MINING, METALLURGY, AND THE INDUSTRIAL REVOLUTION

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MINING, METALLURGY, AND THE INDUSTRIAL REVOLUTION* PART 1

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ABSTRACT


INTRODUCTION

A country’s mineral resources represent an important national wealth. Localization and exploitation of this wealth require knowledge of geology, mining, and metallurgy. The eighteenth century was the century of the Industrial Revolution as well as the Chemical Revolution led by Lavoisier. It was also the beginning of mining and metallurgical education when schools of mines were created to teach future miners, metallurgists, geologists, and other industry technicians. For a long time, education was in the hands of the clergy and there was general apathy for introducing engineering disciplines in universities. Military activities, especially after the introduction of gunpowder, necessitated the distinction between a military and a civil engineer. The education of the civil engineer grew slowly from an apprentice system to a highly specialized academic discipline. Architects became a distinct group from civil engineers in the Middle Ages during the construction of the great cathedrals.

When the steam engine was introduced in the eighteenth century, mechanical engineers were organized in a separate group. When mechanical engineers drained water from coal mines and the exploitation of these mines started, the profession of mining engineers was created followed by that of the metallurgical engineers who transformed the coal into coke for iron production in blast furnaces, and iron into steel. The processing of coal tar, produced as a by-product of the coke industry, led to the creation of the chemical engineer in the nineteenth century. This was later developed further, particularly in North America, when the petroleum industry was founded. During nearly the same era, electrical engineers became organized to effectively deal with the numerous power stations generating electricity to serve industry as well as other societal needs.

The first attempts at providing an organized mining education in Europe were made in Germany. In as early as 1702, there was a school of mining and metallurgy in Freiberg, which in 1765 acquired the name Bergakademie. Schools in other countries followed suit. British engineering education, however, took on a different form. There, the aspiring engineer began with an apprenticeship with a working engineer. The explanation for the disparity is partly found in the early success of the British industry. The leading figures of the Industrial Revolution there were not formally trained engineers, showing that people with no theoretical training could develop new technologies. This eventually transformed society and earned England a worldwide reputation as an industrial nation.

Important books dealing with economic problems were published, such as The Wealth of Nations by Adam Smith in 1776. In this work, Smith argued in

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* This is an expanded version of a paper presented at the International Conference honouring Vasily N. Tatseshev (1686-1750) held at Astrakhan State University in Astrakhan, Russia, on October 14-16, 2004.
favour of free trade, among other things. The eighteenth century was also the century of systematization. In Sweden, Carl Linnaeus (1707-1778) proposed a system for flora and fauna, Axel Fredrik Cronstedt (1722-1765) classified minerals according to their chemical composition, and Denis Diderot (1713-1784) published the Encyclopedia in Paris between 1751 and 1777 documenting the technology of that time.

EIGHTEENTH CENTURY METALS

In the eighteenth century, mineralogists, travellers, and analysts played an important role in the discovery of new metals. Mineral specimens from different localities were continuously supplied to laboratories where they were analyzed. As a result, 14 new metals were discovered in addition to the seven metals of antiquity and the three metalloids of the Middle Ages (Fig. 1). In order of their discovery, they are: cobalt, platinum, zinc, nickel, manganese, molybdenum, tellurium, tungsten, uranium, zirconium, titanium, yttrium, beryllium, and chromium. None of these new metals, however, played a major role at that time as compared to the ancient metals.

Nonferrous Metals

The alchemists had endeavored to manufacture gold by transmutation of base metals. It was not until the end of the eighteenth century that the concept was finally rejected. However, these endeavors led to a better understanding of chemical processes and to the birth of the natural sciences. Although the conquistadors found a highly developed mining industry in Central America, their efforts to increase gold production were largely unsuccessful. Most of the finds consisted of silver. It was not until the discovery of deposits in Brazil in 1693, and on the eastern slopes of the Ural Mountains in 1750, that gold production increased significantly.

Apart from its use for a great variety of vessels and utensils, copper was also used in very large quantities to make brass, an alloy of copper and zinc much prized for its resemblance to gold. A high proportion of copper sheet was also used for sheathing the bottom of ships. Mercury was needed for the recovery of gold and silver by amalgamation, the only method then available, hence its importance because both metals were needed to mint coins. Tin was used in large quantities for the production of bronze, bell metal, solder, tinplate, tin foil, and a form of tin amalgam to make mirrors. Lead sheets were used for roofing, piping, and the new lead chambers for making sulphuric acid, invented in 1741 by John Roebuck in England.

It was profitable to extract silver present in lead and copper ores because of the high value of the metal. Silver was removed from lead by cupellation, while that in copper by first fusing the copper-silver alloy with a large excess of lead at a temperature below the melting point of copper. The lead flowed off carrying with it most of the silver—a process known as ‘liquation.’ The lead was then removed by cupellation. Silver was removed from low-grade ores by amalgamation. Both gold and silver recovered were impure and required refining by melting again with lead, followed by cupellation.

Ferrous Metals

The reduction of iron ore to produce metallic iron took place in ancient times in a small furnace two to three metres high, charged with lumps of iron ore mixed with pieces of charcoal prepared from timber. Air required for burning charcoal to supply the necessary heat for reduction was supplied by small bellows. The ore lumps were reduced to iron but not melted because the air draft was not strong enough to generate the high temperature needed for melting. When the furnace was cooled, the lump of metallic iron mixed with partially melted gangue minerals and slag was then removed from the furnace, heated, and hammered to get a consolidated metallic product known as “wrought iron” (Fig. 2). A furnace of this type would produce one or two
kilograms of malleable iron per day, which was enough to supply the needs of that time.

To increase productivity, larger furnaces were built with larger air bellows mechanically operated by large water wheels. As a result, the temperature increased, and the iron produced melted in the furnace. Some iron was tapped directly into moulds in the casting house and the remaining was collected by allowing it to drain into sand moulds (called “pigs”) prepared in the immediate vicinity. The product contained much dissolved carbon and was suitable for casting many items because of its high fluidity. A furnace of this period would be 5 metres to 10 metres high and would produce 10 or 20 tons/day of iron. The maximum size of the furnace was limited by the mechanical strength of the charcoal.

To produce a high-quality iron for tools and knives, it was necessary to refine this iron in what was known as a ‘finery.’ Small pieces of the iron were re-melted in an oxidizing atmosphere to remove as much of the carbon as possible to produce a malleable product equivalent to wrought iron. In 1614 in Birmingham, Mathias Meysey and William Ellyott invented the “cementation process” to make a high-quality product known as ‘blister steel.’ In this process, bars of wrought iron were embedded in charcoal and sealed in chests that were maintained at red heat for ten days. The iron absorbed carbon, but the steel was more highly carburized near the surface than at the core.

Charcoal

Charcoal, the backbone of the iron and gunpowder industries, was produced in piles (Fig. 3). A nine metre to 12 metre diameter flat surface of the forest floor was cleared in which a pole about 3.5 metres long was erected in the centre. Wood was then stacked in four layers around the pole to form a cone-shaped pile. The pole was then removed, and wood chips and kindling were placed down the central chimney hole that was formed. The pile was then covered by a layer of leaves and finally a layer of soil. The charring process started by lighting the wood chips and kindling in the chimney from the top of the mound. To allow air into the pile to drive out the moisture and burn the volatile matter without burning the remaining charcoal, holes were poked through the soil layer. The charring process starts from the top down and requires 10 to 14 days to complete. The soil layer was then slowly raked from the top of the pile to the ground and piled for future use. The remaining charcoal was about one-third the original pile of wood. It was allowed to cool and was then transported to the iron-making site.

Charcoal was later made in brick kilns, either rectangular or conical in shape. These had a manhole on the top for charging the wood, a door at ground level for raking out the finished charcoal, and several holes around the circumference of the kiln to control the air inlet. The operation of kilns was similar to that of the pits. The problem with this technology was, however, that it led to deforestation and gradually increased the cost of production. A furnace producing 20 tons/day of pig iron consumed about 200 tons of charcoal which were obtained from 0.8 acres/day of forest, or 292 acres/year. Once all the local trees were cut down, wood or charcoal would have to be transported from far away, usually by wagons drawn by horses, which meant additional cost.
MINING, METALLURGY, AND THE INDUSTRIAL REVOLUTION *PART 2*

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THE INDUSTRIAL REVOLUTION

The Industrial Revolution started in England in the eighteenth century and occurred in two stages: the first, when coke replaced charcoal in 1709, and the second, when the steam engine became widespread in 1780s. As a result, pig iron was produced in increasing quantities for machinery and construction purposes. Today, the yearly production of iron exceeds that of all other metals combined over a ten-year period. It is a huge industry that started from a modest furnace producing 1 to 2 kg/day of metal to a gigantic reactor producing 10,000 tons/day.

The Use of Coke

Once coal mining became safer, there were many unsuccessful attempts made to replace charcoal by coal. The problem was solved by first transforming coal into coke. The Industrial Revolution was led by Abraham Darby I (1677-1717) of Coalbrookdale near Birmingham in 1709 when he substituted charcoal with coke. Coke is produced from coal by baking; it is porous and can withstand high mechanical pressures. Hence, larger furnaces were built which resulted in a further increase in production. Coal could not be used because it contains appreciable amounts of objectionable sulphur impurities, and also because it softens during heating and renders the charge impermeable.

Coal mining was also unsafe because of the natural gas explosions until Humphry Davy introduced a safety lamp for miners. Further, a great effort was needed to pump out the water flooding the mines. Using coal solved the problem of cutting down trees from the forests which were needed to build ships and homes. The Coalbrookdale furnace at night was captured in a painting by a contemporary artist (Fig. 4).

Coke became available at a much lower cost than charcoal, however, iron produced using coke was of inferior quality because of the large amount of impurities. Coke was first produced by piling coal in mounds and partially burning it out in the open air in the same way charcoal was made. Beehive ovens replaced the open air method in 1763 in which the volatile matter was burned to supply heat for carbonization. The first attempt to recover the volatile matter was with the horizontal retorts system. The gas collected was known as coal-gas and was first used for illumination and later as fuel; large batteries of vertical retorts are now used. Volatile matter collected proved to be an important source of chemicals. The distillation of the tar and the separation of its different components became the basis of the organic chemical industry in the nineteenth century. Today, a coke manufacturing plant is a battery of hundreds of vertical retorts assembled together.

Fig. 4. Coalbrookdale at Night, a contemporary painting by Philip James de Loutherbourg (1740-1812), now hangs in the Science Museum, London.

Pig Iron

Pig iron produced in the coke blast furnace contained 3% to 5% carbon and other impurities which were not present in the iron produced in the charcoal furnace. It was hard and brittle, and of inconsistent composition, but was cheap and of high fluidity which simplified casting. Pig iron was used for making pots and pans, fire grates, anchors, cannons, cannon balls, and some machine parts, especially those needed for steam engines. This was particularly important in terms of warfare as before the arrival of pig iron, cannons were made of bronze or brass which were more expensive. Once blast furnace technology using coke was established, efforts were made to save on coke consumption and to cope with increased productivity. This took place, however, in the first half of the nineteenth century.

The availability of large deposits of iron ore and coal, and the undesirability of reliance on charcoal for iron smelting, were stimuli for technical development. The production of large amounts of iron allowed for the casting of a large number of cannons as well as the production of armoured plates for battleships. As well, in 1779 it led to the construction of the first bridge made of iron in the world (Fig. 5), located across the Severn River near Coalbrookdale. The importance of this bridge lies in the fact that although iron had been used for thousands of years, it had not been used in a major construction project because there was not enough of it. Outside Britain, the adoption of coke furnaces proceeded very slowly. From 1781-1785, the first continental coke furnace for iron smelting was erected at the...
In 1784, Henry Cort (1740-1800) invented the ‘puddling process’ in which by careful control of air and time of heating in the puddling furnace, it was possible to directly transform pig iron into cast steel (Fig. 6). The goal was to retain a sufficient carbon content in the product to render it hard but not brittle. The correct conditions for this were determined by experience since the role of carbon in steel was not yet known. The process was tedious and expensive; in the early furnaces, it took three to four days at high temperatures to produce a few hundred kilograms of the product, but this was the price to pay for a high-quality steel. This cast steel was used for making special tools, knives, springs, etc. However, many puddling furnaces were later constructed, the process was mechanized, and the material became so popular that Gustave Eiffel used it to construct his 7,300-tonne tower in 1889 on the occasion of the hundredth anniversary of the French Revolution.²

The influence of steel's carbon content upon hardness was not realized before 1750. The first to analyze carbon in iron was Toberm Bergman (1735-1784), a Swedish chemist. A thesis on this topic was submitted by Johannes Gadolin, a student of his, in 1781 at the University of Uppsala. A few years later, French chemist Guyton de Morveau (1737-1816) arrived at the same conclusion—the conversion of iron into steel was due to its combination with carbon.

The Steam Engine

The steam engine came at a time when wood was used as the main fuel for industry and households. Wood was also needed for the construction industry and for shipbuilding. The steam engine required a huge amount of fuel which could not be satisfied by the shrinking forests. As a result, attention was directed towards the exploitation of coal. Once the safety lamp was invented and coal mining became relatively safe, the industry started to shift from a wood burning to a coal burning economy. The steam engine was responsible for solving the problems in the iron industry. The growth of the industry suffered from the following:

- Water power was neither abundant nor reliable. Power was needed for operating the pumps to drain water from coal mines, bellows to blow air in the blast furnace, hammers for forging, and rolling mills.
- The use of coke necessitated a more powerful blast than that obtained from water-driven bellows because of its higher ignition temperature.
- A cheap way to transport coal in bulk to the coke-making plant which was located near the blast furnace.

The steam engine was invented to fulfill these needs. The idea of using steam for doing work goes back to 1695 when Denis Papin (1647-1712), a French Huguenot who found refuge in England in 1679, demonstrated this principle in a simple model. Newcomen’s machine, invented in 1712, was the first attempt to solve the problems associated with this idea. However, it used large amounts of coal to boil water to generate steam which was then condensed by cold water spray to create the vacuum needed to operate the machine. It was James Watt (1736-1819) who, in the 1770s, successfully built a machine that required less coal by introducing a separate condensing chamber for the steam so that the cylinder could remain hot throughout every stroke. However, it was not until 1784 that the steam engine became a reality and started to replace the water wheel. The bellows were no longer needed and air could be blown in the furnace through tuyeres. In the 1820s, George Stephenson solved the problem of coal transportation by inventing the steam locomotive.

The utilization of ample power was made possible by the steam engine. This had a tremendous impact on industry and commerce, and was also responsible for the second stage of the Industrial Revolution, which can be summarized as follows:

- Work once performed by hand could now be done on machines powered by steam engines.

² It is rather surprising that Eiffel preferred to use puddle steel over Bessemer or Siemens-Martin steel; both were already available at that time. This was confirmed by the curator of Musée du Fer in Nancy, France.
HISTORICAL METALLURGY

- The manufacturers no longer had to depend on the water wheel or the windmill for their source of energy.

- Large cotton mills were established in Lancashire where cotton was imported from the colonies and the textile products were exported back to them.

- Steam ships replaced sailing boats which meant faster transportation at sea.

- A system of canals was created in England for the cheap transportation of coal by water. This was later replaced by trains powered by steam locomotives. Trains also replaced horse-driven wagons which meant faster transportation on land.

- The food industry greatly benefitted from the steam engine. Improved technique for rolling wrought iron plates favourably affected the manufacture of tin plate for food containers and utensils needed for the navy.

The British machine economy encouraged many foreigners to visit Britain for the purpose of studying the new technology. One of these was French government official Gabriel Jars (1732-1769) who visited England in 1764-1765 and wrote his observations in his book Voyages Metallurgiques, published in 1774, five years after his death.

Further Development

The Industrial Revolution continued in England when steel was produced faster, cheaper, and in greater amounts in the nineteenth century when the Bessemer process was invented in 1856. The tedious and expensive ‘puddling process’ could now be replaced by a fast process that did not use fuel—heat required to keep the metal molten was generated by the oxidation of the impurities themselves present in the iron. Tons of pig iron could be transformed in less than half an hour by simply blowing air through the molten metal. The product became known as ‘mild steel.’ A few years later, in 1863, Wilhelm Siemens in England and Pierre Martin in France developed the open hearth furnace that became known as the Siemens-Martin process.

This placed England ahead of other European powers in iron and steel making. As a consequence of the Industrial Revolution, there was an over supply of products and a need for markets as well as for raw materials; colonization was the solution to this problem. In addition to steel making, Britain was the centre for copper, zinc, tin, and platinum metals production. Copper matte was shipped from as far away as Chile and Montana in the United States to be refined in Swansea, Wales. William Champion in Bristol was the first company in Europe to produce metallic zinc from calamine and zinc blend in 1702. Bristol was also a centre for brass manufacturing while Cornwall was a centre for the production of tin. Innovation in spinning and weaving also took place in England as part of the Industrial Revolution.

The Transition from Wood to Coal Economy

When wood was used as a basic fuel, as charcoal in blast furnaces, as a major component in gunpowder, and as a basic material for shipbuilding, a chemical industry based on wood by-products emerged. Wood was the source of tar, pitch, and resin needed as a preservative, particularly for timber for shipbuilding. Potash was recovered by leaching the wood ash with water and was used for making soap and glass. Turpentine was used as a solvent and for making lamp black for inks. Acetic acid was also obtained as a by-product of wood distillation in the form of calcium acetate from which acetone was made by dry distillation. All these were widely used materials.

When coal replaced wood, other industries came into existence, especially when the volatile matter was collected during the carbonization process. Coal gas in the early years of the industry was used almost entirely as an illuminant. Later, gases became a source of ammonia, elemental sulphur (from H2S), and gaseous fuel. The coal tar was distilled to produce a variety of organic compounds like benzene, toluene, phenol, naphthalene, anthracene, etc., as well as pitch. This became the basis of the organic industry for manufacturing dyestuffs, explosives, pharmaceuticals, etc.

Gunpowder made from charcoal, sulphur, and saltpeter remained as the only explosive available during the eighteenth century. It was gradually replaced by nitrocellulose and nitroglycerine and other compounds only at the end of the nineteenth century.
MINING, METALLURGY, AND THE INDUSTRIAL REVOLUTION PART 3

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THE CHEMICAL REVOLUTION

Whether wood or coal were used as a fuel, the nature of the flame generated remained a mystery for centuries. A theory was put forward by German alchemist Georg Ernst Stahl (1660-1734), in 1723, to explain combustion; it was called the “phlogiston theory” stemming from the Greek word meaning flame. According to this theory, everything that can be burned contains a phlogiston which escapes in the form of a flame during combustion. Phlogiston could be transferred from one body to another, and resorted to the metallic claves by heating it with substances containing phlogiston, such as charcoal, coal, and oil, when the metal was produced.

Metal ⇔ Calx + Phlogiston

When bodies burn or are calcined, phlogiston escapes. When the original bodies are recovered by reduction, phlogiston must be replaced. Oil, wax, charcoal, and sulphur, which are all combustible bodies, are rich in phlogiston and may be used to restore bodies to a burnt material from which phlogiston has escaped. For example, when heating zinc to redness, it burns with a brilliant flame, hence phlogiston escapes; the white residue is calx of zinc. If it is heated to redness with charcoal (rich in phlogiston), zinc distills off.

Calx of zinc + Phlogiston → Zinc

It is similar with other metals. If phosphorus is burned, it produces an acid material, and much heat and light are emitted; hence, phosphorus = acid + phlogiston. If the acid is heated with charcoal, phlogiston is absorbed and phosphorus is reproduced. Of importance to metallurgy is the understanding of the smelting process. It was believed that when an ore was heated with charcoal or coal, it takes up the escaping phlogiston in the fire to form the metal:

Ore (oxide) + Phlogiston (from coal) → Metal

It was French chemist Antoine Laurent Lavoisier (1743-1794; Fig. 7) who, in 1772, finally directed the fatal blow to the theory when a few years earlier oxygen was discovered, and he interpreted the phenomenon of combustion as an oxidation process. This opened the way for the reform in chemistry and its application in processes for metal extraction.

SCHOOLS OF MINES

The first schools of mines were established at the beginning of the eighteenth century, usually in mining districts, as private vocational schools. Mining councils, appointed by the rulers, played an important role in recom-mending subsidizing such schools and founding new ones supported by the state. As time went by, these schools were elevated to mining academies. The sciences of forestry and salines are closely related to the mining and metallurgical industries, and formed part of the curricula in some schools of mines. Forests supplied wood for the mines and fuel for the smelters while salines supplied salt for the chemical industry. Some of these schools were started by private individuals; others were created by the ruler or by the state. Gradually, the need for qualified administrators for the mines and smelters, and for teachers for these schools, grew. As a result, some schools were elevated to academies or became technical universities, some were closed due to exhaustion of the mines or other reasons, some were moved to other developing regions, and some remained as vocational mining schools. It was in the Ural district that administrator and educator Vasily N. Tatischev (1686-1750) founded a number of schools in the metallurgical plants that he created.

Methods of analysis for precious metals were well established in what was known as “fire assaying.” One of the basic courses taught at the first schools of mines was metallurgical chemistry. Fire assaying, the predecessor of analytical chemistry, was a major component of this course. It dealt with the determination of precious metals in ores, the use of fluxes, and the formation of slags. It included furnaces, combustion, balances, and numerous chemical manipulations. Students also received laboratory training in this discipline. These laboratories were the first known chemical laboratories and were copied by French chemists in their schools. This concept was further developed in Germany by Justus von Liebig who studied in France in one of these laboratories. Fire assaying was also the
cornerstone in mints to control the quantity of precious metals in coins. Important literature dating from the Middle Ages is available on this subject.

With increased knowledge in metallurgy and chemistry at the end of the eighteenth century, it became necessary to split the metallurgical chemistry course into two: chemistry and metallurgy. This took place for the first time in Freiberg in 1795. The amalgamation process dominated eighteenth century metallurgy. At that time, mercury was as important as petroleum is today, because of its use in extracting gold and silver from ores needed for minting coins, and also because of its use in making mirrors. The toxicity of mercury and other metals, such as arsenic and lead, were known and many metallurgists alerted those responsible for exploiting the mines to their danger. The teaching staff at the schools of mines contributed greatly to the advancement of mining, geology, chemistry, and metallurgy.

**EPILOGUE**

While the literature on non-ferrous metals started with Vannoccio Birungioccio (1480-1539), Georgius Agricola (1494-1555), and Lazarus Ercker (1530-1593) in the sixteenth century, that on ferrous metallurgy started with Rene Antoine Ferchault de Réaumur (1683-1757) about two centuries later in his book, entitled *L’art de convertir le fer forge en acier*, published in 1722. Today, extractive metallurgy is usually divided in two sectors, ferrous and non-ferrous, because of the large-scale operations in the ferrous sector. Steel production in one year exceeds that of all other metals combined in ten years.

Ferrous metallurgists have been leaders in all sectors of the metallurgical industry. For example, the copper industry adopted many technologies first used in iron and steel production. Thus, when Bessemer invented the converter in 1856, it was adopted in the copper industry ten years later. Then, when high-grade massive copper sulphide ores were exhausted and metallurgists were obliged to treat low-grade ores, the puddling furnace was adapted in the form of a reverberatory furnace to treat the flotation concentrates. Continuous casting first started in steel plants and was adopted later in the non-ferrous industry. In general, the copper industry was in the footsteps of the iron industry although the two chemistries are far apart. It is also remarkable that the pioneers of the Industrial Revolution in England did not have any academic training and the first school of mines in England was founded in 1851, nearly a century after similar schools on the continent.

The beginning of capitalism was a direct result of the Industrial Revolution that took place in England and that was based on coal and iron. Iron continued to be the core of the industry, but once petroleum was discovered in North America, the centre of gravity of imperialism shifted from Britain to the United States. The shift became complete after World War II and the new Industrial Revolution became based on petroleum and aluminum. Change is inevitable and progress cannot be stopped; however, it often leads to the loss of skills, experience, and jobs.

**SUGGESTED READINGS**


