Fuel For The Metal Worker

The Role of Charcoal and Charcoal Production in Ancient Metallurgy

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As an accidental by-product of combustion, wood charcoal has certainly been known for as long as fire itself. Very probably its peculiar properties, such as smokelessness and high burning temperature, were appreciated early on and even taken advantage of from time to time. At some unknown point in the past, however, charcoal began to be produced for its own sake, and not simply as a by-product in the course of building fires for other purposes. Eventually it became a commercial product, and charcoal production became another way to earn a living. The wood from which charcoal is made became an important industrial resource, just as essential to the production of metal as the ore itself.

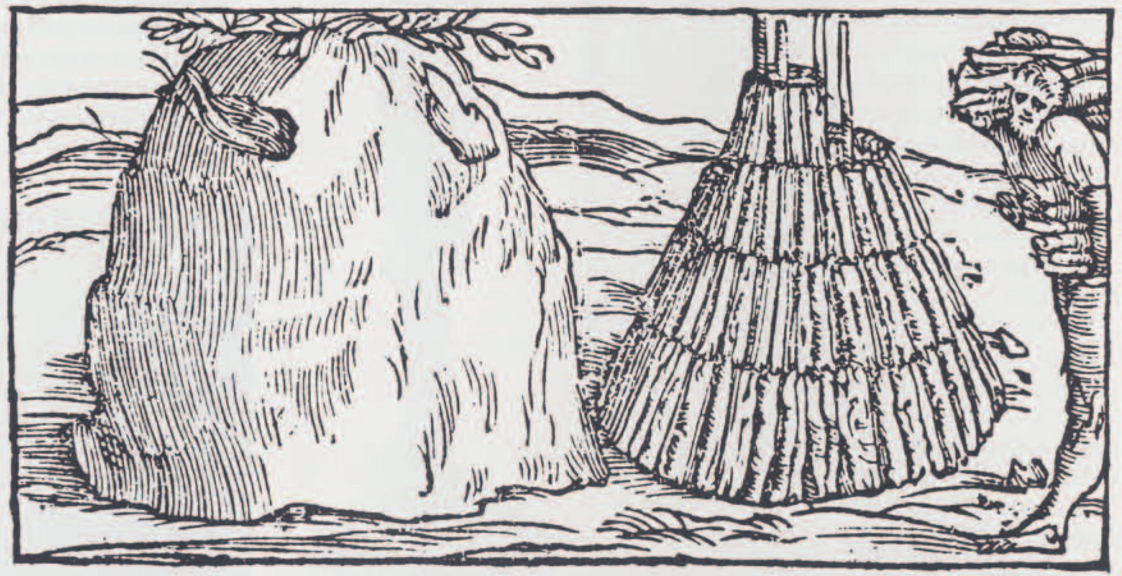
The destruction of vegetation for the production of charcoal, however, had far greater environmental implications over far wider areas than ancient mining ever had. To understand the role of charcoal and charcoal production in ancient metallurgy and in the relationship between people and their environments, we must first understand something about the conditions under which the extraction of metals takes place. Let us begin with the earliest of those metals which have lent their names to the major epochs of the ancient world—copper.

Copper can be found in native, that is, metallic form and was worked in many parts of the world both before and after smelting began. But dependable production in useful quantities relies on mineral ores in which the metallic elements appear in chemical compounds set in a rocky matrix: the smelting process separates the metal from the ore. Copper oxide ores such as malachite and cuprite are not difficult to smelt and are also easy to mine since they lie near the earth's surface. When these ores are heated to a temperature in the range of 1100 to 1200° C, the copper is freed from its compounds and merges into droplets. If the ore's non-copper residues, or *slag*, are thick rather than free flowing, these droplets are trapped inside and can be recovered only by breaking up the cooled slag and picking out the hardened droplets, called *prills*. Adding a *flux* such as iron oxide, sand, or ash helps melt the slag so that the copper droplets can sink to the bottom of the furnace while the liquid slag floats on top, where it is removed by tapping it off while hot, or breaking it away when it cools.

For a successful smelt, a number of conditions must be met. The ore should be properly selected; it may also be enriched by breaking or crushing and culling the portions with high copper content. If it is not already an oxide ore, it can be turned into one by roasting it slowly over an open fire.

The smelting temperature must be high enough to melt the copper and to liquify the slag. This temperature is too high to be achieved in an open hearth, but it is reached easily in an above-ground or pit furnace with a good draft. Charcoal, because it burns hotter than wood, is an excellent fuel. There are other reasons though for preferring charcoal over wood or other traditional fuels such as grasses or dung. To understand these, we must look more closely at what happens during the combustion phase of smelting.

Combustion is an oxidation process. That is, oxygen must combine with the carbon, hydrogen and hydrocarbons of which all fuels are made in order for the fuel to burn. In many pyrotechnological processes, such as ceramic production and metallurgy, the atmosphere in which combustion occurs is critical. There are two extremes. We speak of a reducing



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Sixteenth century European woodcut showing the construction of charcoal piles. Plate reproduced from *The Pirotechnia of Vannoccio Biringuccio* (1540) courtesy of Basic Books Inc., 10 East 53rd Street, New York, N.Y.

2
Sixteenth century European woodcut showing charcoal in pits. Plate reproduced from *The Pirotechnia of Vannoccio Biringuccio* (1540) courtesy of Basic Books Inc.

3
Abandoned copper mine in Turan, Iran. Iron-rich gossan caps shallow veins of copper ore. Weathered oxide ore bodies such as this are common arid land mineral formations.

4
Remains of a copper smelting site in Turan. Piles of black, glassy fragments of discarded slag are frequently all that remains of this once active industrial activity.

atmosphere when the oxygen is insufficient for complete combustion to take place: we speak of an oxidizing atmosphere when the draft in a furnace is strong enough to provide more air than necessary for the fuel to burn. The excess oxygen will combine with any other suitable substance it finds, for example the metal being smelted.

Roasting in an open container over a wood fire is an oxidizing process. The aim is to drive off the sulfides or other impurities in the ore and replace them with oxides. However, the problem in smelting is one of reduction. The aim is to remove oxygen from copper-bearing compounds, not add more. In our simple model of copper smelting, closing the draft would create a reducing atmosphere, but it would also probably lower the furnace temperature below the point where smelting takes place. There is, fortunately, an alternative. Instead of closing the draft, a reducing fuel can be used, and that is precisely where charcoal comes in. Unlike wood, charcoal is composed largely of pure carbon, the other elements having been burned off in the charring process. It produces quantities of carbon monoxide gas when burned and creates an oxygen-starved atmosphere.

Coal is also a carbon-rich reducing fuel, and it might seem equally suitable. But besides the hard work involved in coal mining and the distance over which it would need to be transported in many cases, coal contains a number of impurities which are damaging to metals. Although it was occasionally used in Classical antiquity, nowhere did it replace charcoal as a major industrial fuel until a way was found to remove the harmful impurities. This process, called coking, appeared in Europe in the 17th century and had profound implications for the technological and economic development of the western world. (The main impurity in charcoal is ash, which coincidentally has fluxing properties and so is a desirable addition.)

Roasting does not require charcoal, and needs only an open fire. It uses relatively little fuel, because low heat suffices and with certain ores, once begun, the process is self-perpetuating. For smelting metals, including copper, charcoal appears to be the better fuel. However, copper oxides need an atmosphere only slightly reducing to smelt, and undoubtedly wood was sometimes used, though the bulk of the evidence indicates charcoal as first choice. After smelting, copper must again be heated to temperatures of about 1100° C for the molten metal to be cast into a mold. After cooling it may be filed and cold hammered to refine its shape, remove rough edges and to harden it.

In contrast, to smelt iron a strongly reducing atmosphere is absolutely essential and only a carbonized fuel will do. The extraction of iron is, moreover, a two-step process. Iron does not melt at the temperatures obtainable in these early furnaces, and the product is not an ingot of metal but a viscous, spongy mass of iron, slag, and charcoal, called a *bloom*. To remove the iron, the bloom must be taken hot from the furnace and forged on an anvil to squeeze out entrapped slag and charcoal. Such forging may require several heatings, each with charcoal, at temperatures of about 800° C before the iron is ready to be worked into its final shape.

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Map of Iran, showing the location of the charcoal production sites mentioned in the text.

Thus, charcoal was used in Near Eastern metallurgy for two important technological reasons: it is a hotter fuel than wood, and it creates a reducing atmosphere because of its high carbon content. Of course it required time and labor for production, which must be added to the economics of the industry.

Despite its importance in metallurgy, though, and its common recovery at industrial sites, little is known about the production of charcoal in the ancient world. It is clear from the few remarks in Sumerian and Akkadian texts and from later, more detailed Classical treatises, that a great deal was understood about the manufacture of charcoal—that hard woods such as oak or desert shrubs made the best charcoal for smelting, that the wood should be green rather than dead when cut, that different methods of carbonizing yielded different qualities of charcoal. But these sources are tantalizingly incomplete. Near Eastern archaeologists have had to rely on figures drawn from much later periods in the forests of Europe in order to make estimates for such economically and ecologically useful matters as labor requirements for fuel supply, yields of charcoal from cut wood, and methods of production. There are no readily accessible ethnographic descriptions from the Near East, where the same kinds of fuel wood are still being used.

Recently, while doing research on traditional fuels in Iran, I obtained some figures and descriptions that may help remedy this lack. They come from the Iranian Plateau, an arid zone where mining and smelting have a long history, stretching at least as far back as the 5th millennium B.C. and continuing up to the present time. The material is drawn from three sources: a report based in part on observations made near Shiraz (Uhart 1952), a monograph written in Persian on charcoal production in Iran including field observations made near Tabas (Mojtahedi 1955), and a recent reconstruction of rural fuel supply and demand in Tauran, 150 km. south of Sabzevar (Horne 1982).

Charcoal production has been prohibited in Iran since 1966, though the prohibition is not totally effective, especially in the most isolated areas. Before that, and before the distribution system of fossil fuels was set up, enormous quantities of charcoal were needed for domestic and industrial use, from heating samovars to smelting metals. Within the city, charcoal has a number of advantages over firewood. It is smokeless, compact and therefore easy to store and transport. It is competitive in price with wood because transportation costs are lower. More importantly, as we have seen above, for some industrial purposes only charcoal will do. In the hinterlands, where most charcoal production took place, firewood, brushwood and dung were probably always the most important fuels. When charcoal was produced it was for export to the city or for local industries such as metallurgy, rather than for domestic consumption.

In the forested regions of the Caspian and Iran's northern mountains, charcoal was often produced in above-ground stacks or kilns: underground pits were more typical of the plains and slopes of the more arid central plateau. These pits varied in size. In the Shiraz area they were small—1 to 1.5 cubic meters—and produced only 60 kg. of charcoal each. In Tabas they measured up to 10 cubic meters and yielded 500 to 700 kg. of charcoal; those in Tauran were of about the same size. The difference may be tied to the method of transportation. In Shiraz the wood and charcoal were carried on the backs of the workers, who

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Firewood *par excellence.* On the Iranian plateau, wild almond (*Amygdalus eburnea*) made ideal charcoal for metalworking. As a result, it has been eradicated from much of its natural range, as have many other desert species.

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Domestic firewood. In rural areas of the Middle East the daily supply of bread is baked in earthen ovens fueled by fragrant desert shrubs such as sagebrush (*Artemisia herba-alba*) which is being unloaded here.

had no pack animals to help. The charcoal was loaded into 30 kg. sacks and carried to the road, where it was picked up and taken to the city by truck. In Tabas and Tauran, wood and charcoal were moved on camel back; 500 kg. is two or three camel loads. Whether transportation made the difference is only surmise, however; other factors such as the nature of the terrain may have been more important.

Pits were located in relation to stands of wood and brush (and in Shiraz also as near to the road as possible) rather than in relation to settlement. In Shiraz the wood was Persian oak; in Tauran wild almond, pistachio, saxaul, and a woody shrub, *Calligonum*; and in Tabas the same species plus tamarisk, juniper, and another woody shrub, *Zygophyllum*. All these species are hard desert woods that burn with an especially hot flame and had to be cut live to be used for charcoal. They were either roughly chopped down or, if large, pollarded; otherwise they were uprooted with an adze and the roots were added to the pit as well.

The pits were bell-shaped and lined with stone to prevent earth from mixing with the charcoal. The only passage for draft was the mouth of the pit itself. A basic charge at the bottom of the pit was lit so that the fire would spread as the pit was filled, and only a small opening was left for draft until the wood had lit throughout. The top was then sealed to extinguish the flames and allow the charcoal to smolder. When fully carbonized the charcoal was allowed to cool before being removed and

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Copper pots and pans. In spite of the spread of aluminum and enamelled wares, copper ware has still not been replaced for the essential chores of food processing and preparation in large quantities. Shown here: cheese making in a village in Turan.

loaded into sacks to be taken to the city. In Shiraz this was a two man operation. In Tauran and Tabas three or four men may have worked together.

It took one day to dig and line the pit in Shiraz, one day to carbonize the wood and two to extinguish the fire, plus an unspecified amount of time to cut the wood and fill the pit—about five days work for two men from start to finish. However, they apparently worked a series of pits at once, actually producing 60 kg. a day, 30 kg. each.

In Tabas it took six to seven days from loading the charge to removing the charcoal. In Tauran each charge apparently took about five days. Assuming five days for a 500 kg. yield and seven days for 700 kg., and two workers working only one pit at a time, 50 kg. a day might be produced by each person, 30 kg. each by three men and 25 kg. each by four men.

By most ethnographic accounts, charcoal burning in Iran has traditionally been a part-time job, undertaken by poor farmers or herders to supplement their income and enable them to buy tea, sugar, cloth and other supplies from the city. It was also a stop-gap to fall back on when crops or pasture failed, or a worker found himself temporarily unemployed. Men worked alone, which usually meant being away from their families for days or weeks at a time, and for little cash return. The single exception seems to be Azerbaijan (northwestern Iran) where groups of Turks have for many years specialized nearly year-round in charcoal, timber, and firewood production (Uhart 1952 and Robertson 1843).

None of the accounts indicate systematic protection of wood lots or controlled collection until the central government stepped in in the 1960s. Private landowners or tribal groups could of course refuse permission for wood collection on their land though they might not be able to enforce their refusal.

What has been the impact on Iran's environment of all this charcoal production? Descriptions abound of forests destroyed, shrubs uprooted and landscapes bared by fuel cutters, but there have been few attempts to quantify the damage, nor to consider what the effects may have been under less densely populated conditions, or differently organized ones.

Charcoal has a caloric value about double that of air-dried wood. It is this higher caloric value that makes it more compact than wood per calory and easier to store and transport. However, the primitive methods described above do not convert wood to charcoal very efficiently, and what appears to be a caloric gain is in reality a great loss. Uhart's experiments near Shiraz produced a wood to charcoal yield (by weight) of only around 14%. (This figure is considerably lower than the 20 or 30% often cited but based on European data). That is, charcoal has only twice the calories

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A copper tea kettle and ladle from Turan—black from the smoke of wood fires.

of firewood, but destroys perhaps seven times the quantity of vegetation as does an equivalent weight of firewood. Thus, it makes a real difference in terms of environmental pressure which form of fuel is chosen, which a simple caloric comparison does not reveal. However as we saw, there was no real option for early metallurgy. We should look not at comparisons with wood fuel, as one might if assessing domestic fuel use, but at some absolute requirements in metal extraction.

Copper smelting was the first pyrotechnological industry to require charcoal. What was the magnitude of that requirement?

Five kg. of copper, enough for perhaps 20 shaft-hole axes, might be produced in a single smelt in a relatively advanced furnace of the type described at the beginning of this article, and known archaeologically. According to the few estimates available, the charcoal to copper ratio for smelted oxide ores is at least 20 to 1 (based on historic records in Europe) and perhaps as much as 40 to 1 (based on smelting experiments by Tylecote). A five kg. smelt, therefore, would use 100 kg. of charcoal (to be conservative). It would take 3.3 man days of labor to produce (at 30 kg. per man per day) and would use 700 kg. of wood.

If this estimate of 20 to 1 for a charcoal to copper ratio is accurate (and there are only a few studies to substantiate it), then by all accounts iron uses much less charcoal for extraction than copper does. This may come as a surprise in view of our picture of the environmentally destructive consequences of the coming of iron. Nonetheless, a variety of ethnographic and experimental reports indicate that iron requires no more than 10 kg. of charcoal for each kg. of iron produced, counting in both smelting and forging.

The reasons for this difference lie in the production technologies of the two metals. It is true that iron has a higher melting temperature than copper and needs a more reducing atmosphere. We saw, however, that iron is smelted below its melting temperature. Furthermore, copper slag, unlike iron slag, must remain melted during the process in order for the melted copper to pass through and sink to the bottom of the kiln. In these ways copper extraction appears to be the more fuel intensive of the two.

Given a technology for extraction and a utility for the product, iron had the advantage over copper of being far more abundant in the earth's crust. In addition to finding the ore more easily available, did early iron workers find their fuel costs lower? For the time being the question must remain open. It should be remembered, though, that even if in relative terms iron was more economic of fuel than was copper, in absolute terms the iron industry was much more active, and it developed at a time when population densities were greater than they had ever been previously. Iron is less durable and rusts faster than does copper, which can be melted down and reused. And, most significant of all, iron was a democratic metal. Far greater

quantities were produced and distributed than ever had been of copper or bronze.

Thus, fuel needs for metallurgy were high indeed. And of course fuel for this industry is only one of a set of competing demands: vegetation was needed for domestic heating and cooking (perhaps on the order of 1.5 tons per person per year in the rural Near East before the introduction of kerosene), for pasture, for construction, and for other industries such as pottery and brick making.

On the other hand, wood is a renewable resource. If cutting rates are kept low enough that wood stands can regenerate and remain productive, the supply need not deteriorate, although the ecosystem will most certainly be altered. Unfortunately, there are no indications of how wood supplies were managed at Near Eastern smelting sites. However, the total metal production at some sites in the Near East and elsewhere has been estimated from slag deposits, numbers of furnaces, and the quantity of ore mined. With these data some archaeologists and historians have tried to assess the environmental impact from metallurgical activities. Was wood the limiting resource in pre-industrial metallurgy? Opinions differ: for Roman Britain it has been suggested that ores and fuel gave out at about the same rate (Cleere 1976); for 18th and 19th century Scotland that proper management maintained an undiminishing supply (Lindsay 1975); for ancient Israel that periodic destruction of the acacia supply shut down the mines completely, and hundreds of years passed after each abandonment before they could be reopened (Bachmann and Rothenberg 1980).

We have learned a great deal about the chemistry and mechanics of metallurgy as a technology in the ancient Near East and about the distribution of the product in the form of finished artifacts. Now we are at the point where we should also ask questions about the ecological and social contexts of production. More quantified experiments, historic research, ethnographic study and careful reconstructions from archaeological data will help us better understand the role of charcoal and charcoal production in ancient metallurgy, and therefore in the processes of cultural history and change.

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