many with plans to forge the iron in our own smithies, while some of us are now fascinated with the intellectual challenge and the tactile satisfaction of making iron. We will be there for next year's workshop.

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For Further Reading

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