Richly Detailed Plate From Agricola's Classic "De Re Metallica"

MAN, METALS AND MAGIC:

A WALK ALONG THE METALS ROAD OF ANCIENT METALLURGICAL HISTORY.

Man, Metals and Magic: The Ancient History of Metallurgy

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"The Beginning of Metallurgy"

Chapter I

Over the years, it has often pointed out that man existed for a very long time. While indisputable, that is hardly remarkable because due to lack of experience, man's development came slowly. However, we can take as our starting point, the first Ice Age. About 500,000 years ago, there was a creature on earth that we recognize as being something like a man, which could stand upon his hind legs, and thus was able to use his front limbs for other, more interesting purposes. His physical change resulted in mental development, and as he was obliged to think, his brain grew.

Direct evidence of these primitive man-like creatures is rare. There were probably few of them and their remains were rarely preserved. Anything edible, including bones, was likely eaten by animals that, like the younger generation, had bellies but no palates. Primitive man left more abundant evidence of his development in the implements that he made for himself from flints, which altered in form and improved as the millennia went by.

The idea of making a tool by chipping and shaping a flint must have taken thousands of years to mature, for it involved the animal intelligence that prompts a monkey to throw a coconut, and logical reasoning that allows an end to be achieved by first performing a seemingly unconnected operation. In this case, the aim was to kill, and the intermediate action was to make a weapon. This dawn of thinking -- crude though it was -- marks the beginning of the Stone Age, and the improvements in the way flints were fashioned.

About 100,000 years ago, Piltdown man was once supposed to have existed. Although the scant evidence offered by remains of a creature found in Sussex was later written off as a hoax, the flint implements found in the vicinity indicate advances had been made in working stone. Flints were no longer just crudely chipped, and could be distinguished as tools for specific uses (knives, axes, borers.)

Then came the precursor to Homo sapiens -- the Neanderthal -- so similar to man, as we know him, he might be regarded as human. He made fires, which was an extremely important advance, sheltered him self in caves and was right-handed.

Following the worst of the last Ice Age, approximately 35,000 years ago, Neanderthal man was displaced from his dominant position by another creature – our first ancestor. The Homo sapiens were similar in many respects to the Neanderthal. However, they could talk, were more intelligent, and the skull and digits were very like our own.

The Real History of Mankind Begins

Here, too, is where metals make their appearance, for during the latter part of the Stone Age metals were known and appreciated both for their ornamental and utilitarian value. Gold, silver and copper are the metals that most commonly occur in the native form. That is, they occur *as* metal and not in the usual guise of chemical compound. The most important sources of metals (except gold) do not occur in this convenient way, but as complex minerals whose treatment to yield metal may be intricate and expensive.

Of these three native metals, it is likely that gold was the first to be discovered, for it is the most widely distributed. As it is very resistant to corrosion, the bright surface of a gold nugget would attract the attention of an observant primitive man, and no doubt kindle his disgust when it would not chip or break, as did other stones. However, its appearance was pleasing, and the metal was so ductile that although it was not a first-rate material for armament, it made a pretty ornament and might even be temporarily sharpened into a blade. When the Spanish invaded the American country in the 15^{th} or 16^{th} centuries, the Incas were found to have almost no metallurgical knowledge; yet they used native metals very largely. Incredible as it may seem today, many of their axes and knives were of gold, which they valued much as we value iron – for its utility, not because of its scarce.

But native gold and, more particularly, native silver could not be used a great deal, for their rarity and their softness precluded wide application. Copper, however, was found much more commonly. Although fairly easily corroded, the shining metal surface might be revealed by stream erosion, or by fortuitous inquisitive scrapings. Once discovered, and once some significance had been attached to the discovery, the locality would be searched for more. Whereas the widely distributed metal gold was found as small nuggets or disseminated in quartz rocks, native copper might be discovered as very large masses, probably too big to be moved. A lump of copper hacked off would be beaten and hammered until it became a suitable shape, and during this process it became harder.

This phenomenon of work hardening occurs in all metals but only below a characteristic temperature, which for some metals is somewhat below atmospheric. Fortunately for primitive man, copper hardens at ordinary air temperatures. After hammering, it could be sharpened to make a blade, or pointed to make a spike. By our standards, of course, the metal would still be fairly soft, but it was hard enough for many purposes; and it had the advantage over stone and flint that it was much more easily worked into shape. It is doubtful whether prehistoric copper weapons were hardened by any other process; as far as it is possible to tell, both native copper and smelted copper (which will be described later) were hardened only by this means.

The period was a very long one during which man used stone and metal by manhandling them into shape. In the most civilized localities it ended only about 6500 years ago; in some restricted areas it continued into the last century. As recently as about 550 years ago, there were vast parts of the world where the inhabitants had not been introduced to more advanced techniques. Before the Metal Age began there were two vital discoveries to be made: (1) that metals could be melted and cast to form the impression of a mold, and (2) that metals could be produced from mineral-bearing rocks.

Before we can satisfactorily follow the early history of metals, it will be necessary to define some of the terms that have to be used. Thus, for the moment continuity will be laid aside and we will digress to include some necessary definitions.

Terms Used to Describe the Early History of Metals

A mineral is any metallic compound that occurs in the earth's crust. A fairly broad interpretation, it means virtually anything in the earth's crust that is not vegetable is mineral. If a particular mineral deposit occurs in sufficient abundance to be profitably mined and treated to extract its metallic component, then it is called an ore. The worthless material that somehow or other has to be expelled during the process of extracting the metal from its ore is called "gangue." For example, ironstone may occur as a siliceous deposit of which, say, half is iron compounds and the remaining half are silicates of calcium, magnesium, aluminum (as well as many others) that make up the gangue.

The metal is usually produced from the ore by smelting. Broadly speaking, this involves heating the ore with carbon (as coke) and fluxes to a high temperature, so that the metallic compounds will be reduced to form liquid metal and the fluxes will combine with the gangue to produce a slag. Slag and metal form two distinct liquid layers, and can be separated. Usually the metal is the heavier, lower layer. The nature of the ore and a suitably arranged smelting process allow only the desired metal to be produced, although, of course, fairly heavy contamination may occur.

It may be economic to re-treat the slag to recover any valuable constituents; and it may also be advisable to refine the metal, producing a more marketable product, and perhaps incidentally recovering some valuable metallic impurities. In this way, much of the silver, gold and platinum of the world is produced during the refining of copper.

Having cleared away enough of this undergrowth to see the path once again, we can continue with the affairs of primitive man, who, by dint of groping and floundering, eventually found these things out. There is some doubt whether he first discovered that ores could be smelted to produce metals, or that the native metal he had known so long could be melted. It does seem, however, in light of the metal articles he left behind, that smelting was first known;

and this is not surprising in view of the accidental way in which the discovery must almost certainly have been made.

Copper was the first metal to be extracted from its ores. And the most popular of the current theories of primitive man's discovery is that by pure chance he built his hearth of rocks containing a copper mineral, which was reduced to metal by the charcoal produced in the fire. Now, it is unlikely that such an occurrence would be noticed immediately; and if it were, there is little chance that much significance would have been attached to the phenomenon. But in a copper-rich region it would inevitably happen many times, and eventually some association would be made – it is supposed – between fire and the fused copper produced from rock of a particular kind. In this manner, by the way, lies the strength of the theory, as opposed to rival theories, for it is more than unlikely that a single chance production of metallic copper would have attracted much attention. The pretty story – and it is one of a number – of the Egyptian lady who accidentally dropped her cosmetic, which was made of malachite (copper carbonate), into a charcoal fire and observed its reduction to metallic copper is doubtful on that score alone. What is more, one cannot easily believe that an Egyptian lady so intent on obscuring the work of nature would be so capable of revealing it. The campfire theory seems far more plausible.

The repeated production of copper under these conditions made its mark on the brain of primitive man; metal could be extracted from its ores. Such a happy accident could hardly be responsible for leading him to melt native metal. A man, however primitive, could not be expected to throw his valuable copper weapons or his wife's equally treasured gold ornaments on his campfire, nor be credited with the intelligence of noticing what happened if he did. Most likely he would not repeat the operation so many times that it would make any impression upon him.

Thus far, we have avoided dates and locations -- the former, because of the recognized difficulty of dating prehistoric events, and the latter, because the absence of evidence of metal-workings in certain parts of the world is not conclusive of metallurgical inactivity. There may well have come a time when man was so hard-pressed for materials that he melted and recast his earlier weapons and tools; we do it today, without giving a thought to the difficulties we are making for posterity.

Earliest Copper Workings

The earliest copper workings, which may be dated about 6000 B.C., have been discovered in parts of the Middle East, particularly around Ur in the Fertile Crescent, where like agriculture, it seems likely that the art of metallurgy was first practiced. Here, probably at Sumer in Mesopotamia, the land of Shinar mentioned in Genesis, the first civilized community existed, for the silt deposited from the Tigris and the Euphrates as they entered the Persian Gulf produced a fertile land that attracted the peoples of the northern reaches of the rivers. As more immigrants settled it became necessary to organize a scheme of irrigation, and an agricultural community developed, which, in addition to growing crops could spin, weave and make pottery. It had its wars too; but the weapons were made of stone.

Then came the Great Flood, supposedly about 4000 B.C., destroying all the low-lying farms and villages, exterminating the inhabitants, and laying waste to all that had been built. After the waters had subsided and the face of the ground was dry, the fertile land again attracted inhabitants of the north, who in addition to reviving the agriculture of the Delta introduced new arts. Among these were those of melting and casting copper, silver and gold, and of making copper from its ores.

The ornaments and weapons found during the excavations at Ur imply that the casting of metal had begun about 3500 B.C. And it seems that in this locality there was an interval of about 2000 years between the first crudely hammered metal article and the earliest cast one. Remains of primitive copper workings have been found at the sites of other early civilizations – in the Nile valley in Egypt; and at Mohenjo-daro, which appears to have been the center of an early Indian culture at Sind. A complete survey of this subject would fill several books, but there seems to be no evidence to suggest that in any of these places metallurgy was more advanced than in Sumer. The general progress of the art of producing and using metals followed much the same sequence. It is only the speed of the advance and the time over which each state of development lasted that differed very greatly.

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"4000 B.C. – 1400 B.C."

Chapter II

The Chinese, who are credited with so many proverbs, are said to have the adage that "the *shortest step may be the beginning of the longest journey*." It was the smallest conceivable advance that led primitive man to make a shallow cavity in the hearth of his fire to collect the metal he had learned to make. And it was a long eventful journey through the ages to the mid-twentieth century when furnaces were smelting 2000 tons of charge each twenty-four hours. A long eventful journey, it is also a fascinating one, full of incident. However, as our object is to outline a history of metallurgy, indicating where it has influenced and been influenced by contemporary events, we will follow a metal path so as to resist the temptation of turning aside and getting lost in the bush.

Metallurgical progress is outlined by the early manufacture of bronzes in the East; the vast, and unfortunate, impetus that the Roman occupation had upon mining; alchemy; the significance of iron making in the Middle Ages; the revival of industry in the 16th and 17th centuries; the metal production of America leading to a world supremacy; steel making and the machine age; and the development of metallurgical science.

The relationship between metallurgical development and our civilization is, of course, an inevitable one, but it is not always possible to differentiate between cause and effect. Clearly, in the very beginning, the discovery of copper led to the use of the metal for implements, and it was not a demand for copper that inspired its discovery. At the other extreme, it was the need for specific engineering materials that often led to the search and the invention of suitable alloys, which were not previously known, and only later applied.

In early times the discovery usually suggested a use, much as a child who finds an empty box will think of something to do with it. In more recent times the demand is prior. Once it is made, sooner or later it will be met – much as a child will demand a model railroad, and, if he makes himself a big enough nuisance, will probably get it. After one demand has been satisfied, more applications may well be found, modifications made, and so on. The child who found the empty box may kick it around the house, or make something of it; the one who has been given a model railroad may stamp on it, or alternatively demand a bigger one. So it is with practical discoveries. They may be used or abused, left idle or developed. Progress has been made by the alternate surging of invention and necessity; a game of scientific cat and utilitarian mouse.

At an early stage in this game, man made a shallow trough at the bottom of his campfire hearth, collected the metal there, and then beat it into shape. Gradually he developed this trough into a primitive furnace by digging a small hole and purposefully smelting metal in it by charging layers of charcoal and copper ore on a charcoal fire burning at the bottom. The hearth was made on the side of a hill. A stonewall was then built around the hearth to extend it upward. The wind, thus encouraged the fire, and the charge melted more rapidly. Any slag and unburnt charcoal were raked off and the metal cooled after all the ore was reduced. As soon as it had become solid, the copper cake was pulled out and broken up while still hot and brittle, and the pieces of copper were hammered to make suitable implements.

Analyses of such prehistoric copper show a complete absence of sulphur, indicating the use of oxidized ores or native metal. This is what one would expect, since the oxidized ores of copper occur at, or near, the surface and are the most readily available.

These advances led only to a more thorough exploitation of the natural resources of metal. Smelted copper was used in much the same way as native metal had been. Presumably, it was not long before the idea of casting was born. It became apparent that the lower surface of the metal cake assumed the shape of the hearth. By making the hole with suitable contours, it became possible to reduce the amount of work needed to chip and hammer the metal into shape. Simple forms like axes and blades could be cast, but they were limited in value, as their upper surfaces were bound to be flat. Then castings were made in simple impressions cut into rock or pressed into clay. Before long, hollow molds were made of two pieces of stone held together so that a casting could be made that was shaped on all sides. Simultaneously, improvements were made in the smelting process. The hearth became bigger and relied more upon wind to stimulate the process that went on within it and certainly before 1500 B.C. bellows were introduced to produce a direct blast. The crude copper was refined through re-melting it in a deep, clay-lined hearth. The clinker and dirt that rose to the surface of the liquid metal were skimmed off, leaving a cleaner, purer material. Eventually, clay crucibles were made that dropped into the hearth. They could be lifted out so that metal might be poured into molds. Before the idea of a crucible was known, it is not known just how molten metal was transferred from hearth to mold. Presumably, a hot stone ladle or suitably cut channel was used.

In spite of this progress, stone implements were still widely used because copper is a soft metal and prehistoric man needed a harder, stronger metal. In some localities he was lucky enough to produce one owing to the nature of the ores he used. In these favored places the ores contained minerals in addition to those of copper, which were simultaneously reduced during the smelting process. Notable among these was cassiterite (tin oxide). Consequently, by accident rather than intention, an alloy of copper and tin was produced, rich in copper and something like the material we now know as bronze.

Its advantages were appreciated – it was harder and would more readily work harden than copper and, it was a better metal to cast, producing a sounder casting with a more faithful impression. Over time, it was realized that smelting together copper tin ores from different localities could make the alloy. For a long while, however, it was a mystery as to why the “copper” that was made in this way was so superior. It was only later that man learned to make bronze by melting metallic tin and copper together. As the proportion of tin in a bronze is quite critical (to give adequate properties for various purposes there should be between 1 and 10% of tin) the prehistoric production of bronze must have been a chancy business. While we can get some idea of the extent of bronze culture by the number of tools, ornaments and weapons that have been left behind on various sites, there is no indication of the vast number that must have been made, discarded and remelted; the same mystery surrounds many contemporary foundries. Tin ores, however, are not nearly so widely distributed as copper ores. Therefore, in some places the Copper Age was a prolonged one, and stone implements were used throughout most of it.

The Bronze Age

The bronze culture of Egypt was comparatively slow in developing, as the Egyptians' source of copper was the Sinai Peninsula, where tin did not occur. On the other hand, the use of bronze in Sumer began much earlier. In some areas the Bronze Age began so late as to be almost non-existent, for as a result of the knowledge brought by invaders or immigrants, the use of iron soon followed that of copper. This was so in Peru, where bronze was only just beginning to be made in the 16^{th} century when the Spaniards arrived. In North America iron follows copper without any Bronze Age supervening.

The opening of the Bronze Age in the Ancient World not only represented the first production of a truly useful metal. Because of the comparative scarcity of sources of tin, it led to trading. The inhabitants of the second city of Hissarlik (the site of Troy) learned the art of bronze making about 2000 B.C. and discovered, too, that copper and tin could be obtained from Central Europe. Egypt, without tin and, therefore, without bronze, traded with Hissarlik and Crete. Further, about this time, bronze implements – probably from Hissarlik – reached Portugal and Spain. Soon afterward knowledge of the alloy spread along the coast of Western Europe to Great Britain.

About 1900 B.C. Hissarlik was burned down and its' commerce necessarily ended. Consequently, Cretan trade assumed greater importance. Much of this trade was with Egypt, which, however, about 1800 B.C. suffered a series of political misfortunes and eventually dropped out of the picture. As an outlet for their merchandise the Cretans were forced to find markets in Sicily, Spain and southern Italy – a process that ended with the exhaustion of their available tin. This was a fate that in turn was to come to many countries.

By this time, however, the Middle Europeans and the Spaniards had learned how to make bronze, and the cessation of supplies from the East acted as a stimulus to native industry.

Because of Spanish manufacture, more bronze implements found their way into Britain, via the coast of France. But very soon the Spanish ores temporarily came to an end, for in those days only the most accessible deposits could be used, and hidden ore bodies were neither discovered nor exploited. Of necessity the Bronze Age began in Britain.

Another dissemination of bronze culture was brought about by the drought about 1600 B.C. that compelled the inhabitants of Turkestan, that country to the east of the Caspian Sea, to migrate to Mesopotamia and Egypt, and also to parts of Europe, India and possibly China. They had learned to make and use metals. Their domestication of the horse also gave them a superiority, which enabled them to form powerful settlements or dominate communities whose ways were more primitive.

The purpose of this brief account is to show how the advent of the Bronze Age increased the tempo of man's life. Before it, trading was almost unknown; exploration was inspired only by the fertility of the land, and by the animal instincts that prompted battle. Then, in a comparatively short space of time, the world was no longer so obviously divided into East and West. By about 1800 B.C. there were centers of bronze making dispersed over much of the known world.

The beginning of the Bronze Age in China is less clearly defined. Most surely it does not date so far back as the Sumerian bronze Age, for the earliest Chinese civilizations were in the valley of the Yellow River, where there were no obvious mineral deposits and the community was essentially an agricultural one.

The oldest Chinese bronze objects are supposed to date from about 2200 B.C. and about that time, metal mining began. If one accepts a traditional Chinese belief that the knowledge of bronze came to China from the West, this date is not an improbable one, for in Sumer bronze was known as early as 3000 B.C. The fact that there is little or no evidence of trading may be accounted for by the early exhaustion of raw materials in Sumer. The art of bronze making may have spread to China from this source, and the Chinese may well have been taught to find and use their mineral deposits. One must, presumably, believe either that this is possible or that Chinese metallurgy does not date back so far as 2200 B.C.

Although the Egyptians made a late start in the manufacture of bronze, their technique of casting soon became well advanced. Further, when they first dominated Syria soon after 1400 B.C. sources of tin were made available, and castings in bronze became much more common. No attempt will be made here to give even the barest outline of subsequent events in Syria, Egypt and Sumer (which by this time was part of the Babylonian Empire), for these are as involved as 20th century European history. Simply bear in mind that by 1400 B.C. bronze was made throughout most of the Ancient World, as well as in parts of Europe and China.

In all probability the Egyptians were responsible for the introduction of the *cire perdu*, or "lost wax," method of casting, which allowed metal articles to be made in exact replica of a model. Essentially, the process involved then, as it still does, making a solid model in wax to be covered with clay. Heating it hardens the clay and the wax is melted out, leaving a clay mold the exact negative of the model. Molten metal is then poured in, and allowed to solidify before the mold is broken away to allow the bronze casting to be removed. If a hollow casting was needed, then a core was fashioned roughly the same shape as the object to be made, and was coated with wax, which was molded exactly to shape. The clay mold was made over this, the core fastened to it by thin supports, and the wax melted out. Then metal was poured into the space that the wax occupied to produce a hollow replica. It is vital that the core should be firmly held, and the way in which the Egyptians did this is not known with any certainty. In later years iron struts were used, but this method is not very probable before about 1400 B.C. Bronze or copper struts would probably have been melted by the metal poured around them, and it is not very easy to imagine stone being used. However, this argument involves a bone of contention that will be gnawed later.

One of the earliest examples of "lost wax" casting is the statue of Pepi I and his son, dated about 2600 B.C. It is made of hollow copper or bronze, and the reproduction of detail illustrates how the Egyptians were masters of the art of casting at this early state.

The danger that metal might solidify before it had filled the mold was appreciated by the Egyptians who prevent this by allowing the metal to run by more than one entry, and also by heating the mold. Intricate castings, which could not be made in one piece, were fashioned in sections that were joined together by a mortise joint or by a bronze pin, and these devices show a remarkable facility.

The man who could make metals was, as one would expect, a powerful and important figure. His power sometimes led to his being worshipped. Alternatively, he might have been hated. In some tribes, apparently to call a man "a smith" was an extreme form of abusive language. Not surprisingly the metal-makers' craft was associated with magic and wizardry. Perhaps that is how the name "blacksmith" came about. After all, if a man could turn a piece of hard, dull rock into soft, bright metal, he was certainly one to be held in respect, or fear. Consequently, the smith's hammer was a sign of power, and an oath taken over his anvil could never be broken.

Further, the smith was supposed to be able to foretell the future by looking at the molten slags in his furnace. Of course, the contemporary metallurgist should be able to foretell the *immediate* future by looking at his slags – he may even foretell the value of some industrial stocks – but the old smith's abilities went further than that. It is, perhaps, a pity that 20th century metallurgy has lost its supernatural associations. The most we can do in this sort of respect is to fool our admirers with thermo dynamic jiggery-pokery. And then we are all too often found out!

The uses to which copper and bronze articles were put during the period 3000 to 1400 B.C. should be considered cautiously. Today, we use aluminum for aircraft, but in 100 years time we may not. It is not very likely that aluminum planes will be left to slowly corrode away on garbage dumps. Consequently, the archeologist of 6000 A.D. may have no clue of what was once a valuable usage of aluminum. He may, however, discover an aluminum hot-water bottle discarded by English settlers and buried in an ancient rubbish dump, or some relics of an aluminum bottle opener. If he were hasty in drawing conclusions, he might say that the people of 2004 A.D. used aluminum mainly for hot water bottles and bottle openers.

It appears that the communities in the Ancient World, which practiced the art of metallurgy used bronze and copper for ornaments and weapons. This does preclude the possibility of more extensive uses. The greatest sources of bronze relics of this period lay in the tombs and temples of the rulers of the East, where ornaments and weapons were placed at the side of the dead to help them on their journey. Other remains have, of course, been found. But they are more rare and so we may get a distorted impression of the variety of purposes to which bronze was put. Yet, owing to limited resources and primitive methods, it is quite possible that bronze was not much more widely used until a later date, when it served for coins and a variety of household pots and pans, as well as for weapons.

Although until 1400 B.C. bronze and copper were used for the purposes that man's imagination and craftsmanship allowed, other metals were known too. They have been given no place in this account because bronze was by far the most important, both for its utility and because it opened up world trading, and the age is properly called a Bronze Age.

However, as already pointed out, gold and silver were known before the discovery of copper and, with the advent of melting and casting practices these metals were used more extensively for ornamental purposes.

In nature, silver often occurs with lead, whose sulphide mineral (galena) is bright and lustrous. Possibly then, mineral lead was noticed as early as silver. Evidence seems to indicate, however, that the metal was not made use of until a later period. Shapeless lumps of lead have been found at the site of Hissarlik, at a level dated about 3000 B.C. while an equally old lead relic in the form of a figure was found in the temple of Osiris at Abydos on the banks of the Nile. The metal, even though it may have been known in restricted localities, was certainly not appreciated for there is no evidence of a spread of "lead-culture."

One cannot be certain whether the metal was smelted or found native, for although lead does not normally occur in its metallic state, it is conceivable that it might have been produced by an accidental fire and discovered later. If, however, the lead objects of this period were smelted purposefully by man, it is difficult to explain why there are so few of them and why the value of lead was not exploited. Exploitation came much later. Although in 1400-1200 B.C., it was possibly used for coins of some sort, it was not until about 500 B.C. that its uses became at all extensive. Our arbitrarily chosen limit of 1400 B.C. up to which date events of metallurgical interests have been outlined, is of significance real, or false, depending upon which side of the fence one stands. One side of the fence thinks iron was first produced at this time. The other side of the fence will dispute the choice of 1400 B.C. An accurate estimate seems to have defeated the archeologists, but for the purposes here, 1400 B.C. is as good as any.

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"1400 B.C. - 500 B.C."

Chapter III

Iron – ***"the most deadly fruit of human ingenuity"***

By 1400 B.C. the arts of metallurgy, pottery and agriculture were well advanced compared with scientific knowledge. It was generally believed, for example, that the earth was rectangular and the sky held up by mountain peaks; that the stars hung by ropes from the sky, and the sun floated round the earth on a never ending river cruise. And, widening the discrepancy between the lack of understanding of the natural sciences and the advanced state of metal culture, iron began to assume an ever-growing importance – iron, "the most deadly fruit of human ingenuity." But even before 1400 B.C. its use had not been entirely precluded by any lack of "human ingenuity," because some remains of iron date as far back as 4000 B.C. For, although iron may not have been smelted until much later, and although it does not occur native like gold and copper, primitive man was provided with small amounts of iron from other than terrestrial sources.

Despite several recorded falls of celestial iron – meteorites – throughout the ages, many scientists until the 19th century were rather embarrassed and ashamed to have to admit the possibility. Then in 1803, there was an obligingly spectacular downfall of meteorites in Normandy, which was sufficiently uncompromising to convince most of the doubters. So, although there is no truly native iron produced on earth, pieces of the metal have been hurled at us and may have been discovered by primitive man.

The presumption that primitive peoples used meteoric iron as a rare and valuable material is substantiated by an analysis of their metals. While archeologists, understandably, do not encourage metallurgical analysis of their finds, early irons that have been investigated show a high nickel content, which is peculiar to meteoric irons and is not a characteristic of iron made directly from ores found in the earth's crust. This high nickel content also goes a long way toward explaining the good state of preservation of most of these old articles – an effect of the presence of nickel, which was profitably rediscovered thousands of years later. Such iron could be hammered and worked just like native gold and copper, and it became harder than either of these. But it was much more highly prized, largely on account of its rarity and because it was more obviously "heaven-sent" than other metals.

In support of the idea that early iron was meteoric in origin it may be pointed out that religious and other ancient writings frequently associate iron with the heavens. Further, later developing civilizations, when explorers from more advanced civilizations first discovered them, were reported to know and use meteoric iron. The inhabitants of South America, for example, had not learned how to smelt iron when the Spanish subjugated them, but they made some implements from the iron of meteorites. And the Eskimos relied upon meteoric iron until as late as the 18th century, when European trade provided them with the smelted material.

On the other hand, it is argued that as iron ores occur very widely, and since the metal is easy to produce from them, it is likely that iron smelting began as soon as copper smelting, or perhaps before. But the smelting of iron is really not so simple. Or at any rate, although it may seem to be today, it would most certainly not have been to primitive man, for a temperature far higher than that achieved in his crude hearth is necessary to make iron that looks anything like a metal.

When the simple smelting process as it has been described is applied to iron, it yields only a spongy material without any metallic properties or obvious use. It is quite possible that, like copper, iron was produced accidentally many times in the campfire, but, as it completely lacks luster, it may have gone unnoticed repeatedly. To transform it into a useful metal it is necessary to forge it. That is, the spongy lump has to be hammered and reheated alternately until most of the slag associated with it has been squeezed out. This produces wrought iron, a material, which until the introduction of cheap steel in the 1870s A.D. was of first-rate importance, and today still has valuable, but limited, applications. But it is difficult to imagine so elaborate a process being conceived or practiced as early as 400-300 B.C., and irons which pre-date 1400 B.C. do not exhibit the structure that is characteristic of wrought iron. On the contrary, their analysis implies a meteoric origin. However, comparatively few prehistoric irons of this antiquity have been examined so the second argument has less force than it might have.

Another argument that has been put forward in support of early iron smelting is that much of the stone masonry of pre-1400 B.C. could hardly have been achieved with copper or even bronze tools. If one answers the exponents of this point of view by suggesting that primitive man was more patient than we are, and that, although the process would be tedious, it would not be impossible to carve stone with bronze chisels, they reply most defiantly: “Try it.” It is doubtful, too, whether meteoric iron occurred in such profusion as to allow its use for such a commonplace purpose as a carving stone. Another argument is that the only answer (an unsatisfactory and dangerous one) is that these early people had very much more patience, and perhaps a little more ingenuity than that with which we credit them. Of course, if we allow them enough ingenuity to carve stone in a way we cannot image now, more than 6000 years afterwards, perhaps we should credit them with sufficient inventiveness to smelt iron.

The fact that the few remaining iron implements that antedated 1400 B.C. are of a composition that implies meteoric origin does not allow any conclusions to be drawn on this subject, for ordinary man-made wrought iron -- except under the most artificial conditions even more preservative than the static dry atmospheres of Egyptian tombs – would rust away in a comparatively short time.

However, even if one insists that iron was made as long ago as 4000 B.C. it is not until about 1400 B.C. that its use begins to assume importance, and for that reason alone, it seems quite justifiable to suggest that this date marks the beginning of the Iron Age.

Probably the earliest known man-made iron article is a dagger blade found in the tomb of Tutankhamen, which was placed in such a position as implies that it was a most treasured possession. The dagger dates from 1350 B.C., while only 50 years afterwards there is the first known recorded reference to man-made iron. The reference is in a letter written a little after 1300 B.C. by the King of the Hittites, and is of a “sorry-for-the-delay” type, of which he may have been the originator. He wrote to the Egyptian Pharaoh, Rameses II . . . “*there is no good iron in the house of my seal at Kissuwadna, for it is a bad time to make iron. I have written ordering them to make good iron, but so far they have not finished it. When they do, I will send it to thee. Behold! Now I am sending thee an iron dagger blade!*”

The letter from the King of the Hittites is said to indicate that while iron was probably in very short supply, and that the art was confined to limited areas, differences in material quality were already appreciated. It seems more probable, however, in view of the unsettled relations between the Hittites and the Egyptians, that the reference to “a bad time to make iron” was simply a political excuse. Only later civilizations have been sufficiently sporting to provide their enemies with arms.

To those of us who have no more than a general acquaintance with the affairs of the Ancient World, the origins of iron making seem to be wrapped in an almost impenetrable obscurity. The Hittites, between 1500 B.C. and 1400 B.C. were becoming increasingly powerful, due largely to their early knowledge of iron. Whether they discovered or only learned the art of iron making at second hand is questionable. It has been supposed for a long time that the art originated somewhere in the mountainous country to the south of the Black Sea, and this is substantiated by the fact that suitable iron ores are found there. A study of the nature of the remains of early iron objects has indicated that appropriate ores were available in the foothills of the mountains to the southeast of the Black Sea, which was dominated by the Hittites. Further, this belief is supported by legend, and together they indicate that iron was first made in the valley of the River Halys, which flows from the mountains to the Black Sea.

The Hittites traded their metal to the Palestinians, for implements have been discovered in Gerar, which are believed to date from about 1350 B.C. Within a hundred years or so, the art of iron making had been either learned or discovered in Palestine. Furnaces dating to 1200 B.C. have been unearthed at Gerar, together with iron objects that were made there.

We can summarize by asserting that iron was first made in the north of the Ancient World – a belief that is not without its romance, for copper smelting was introduced into Mesopotamia by settlers from the north. No one knows where these settlers came from, and no one is positively certain where iron was first smelted, nor can the position be contradicted that both originated somewhere in that mountainous country between the Mediterranean and Caspian Seas.

The way in which these old metallurgists made their iron can only be surmised from the type of metal they produced, and from the methods used by later primitive peoples whose techniques are more adequately recorded in history. In all probability they had discovered the value of building a deeper hearth, either by digging a larger hole or by making a cylindrical clay wall around an existing hearth, and so produced a higher temperature and more metal. Charcoal and ironstone were charged on a lighted fire, and a draft was induced by bellows, which blew air through clay tubes inserted near the bottom of the charge. After many hours had elapsed, during which more charcoal may have been added, the furnace was cooled sufficiently for the spongy metal to be removed -- dirty, unmetallic in appearance and contaminated with clinker and gangue. Therefore, only the cleaner portions were selected, and forged by alternately heating and hammering them. One can only presume that, in the very earliest days of iron making, the hot metal would be handled with green wood tongs or stones, and hammered with a heavy stone. In doing this, adherent impurities would detach themselves and the pockets of earthy slag would be strung out. This improved the mechanical properties enormously, for while a lump of slag produces a region of weakness and consequently results in easy fracture, strings of slag do not cause such a local rift in the metallic structure. Further, the forging operation reduced the sponginess of the metal, and after sufficient working, the iron could be hammered while still hot into suitable shapes.

The operation of forging, then, necessitated heating and reheating the iron in a charcoal fire – a process that inevitably resulted in the outside of the metal absorbing carbon. When one is first confronted with the fact that a hot, but solid, element may take into its structure a second element, the concept can be difficult to accept. But solid diffusion of this kind does indeed occur. In fact, it plays a crucial part in all aspects of metallurgy, including heat treatment of modern steels, when carbon atoms diffuse to produce one of many characteristic structures, when oxide ore is reduced in the blast furnace to metal before the charge becomes molten. Then, in the production of the duralumin types of alloys, it is a diffusion of atoms of a number of elements within the metal that produces the effect of "age-hardening" and, consequently, the vital properties of the alloy.

The classic experiment, which illustrated solid diffusion, involved clamping together a flat surface of gold and copper. After many years had elapsed, analysis showed that the copper had become contaminated with gold and *vice versa.* Heating a metal weakens the bonds that hold its atoms together, and so diffusion is quicker at higher temperatures. Yet, although the effects of diffusion are well known, its mechanism is not always clear, and a complete understanding would probably solve many problems that confront the metallurgist today.

But, to return to 1200 B.C., or thereabouts, it was inevitable that carbon should be taken into the outside of the forged iron. Now steel is essentially an alloy of iron with up to about 1.5% of carbon. As this is the kind of material that was produced at the surface of forged iron, it is often suggested that as early as 1200 B.C. steel was being made. This is a misleading and almost improper suggestion, for steelmaking involves the production of a uniform, homogeneous material, which this certainly was not.

The old iron maker was in effect inadvertently case hardening his iron in a way that is very similar to modern case hardening processes for steel. But to suggest that he was *making steel* would be as incorrect as to assert that the baby thrashing the piano next door is making music. What is more, he did not at first realize that it was heat rather than the hammer causing the hardening. It was not until 3000 years later that the part carbon played in the operation was appreciated. But whether the process was understood is of minor importance. The fact of over-riding importance is that at last man had at his disposal a powerful material whose potential uses were almost without limit, as future years were to show.

Within a few centuries it was discovered that quenching carburized iron made it considerably harder still. This knowledge was later used to advantage by the Greeks and the

Romans. The inferiority of wrought iron weapons was shown as late as 220 B.C. when, in a battle between the Romans and the Gauls of Insubres during the early part of the Roman conquest, the Gallic swords of iron bent so easily that they had to be straightened after the first thrust. The Romans took advantage of this, and after taking the first thrust on their spears and armor, they attacked and beat the Gauls who were bent on straightening their weapons.

The discoveries made in Gerar (Palestine) show by their variety that iron was beginning to have its first real uses. Just as bronze replaced stone, so did iron begin to replace bronze, and further, many additional uses were gradually found for the metal. At Gerar site knives, hoes, sickles and other agricultural tools were discovered, and no doubt the Palestinians were well pleased with their new metal. But it could not be cast, and production of molten iron, except perhaps accidentally, did not begin until more than 2000 years had passed.

While the Hittites were exploiting their knowledge of iron making, both in trading and in waging war, the use of bronze spread through Europe as far as the Baltic. Progress in European bronze culture is shown by developments in the designs of axes and swords. The Baltic countries, in the 12th century B.C. produced gold and bronze of exceptional quality and became wealthy lands. They traded with other parts of Europe, but presumably had no need of overseas markets. After the never-very-extensive bronze importations from Span ended, Britain made more use of her own tin deposits in Cornwall. Ireland, which had no tin, traded in its' gold and regular trade between Britain and Ireland opened up.

In an account of this kind, leaps must be made either in space or in time, depending upon the review being geographical or chronological. So, jumping across to the Middle East again, we find the Hittites suppressed. History shows repeatedly that it is a country's own power, which so often results in its destruction, for power breeds enemies. The Hittite empire in Asia Minor was no exception, for in 1200 B.C. it was destroyed. Egypt, which was weakened after its spectacular building enterprises under Rameses II, was in the power of a priesthood that, whatever effect it had upon the country's morals, had a detrimental one on its metallurgical progress. The whole of the Middle East, which up to this time had led the world, was in a state of turmoil.

As a result, China, the Baltic States and Europe began to catch up culturally, while the rest of the civilized world marked time. Iron made a cautious entry into parts of Europe and the Baltic and its use slowly began to supersede that of bronze. In China, the renowned Chow Dynasty had begun, and while iron was not introduced, as far as one knows, for another 400 years, the Chinese civilization temporarily prospered and the most beautiful bronzes were made for domestic use.

For purposes of this account, only historical events that bear upon metallurgical development will be included. Thus, the next few hundred years can be skimmed over lightly, for we have seen already that the use of bronze spread over most of the then known world, and that by 1000 B.C. iron was beginning to be known. As future years showed no comparable achievements, they will be dealt with only briefly.

The early Iron Age in Central Europe is usually divided into two convenient phases. The first, the Hallstatt Period, is named after the center of the salt industry that existed at Hallstatt, Austria. Because the salt industry was important in an essentially agricultural community, the spread of culture quite naturally developed around it. Evidence of this was found in 1846 A.D. when a prehistoric cemetery was unearthed, with its earlier bronze weapons and later iron axes and swords. Hallstatt culture penetrated into many parts of Central Europe sooner or later and spread northwestward. The period ended in Central Europe about 400 B.C. when Hallstatt was no longer the focus of development and industry, and the second phase began. The La Tene phase was not marked by any striking metallurgical advance, but rather by a characteristic difference in style. In France the use of iron followed later, and in Britain later still. Even so, iron making was fairly widespread at the time of the Roman landings in Britain in 55 B.C.

Turning eastward again, there were some significant changes. Brass (an alloy of copper and zinc) was discovered, presumably accidentally, at some time during the period under review. The exact date of the first brass to be made, like its location, seems to escape accurate definition. Dates from 1600 B.C. to 600 B.C. are cited. Persia, China and Palestine are most commonly accorded the honor of being its birthplace. The discovery of brass must have been as fortuitous as that of bronze, for zinc ores when smelted alone produce zinc vapor, which becomes oxidized. The product is not a metal, but a scattered white powder. When, however, zinc ores and copper are smelted together the copper, producing the alloy brass, absorbs the zinc vapor. It was probably under these circumstances that the early articles were made. Perhaps its' value was not appreciated, or the method by which it was made could not be repeated, for there is no indication that the alloy was used much or even known, apart from a few instances, until the time of the Roman Empire, when brass currency was introduced.

Roman currency was not, however, the earliest system. The first reliable one evolved in Lydia, in the Aegean, where a standard alloy of gold and silver (electrum) was used and stamped, in about 700 B.C. This encouraged the trading that had already become well established in the Aegean region, where the valuable line of harbors in Phoenicia assumed great importance in the centuries subsequent to the downfall of the Hittites.

Phoenicia was a powerful country, and from the 12th century B.C. the Phoenicians and later their successors, the Carthaginians, controlled the mines in Spain until the time of Roman domination. They traded with Britain, and it is very possible that they bartered for Cornish tin ores, which like their mineral deposits in Spain were to be governed by the Romans. That the Phoenicians traded with Britain for tin ores is controversial. They, as had others before them, obtained tin from what Herodotus in the 5th century B.C. was the first to call the Cassiterides, or tin islands. The whereabouts of these islands is not at all certain. The matter is confused by the fact that the Phoenicians endeavored to mislead the Romans as to their source of metal. Hence, Roman records on the subject are not reliable and there is little other evidence of the routes that were followed or the subsequent destination. It seems possible that the Cassiterides were, in fact, Cornwall. While Cornwall is not an island, geographers of that period had a carefree recklessness not found among cartographers today. It is also possible that adjacent islands (now the Scilly Isles) were included among the Cassiterides, although they would probably yield little ore.

It should also be recorded in this period that China began to make her own iron about 700 B.C. Her increased resourcefulness had little effect until 500 years later when the Chinese Empire dominated the East as the Roman Empire dominated the West. Meanwhile, however, in Greece, after the defeat of the Persons in 500 B.C. there came the welcome beginnings of scientific thought.

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Man, Metals and Magic: The Ancient History of Metallurgy

"500 B.C. - 500 A.D."

Chapter IV

Ancient Greece was not a nation in the modern sense, but was composed of a number of city-states, some of which possessed several external colonies. Neither the geography of Greece nor the temperament of its peoples encouraged national unity, nor perhaps was the time sufficiently advanced for it. The mountains and the sea provided natural obstacles between scattered communities, and the independence of the Greek showed itself in his desire to rule his own city rather than to elect some one else to govern his own country. Athens, Sparta and Corinth are perhaps the most familiar names among the city-states. Colonies existed along the north coast of the Black Sea, in southern Italy, and along a vast stretch of the North African coast between Egypt and Carthage.

Silver Mines and Ships

It was this Greece that the Persians sought to subjugate in a great empire building campaign. Under Darius I their territory included Egypt, Asia Minor and Syria in the west, and stretched eastward as far as India. Then in 490 B.C. after the Persian fleet had conquered islands in the Aegean, the Persian armies landed in Attica where, at the battle of Marathon, the Athenians defeated them. Nevertheless, Athens was still threatened and the Persian fleet, although it had sailed out of Aegean waters, remained a serious menace. Themistocles, a Greek statesman, had for many years insisted that without adequate sea power Athens could not be safe from attack. At last his persuasive arguments were heard. But the enterprising shipbuilding program he suggested needed vast financial resources. Fortunately, it was at this time that a rich vein of silver was struck in the mines at Laurium, near Athens. The ore was mined and the silver extracted and sold, and ships were built. In 480 B.C. they fought and destroyed the Persian fleet in the Bay of Salamis. Athens was no longer in danger, and many Greek cities that had previously been conquered were liberated. But without Themistocles wisdom and without the silver mines at Laurium, the story of Greece might have been a very different one.

The mines, leased to citizens by the state, were worked in a way that shows considerable technical development from the primitive scrapings of 1000 years earlier. In the mines at Laurium, shafts were sunk to depths of nearly 400 feet, and cutting steps in sloping shafts gave access to the underground workings. While fires helped ventilation, conditions were severe so slave labor was used. The slaves were usually prisoners of war – frequently inhabitants of conquered Greek cities – who were freely bought and sold in the slave market. But the conditions that were imposed upon them, although unpleasant enough, were generally not so horrible as they were under later Roman rule. A slave might, for instance, be directed into a business house, eventually acquire property, be set free, or even be the beneficiary under his master's will. In the mines, however, such liberties were not common. Chains and brands were often the fate of these unfortunate people, whose lives were made more awful by the poisonous atmosphere that was produced at the mine surface by roasting the sulphide ore there preparatory to smelting it.

By the light of oil lamps, the slaves hacked with iron hammers for long shifts and their produce was carried in sacks to the surface. There it was hand-sorted and crushed in crude mills or mortars. The crushed ore was then subjected to a stream of water, which carried away the light, sandy material and left the valuable mineral to be roasted and smelted to produce a lead-silver alloy. This process of concentrating the mineral has remained in principle unchanged. So, too, has the method used by the Athenians in extracting silver from the lead by a process of "cupellation."

This involved heating the molten alloy in a shallow clay basin, known as a cupel, and blowing air over the surface. Lead oxidizes preferentially to silver and so lead oxide was produced, which was removed from the surface of the melt, while a proportion was also absorbed in the material of the cupel. After sufficient oxidation, only pure metallic silver remained in the basin. The separated oxide and discarded cupels were heated with charcoal to recover the lead. In more modern times, the process used remains much the same, except that it is made more efficient by a preliminary process that effects a concentration of the silver by simpler means. Cupellation is the same; it is only the conditions under which it is used that have altered. If gold occurred with the silver and lead in the original alloy, the cupellation process produced the gold-silver alloy, electrum. When it became possible to separate gold and silver is high controversial, but it was certainly before the Christian era, and may have been as early as 300 B.C.

The rich resources of the mines allowed the introduction of silver coinage at Athens, and this uniform currency together with the power of the Athenian fleet, brought Athens into a predominant position in trading with the rest of Greece and Asia Minor. The Athenian silver mines played an important part in history.

The Greeks were also capable iron makers. While the Egyptians knew the hardness conferred upon a carburized iron by plunging it hot into water, it is believed that by 400 B.C., the Greeks had learned that a subsequent tempering operation -- involving heating the metal to a fairly low temperature -- relieved it of its brittleness. Iron heads to lances and arrows, scythes, sickles, chain links, files, chisels, swords, razors – all these in iron (and what many would call steel) were made by the Greeks. Archimedes is said to have constructed a ship whose sides bristled with iron spikes and other devices to discourage a boarding party. Iron was becoming important in man’s life and culture.

In subsequent years, the Peloponnesian Wars saw supremacy pass from the Athenians to the Spartans and eventually to the Macedonians. Throughout these seemingly disturbed times, the foundations of philosophy and scientific thought were being laid.

Archimedes of Syracuse

Of the great men that studied a wide diversity of subjects in that first rational endeavor to understand the nature of things, it is Archimedes of Syracuse who has the distinction of taking the first step towards an appreciation of metallic structure. The story of his discovery -- that for equal weights different materials displace different amounts of the fluid in which they are immersed -- is well know, but colorful enough to be retold.

King Hiero, suspecting that his goldsmiths had alloyed silver with the gold he had given them to make his crown, asked Archimedes to demonstrate whether this in fact was so. We shall never know whether an inspired guess or an involved process of logical thought led Archimedes to realize while bathing that a body displaces water according to its volume and not accord to its weight. So for equal weights, a light metal would displace more water than a heavy one. The gold-silver alloy of the crown should displace more water than pure gold of the same weight.

Archimedes jumped from his bath and ran down the street shouting “Eureka! Eureka!” – which means, “I have it! I have it!” No doubt the citizens were inclined to believe him. The king’s suspicion, by the way, was eventually proven. So the weight per unit volume, or density, of a metal was discovered to be something characteristic of the metal. This applies to all substances, of course. A facetious mind cannot help reflecting that the course of science might have been substantially delayed had the Greeks used shower baths, rather than tubs.

If the story of Archimedes is a true one, then it is difficult to accept the Greek accounts of the touchstone, which was used to estimate the purity of gold. Touchstones, which were black pebbles of a certain kind usually taken from the river Tmolus, had been described and their use well known before the time of Archimedes.

On rubbing gold across them, a streak was produced whose color depended upon the purity of the metal, or if a gold-silver alloy were used, upon the amount of silver in it. According to the writings of the time, the test would allow a quantitative estimate to be made of the purity of the gold. This is rather difficult to believe, however, for it was not until the 15th century that the test was systematized so that by a comparison with streaks made by alloys of known composition an estimate could be made.

The repercussions of Greek thought were felt after the lapse of more than 500 years, first by the Arab alchemists who, as we shall see, based their hopes of the transmutation of metals upon misapplied Greek philosophy, and later, more effectively by the 18th and 19th century thinkers and scientists. The wisdom of the Greeks cannot be said to have had an immediate or wide effect, but the effect was there, an influence in the next two millennia.

In their writings, the Greek philosophers often mentioned metals, describing methods of mining and extraction, occasionally with amazing clarity but more often with annoying vagueness. In either case, their records are valuable in that they provide firsthand evidence of contemporary practices. Their descriptions include the earliest account of the production of mercury from its sulphide mineral, cinnabar. It involved rubbing cinnabar with vinegar in a brass mortar with a brass pestle – an experiment that, on account of its complete futility and absolute safety, might well be included in home chemistry sets. That mercury was known, however, is quite apparent and because of its liquidity at room temperature, it was not regarded as a metal. This peculiar property of mercury resulted in mystical properties being ascribed to it – a belief that lingered into the early 20th century.

While Greece demonstrated its intellectual capacity during the 500-odd years before the Christian era, India, which was as far removed culturally as geographically, had begun the first real production of steel. Wootz steel, as it was to be called, was produced by a development of the carburizing process that was known to the ancient Egyptians.

The Indians produced a sponge iron in a furnace that was remarkably like the earliest blast furnace (which was not to be generally introduced until the 14th century). About four feet high, a blast was applied at the bottom while the charge was made at the top. Apparently, the temperature reached was not sufficient to yield a liquid product. The sponge iron so made was hammered to expel the slag, broken up and packed tightly with dry wood chips into a clay crucible. The metal was then covered with green leaves and the crucible sealed with clay to prevent the ingress of air. A number of these crucibles were piled up and put into a stone furnace, and packed around with charcoal, which was kept burning with the aid of an air blast. After a few hours, the crucibles were taken out and cooled. The pieces of iron had absorbed carbon throughout their section, producing the alloy, steel, which had such superior properties of strength and hardness. The steel pieces were then heated and hammer welded into bars.

It was steel of this kind that later was to be used in Damascus, in making the swords for which that city became famous. The swords were made by using a hammer to weld together a pile of alternate bars of iron and steel, which were then reheated and hammered until their thickness had been appropriately reduced. The sword that was shaped from this material had a structure consisting of alternate wafers of iron and steel, and these produced the typical damask pattern when they were suitably corroded. The corrosive agent used is not known, but it was perhaps a dilute acid, which would discolor the steel sections, leaving the iron comparatively bright.

The Roman Contribution To Metallurgical Progress

During this pre-Christian period, metallurgical activity was not confined to the heads of the Greeks and the hands of the Indians. The small city of Rome in Italy had shaken off its imposed monarchy and was struggling for freedom at home and an empire abroad. She attained both. By 100 B.C. the Roman Empire included all the countries at the north of the Mediterranean Sea, and during the next century or so it acquired the North African coastal countries as well as Gaul and Britain.

The Roman contribution to metallurgical progress was not so much a gain in knowledge as an improvement in organization – an efficient administration but no back-room boys. The earliest Roman republic, near the mouth of the Tiber, had no ore deposits and was of necessity an agricultural community. The Romans made pottery, hewed stone and mixed mortar. As their territory was extended into Italy, mines were acquired by the state, although many remained in private hands. In either case, Rome became richer.

The first mines to contribute to Roman Wealth were in those parts of Italy that came under early rule. Prospecting was prohibited and soon the existing Italian mines were closed. Perhaps this was because the Romans felt their own soil was too sacred to be exploited, or they may have wished to conserve their resources. Further, as there was initially so great a production of gold at Aquileia, in the north, that its value was considerably diminished and prices rose alarmingly. Some control had to be exercised. There was the popular belief, too, that minerals grew as crops did, and that a mine, which had lain fallow, would prosper on being re-opened. For reasons of this kind, the Italian mines remained unworked until the conquest of Spain made gold, silver, lead, and bronze so plentiful that home produce became unimportant, and the order was widely ignored.

Usually the mines that the Romans exploited throughout their empire were either leased to the highest bidder, or controlled by a state administrator, who may have worked them himself or sublet them for a rent proportional to the number of employees. There were other controls as well, and the inevitable restrictions bound up with a state enterprise of this kind produced fixed prices and stipulated markets. This was most particularly so with respect to the metal that had to be produced for the imperial mint. Chief among the contributors to the wealth of the empire was Spain, whose mines, like all Roman mines, were worked by slaves. From the accounts one reads it appears that the slavery of Imperial Rome was far more brutal than that imposed earlier by the Greeks.

While the Athenian mines had become poorer, the mines in the south of Spain were worked to greater depths and produced vast quantities of gold, silver, copper, lead and tin. The workings were unhealthily similar to those in Greece. At lower levels water was frequently encountered and the mines had to be drained. This was accomplished by using the Archimedian screw pump, which was not the new invention that its name implies. Archimedes is said to have seen it in the Nile valley in 200 B.C. where it was used for irrigation. This, however, was its first appearance in mining techniques. It may represent the first application of a machine to mining operations.

The Romans made no extraordinary metallurgical discoveries. By this time lead was beaten into sheets and pipes – an industry presumably stimulated by the Roman habit of bathing. Silver was extracted from argentiferous lead ores by the methods known to the Greeks and already described. Tin was known as a metal by this time, not merely as a something, which was the difference between copper and bronze. The Romans were the first to use it as a lining for food containers. In Spain, the Romans made no improvement to mining conditions. The shafts and tunnels were small, the tools used were primitive, and working conditions were pitiable. What the Romans did, however, was to organize their mining so that it benefited and enriched Rome. It did this, of course, at the cost of continued slavery, but in those days slavery was not a matter of social abhorrence.

The Spanish mines were usually leased to contractors, and each mining district was under supervision of an imperially appointed office (*procurator metallorum*). The contractor sold his metal, or used it in manufacture, according to the restrictions imposed upon him. Additionally, he collected taxes from all members of the local community. On the debit side, the contractor paid his employees, and was responsible for the upkeep of the public baths. This is not so peculiar as it may seem at first glance, for the local community depended upon the mine for its livelihood, and upon the baths for the only social life which a mountainous country could offer in those days.

Spain also possessed rich deposits of cinnabar (mercuric sulphide), which have been worked at Almaden, in the south, from times before the Roman occupation. The first distillation process for producing mercury, by heating cinnabar and condensing the vapor, was described about 370 B.C. Mercury's property of amalgamating with other metals was also known. Much later, at an unknown date but probably not before 1500 A.D., the powers of amalgamation were used to extract metallic silver and gold from sandy materials. It seems fairly conclusive that the Romans did not practice this application.

Just as the Romans prized Spain for its metals, so to a large extent they were prompted to occupy Britain for its expected mineral wealth. In fact, they seem to have considerably over rated the potentialities of the country. However, they came to Rye in 44 B.C., strode out to the Severn and beyond, opening up and commandeering mines that in modern times are pretty well worked out. They exploited with hungry efficiency the deposits, which before their arrival had been worked reasonably and unhurriedly. Britain's mineral wealth was diminished considerably during the Roman occupation, and the native Britons benefited only very indirectly. The copper mines in Cumberland, North Wales and in the Isle of Anglesey were soon put under Roman rule. The tin mines of Cornwall were unimportant in comparison with their Spanish counterparts. However, in the 3rd century A.D. the Romans occupied the extreme southwest to mine tin when the value of the pure metal for lining food containers was discovered. But, most strikingly, they unmercifully exploited the lead mines, for lead was particularly needed for water pipes and was even more important for the silver it contained. The mines in Flintshire, Shropshire, Derbyshire, Yorkshire and Somerset were easy to work, for the upper deposits were still rich. All these swelled the imperial Roman purse during the 400 years of occupation.

Although the Romans contributed little to the natural progress of metallurgical knowledge, minor improvements were inevitably made. The first furnaces used in lead extraction were simple hearths built upon hillsides. Later, they developed into something more furnace-like, with stone-walls and hearths made of clay and clinker above ground level. Even so, it was still necessary to ladle out the metal, for the structure was not sufficiently robust to allow a tap hole to be spiked and prodded for the metal to run from.

To the Romans' credit, however, is the first purposeful manufacture of brass, which they used for coinage and which, for many years, had a higher value than bronze. They were aware, too, that with a lower content of zinc, the alloy could be beaten into thin foil. Accordingly, they used a brass containing 11-20% zinc for decorative purposes where thinness and a good color were needed. In subsequent years, brasses of this composition became known as gilding metal, or Dutch leaf, because of their similarity in appearance to gold leaf. The brasses, which the Romans used for coinage, contained more zinc (21-28%).

Although there was an understanding of suitable compositions for appropriate purposes, there is no evidence that zinc was known as a metal, to be added to copper in varying proportions to make different varieties of brass. Simply, we presume, suitable combinations of copper with zinc ores were known to yield a metal that had more or less definite uses.

The Romans were also responsible for a wider use of existing materials. Bronze was employed not only in making statues, implements and weapons, but also for furniture, cooking pots, and razors. Even an artificial leg has been unearthed, dated about 300 A.D. Lead was given an additional use new to Europe, but first known in Egypt, as a constituent of bronze. Presumably this was only to cheapen the alloy, for the mechanical properties were bound to suffer. Although the Egyptians knew that corroded leaded bronzes produce a pleasant green patina that looked well on statues, the Romans often used the alloy where strength was more important than appearance, adding as much as 10% of lead. One might believe that the measure was an economic one, but in view of the great resources of copper and tin, this is not a very adequate explanation.

The iron production of England during the Roman occupation was not as remarkable as that of Spain, whose manufacture was indeed renowned throughout the world until the 18th century. However, iron was known and used before the Romans came to England, although only in very small quantities. Its uses were confined, and its rarity is indicated by its use in bar form for currency. During the years of Roman rule, foundries and furnaces were set up, at first in the south and always in wooded areas, where charcoal could be readily available. Iron production increased to an extent where export was possible, and this trade continued until the Romans left England. It may not have been very large for the comparative scarcity of iron ensured a high price, as the Romans were quite well aware.

The Romans did not use their wealth as coldly or efficiently as they had gained it. Much of it was used to buy luxuries from the East. Pliny estimates that the equivalent of about 1 million pounds in coinage was sent to India and Arabia each year to pay for silks, spices, and other extravagancies. The Romans worked out the readily available metal, paying it to foreign countries and even to their enemies, while internal coinage had to be debased.

The resulting economic disorder contributed to the break-up of the Roman Empire. Europe was still weak after the plague of the late 2nd century A.D., the Roman rulers became more autocratic, and the people they governed grew more discontented. In the early 5th century the whole of Europe became prey to the barbarian invaders, and the Roman Empire, largely inspired by the lust for metals and built by their exploitation, was at an end.

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Man, Metals and Magic: The Ancient History of Metallurgy

"Arab Alchemy"

Chapter V

It is not only from a metallurgical viewpoint that the world was unproductive and chaotic during the period that followed the Romans' downfall. In the West, most manufacturing processes, mining – and also what, for want of a better word we may call culture – fell to their lowest condition. The only exception seems to have been iron making, which still prospered. The Middle East was in a more or less continual state of war, and while in modern times it is an unhappy fact that war affords a stimulus to invention and an incentive to greater effort, in the 5th and 6th centuries A.D. this was certainly not so. China, the eastern counterpart of the Roman Empire, after a period of suppression became reunited in the Sung and Tang dynasties. It is quite possible that she was metallurgically ahead of the rest of the world, but the state of affairs there is uncertain, and had no real repercussions elsewhere.

Through this vast continent of history, we are fortunately traveling only on the main metalled roads, and the next important system of them that we meet is that marked by the Arab conquests. By 725 A.D. the Arab empire stretched from China in the east to Spain in the west. It stretched so far and so perilously that it could not be long lived. But the Arabs, despite their political shortcomings, brought about the rebirth of Greek science and philosophy, which had so long lain dormant. Through their alchemical researches they made discoveries that laid the foundations of chemistry and contributed to many other branches of science.

There is, or was, more to alchemy than the popularly supposed search for the Philosopher's Stone – that curer of ills and transmuter of metals. Alchemy implied a postulate of the unity of matter, upon which an entire philosophy could be, and was, built.

Aristotle, about 350 B.C. had propounded the theory of the Four Elements – Earth, Air, Fire and Water – material elements derived from the two pairs of abstract opposites Hot and Cold, and Wet and Dry. The theory was not entirely new in 350 B.C. for the postulate was really a crystallization of much earlier beliefs and hypotheses. Clearly, the idea of linking opposites was supported experimentally in, for instance, the transition of cold wet water to hot dry steam. Thus, if we are believers in the theory of the Four Elements, should it not be possible to convert any one material into any other? And surely, too, this being the case, there should be one primary element from which all others are derived.

From such arguments, in the early centuries A.D. there developed the belief that there existed an agent, which could effect the transmutation of one element into another, and this was named the Philosopher's Stone. Since it could "perfect" base metals into noble ones, it should also (as the Elixir of Life) be capable of righting bodily imperfections by curing all illnesses and conferring long life.

The Arabs – and in subsequent years many scientific philosophers – occupied themselves with such suppositions, straining analogy to the limit, while less scrupulous people ignored the rainbow philosophy and worked only for the promised pot of gold. If their original assumptions were wrong, although not unreasonable ones to make, the work that the Arab alchemists accomplished made a real contribution to scientific knowledge, and an understanding of metals and their compounds.

Clearly the fault of their reasoning lay primarily in equating change of state with change of inherent structure. The original Four Element theory alluded to changes of property, or quality, such as the change from solid to liquid. However, alchemists thought that the internal constitution of materials could be altered. (We now know that it can, of course, but we should not confuse the issue by dealing with the conclusions of modern science). One has rather less patience with the 17th century alchemists than with their Arab "ancestors" for one feels that they should have learned better by their time. Indeed, Robert Boyle, in 1661, published his skepticism about the doctrine of the Four Elements and introduced the concept of an element much as we now understand it. But this was not orthodox for 100 years or so after his time.

To return to our chronological survey – the Arabs introduced the sulphur-mercury theory, which was directly derived from the Aristotelian theory of the Four Elements. Alchemical terms were delightfully vague and open to wide interpretation. Just as Fire was associated with combustion, so, in an abstruse way, was sulphur. Similarly, the element Water, associated with fluidity, could be identified with mercury, which was further representative of fusibility and metallicity.

Thus in the 8th century, an Arabian alchemist, Abu-Musa-Jabir-ibn-Haiyan (probably Geber, which we shall call him) propounded the theory that all metals were derived from mercury and sulphur and that, in perfection, gold would be produced by their marriage. This production presumably was supposed to happen in the earth, but as a result of "accidents" of impurity and so on, other minerals were unavoidably formed as well. Sulphur and mercury were associated with masculinity and femininity, respectively. Further, the seven known metals were linked with the heavenly bodies. Geber did many useful researches and produced arsenic and antimony from their respective sulphides. Of course, they were not recognized as metals in the same way that iron and copper were. Apart from the fact that the characteristics of metals were not sufficiently well known to allow it, such thinking would have been very inconvenient. After all, there would not be enough planets.

Other Arab philosophers in their common search made similar contributions, not only to a knowledge of metals and their compounds, but also to medicine, astronomy, optics and mathematics. Needless to say, their work over 700 years, which was to be followed by alchemical researches in other parts of the world until recent times, did not produce the Philosopher's Stone.

Fiction though the Stone may have been, the search for it was certainly real, and the alchemists' work had many valuable results and interesting effects. The results cannot be easily itemized and no attempt will made to do so for in addition to the contradictory profusion of alchemical works, many factors make an exact account difficult to produce. Frequently, the alchemist wrote under an assumed name and the actual writer is no longer known. Sometimes manuscripts that alchemists reported to have discovered, and which they ascribed to greater personalities than themselves, were in fact, their own work. Additionally, and perhaps most confusing of all, is the mystical jargon in which they wrote, principally in order to confuse any less learned aspirants, and to frighten them away. We should not, of course, be too shocked at this habit, for it is still practiced, though perhaps more subtly. In alchemical writings it was carried to such extremes that it is difficult to differentiate between the factual and the allegorical. While we cannot categorize the findings of the alchemists, we can describe the broad effect of their work.

Firstly, we are indebted to the Arabs for a new beginning in natural philosophy. Their alchemical researches led them far and wide into the fields of medicine, mathematics and astronomy, in which notable discoveries were made, and new concepts introduced. This rebirth of philosophical thought led to a logical, or quasi-logical, method of approach.

Secondly, the Arabs were more than thinkers. They *did* things, introducing experimental techniques and inventing laboratory apparatus. Geber described, presumably in the 8th century, the construction of furnaces, and also the uses of the Vase of Hermes (a sealed vessel in which many alchemical operations were carried out). It was known, too, as the Philosopher's Egg, for it was egg-shaped to symbolize fertility.

Another Arab, Rhasis, was given money to build apparatus for his researches, so that he could demonstrate the transmutation of metals to the Prince of Khorossan. (Rhasis is said to have written a book on his method of producing the Philosopher's Stone, which he presented to the Prince. When the experiments failed, the Prince threw the book at Rhasis, and the blow proved fatal – which, perhaps, shows that while a little knowledge is a dangerous thing, a whole bookful may be catastrophic). In all the alchemical texts and illustrations of the period, it is clear that apparatus, although of a simple kind, was in use. This represents a most important step in the progress of scientific method. Just as Greek learning took many years to spread, so too, the results of alchemical researches were not reaped directly. They were gleaned rather than harvested. Perhaps it is because of this difficulty of pinning down any important single result of alchemical inquiry that the subject is so often dismissed as unimportant. But it did at any rate provide the vital link between Greek philosophy and the science of the 17th and 18th centuries.

Man, Metals and Magic: The Ancient History of Metallurgy

"500 A.D. – 1500 A.D."

Chapter VI

ALCHEMICAL THEORY did not permeate the western world for some time. While the Moslem empire of the Arabs grew around the Mediterranean, England – invaded by the Angles, Saxons and Jutes – passed through its most obscure period. Historically the period is a vital one to Britain for during the two centuries that followed the Romans' departure, changes took place – with little enough significance to the people that experienced them – that among other things, were to determine very largely the character of the people, their economy and their language.

The obscurity of this period is primarily due to a deficiency in valuable contemporary documentation. Such evidence might have been literary, as it was to some little extent in Roman times and to a greater degree in the middle ages. Or it might have been provided by material remains, as much of the history of the Roman Empire and before has been put together from relics that archeologists have unearthed with the hand of care and interpreted with the eye of faith. But there is a lack of such useful evidence in early Anglo-Saxon times for most material pertaining to this period is obtained from cemetery sites.

The objects, which were buried in the early Anglo-Saxon grave, included articles that the occupant had made or that were thought to be valuable. But sufficient iron implements and weapons have been found in excavations to enable the archeologist to say with certainty that iron making was still playing a valuable part in that dark period of the 5^{th}, 6^{th} and 7^{th} centuries.

Excavations have shown that iron was used for weapons and agricultural implements. More importantly, there had been no decline in manufacturing skill that prevented the production of domestic articles like chains, bowls, caldrons and personal ornaments such as brooches and buckles. The smiths of pagan Saxondom then, did not lose their art. Indeed, the view has been expressed that as a result of the departure of the Romans, they were able to work with a new originality. Nor had they lost the independence that we have come to associate with the smiths for around 700 A.D. when Ecgwin, Bishop of Worcester, went to Alcester in Warwickshire to preach the doctrine of Christianity (at this time Christianity had spread pretty well throughout Britain), they demonstrated their feelings by clanging their hammers and anvils so the bishop could not be heard above the din.

By the late 7^{th} century pagan practices had become rare, and the habit of burying the dead with their personal belongings came to an end. Christian doctrine was generally accepted in England, and the crude civilization of the last 100 years developed into a much finer way of life. This was reflected in many directions, both in arts and in industries. Culturally, Britain was further advanced than the rest of Europe.

Northumbria, which included most of what is now Yorkshire, was the focus of rejuvenated industry and produced knives of a fine quality, which found their way into Europe where they were acknowledged to be superior to other types. They were made of iron that was work hardened and carburized during forging. The cementation process of steel-making (which involves a controlled carburization, by packing pieces of iron into carbonaceous material and heating them to a temperature of 1800-2200^{O}F.) was not introduced into England until the 17^{th} century, although it was known in Spain and other parts of Europe much earlier. The process of carburizing used by the makers of English knives was, in effect, fairly similar. As the knife was of thin section, carbon would be absorbed pretty well throughout, and the consistent quality of the products implies that the process was "understood" and controlled. The fact that English knives of the 7^{th} and 8^{th} centuries were far-famed has an interesting significance, for evidence shows that such cutlery was made near Sheffield, which retained its reputation as a steelmaking center.

The centers of learning were the monasteries where, in addition to the more worldly arts, iron making and metalworking were practiced. Laymen who lived in their homes outside the monasteries helped the monks in these pursuits. The metals were often used within the monasteries for ornamental and utilitarian purposes, for screens, lamps, and bells. The iron that was made was used in the monastery, disposed of locally, or sold to merchants from farther a field.

The monks became well known for their iron making and bell founding. Notable among them were Ethelwold, Bishop of Winchester, and Dunstan, Bishop of Abingdon, who in the 10th century founded bells for the Abbey at Abingdon. Each of these bishops has, apart from his greater contributions in other directions, metallurgical achievements to his credit. There is a legend of an encounter between St. Dunstan and the Devil, during which St. Dunstan seized the Devil's nose with the tongs he used at the forge. Although it is only a colorful story, it does somewhat illustrate the association between monastic life and industry (and possibly between industry and the Devil), particularly with respect to iron making. The records they left substantiate that monks were skilled in metalwork. In the early 11th century the Abbot of Abingdon, a most capable goldsmith, was requested to make a crown for Henry IV.

After the Norman Conquest, the position became very different. The newly appointed Norman abbots had no traditional skill in metalworking or, for that matter, in most arts. What was worse, many pieces of existing craftsmanship were destroyed or looted. As a consequence, laymen who were employed for that purpose executed most of the necessary works of art in the monasteries. Sometimes, however, a man so employed became a monk and possibly trained others within the monastery. Even so, craftsmanship was no longer so integral a part of the monastery, and it was particularly the more delicate arts, wood carving and precious metal working, that suffered.

The learning of the monks continued, however, and began to spread outside the monasteries. Arab alchemy, and through the Arabs, the earlier Greek ideas, began to be known in Europe. This was aided by the manufacture of paper, although the wider dissemination of written work was impossible until the later introduction of printing. Among European philosophers of this period, Roger Bacon, a Franciscan monk, is outstanding for his strenuous and fearless battle against prevailing ignorance, for his amazing forecasts of scientific developments, and for his insistence on experiment. Brilliant men are necessarily born before their time, and the worth of Roger Bacon was not immediately appreciated.

The iron making of the monks did not suffer like their finer arts after the Conquest and contributed to the general expansion of the iron industry in England during the 12th century and after. One reads of three forges given by the Norman Lord of Monmouth to the Benedictine Priory in exchange for land, of the forge in Louth Park belonging to the local monks who had permission to fell beeches and elms for charcoal burning, and of the Abbey of Flaxley in the Forest of Dean, where monks were allowed to take two oak trees each week as fuel for their forges.

There are two features in connection with the iron making of this period that are particularly important. First, the same process, essentially, was used to make iron as the Hittites, e.g., it was forged to remove the slaggy material and hammered into shape. Second, the furnaces and forges were heated by charcoal. During the expansion of the iron industry, this inevitably led to a severe cutting of the forests in which the forges were operated, which eventually produced a most critical situation in Britain.

Iron ore was taken from the earth by digging a pit about six feet in diameter. When the miner struck a seam of ore, he dug away all around it, leaving a bell-shaped hole. There were none of the elaborate tunnellings that were used for mining lead. The ore was easily obtained and when the miner had taken all the readily available ore from one bell pit he dug another. The ore was carried to the smelting furnace, which was usually situated in a wooded locality. It was more economic to carry the ore than the wood, for so much wood was needed. As trees were consumed, the furnaces were moved. Terrific amounts of timber must have been used, for in the Forest of Dean alone in 1282 there were 72 forges and, one presumes, many furnaces.

Nevertheless, the supply of iron in England was not enough to meet home demands, and foreign metal had to be imported from Spain and Germany, where techniques were similar in most respects to those in England. In fact, the type of furnace used in England, the Catalan forge (the word forge is misleading for it was a furnace) was first used in Spain. It was a simple hearth type of furnace built of stone, into which the ore, flux and charcoal were charged on top of a wood fire and blown by an air blast introduced by a tuyere into the charge. The slag and sponge iron collected at the bottom of the hearth, and after about six hours, the lump of iron was removed and taken to the forge.

Here it was softened by a fire (encouraged by bellows) and worked until the metal was fairly free from slag and in the form of a round ball, called a half-bloom. This was taken hot to be beaten into a bar of a useful shape, and in this operation the iron had to be re-heated several times. The hammers were no longer wielded at the expense of a sweating brow and bulging biceps, but were usually actuated by a water wheel, whose projecting arms raised the hammer, which then fell on the hot iron. Water wheels eventually became widespread, particularly in Sussex when that county was the center of English iron making in the 16th century.

The First Blast Furnace

The furnace used by the Germans was similar to that used by the Spanish, but the furnace was heightened early in the 14th century, which made necessary a greater pressure of air through the tuyere. Actuating the bellows by a water wheel mechanism attained this. As a result of further increases in height, the charge took progressively longer to travel through, and the time of contact between the sponge iron and charcoal was increased. Now, while the melting point of iron is 2800^{O}F, this is progressively reduced as the iron absorbs more and more carbon. At a composition of 4% of carbon the melting point is only about 2100^{O}F – a temperature that was attained in a furnace of this kind. So the product was no longer a pasty, slaggy mass, but molten.

This, then, was the first blast furnace. Over the years it has been made bigger, the number of tuyeres has been multiplied and the blast pressure increased. Consequently its production is vastly greater. Undoubtedly it has become the most essential of all metallurgical devices, for upon it depends the production of pig iron, from which in turn, steel is made. This was not so in the 14th century, of course. But we are now in a position to appreciate, as we can look back and see discoveries fall into their proper perspective, that this small furnace in which molten iron was first produced was the seed from which all modern industry has sprung. The production of iron by this method is the most noteworthy advance since the manufacture of bronze. As far as our civilization is concerned, it is possibly the most important discovery ever.

It is difficult to say how much this was appreciated at first, for presumably the furnace was expected to produce only more sponge iron for the forge. Instead, it yielded a liquid iron, which on solidifying was hard and brittle and could not be forged. Probably, therefore, some time elapsed before any great importance was attached to the discovery. The medieval metallurgist did not produce steel from blast furnace iron as in the modern world, and consequently the only value of the metal was for uses to which it could be put directly – that is, as castings. The first purposeful castings in iron are supposed to have been made in Sussex, England, but the country is only accredited with the distinction because of lack of positive evidence.

Discovery of Gunpowder

Probably more dramatic in its immediate repercussions than the production of iron in the blast furnace, was the invention of gunpowder, another discovery that cannot be given an exact date or location. Throughout the centuries, clumsy weapons – the catapult, the ballista, the trebuchet and the mangonel – had been evolved. Now, concurrent with an improved skillfulness in metalworking, came gunpowder. The possibilities of this combination were obvious and the result inevitable.

Taking a rough average of all estimates, it appears that a German monk invented cannon at the beginning of the 14th century. That a monk was actually responsible is doubtful, and the date is equally questionable. The first use of cannon by the English is supposed to have been at the siege of Cambrai in 1339, or at Crecy in 1346.

It is indisputable, however, that the use of the cannon came rather before sound iron castings could be made, and therefore early guns were of bronze, brass or wrought iron, and they fired a stone. Within ten years of Cambrai, cannon already had an important place in the art of war waging. Their use, extended to naval warfare, was sufficient by 1345 to warrant the Keeper of the Wardrobe at the Tower of London being charged with the repair of ship guns and the adequate provision of ammunition for them.

One cannot help wondering whether public reaction was as confused and stunned in the 14th century by the introduction of the cannon as it was in the 20th century when the first atomic bomb was dropped in Japan. For just as the atomic bomb represented the first use of nuclear energy as an explosive force, so the cannon represented the first application of the violence of a chemical reaction to war making.

The Black Death of 1348-49 had a retarding effect upon metallurgical industries in Europe. It is said to have originated in the East, and appeared in England in August 1348, spreading throughout the country so that by 1349 Ireland and Scotland were as awfully affected. Had it not been for this terrible disease, the inevitable improvements in gun making might have come earlier. As a result of the 1,500,000 deaths (out of Britain's then population of 4,500,000) production fell, prices rose, and labor was at a premium. In an endeavor to ease the situation, Parliament passed the Statute of Labourers (1351), which among other things made it compulsory for a man to accept work at pre-Black Death wages. This law, which was re-enacted many times, was not successful despite the threatened branding of those who resisted it. Equally unsuccessful was the law of 1354, which forbade the export of iron. The general relevant effects of the Black Death, which only put them selves right gradually, were that natural progress was delayed and iron doubled in price. Steel, being very expensive and largely imported by the Hanseatic League, suffered a severe loss in demand.

European steel at this time was made only by cementation. The process had developed from the primitive carburizing technique of the Egyptians, but had not altered in principle. Because of the blisters that formed on the surface of the metal during the process, the product became known as "blister steel."

Perhaps the premature stunting of the demand for steel as a result of the Black Death explains to some extent the fact that the steelmaking process was so long delayed. It is not unreasonable to suppose that, knowing as they did the superior properties that could be conferred upon iron by carburizing, and having at their disposal the means of making molten iron, the 14th century smiths might, under less trying conditions, have introduced a melting and refining technique for steelmaking. As it was, the process of "fining" cast iron (to make it more malleable) was not discovered until the late 16th century. It was not until 1740 that steel was made by a melting process, and only in the late 19th century was a large-scale technique introduced.

No doubt the long delay is principally explained by the fact that nobody had the capability or perhaps the luck to make the necessary discoveries. Further, there was no great demand throughout the period to provide the needed incentive. Had the Death not scourged Britain the natural increase in the use of steel would probably have continued so that its eventual production on a large scale would have become necessary at a rather earlier date.

The Development of the Cannon

Although the Black Death retarded the progress of the iron and steel industries, and with them, the development of the cannon, it was not very long before wrought iron guns were being made in England and used abroad. The English left two of the earliest wrought-iron guns, which like the brass and bronze guns were breech loading, at Mont St. Michel, Normandy in 1424. These are fairly typical of the cannon made in the late 14th and early 15th centuries. They weighed 5.5 tons and 3.5 tons, and were about 12 feet long with calibers of 18 and 15 inches, respectively. Wrought iron rods were lashed longitudinally onto a mandrel to make the gun barrels. The rods were held in place by heated iron hoops, which contracted as they cooled. The mandrel was then removed, and the iron bars formed a barrel securely held by the hoops. Possibly molten lead was poured into the interstices, and the bars may have been roughly hammer-welded. If so, the caliber of the gun would be sufficient to allow a hammer to be used within the barrel.

By the end of the 14th century, the art of cannon making was fairly widespread. On the Continent, cast bronze and brass were used, while England employed wrought iron as well. Despite this, it is said that Continental iron was superior to English iron. The little steel that was used in England was largely imported – principally from Spain, but also from Sweden, Norway and Germany. Frequently, the Spanish iron maker went to English fairs where he sold his metal to the bailiff, who bought what would be needed on the farm. A smith employed at the farm would use it to make the necessary nails, horseshoes, and tools. The great fair at Stourbridge was a market for the Spanish and the Sussex iron makers alike. As a result of an insufficient amount of iron that was made in England and its importance in ordnance use, it was too expensive to be used very much domestically. Jugs and pans of brass were more common than ironware, and they served a more utilitarian purpose than decorating the mantelpiece. It is popularly believed that in the reign of Edward III (1327-77) the iron pots and pans in his possession were ranked among the Crown Jewels.

At the beginning of the 15th century, blast furnaces were introduced into England, and this together with the steady immigration of Continental iron workers to England during the 14th, 15th, and 16th centuries, led to an expansion of English iron making. Consequently the country became less dependent upon foreign supplies. Then, in 1463, an Act of Parliament restricted the importation of many iron articles, including wire, the product of an industry that was later to thrive in England.

The expansion of the iron industry coincided with the increased facilities for spreading knowledge that were afforded by the introduction of Caxton's press in 1477. This eventually resulted in a wider and more rapid dissemination of knowledge than would have otherwise been possible. Until literature became widely and cheaply available, the practical difficulties attendant upon studying was usually insuperable. The student had either to have the opportunity and means of obtaining manuscripts or of traveling so that he could acquire his information at first hand.

The discerning reader will have noticed that the preceding section on iron making has been confined to Europe, and largely to England. This is not accidental, for the art sprang up there, and apart from an unproductive period between the middle of the 16th and 17th centuries, Britain remained the greatest producer of iron until the late 1800s. Before the manufacture of cast iron is considered (a long delayed advance in view of its discovery at least 100 years before) we must leave Europe and turn westward, where in preserving the chronology of this historical survey, we (with Columbus) discover America in 1492.

The Conquest of America By the Spanish

The story of the conquest of America by the Spanish is a story of the lust for gold. It is well known that Columbus was intent rather upon finding a direct route to India and China by sailing westward, than upon exploring the world for discovery's sake. When he landed on the Bahamas in 1492, the idea that he had reached India was encouraged by the gold ornaments the natives wore, and by having been told that more gold lay towards the south. He went by way of Cuba to Haiti, where he seized the gold that the natives obtained from the streambeds there.

In the early 16th century, after Columbus' death, a Spanish expedition was sent to Mexico. Off the coast it was greeted by the envoys of the Mexican chief Montezuma, who brought with them priceless presents, and a request for the expedition to leave. Tempted by the former and unperturbed by the latter, the expedition went on into Mexico. Further promises of gold had an affect quite opposite to that intended, and after a brutal and confused battle the Spanish conquered Mexico in July 1521.

At first the gold resources of the country were disappointing. The collected treasures of Montezuma, accumulated by him and his predecessors over many years, raised the hopes of the invaders too high. But within 20 years, rich deposits of gold and silver were worked – with a percentage of the extracted wealth going to the King of Spain.

A further expedition was directed to Peru in 1531, where aided by the circumstances of a civil war at the time, the small party finally subjugated the country. In the end, and before many years had passed, the whole of the west coast of South America and on to include Mexico, was in Spanish hands. The mines and deposits in the productive areas were being worked by native slave labor in a way that would have seemed brutal 2000 years before. The deposits were rich. Smelting processes were carried out in a primitive hearth without the use of bellows, but relying upon the wind, or the breath of a slave who blew through a tube. In time methods were improved when European metallurgists were brought to the Spanish possessions. But working conditions remained pitiable for many years.

By 1567 the amalgamation process had been introduced for the recovery of native silver. The native silver, which the Conquistadores obtained, was unavoidably contaminated with earthy material. To separate these, the mixture was washed over mercury, when the silver was captured and the dirt was swilled away. The amalgam was collected and then heated to distill off the mercury, leaving behind pure silver. As the Spaniards had vast deposits of cinnabar (a sulphide mineral of mercury) in Guancavelica, the process could be economically exploited, and it led to a greatly increased production of silver from native deposits. Later the amalgamation method found wide applications in extracting gold, which behaves in the same way as silver.

Owing to unreliable evidence one cannot be certain how far metallurgical techniques had progressed before the conquest of South America. It seems, however, that the natives had not advanced very far in any cultures and their extraction and use of metals were primitive. In most places they had only just begun to learn the value of bronze, and almost all of the pre-Conquest implements were made of copper, or even of gold and silver.

So, from our point of view, the exploitation of South American in the 16^{th} century is of interest mainly because it opened up new resources that are still vast and vital. While there was little contribution to the progress of metallurgical methods, in forming an opinion of the Spaniards' metallurgical achievements, one must, when their conquests are considered, weigh their bravery and exploits again their brutality. Their initial lack of progress has to be balanced against the improvements that their buying power stimulated, and the slavery they enforced set against the prosperity for which they were responsible. The final state of the balance sheet depends upon the temperament of its auditors.

England's Developing Reputation for Ordnance

Meanwhile, English iron making and gun founding continued. By the end of the 15^{th} century, cast iron cannon balls were being made, and the explosive shell had been invented. The greater precision allowed by a cast iron shell over the rough-hewn stone shot resulted in more accurate and forceful firing, while putting a greater strain upon the gun. By this time too, gunpowder was more certain and violent in its explosion. A state of affairs was reached when, due to the tendency of cannons to burst, the hazards were probably as great to those firing the guns as to their enemy. One can appreciate the birth of the expression "sticking to one's guns."

England quickly achieved a high reputation for her ordnance, and became independent of imports. Additionally, during the reigns of Henry VII and Elizabeth I there was a strong demand for her weapons abroad. In the 1580s it was suspected that Spain was importing English guns -- which, as a result of her American acquisitions she could certainly afford to do – in order to equip her Armada. For a time, therefore, the export of iron and brass was forbidden. Some, however, was still smuggled out of the country, and a number of English cannon are said to have reached Spain.

An unfortunate effect of increased iron making was the further destruction of England's forests. Fears began to be expressed about a future shortage of timber for domestic purposes and shipbuilding. Acts of Parliament were passed restricting the areas from which wood might be taken, the most limiting being the Act of 1584. It forbade the erection of new iron works in Surrey, Kent and Sussex, and ordered that iron works already in those localities were not to use timber "one foot square at the stub." Although the Acts were not strictly enforced, they served at least to check the consumption of the English forests by the iron makers. Consequently, Britain found that she had made a home market for iron that she could no longer satisfy. As a result, she had to look abroad for supplies.

With the reduction of British iron production, she looked to Sweden for iron imports, and the development of the Swedish industry roughly paralleled Britain's. Sweden however, having the natural advantage of immense forest, and without England's obligation to maintain and build a Navy, was not compelled to cut down her production as Britain was in the 16^{th} and 17^{th} centuries. During this period, Swedish iron making assumed an increasing importance and was eventually responsible for about one third of the world's production – 80% of which she exported. Her exports to Britain sometimes equaled the amount that Britain herself was able to make. Perhaps it should be pointed out here that Finland was until 1809, part of the Kingdom of Sweden, and therefore contributed to Swedish output.

Being, perhaps, so completely acclimatized to the gigantic production figures of the modern world's blast furnaces, we neglect to consider the small scale of 17^{th} century operations and comparatively restricted demand for iron products. Around 1700, world production of iron was between 100,000 tons and 150,000 tons per year, whereas by the middle of the 20th century, worldwide iron and steel production were on the order of more than 312,000,000 net tons. Regrettably, those figures did not imply that man had become any more capable of using our iron sensibly.

By 1730 Swedish production was beginning to meet serious competition from Russia. About this time, too, the world picture of iron making was completely changed by the introduction of coke, which replaced charcoal. But we are jumping too far ahead, for the discovery of coke making was preceded by quite a different sort of contribution to metallurgical progress – the publication of metallurgical textbooks.

* * * *

Man, Metals and Magic: The Ancient History of Metallurgy

"Three 16th Century Experts"

Chapter VII

OUR HISTORY OF METALS, so far, has depended largely upon the findings of archeologists or the writings of authors not always reliable, or inexpert, if reliable; or, if expert, as historical experts rather than as metallurgists. However, in the 16th century three books were published by three men whose metallurgical knowledge was expert.

One book is *De Re Metallica*, by Georgius Agricola. Originally published in 1556, in 1929, it was most capably translated by the 31st President of the United States, Herbert Clark Hoover (1929-1933) and his wife, Lou Henry Hoover, into English and supplemented with valuable footnotes. The second book is The *Pirotechnia of Vannoccio Biringuccio*, published in 1540, translated and annotated in 1942 by Cyril Stanley Smith and M. T. Gnudi. The third 16th century book is the *Autobiography of Benevenuto Cellini*. While no one would suggest this latter book contains very much metallurgical information of value, it is, at least an interesting account of one metal worker's life.

Perhaps it would be as well to dismiss Cellini's book first. Cellini was born in Florence in 1500. Most people who knew his work acclaimed his capabilities as an artist in metals, but no one, it seems, thought quite so much of his work as Cellini did. The life story reveals a conceit and arrogance so enormous as to be amusing, but Cellini did have something to be conceited and arrogant about.

The books by Agricola and Biringuccio overlap in some sections, but are essentially complementary. Agricola considers prospecting and surveying, in addition to smelting, refining and assaying methods. While Biringuccio describes smelting, refining and assaying, he also covers casting, molding and core making, and the production of certain commodities – bells and guns, for instance. If one were to categorize their respective specialties, perhaps it would be true to say that Agricola was a miner and extractive metallurgist. Biringuccio was, rather, a fabrication man, who in those times, found it necessary to make his metal before he might use it.

Since we have often followed our metal thread through a cotton-wool industry and have necessarily left a number of subjects untouched for the sake of continuity, a survey of the books by Agricola and Biringuccio will allow us to fill in some of the details of metallurgical practice that have so far been omitted. In all fairness to Biringuccio, Agricola and their respective translators, it must be said that their texts have a completeness far beyond that which can be conveyed here. After reading them a man might survey, prospect, mine, extract, assay, found and fabricate with the confidence of a 20th century housewife making a cake after reading, "Every Woman's Cook Book." The aim here is not to reproduce the cookbook, but to offer a crumb of the cake.

The view of Agricola and Biringuccio were advanced for their time. Agricola debunks the divining rod and writes very sensibly about the value of observing natural phenomena (outcrops, vegetation, mineral springs) for effective prospecting. He and Biringuccio were unhappy about alchemical theories and even more so about some alchemical practices.

Agricola could not accept the alchemical view that all mineral deposits were formed by the interaction of sulphur and quicksilver. In putting forward his opinion that openings in the earth were formed by eroding effect of subterranean waters and later filled by "juices," he annoyed not only the alchemist but also those who held a literal belief in Genesis, which, of course, implies that rocks and minerals were formed at the same time.

Biringuccio's opinions of alchemy were, roughly, that he applauded the work of the alchemists in that they were practical men doing research. But he was impatient of those alchemists that strove to produce the Philosopher's Stone. He thought it more commendable to "get gold from ores rather than by alchemy." However, if the metallurgist of those days did not allow himself to use some of the alchemical jargon, he would be as lost for words as a contemporary physicist forbidden to use the terms “positive” and “negative.” So we should not be surprised when Biringuccio writes: “*In my opinion antimony (antimony sulphide) is a composition made by nature to create a metallic mineral that is overflowing with an undue proportion of hot and dry material and with its moisture poorly mixed.*”

There is, it seems, evidence that Agricola obtained some of his material from Biringuccio. The two men communicated with each other, and a comment of Agricola’s acknowledges that Biringuccio’s material did “refresh his memory.” The translators of Biringuccio’s book point out that this “refreshing” consisted in a literal lifting, with no acknowledgement. In fairness to Agricola it should be pointed out that he was the younger man. Whereas Biringuccio was born in Sienna in 1480, Agricola was born in Saxony in 1494 and his interests were so diversified that he must, of necessity, have cribbed a great deal of his material from other sources. Since Agricola was a student of and wrote texts on philosophy, medicine and natural sciences, we should not expect him to have so great a personal knowledge of metallurgical subjects as Biringuccio, who was essentially a metal worker. Whether Agricola was or was not guilty of lifting his information from elsewhere is of far less importance than the fact that he wrote down methodically and complete the information he acquired. But Biringuccio’s greater familiarity with his subject seems apparent in his writings.

Georgius Agricola and “*De Re Metallica*”

As well as discarding alchemical hypotheses, Agricola refuted the popular opinion that ore veins in certain directions were the richest, with directional variations depending on the metal. The reasons behind these beliefs were connected with the effect of the planets, and more particularly with the Sun. By the middle of the 16th century these ideas were becoming shaky and Agricola disposed of them. Similar notions, equally destroyed by subsequent experience and fact, were held about rivers and streams that carried deposits.

However, Agricola’s debunking did not extend to many of the superstitions of the miners, for in describing mining conditions he refers to “demons of a ferocious aspect” that “are expelled and put to flight by prayer and fasting.” Some demons, called “kobalos” because of their habit of mimicking miners, were supposed to be of a gentle nature, unless roused. Nevertheless, German miners who sustained injuries from certain corrosive minerals held that these little men were responsible, and hence the mineral was associated with them, and was called “kobalt.” This is one account, and a pretty one, of the derivation of the worked “cobalt.”

While some demons were relatively harmless, and others might be exorcised, others apparently were always troublesome, although some of the more tangible unpleasant features of mining had begun to be eliminated. Since the time of the Athenian mines -- where if ventilation was provided at all, it was by fires lighted at the bottom of the shafts – more efficient devices had been introduced. Fresh air was blown into the top of the shaft by fans or by bellows actuated by manpower or by the wind or a water wheel. It is significant that water wheels at the time, used for this purpose and for blast furnaces, were of the overshot type: that is, water was directed from a stream to the top blades of the wheel, which did not dip into a stream like the mill wheels of a later yesterday.

Mining machinery was still crude, but had improved over the centuries. The Archimedian screw pump was used to drain mines in some localities, but the lift pump was more widely applied to mine drainage, either in the usual reciprocating form or as a continuously operating machine. The motive power for these pumps, and for windlasses that drew buckets of ore from the mine, was provided by water wheels, or by men who might work a kind of treadmill, or by horses trotting a never-ending circle.

The mines were accessible by descending on a rope, or by a sloping shaft where one might find steps or not, or by sitting on the dirt and sliding down. In the mines, the tools used were of iron, but in design they had not altered much over 2000 years. When all is said and done, a spade is a spade. Until real mechanization with its pneumatic drills and power driven cutters was introduced, mining tools could not be very much changed. Some manual tasks had been eased and in most cases trucks that ran on wood rails were used to convey the ore to the surface.

Although gunpowder had been invented 100 years before the stocktaking date of 1560, it was not used in German mining practice until after Agricola’s death. In England, its use in this connection was delayed for a further 100 years. The method of breaking up rock was by wedges and hammers, and also by fire setting, which was known since the days of the ancient Egyptians. This involved lighting a fire under the rock to be broken so that expansion would cause it to crack. If it were obstinate water would be thrown over the heated surface. The practice was a dangerous one and difficult to control. There was always the risk of a fall and also the hazard of asphyxiation from the fire's smoke and the fumes from the hot rock.

There had been little change by the 15th century in the methods used for breaking up the ore before it was sluiced with water to wash away the earthy material. The primitive crushers were either small hand-operated pestles and mortars or millstones that could be turned by men or horses or waterpower. Then, in the late 15th century, the stamp mill was invented. It consisted of a row of vertical shafts, each with a heavy iron shod block at the bottom that dropped on an iron plate. By a system of cams, each shaft was lifted and allowed to fall freely, crushing the material on the iron plate. In any crushing operation, ancient or modern, it is ideally necessary to separate each particle of earth from each particle of mineral so that subsequent concentration, by washing, for example, can work efficiently. Depending upon the nature of the ore deposit, this may have necessitated grinding the material from the stamp mill between millstones in order to make it sufficiently fine.

The ways in which the crushed ore was treated to concentrate the mineral were many variations of a simple enough theme. Essentially, all the methods consisted of subjecting the powder to a stream of water so the lighter, earthy material was washed away, while the heavy mineral sank and could be collected. Such a method was applied to ores of gold, silver, copper, lead and tin, and had been known for thousands of years, for gold washing dates back to about 4000 B.C. By the 16th century the water carrying the ore was directed through channels down chutes into tubs, and out of spouts in a way that would delight even the most surrealist plumber. Although the method had been made more elaborate and more efficient, the principle was unchanged.

Agricola described in some detail the ways in which ores should have been assayed in order to tell whether they were worth mining and extracting. Although the value of an ore deposit depends upon many local features and prevailing economic conditions, it is dependent in the first place on the amount of metal it contains. The science of assaying grew naturally from the time that a metal was obtained from its ores by anything more than an accident. By the appearance of a deposit, the miner and metal smelter might get a good idea of its value. The alchemists, with their introduction of chemical apparatus and experimental methods, made the next step. By the 16th century there had grown the idea of assaying an ore by putting it through a small-scale process similar in most respects to the smelting operation that would be used to extract metal from it. In all probability such a method may have been employed long before, but none of the techniques was recorded until the early 16th century.

Agricola was the first to write a comprehensive scheme of assaying for gold, silver, lead, copper, tin, quicksilver and bismuth (the minerals of which were known, while its metallic properties seem to have been in some doubt). As some assays used today depend upon the same fundamental of extracting the metal from a known weight of ore, and so determining its percentage, it is not surprising the methods Agricola described are very similar to modern methods. Even though solution and precipitation processes were known to 12th and 13th century alchemists, they were not applied to assaying until some time later.

That assays should have been made by the 16th century was natural and inevitable, but that they should have been systematically described in a way that still bears critical reading is one of the first signs of metallurgy taking on a scientific aspect.

The smelting of copper, lead, tin and iron was usually carried out at the time in small blast furnaces about 5 feet high and 2 or 3 feet square, with six furnaces built into the same structure so they could be conveniently attended. The hearths were made of rammed clay and charcoal, and in front of the tap hole was an open hearth of the same material, from which the smelted metal was eventually collected. The bellows house was situated behind the furnace structure, and by the 16th century bellows had reached the surprising size of about 6 feet in length. In design they were very similar to those that were used domestically in the days before firelighters.

Chambers were sometimes built over the tops of furnaces where solid material in the smoke was deposited for later collection, while the gases, relieved of some of their solids, passed out through a chimney at the top. Today the collection of suspended matter from smokes is a highly important economy in most works. It is interesting that, despite the much inefficiency of older techniques, this practice was common in Agricola's time – and it was by no means new then.

Agricola described the smelting processes and explained the ways in which gold and silver, produced by cupellation, could be separated.

De Re Metallica contains a complete account of the method of extracting silver from copper that remained standard practice until early in the 20th century. The process involved melting the silver-rich copper with lead, in an air-free atmosphere, and casting the resulting metal into cakes, which were subsequently heated to a temperature above the melting point of lead, but below that of copper. The lead gathered the silver from the copper, which was sufficiently concentrated in silver to be run off and cupelled, while the copper was taken to be refined.

From the nature of his remarks on iron making and their comparative brevity, it seems likely that Agricola was not perfectly familiar with recent developments. He referred to a furnace like the blast furnaces he had previously described, but of a greater size, and he spoke of its producing molten iron. Further, he wrote, "*from this kind of [iron] ore once or twice smelted, they make iron that is suitable for reheating in the blacksmith's forge,*" which, as the translators point out, might well allude to a process introduced in his time of making a malleable iron from the brittle product of the blast furnace. This technique, known as "fining," involved melting cast iron in a hearth where it was mixed with charcoal and oxidized by an air blast and iron ore. The process is a horrible one to analyze, for while the carbon content of the cast iron was reduced by oxidation, so must carbon have diffused into the metal from the hot charcoal that surrounded it. Nevertheless, the carbon content of the iron was reduced and the melting point was thereby raised. When the charge became pasty it was removed and forged. Agricola was wisely brief in dealing with so strange a process that was, in fact, very widely used until the middle and late 19th century.

The Pirotechnia of Vannoccio Biringuccio

We can now take up the story from Biringuccio's book. As appropriate an introduction to it as any is the description of the founder:

> "The founder is always like a chimney sweep, covered with charcoal and distasteful sooty smoke, his clothing dusty and half burned by the fire, his hands and face all plastered with soft muddy earth. To this is added the fact that for this work a violent and continuous straining of all a man's strength is required, which brings great harm to his body and holds many definite dangers to his life. In addition, this art holds the mind of the artificer in suspense from regarding its outcome and keeps his spirit disturbed and almost continually anxious. For this reason they are called fanatics and are despised as fools. But, with all this, it is a profitable and skillful art and a large part is delightful."

Biringuccio gives us our first insight into methodical foundry practice. That is, insofar as foundry practice was, or one might add, is methodical. Good founding is not a matter of fortune, he points out but requires skill and diligence. Good clay must first be obtained but an assessment of its qualities must depend upon trials. It should be "neither unctuous nor lean, neither wholly tender nor rough." It should dry without cracking, hold its shape and resist fire.

As to gating and venting molds, Biringuccio is frank: "*The more vents you make in your molds and the wider the entrances, the surer you will be of a good result in your casting, if you have melted well. I neither know nor am able to say any more about this.*"

That a careful selection of alloys could produce a better product was emphasized: "*It is possible with alloys to reduce considerably the ordinary measure hitherto used and to make guns lighter, a thing that results in easier moving of them and a great saving in expense to the patron who has them made.*" While Biringuccio seemed to appreciate the unpleasantness of gun making, he described it in detail, as well as the manufacture of iron cannon balls.

In a section on bell making, Biringuccio's book contains a surprising description of how cracked bells may be salvaged by welding them. The bell is laid in a pit and a core is fitted inside the bell. A furnace is constructed so its flame impinges on the cracked part of the bell and, when it reaches the right temperature, melted bell metal is poured on.

Following are a few comments of Biringuccio's on diverse subjects – and remember they were made over 500 years ago – which indicate a clear perception of his subject.

On Alloys: "*Alloy signifies nothing but the mixture of one metal with another in friendly companionship.*"

On Steelmaking: "*Steel is nothing more than iron, well purified by means of art and given a more perfect elemental mixture and quality by the great decoction of the fire than it had before.*"

On Wire making: "*Wire is drawn of every metal excepting tin and lead because of the need of strong bindings, which must enter the fire while bound.*"

And we close this chapter with a fascinating chapter heading quote from Biringuccio's book -- although perhaps some of its wistfulness is due to translation.

"*Discourse and Advice on how to operate a mint honestly and without profit.*"

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Man, Metals and Magic: The Ancient History of Metallurgy

"1500 A.D. – 1850 A.D."

Chapter VIII

In Chapter 6 we left England's iron industry in a perilous position caused by the Acts of Parliament, which severely restricted the cutting of timber for charcoal burning. Critical situations are particularly interesting to examine retrospectively, and this one is peculiarly significant. Between the end of the 16th century and the beginning of the Industrial Revolution (about 1760), iron making in England passed through a phase that may be experienced again, when in no more than 100 years, Britain will be faced with a coal famine far more critical than the timber shortage of 1580.

The use of coal as a substitute for charcoal had never been seriously considered, although its value as a fuel had been exploited since Roman times and possibly before. The objection to coal for iron making was based upon the volatile constituents that are evolved on heating and which contaminate the iron. It was through a strange oversight that, while man knew how to drive the volatile matter from wood by burning it to charcoal (a familiar process since the very first days of smelting), the idea of applying the same technique to coal was so long unrealized. Charcoal was made by incompletely burning a pile of wood covered with earth and leaves. When the bottom of the pile was fired, some of the wood burned completely and heated the rest of the pile, which surrendered its volatile constituents, thereby producing charcoal – in an inefficient but happily rural way.

This was the sort of process that the early patentees may have had in mind at the beginning of the 17th century when they suggested, as Simon Sturtevant did in 1612 when he said, "*coal could be ridded of those malignant properties which are averse to the nature of metallique substances.*" Whatever these processes were (for they were all mysteriously disguised), they failed. Then, in 1620, Lord Dudley took out a patent on behalf of his son, Dud Dudley, for "*melting iron ewre and of making the same into caste workes or barrs with sea-coles or pit-coles in furnaces with bellowes.*" From the text of the patent rights, it seems that Dud Dudley suggested using coal and not any semi-burnt product. He tried out his scheme in some of his father's furnaces in Worcestershire but with indifferent success. The iron makers were averse to the scheme, and it is said that they instigated riots at his foundries and slit the bellows of Dudley's furnaces – taking the wind, as it were, out of his sails. A further setback was caused by Britain's Civil War of 1642-49, when Dudley joined the Royalists. He later tried again to smelt iron with coal but was unsuccessful.

Dudley has his place in history in spite of ill-success, for his efforts eventually led to more fruitful attempts to use coal in iron making. However, it was not until about 1715 that Abraham Darby produced coke. Another 30 years passed before it was regularly used in any ironworks. By this time, England's iron industry had deteriorated sadly. During that Civil War many of the Sussex forges and furnaces were destroyed, and the continued fear that England's navy would suffer from a lack of timber caused ironworks in the Forest of Dean to be dismantled soon after the Restoration in 1660. From this time onwards iron production dropped progressively, until in 1740 there were only 59 furnaces in the whole of England and Wales, each making less than 300 tons of iron per year. Britain's previous abundance of iron had made her so dependent upon it that she consumed much more per head of population any other country in Europe. Now, to meet her demands, imports had increased enormously – to approximately 30,000 tons in 1740.

Imported iron was largely obtained from Sweden, Russia and Norway, and, in the 18th century, from North America. The first English colonists who settled there (Jamestown, Virginia) lost no time in exploiting the natural resources of the country, for in 1608, only a year after their arrival, they exported a few tons of iron ore to England. And in 1619 there began an ill-fated scheme to build an ironworks in Virginia. This was first delayed by the deaths of the men in charge, and later the attempt was abandoned completely after the Indian massacre of 1622 at Falling Creek, near Richmond.

The first rating producer of iron in the United States was a plant established at Hammersmith, Massachusetts. Although this ironworks suffered continual financial setbacks during most of its existence (1644-78), it was an ambitious venture. Even though it did not remain in operation for many years, it trained men who subsequently constructed and operated other, better fated, ironworks. Less tangibly, it represented a remarkable industrial exploit whose eventual issue was the thriving contemporary iron and steel industry of the United States. Other plants had been built by 1678, and they were producing enough iron to export to England. The American iron industry has not looked back since.

It was not until the mid 18th century, however, that iron production in Britain showed any improvement, and this new life was to be short-lived. The use of coke in iron making was now accepted, and new furnaces and forges were established – not in the forest, but on the coalfields. As a result of the good quality of coal and increased demand for iron, the industry expanded rapidly. During the next 100 years Britain was the greatest iron producer in the world.

The important aspects of these 200 years of iron making are: (1) the manufacture of coke overcame the problem of timber shortage, and without coke making it is difficult to believe that industrialization would have occurred, and (2) North America has already and so early crept into the picture.

But in presenting this account of the fall and recovery of British iron making and the birth of American industry, we have skimmed rapidly a period of two centuries, which included many other important advances that were to contribute during the next 100 years or so to the spectacular progress of European industry.

The Reign of Western Europe

From this point our account becomes geographically centered on Western Europe. As far as metallurgical advance is concerned, the East, which last shone brightest during the Arab conquests, has long passed its heyday. The North American continent has not yet predominated the scene. Western Europe, led by Britain, is to enjoy a period of a few hundred years when it leads the rest of the world in production as well as in the research and discovery, industrial and more purely scientific, that made its industries thrive.

One achievement was the establishment of the steel making process that was to be the forerunner of modern day techniques. This was the crucible process, introduced in 1740 by Benjamin Huntsman, a Doncaster clock maker. Although it was basically similar to the Indian method of making Wootz steel (and therefore, like almost everything else, cannot be said to be entirely new), this was the first steel melting process sufficiently reliable to be accepted and used in many parts of the world.

In making his clock springs, Huntsman was obliged to use “shear steel,” which was produced by forging bars of “blister” steel together until the irregular carbon content across the section had been fairly well evened out. Despite these efforts, however, the steel was not sufficiently homogenous for Huntsman’s purposes. As a result, he reconceived the idea of melting and casting the metal to produce a uniform product. To keep his secret he moved to the small village of Handsworth near Sheffield and conducted his researches there. His greatest obstacle was to find a sufficiently refractory material for making his melting crucibles.

At length this difficulty was overcome, and by 1770 the steel made in Huntsman’s factory near Sheffield was acknowledged to be far superior to blister steel. The process involved melting blister steel with a flux in a clay crucible about one foot high, which was surrounded by an air-blown coke fire to produce the necessary high temperature. After five hours or so, the metal was cast into ingots and subsequently forged. It was hard and strong and would take a fine edge. It therefore came to be used for making knives, blades, and razors,

Sheffield, already known for its steel, became famous and many legends grew around it. One of these was that the water in Sheffield was superbly efficient for quenching purposes, and that this was in some way responsible for the good properties of Sheffield steel. Until the late 19th century, water was sometimes shipped from Sheffield to steelmakers in other parts of the world, who attached an almost religious belief to its powers.

Huntsman's steel was very expensive, and its use was necessarily limited to tools and special machine parts. It had no constructional application as no one thought seriously of using steel in a big way. But the process was more than a method of making high-quality steel for it showed the way to the more economic processes introduced by Bessemer and Siemens in later years.

Crucible steel was first made in the United States about 1812. The early experiments were not successful. However, when good quality clay was found for making the crucibles, the situation appeared more hopeful. It was not until two brothers named Garrard emigrated from England to Ohio where they established the Cincinnati Steel Works that a good grade of crucible steel was being regularly made by 1832. The financial disturbances of 1837 were responsible for closing the plant, and after that date and for many years thereafter, imported steel undersold the American product. Crucible steel making reached an all-time high in the United States at the surprisingly late date of 1916, when 130,000 tons were made. But this represented only 0.3% of the total steel production of that year.

As illustrated by this brief account of the development of iron making and the introduction of steelmaking in the 17^{th} and 18^{th} centuries, western Europe only gradually became ready for what is so inappropriately called the Industrial Revolution – inappropriate, because the process of industrialization was essentially evolutionary.

An industry that was later to flourish with steel manufacture was that of making tin-plate. The date at which tinning was first practiced is as obscure as the date at which tin was first made. However, in 1620 the art was introduced into Saxony from Bohemia where it had sprung up, and according to Andrew Yarborough, it was brought by him to England in 1670, when a plant was opened on Monmouthsire Wales that was not to become firmly established until 1720. (Perhaps it should be made clear here that tin plating is not an electrical process like, for example, chromium plating. It essentially involves dipping sheet iron or steel into molten tin, which adheres to the sheet, solidifying to form a protective and fairly non-corrosive film.) During the late 18^{th} century the canned food industry developed, and contributed very largely to the expansion of the world's tin trade, and grew to eventually consume about one half of the world's tin production.

The manufacture of tin-plate was only one of the industries that grew in Wales. The wire drawing trade was expanding as well. This was largely made possibly by the erection at Tintern, Monmouthshire in 1567 of the first water powered works. In 1566, very rich copper deposits were discovered in Cumberland and zinc was found in Somerset. The Society of the Mineral and Battery Works was granted the monopoly of manufacturing brass and iron wire (1568) and by 1605 many different grades of wire were made by them or by their lessees. Most of the wire was used for wool carding – for the wool industry was flourishing. In 1630, a Royal Proclamation prohibited the importation of any foreign wool cards and also the trimming and resale of old ones. The remainder of the brass wire was used for making pins. It is a remarkable fact that, although pins were made by hand, a good worker produced up to 24,000 pins each day.

The monopoly, however, eventually resulted in a lack of development in the industry. This led to an Act of Parliament in 1689, which removed restrictions on the mining and use of copper. Authorities have not always acted so commendably. Increased accessibility of copper resulted in the erection of many battery works – so called because of the way the metal was hammered into sheets. These increased the exploitation of and founding of more uses for copper and its alloys bronze and brass.

Most of the copper ores mined in England, as well as the imported ones from Spain, were smelted in South Wales at Neath, and later at Swansea, where by the middle of the 18^{th} century, coal was used instead of charcoal. It was in Wales that the reverberatory furnace was developed. Its essential difference from the blast furnace is that the fuel and ore are not in contact with each other. The early reverberatory furnace consisted of a shallow rectangular hearth over which hot gases from a coal fire were drawn by a good draft, and the heat was reflected on the charge by a low roof. It was particularly suited to the smelting of sulphide ores (where treatment was a complex operation) because it was easy to control. Whereas the descending charge of a shaft furnace could not be readily adjusted, the reverberatory furnace allowed conditions of temperature and atmosphere to be altered, and each charge could be dealt with separately. Although the copper smelting process has changed considerably since those times, the reverberatory furnace continued to be quoted in textbooks as being the better process.

Britain became by far the largest producer of copper, and during the 18th century found a greater use for the metal in the alloy with zinc. Heating copper surrounded by zinc ore and charcoal first made this alloy, brass. Since that time it had been discovered that brass could be produced by melting metallic zinc and metallic copper together. This necessitated the production of metallic zinc, a process that Europe learned from the Chinese about 1730.

Zinc smelting is complicated by the fact that the temperature at which reduction takes place is above the boiling point of the metal. Zinc vapor is there produced, which is so readily oxidized that the production of pure metal is difficult. The process that became established in England about 1740, involved heating the carbonate ore of zinc with charcoal in a sealed clay pot with a tube inserted through its base. The vapor did not oxidize, for the atmosphere in the pot was mainly of carbon monoxide, and metallic zinc trickled down the tube. By 1760, a process had been patented in England for roasting the sulphide ore of zinc to convert it to oxide, which was subsequently reduced to metal in the same way. The distillation process developed in Silesia and in Belgium, and eventually consisted of heating clay retorts containing the charge, while the metal was collected in clay condensers that were luted on the mouths of the retorts. For some time European use of zinc was limited, and the metal was of greatest value as an export. Gradually, it found applications, particularly in brass, which is fairly strong, easily cast and will withstand corrosion. So it became used in engine parts, valves, pumps, and in the machinery that was rapidly finding use in expanding industries.

Just as zinc production in England depended upon an art learned abroad, so the development of England's lead industry during this period was largely due to foreign skill, for Germans had been brought to the country during the reign of Queen Elizabeth I (1558-1603) to improve the techniques and production of that industry.

The Crown also encouraged mining enterprises. Restrictions on felling timber were more completely removed and the burdens of taxation were eased. As a result, Derbyshire and Cumberland became fairly productive regions for a time of both copper and lead. Many of the ventures petered out, however, by the middle of the 17th century, due to a number of factors to which Britain's Civil War were contributory. After a period of inactivity, lead smelting was revived and from about 1750 for the next 100 years, England experienced her brightest period in lead production.

The reverberatory furnace was introduced into Derbyshire lead smelting in the mid 18th century, and replaced the "ore hearths" that had previously been used there. The ore hearth was essentially a small shaft furnace with an opening on one side from which some of the charge could be pulled out onto an iron plate, where it was worked to remove slag and encourage the oxidation of the sulphide. As the ore hearth required the use of charcoal, the coal-fired reverberatory furnace was a popular innovation. In some localities the ore hearth remained in use and with the advent of coke it regained a little popularity. English lead production was already great and increasing. From the early 17th century, metal and ore were exported to the Continent where the Dutch (who were more skilled in these matters than the British) extracted silver from them.

Progress was not limited to industrial production, however. In 1751, Cronstedt in Sweden isolated nickel. The metal had been unwittingly used from very early times in iron of meteoric origin, but Cronstedt was the first to produce it as a metallic element. Like several other metals, the possible uses for nickel were not realized for many years.

Although compounds of arsenic and cobalt had been known for a long time, it was not until the turn of the 17th century that the existence of the elements was appreciated. Schroder prepared arsenic in 1694, and Brandt recognized cobalt as an element in 1735. Antimony and bismuth, mentioned by Agricola in *De Re Metallica*, had been investigated and their properties determined by the middle of the 18th century.

In 1754, Marggraf (a German chemist, better known for his detection of sugar in beet) recognized that alumina (aluminum oxide) was a distinct mineral, and some authorities hold that he identified the metal aluminum. This is somewhat doubtful for metallic aluminum was first produced by Wohler 70 years later, in 1828. And aluminum production on a commercial scale was not made an economic proposition until 1887.

These discoveries and investigations had direct effects that are readily apparent, but it is more difficult to analyze the results that other scientific research of the period had on metallurgical practice.

The 200 years from 1550 were rich with scientists and philosophers – Newton, Galileo, Boyle, Huygens, Gilber and many others – who contributed to the natural sciences. Since the days of the early alchemists (the later ones had become so obsessed with hopes of finding the Philosopher's Stone that their factual observations and logical argument suffered) this was the most fruitful era in scientific and philosophic thought.

Perhaps, in a metallurgical context, Boyle should be specially mentioned, for if he was the father of modern chemistry, then he was certainly the unsuspecting godfather of the metallurgical sciences. Although many of the scientists and thinkers of the time were able to take the Greek philosophies as a starting point, Boyle fortunately rejected the Four Element theory, which had grown so out of hand, and differentiated between elements, compounds and mixtures. Confusion between elements and compounds was apparent in the comparatively lucid *De Re Metallica*. A distinction between them was vital before there could be an understanding of the chemical reactions during metallurgical processes.

The Industrial Revolution

This summarizes the state of affairs before the Industrial Revolution overtook Britain. Then, the inventions of Hargreaves, Arkwright, Crompton and others mechanized the textile business, and spinners and weavers were forced to abandon home industry to contribute to the output of the factory where the new machinery had been installed. At first the mills were water driven, and they were built in the northern counties of England, where such power was available. Before long the steam engine was introduced, and the industries, already firmly established and fortunately placed with respect to coalfields, remained.

The first application of a steam engine, so primitive that we would probably not recognize it as such, was in draining coalmines in the early 17th century. Through the work of Savery, Newcomen, Boulton, Watt and Murdoch (not to mention Polzunov, the sole Russian inventor) the machine was developed and improved. By the end of the 18th century it had been applied to mining for pumping machines, to smelting for actuating the blowers, and to driving the looms and other equipment of the textile industry. The engine, itself depending largely upon iron components, increased iron production in pit and smelter as well as increasing the iron consumption in the factories.

In this way, and in the mechanization of many industries transplanted from the home, the demand for iron grew. While cast iron was suitable for many purposes, its brittleness prevented really extensive use. The process introduced during the 16th century for "fining" cast iron was mentioned in Chapter 7. Its inherent disadvantage lay in the conflict between the air blast decarburizing the iron, and the charcoal in intimate contact recarburizing it.

Understandably, it was necessary to use a powerful air blast to keep things going the right way. This in turn burned up a large amount of charcoal. To add to this metallurgical struggle the hearth was often water cooled, and water was thrown on the charcoal to prevent it burning too quickly. All these factors make up so difficult a balance sheet to explain away, that it is relieving to find that in 1784 Henry Cort patented an alternative process.

The essential difference of his process was that contact between the fuels and iron was avoided, for Cort successfully introduced the reverberatory furnace into iron metallurgy. Probably the earliest application of the reverberatory furnace to iron making was in 1766 by the Cranege brothers. However, Cort effected so many improvements that the process became an accepted practice, rather than a curious exception. The possibility of carburization was eliminated and with it, the extensive blowing machinery that had been necessary.

In Cort's process – the "puddling process" as it came to be called – the hot gases from a coal fire were drawn over pig iron that was charged on the furnace hearth. The charge melted and was oxidized by additions of iron oxide (in the form of iron ore or mill scale). These additions also contributed to the bulk of iron that was produced. As oxidation progressed, the charge was stirred by the furnacemen using long iron rabbles. As it became pasty, it was worked into balls weighing about 80 pounds each, which were subsequently forged into salable shapes.

Cort's process yielded the metal that we have come to accept as wrought iron. It was not only low in carbon, but in silicon, manganese and phosphorus – elements that are present in pig iron and contribute to its brittleness. This new material unavoidably contained slag, just as the earliest smelted iron did. However, as this was strung out into fibers by the forging operation, it was not harmful. On account of its malleability, wrought iron found many applications, and until the late 19th century, it was the most valuable constructional metal.

Another equally important development due to Cort was the use of grooved rolls to make wrought iron bars, which he patented in 1783. Rolling mills, like reverberatory furnaces, were known before Cort applied them to the iron industry. Indeed, it is questioned whether he was, in fact, the first to introduce them to iron rolling. Whether he did or not, he did not benefit by his ingenuity.

When he contracted to make rolled iron for the Royal Navy, Cort invested his entire fortune in expanding and developing his process. He went into partnership with Samuel Jellicoe, whose father, the Deputy Paymaster to the Navy, contributed over 50,000 pounds, and was to receive half the profits that accrued to the partners. In those days, apparently, such a transaction was more openly made than in modern times. In this case, the British Government itself sanctioned the partnership. But even contemporary opinion did not allow Mr. Jellicoe Sr. to borrow 27,000 pounds of his capital from the Navy accounts. On his death in 1789, when this was discovered, Cort's patent rights were confiscated and Cort was removed from his rolling mill. Strangely enough, Samuel Jellicoe was put in charge. This action led both to the prosperity of British ironmasters (for the no longer had royalties to pay) and to Cort's ruin. But Cort's contribution to British industry, unrewarded as it was, resulted in vastly increased iron production – from about 18,000 tons a year in the mid 18th century to 4,000,000 tones in 1820.

While the causes of the Industrial Revolution to Britain are as complex as the historian cares to make them, there could have been no subsequent effects had it not been for the manufacture and use of wrought iron. Britain showed her metallurgical ability, too, in developments in extracting metals, the exploitation of mineral wealth, the manufacture of steel and a growth of industries that depended upon basic metal making processes. These, although they did not precipitate a revolution, at any rate induced the new era. Britain was the first country to experience the glories and infamies of industrial prosperity.

Summary

The years that we have covered so far – from an uncertain date thousands of years ago to the beginning of Europe's industrial era – complete what may be called Metallurgical Ancient History. As time permits, we hope to add a profusion of developments that took place between 1850 and the close of the 20th century. Until then, we hope you have enjoyed this brief journey along the metals road and the survey of the ancient history of metallurgy.

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