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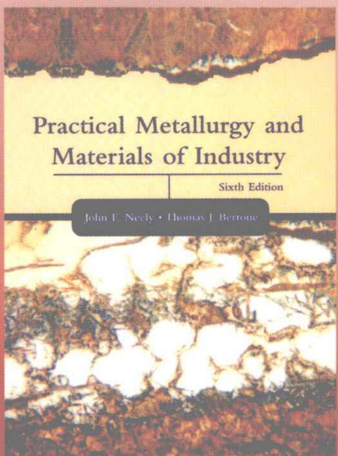
PRACTICAL METALLURGY AND MATERIALS OF INDUSTRY

Sixth Edition

冶金学与工业材料概论

第六版（英文影印版）

John E. Neely · Thomas J. Bertone



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Education

PRACTICAL METALLURGY AND MATERIALS OF INDUSTRY

SIXTH EDITION

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Preface

This textbook on metallurgy and materials is ideally used as an introductory book for both materials science and metallurgy courses and for students whose majors are closely related, such as quality control, machine tool technology, welding technology, and many others. *Practical Metallurgy and Materials of Industry,* Sixth Edition, includes many of the latest industry processes that change the physical and mechanical properties of materials and is highly recommended as a "materials processing" reference handbook in support of design, process, electrical, and chemical technicians and engineers.

The book is intended to be easy to read. We make an effort to explain complex metallurgical terms in clear, practical language within the text. An extensive glossary is also included.

Practical Metallurgy and Materials of Industry, Sixth Edition, establishes a solid foundation for understanding the behavior and characteristics of metals and materials as well as the practices for materials processing currently used in the metals and materials industry. The text also provides the student with a basic understanding of the mechanisms that cause material failures and those that prevent failures.

The highly visual approach in this book uses graphics, drawings, illustrations, and photographs of actual equipment used to produce the alloy and/or perform specific processing operations during product manufacturing. Photomicrographs are often included to show the differences in metals when they are subjected to certain conditions such as heating, forming, or forging.

A reinforcement approach to instruction is used throughout the book by building on previously covered information and by encouraging the student to read the material, use the worksheets, read the case problems, and complete the self-evaluation section at the end of each chapter.

The format of the book is adaptable to the conventional lecture, lab, or individual approach to instruction. Objectives, chapter text, self-tests, and worksheets are intended to help both the student and the instructor: All are consistent in that testing is relevant to the objectives and discussions. The self-test review questions are aimed toward helping the student understand the material. For this purpose, answers to the self-evaluation review questions are found in the appendix. Multiple-choice posttest questions and keys for most chapters are provided in the Instructor's

Manual that is available to any instructor using this textbook. Instructions are also given in the Instructor's Manual on how to set up a simple metallurgical laboratory and on utilizing the text in a variety of educational settings.

It is our hope that students of metallurgy and materials science, machine tool technology, welding technology, quality control, manufacturing, and related technologies will become better prepared by understanding the manufacturing processes that influence the behavior of materials, as well as the materials with which they work.

John E. Neely/ Thomas J. Bertone

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I wish to express my thanks to Mr. Mike Bastian of Accurate Steel Treating, South Gate, California, for his continuing help in providing technical guidance with the latest innovations and state-of-the-art processes for heat treatment of steels.

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Again, my thanks to the many clients of Tom Bertone Consulting, Inc. who were most helpful in providing examples of classic fracture surfaces documented in Chapter 23 on failure analysis. Also, my thanks to Bertone Advertising, Inc., and my son, John T. Bertone, for the preparation and graphics for the fifth and sixth edition book covers.

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Introduction

The ability of human beings to make and use tools is the single most important reason for the tremendous progress leading to our present technological age. The first humans made tools of wood, bone, and stone (Figure I.1). However primitive and crude, the first discovery of metal most likely occurred with humans finding pieces of meteorites and, with time, learning how to pound and sharpen meteorites into useful tools.

The history of the seven metals of antiquity can trace origins back to ~6000 B.C. when humans first discovered gold, and then silver, copper, iron (iron-nickel meteorites), tin, and mercury in a nearly pure or native state. Copper, a red metal, was discovered ~4700 B.C. and widely used for armament and tools by the Mesopotamians, Egyptians, Greeks, Bolivians, Romans, and inhabitants of India and China. Copper was melted and combined with beryllium by ancient Bolivians, who used a long-lost alloying process that scientists today have yet to duplicate. Silver was discovered ~4000 B.C. and widely used with gold as old-world coinage. Lead was discovered ~3500 B.C. The Roman Empire used this abundant, easy-to-form metal to line drinking utensils, pipes, and aqueducts. Tin was discovered ~1750 B.C. and was melted together, or alloyed, with copper by the Egyptians for decorative purposes and to harden and strengthen copper.

Scandinavians discovered rudimentary methods to extract iron from ores by chance observation, finding puddles of metal at the bottom of campfire pits. Humans quickly associated metal-rich ores as the source of the puddle metal and cleverly

(a) (b)

FIGURE I.1 *(a)* Stone saws and *(b)* stone hatchets. *(Courtesy DoAll Company)* observed how wind increased the temperature of fire and the quantity of metal. The addition of a bellows and dried wood to the fire allowed humans to reach the higher temperatures required for the extraction of metal from its ore, thus beginning the technology of extractive metallurgy. The process used to reduce iron ore is believed to have been discovered by the Chinese about 2000 B.C. Mercury, discovered ~1600 B.C., was referred to by the ancients as "quicksilver." The discovery and useful implementation of the metals of antiquity provided our ancestors with the tools necessary for the development and growth of technology and the creation of our modern world.

Somewhere intermingled in the historical documentation and records of the metals of antiquity is the making of the Damascus steel sword. Around 2750 B.C., the first uses of meteoric iron were dated to the Egyptians, and about 2500 B.C., the first iron tools were used in Mesopotamia and Anatolia. Sometime around 2000 B.C., the Hittites in the land east of present Turkey collected the iron ore and melted it in small furnaces. The Hittites are believed to have developed the art of blacksmithing and shared their information with neighboring countries. About 1500 B.C., the first weapons and tool production centers became active in Greece, Cyprus, and Macedonia. The Greeks discovered that quenching improved the cutting edge and increased blade hardness. The process of quenching became common practice around 1000 B.C. Near 600 B.C., the Persian and Etruscan blacksmiths learned how to fire-weld iron, while blacksmiths in India began using carburization and repeated hammering to improve the mechanical properties of iron. During the iron period of about 1000 B.C., the Chinese became aware of Western ironworking and hammering techniques. The Chinese also began producing cast iron and, around 400 B.C., effectively using decarburization to produce steel.

Wootz steel was developed in ancient India about 300 B.C. Wootz is the anglicized version of *ukku,* a term denoting steel, in the languages of the states of Karnataka and Andhra Pradesh. Literary accounts suggest that the steel from the southern part of the Indian subcontinent was exported to Europe, China, the Arab world, and the Middle East. Wootz steel is an ultrahigh carbon steel exhibiting metallurgical properties such as super plasticity and high impact hardness, producing a superior blade.

Pattern-welded steel, with twists and chevron patterns in sword blades, can be traced back to A.D. 100 to 200. The steels are folded and inlaid with cast-iron strips and hammered hot to fuse the metal into a multilayered blade. Pattern-welded steel blades were popular for almost a millennium in Europe but came into decline when Europeans were confronted by Islamic armies wielding sword blades of wootz steel, which were much stronger. Pattern-welded steels regained popularity in Europe around A.D. 1700 and were used for the production of gun barrels until the early nineteenth century, when they were replaced by modern alloy steels.

Today, the use of Damascus steel blades, produced by wootz and pattern-welded methods of manufacturing, has spread in popularity over the entire globe (Figure I.2).

Nearly everything we need for our present-day civilization depends on metals. Vast quantities of steels, aluminum, titanium, copper, and nickel alloys are used for automobiles, ships, aircraft, spacecraft, bridges, and buildings as well as the machines required to produce them (Figure I.3). Almost all uses of electricity depend on copper and aluminum. All around us we see the utilization of aluminum, copper, and steels, often in new applications combining metals with plastics and fiber-reinforced composite materials. Some metals such as titanium and zirconium—impossible to smelt or extract from ores just a few years ago—are now used in large quantities and referred to as space-age metals. There are also hundreds of

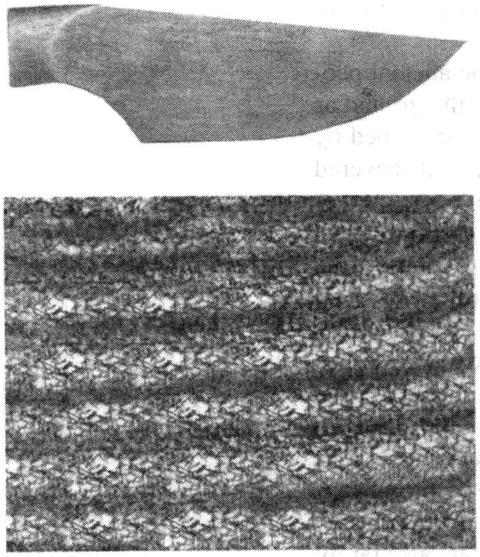


FIGURE I.2 A pattern-welded Damascus blade produces the layered microstructure resulting in superior strength and mechanical properties.

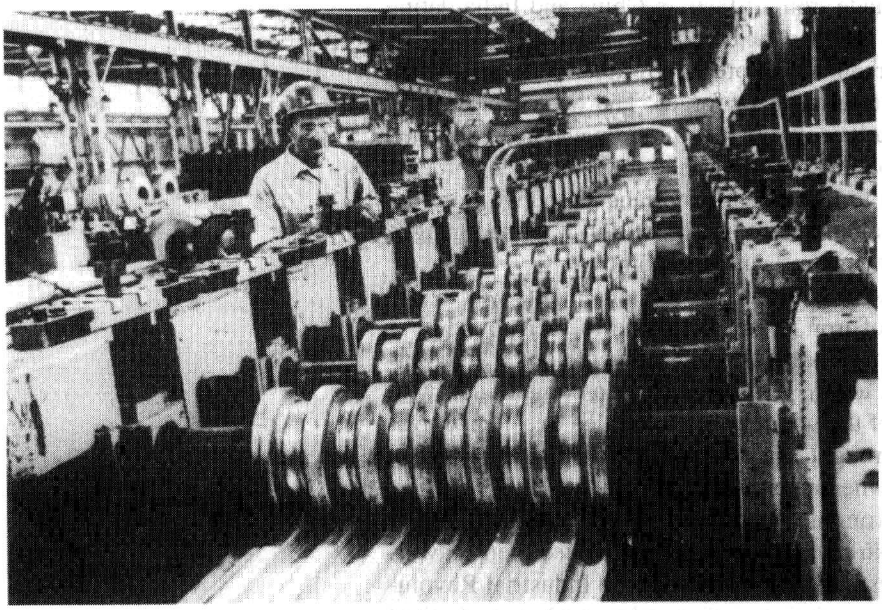


FIGURE I.3 Large-scale production of metal products is achieved in modern steel mills. *(Bethlehem Steel Corporation)*

combinations of metals and nonmetals called composites, along with many new tool steels.

Indeed, because of the heavy use of metals in the present-day world, many metals have been designated as "strategic materials" due to their short supply, such as chromium, cobalt, manganese, and others. These metals are heavily traded in the world marketplace, commanding high prices.

Iron and aluminum are more plentiful; however, the production of even these metals is affected by the ever increasing cost of energy, which may at times result in man-made shortages. Aluminum requires much more energy per ton to extract than steel, and titanium requires nearly 10 times more energy to produce than steel. Aluminum and titanium alloys have increasingly been substituted for steel because they meet the demands of high technology requiring better corrosion resistance combined with a high mechanical strength-to-weight ratio.

Gold, copper, silver, and some other metals were known to the ancient people because these metals were often found near or at the surface of the ground as "native" or "pure" metals. Nuggets of soft pure metal could easily be shaped by hammering to produce ornaments and items of jewelry. Humans soon discovered the process of work hardening, as some metals became harder when hammered or plastically deformed and would hold an edge. Gold and silver are too soft to make cutting tools because they do not work harden. Native copper, however, can be hammered or forged into tool shapes, so copper became a primary armament metal for the Mesopotamians and Egyptians. The discovery of tin and its enhanced mechanical properties and hardness when alloyed with copper gave rise to the Bronze Age, which lasted for many centuries until the time of the Roman era and the use of iron for tools.

Meteoric iron was probably the first ferrous metal used by the ancients. Modern chemical analysis has discovered that meteoric iron is composed of an iron-nickel alloy. Nearly all of the early names for iron defined it as "stone from heaven" or "star metal." Iron is rarely found as native iron, and since meteors are also rarely found, little use of iron was made until a means was discovered to extract iron from ore, accomplished by the Chinese about 2000 B.C. and in Asia Minor about 1500 B.C. Recent discoveries of ancient man-made iron artifacts in China and India dating prior to 3500 B.C. now have scientists revising the time frame in which humans are believed to have discovered how to reduce iron ore into usable items. In ancient times, iron was produced in primitive furnaces or forges. The white-hot heat required to reduce iron ore such as hematite or magnetite into iron was accomplished by forcing air through burning charcoal in close proximity to the ore. This process created a product sometimes referred to by ancient historians as sponge iron, because the iron mass was not molten although impurities within it, called gangue (mostly silicon), were molten due to their lower melting point.

By mashing and squeezing the spongy mass, the molten gangue was nearly removed, leaving a white-hot mass of iron, which could be further pounded or forged into a solid bar. The wrought iron that was produced contained a high percentage of silicon, giving the metal a tough, fibrous quality. In combination with silicon, the very low carbon content of the wrought iron provided excellent corrosion resistance; in fact, some of the wrought-iron nails used in Viking ships buried over 1000 years ago were still intact when recently unearthed.

Humans had come a long way from the first discovery of copper and iron to the development and refinement of extractive processes that created metals available for industrial application. This resulted in the world of the Industrial Revolution. For hundreds of years prior to this vital period, humans made very limited quantities of steel weapons, processed by secret religious rites such as those used to produce the Japanese samurai sword. The Industrial Revolution brought about a transition of metallurgy from art to science, with improvements in methods of ore processing and metal refinement. The first version of the modern rolling mill was invented by Cort in 1783. Wrought iron was the primary iron produced by humans until the invention of the Bessemer converter in 1855, making crude alloy steel available in support of the railroad industry. So-called scientific humans began to study and expand Bessemer's knowledge of metals with the development of the metallurgical microscope by Sorby in 1864. This new view of the structure of metals provided scientists with a tool for a basic understanding of the microstructural changes that take place in metals during heat treatment and thermal fabrication.

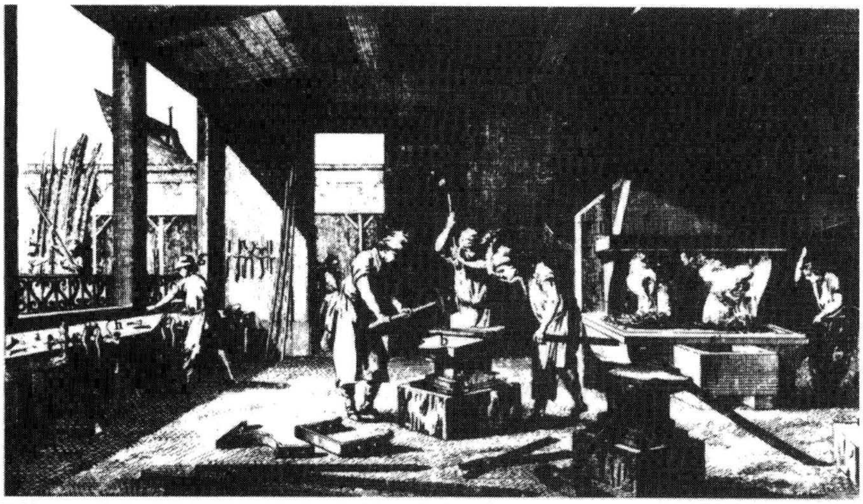


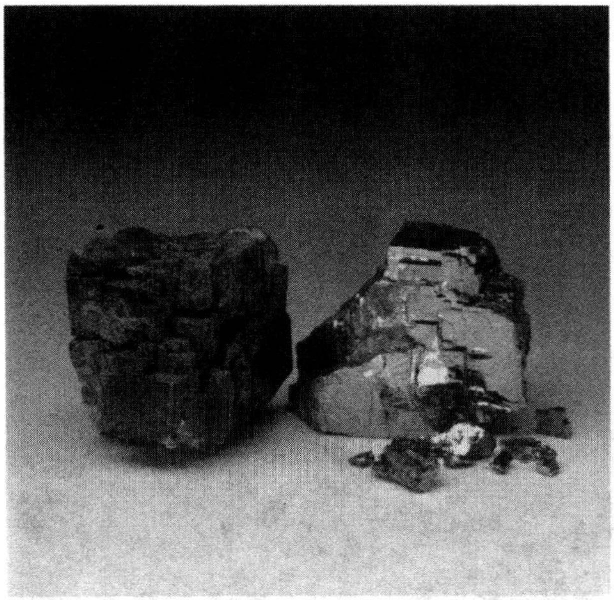
FIGURE I.4 Just prior to the Industrial Revolution, iron working had become a highly skilled craft. *(Dover Publications, Inc.)*

Modern metallurgy stems from the ancient desire to understand fully the behavior of metals. Long ago, the art of the metalworker was enshrouded in mystery and folklore. Crude methods of making and heat treating small amounts of steel were discovered by trial and error. Unfortunately, these methods were often forgotten and had to be rediscovered if the metal craft was not handed down to the next of kin (Figure I.4). Our progress during the Industrial Revolution has led us from those early open forges producing 20 or 30 pounds of wrought iron a day to our modern production furnaces producing nearly 150 million tons of steel yearly in North America.

In this book you will learn how metallic ores are smelted into metals and how these metals are combined into alloys that are cast or wrought into the many diversified products needed for our society today and in the future. To challenge the student of metallurgy and materials science, the metallurgical processes are presented in a self-evaluation format with learning exercises and case problem evaluations with practical examples of failure analysis and resolution of service problems. Where appropriate, safety precautions are given for the safe handling of materials and metallurgical equipment, such as abrasive cutoff saws, acids, and other reagents used for etching specimens. The toxicity of certain metals and materials is also noted.

The study of metallurgy is needed not only by students of metallurgy and materials science, but also by the welding, machine shop, quality control, and industrial technology students who share equal responsibility for the design, development, and implementation of metals and materials processing in industry today. This text is presented in a developmental format intended to give you a greater understanding of the physical behavior and manufacturing processes of metals and materials of industry. This expanded knowledge will enable you to establish a solid materials foundation and help you to become a far more capable and efficient contributor in your chosen profession.

Contents



Chromium (Cr) Ore

CHAPTER 1

Extracting Metal from Ores

Iron is the fourth most plentiful element in the earth's crust. Scientists also believe the core of the earth is a huge mass of molten polarized iron. The separation of metals from their ores is known as *extractive metallurgy*. This chapter will describe how iron is extracted from iron ore in the blast furnace and how the product of the blast furnace, pig iron, is converted by various methods into the steels we know and use today. Pig iron, cast iron, and steels are known as *ferrous* metals, and all other metals are known as *nonferrous* metals. As with other technologies today, the making of iron into steels is undergoing rapid changes to compete in the world markets. Older methods of ore reduction and processes for the metal purification of extracted metals are discussed to provide the student with a solid foundation and understanding of extractive metallurgy. In fact many of the older processes are still in use today. New iron and steel plants are continuously being built and modified to incorporate new processes such as continuous casting of billet steel.

A second section of this chapter is devoted to the description of the extraction of nonferrous metals such as copper (Cu), aluminum (Al), nickel (Ni), and others. The extraction processes and terminology for precious metals, including gold (Au) and platinum (Pt), are also reviewed.

OBJECTIVES **After completing this chapter, you should be able to:**

1. List the various steps, basic materials, and principles involved in making pig iron.
2. Identify various steelmaking processes.
3. Explain several processes used in producing nonferrous metals.
4. Understand the processes used to recover gold from the earth.
5. Calculate the amount of gold present in gold alloys.
6. Identify practical uses for platinum metal.

MINING NATURAL ORES OF IRON

Iron ores are found all over the world, but in the past only certain deposits were considered rich enough in iron to be mined. Not many years ago, most iron and steelmakers in the United States would not have considered mining an ore with an iron content of less than 30 percent, particularly if the mineral were difficult to process. Today, however, a mineral called taconite is a primary source for making pig iron in blast furnaces in this country. Table 1.1 shows that the iron content of taconite ranges from 25 to 35 percent. In the United States, for many years the Lake Superior Mesabi Range produced hematite ore, which contained a high iron content up to 68 percent, but this source has since been depleted. Table 1.1 lists some minerals of iron and their chemical formulas. (*Note*: The chemical symbol for iron is Fe, oxygen is O, hydrogen is H, and carbon is C.)

These ores are removed by open-pit mining (Figures 1.1*a* and 1.1*b*) as contrasted with the more costly and dangerous underground mining method.

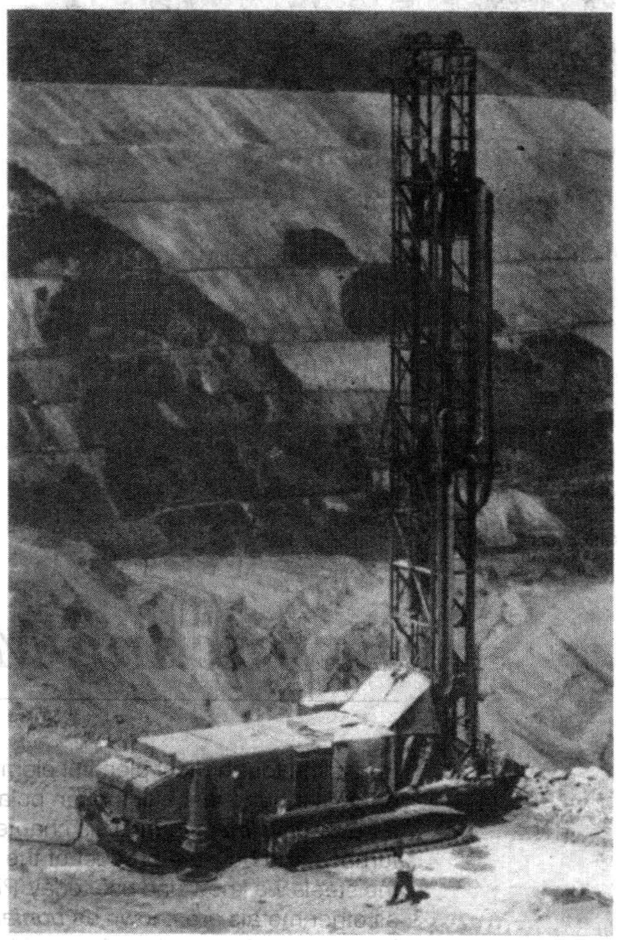


FIGURE 1.1a Open-pit mining showing a 12 1/4-in. rotary drill in the foreground. *(Kennecott Copper Corporation photograph by Don Green)*

TABLE 1.1 Some natural ores of iron

Name	Formula	Iron Content (Percent)
Magnetite	Fe_3O_4	72.4
Hematite	Fe_2O_3	68.0
Limonite	$2Fe_2O_3$, $3H_2O$	59.8
Goethite	Fe_2O_3, H_2O	62.9
Siderite	$FeCO_3$	48.2
Taconite	Fe_3O_3	25–35

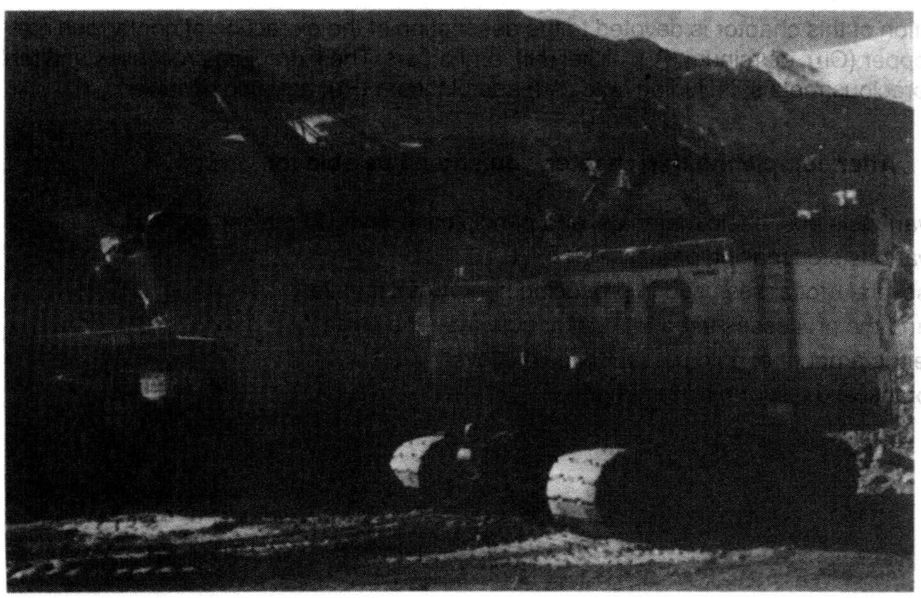


FIGURE 1.1b A 25-yard shovel loading a 150-ton truck in an open-pit mine. *(Kennecott Copper Corporation photograph by Don Green)*

When the ore has been removed from the mine, it is cleaned and separated from the gangue, or worthless rock, by a process called ore dressing. This process could be carried out by any of several methods such as flotation, agglomeration, and magnetic separation. By these processes, low-grade ores such as taconite are upgraded and pelletized before being shipped to the steel mill.

PRODUCTION OF PIG IRON

The iron ore is converted into pig iron in a blast furnace. Figure 1.2 shows the operation of a blast furnace. The three raw materials, **iron ore, coke**, and **limestone**, are put into the furnace alternately at intervals, thus making the process continuous. About 2 tons of ore, 1 ton of coke, and 1/2 ton of limestone are required to produce 1 ton of iron.

One of the three major ingredients in the production of pig iron is coke, a residue left after certain soft coals have been heated in the absence of air. When coal is heated in coke ovens and the resulting gases are driven off (Figure 1.3), coke is the result. Coke is a hard, brittle, and porous material containing from 85 to 90 percent carbon, with some ash, sulfur, and phosphorus. An older type of coke oven, called a beehive oven because of its shape (Figure 1.4), is now obsolete because it wasted gases that were produced during the process. Many useful products are made from the coke oven gas that is driven off: fuel gas, ammonia, sulfur, oils, and coal tars. From the coal tars come many important products such as dyes, plastics, synthetic rubbers, perfumes, sulfa drugs, and aspirin.

Reduction is a process by which oxygen is removed from a compound, such as an iron ore, and combined with the carbon. Hence, when iron ore and coke are put into the blast furnace, the metallic iron is released from its oxide state (formulas in Table 1.1) by reduction. The solid materials—coke, limestone, and ore—enter the blast furnace through the hopper at the top while heated air is blasted in at the bottom. This air is heated in stoves of refractory brick before it enters the furnace. Refractory materials have a high melting point to enable them to retain their shape and strength at high temperatures.

In the furnace, the fuel burns near the bottom, and the heat rises to meet the descending charge of coke and ore. At very high temperatures (about 3000°F or 1649°C), the coke unites with the oxygen in the air blast and is converted to carbon monoxide (CO) gas. The carbon monoxide rises to near the top of the charge in the furnace where it unites with the iron oxide to produce iron and carbon dioxide (CO_2). The carbon dioxide gas combines with some of the remaining coke to form CO again. The flux (limestone) decomposes to form lime and carbon dioxide ($CaCO_3 \rightarrow CaO + CO_2$). Lime (basic) combines with silica gangue (acid) to form the flux—calcium silicate $(CaO) \cdot (SiO_2)$.

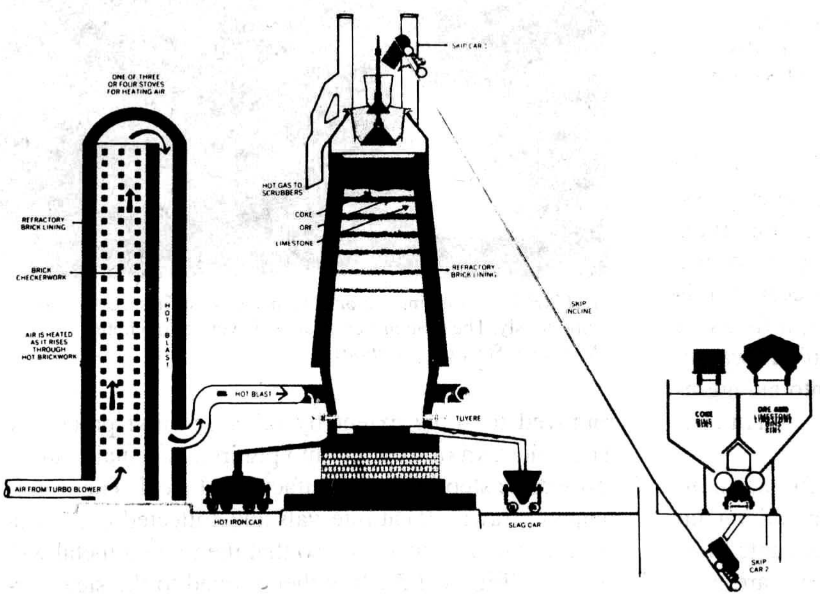


FIGURE 1.2 Blast furnace. Iron ore is converted into pig iron by means of a series of chemical reactions that take place in the blast furnace. *(Bethlehem Steel Corporation)*

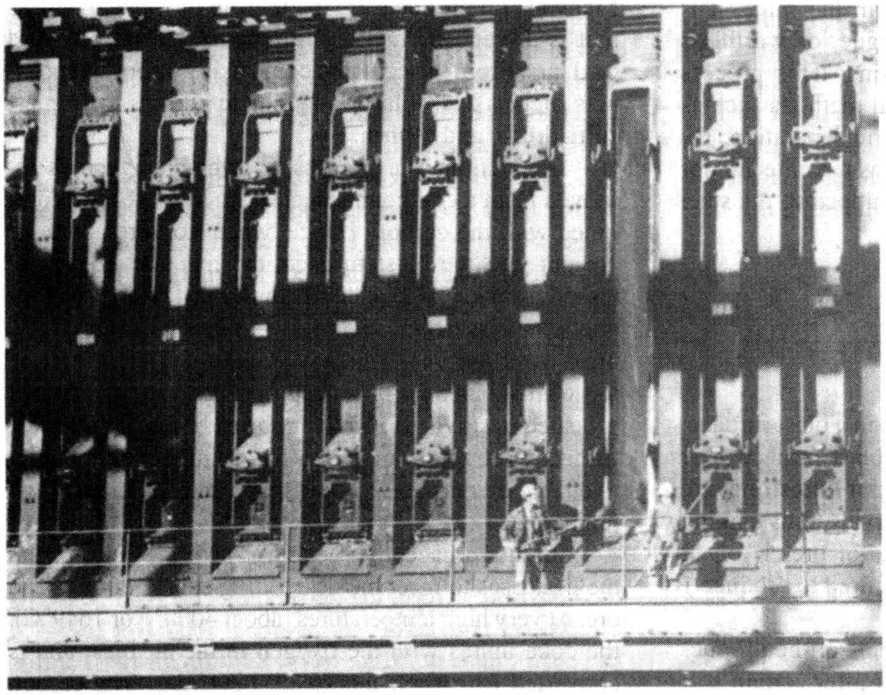


FIGURE 1.3 Between each pair of vertical dividers in this coke oven battery is an individual oven in which coal is heated and converted to coke. *(Courtesy American Iron & Steel Institute)*

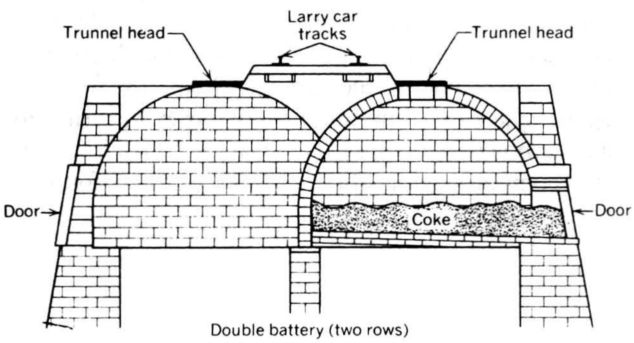


FIGURE 1.4 Beehive coke oven. The coal is charged through the trunnel head from which the gases escape. This method is obsolete because it was wasteful. The gases are not collected and utilized but are lost through the upper vent.

FIGURE 1.5 Tapping the blast furnace. Blast furnaces operate continuously. The molten iron is tapped every 5 to 6 hours. *(Bethlehem Steel Corporation)*

As the process continues, iron is released to the bottom of the furnace, where it remains a molten mass. Here the limestone is used to separate the impurities (mostly SiO_2) from the iron by combining to form a lower temperature melting compound. Because this waste slag is lighter in weight than the iron, it floats on top and is drawn off periodically to be hauled away in slag cars. The slag is sometimes ground into an aggregate that is used for asphaltic concrete roads and in concrete building blocks.

The molten iron at the bottom of the furnace contains from 3 to 4.5 percent carbon, 4 percent silicon, up to 1 percent manganese, and some other unwanted impurities such as phosphorus and sulfur. These are later removed to some extent by other refining processes. The reduction of iron ore into pig iron is actually an intermediate step in the manufacture of steel. The iron is tapped (drawn off) at intervals and collected in a transfer car, which is insulated so that the molten metal will stay hot (Figure 1.5). It is then moved to the steel fur-