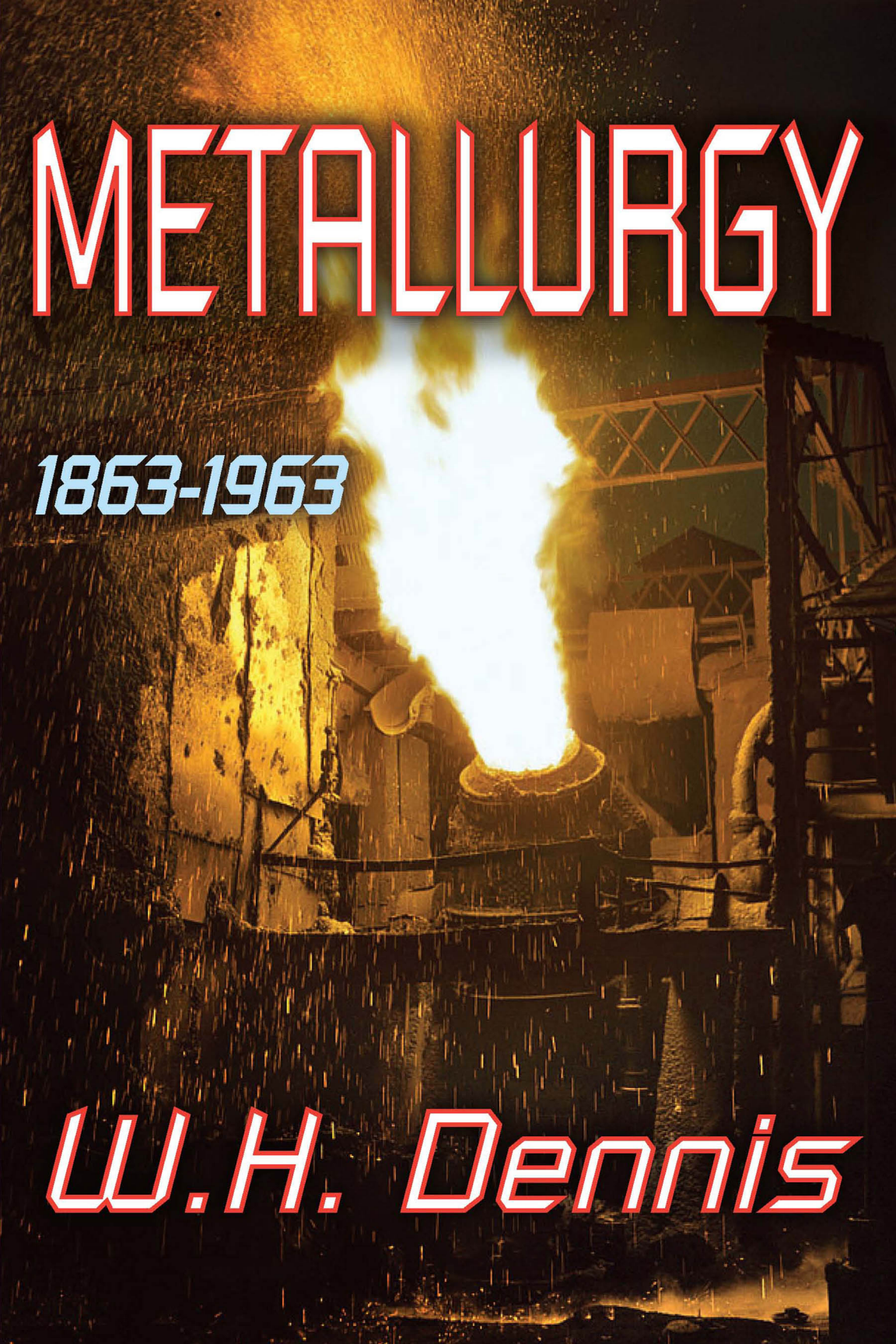
METALLURGY

1863-1963



W.H. Dennis

METALLURGY

METALLURGY

1863-1963

W.H. Dennis

Routledge
Taylor & Francis Group
LONDON AND NEW YORK

First published 1963 by Transaction Publishers

Published 2017 by Routledge
2 Park Square, Milton Park, Abingdon, Oxon OX14 4RN
711 Third Avenue, New York, NY 10017, USA

Routledge is an imprint of the Taylor & Francis Group, an informa business

Library of Congress Catalog Number: 2010003969

Library of Congress Cataloging-in-Publication Data

Dennis, W. H. (William Herbert), b. 1904.
[Hundred years of metallurgy]
Metallurgy : 1863-1963 / W.H. Dennis.
p. cm.
Originally published: A hundred years of metallurgy. Chicago : Transaction Publishers, c1963.
Includes bibliographical references and index.
ISBN 978-0-202-36361-5 (alk. paper)
1. Metallurgy--History. I. Title. II. Title: 100 years of metallurgy.

TN615.D4 2010
669--dc22

2010003969

ISBN 13: 978-0-202-36361-5 (pbk)

CONTENTS

PREFACE

We study the past
Because it is a guide to the present
And a promise for the future.
The struggle for a better world is strengthened
By the hopes, ambitions, and deeds
Of those who were before us.
As we look backward
Our attention is directed forward.

A. B. WILDER

THE above lines from *A History of Steelmaking in the United States* are a reminder that even in the present age of rapid progress and change it is of advantage to take a look back to the past. History in addition to being a record of events is of interest in that trends in the past can often be used to help predict events in the future, and enable problems to be solved by clues furnished from earlier experience. It is in this light that the author attempts a backward look at Metallurgy.

This book is a record of the changes in metallurgy during the past hundred years. Following a conspectus it comprises eight chapters, each dealing with progress in one of the major branches of the metallurgical industry, the object being to select for description the most significant highlights; for it is impossible in a book of this size to attempt a comprehensive record of all metallurgical events during the period. The period covered by the text embraces the century 1850–1950, but the author has not hesitated to prior-date in the interests of continuity, also to record some earlier metallurgical aspects which have passed into oblivion but are entitled to historical record. Appropriate treatment has also been afforded to those developments which best illustrate recent progress made in metallurgical technology.

American metallurgical practice has been given prominence, for by reason of her immense mineral wealth, technical enterprise and abundant supplies of fuel the United States today is

the foremost exponent in the extraction of metals. It is apt, however, to remember that although today physical metallurgy and metal performance form her main interest, Great Britain up to the mid-19th century was the largest producer of lead, copper, and tin, and that the metallurgy of these metals owes much to her pioneer efforts.

The references to literature from which a considerable amount of the material of the text has been drawn have been listed at the end of each chapter. The author wishes to acknowledge his indebtedness to the following for permission to make use of certain of their publications: British Iron and Steel Federation, Oxford University Press, McGraw-Hill Book Co. of New York, the American Institute of Mining and Metallurgical Engineers, United States Steel Corporation, Institution of Metallurgists, and the Sheet Metal Industries *Journal*. Almost inevitably some acknowledgements have been overlooked and for these I must tender my sincere apologies. I also wish to express my indebtedness to my wife for her valuable help in the preparation of the manuscript for publication.

W. H. DENNIS

Ilford, Essex, 1963.

CHAPTER ONE

INTRODUCTION

THE greatest purely metallurgical advance of the past hundred years or so was undoubtedly initiated by Sir Henry Bessemer, and William Kelly, a Kentucky ironmaster, who independently in the period 1850–55 discovered a process for steelmaking; for this invention ushered in the 'Age of Steel' in which we live. The importance of the discovery was that molten pig iron was transformed into steel within the space of some thirty minutes, a procedure that must be contrasted with the method previously in use for its merits to be recognized. Pig iron was first converted into wrought iron, which was then transformed into steel by heating in contact with charcoal for several hours in a cementation furnace. The iron took up carbon but not uniformly, carbon decreasing in quantity from the surface inwards. This heterogeneity gave rise to defects in the mechanical properties, being particularly troublesome to the makers of delicate apparatus. This lack of homogeneity was eventually overcome by Huntsman, a Doncaster clockmaker, who in 1740 succeeded in melting steel in a crucible and casting it. The merit of his invention consisted largely in the manufacture of crucibles which would stand up to the high temperature necessary to melt the metal.

The whole protracted process, involving as it did the production of wrought iron, its recarburization and then remelting in a crucible, occupied several days, and since the crucibles in the final operation held only 60–80 lb. of metal, output was never very large. Thus at one stroke the amount of metal handled by the new steelmaking process was far greater than had ever previously been contemplated. The first steel produced by Bessemer, however, was not of sound quality, the ingot (due to the presence of iron oxide which reacted with carbon) being full of blow holes rendering the metal brittle, fracturing being encountered in the subsequent working and forging. The

trouble was eventually overcome by the addition of manganese in the form of spiegeleisen, a process which had been patented by R. F. Mushet just before Bessemer went into commercial production in 1856. Bessemer paid tribute to Mushet's help by seconding the proposal that the Bessemer gold medal of the Iron and Steel Institute should be given to him in 1876 for his spiegeleisen process.

Bessemer's discovery in 1856 was followed almost immediately by Siemens' open-hearth process in which oxidation of the metalloids in pig iron was induced not by oxygen in an air blast but by oxygen present in iron oxide which was added with the charge of pig iron.

In Bessemer's process the heat necessary to keep the metal in a liquid state is generated by the exothermic heat of the reaction, but in Siemens' process the heat of reaction was not evolved with sufficient speed to keep the metal in a molten condition, and heat had therefore to be supplied from an external source. This temperature was achieved in Siemens' furnaces by applying the principle of heat regeneration, the hot waste combustion gases from the furnace being caused to pass through a checkerwork brick chamber yielding up their heat to the checkerwork. Periodically the stream of hot waste gas was diverted to a second chamber, combustion air being then passed through the heated chamber. At regular intervals the direction of air and gas is reversed, so that each pair of regenerators alternated in absorbing heat from the spent gases and then imparting it to the incoming air and gas. Heat was originally initiated by the burning of solid fuel in a fireplace situated at each end of the furnace, but this was later displaced by the use of producer gas, which was also an invention of the Siemens brothers. As the process took up to ten hours as against thirty minutes with the Bessemer process, it was found possible to exercise far greater control over the steelmaking operation and to produce consistently a more homogenous, reliable and ductile material.

A further advantage of the Siemens method was that unlike the Bessemer method it can use a large proportion of steel scrap. By the late 1860s Britain was already heavily industrialized and large tonnages of cheap scrap were available. The advent of the open-hearth furnace meant that the scrap could be turned to good use.

Pig iron containing phosphorus was unsuited to the produc-

tion of steel by the Bessemer process as originally developed, and as phosphorus is harmful to the properties of steel only those irons low in phosphorus could be used. Bessemer himself by the purest chance had used phosphorus-free iron in his original work. Although this difficulty at the time was not felt very acutely in this country, in Europe vast tonnages of high-phosphorus ores were excluded from conversion into steel. In 1878, however, a Welshman, S. Thomas, working with his cousin P. Gilchrist, realizing that the acid (silicious) lining was responsible for the non-absorption of the phosphorus in the (acid) slag, experimented with a basic slag. By relining the converter with dolomite (a basic refractory) and adding lime, a basic slag was produced capable of retaining the phosphorus present in the pig iron. This simple modification enormously extended the scope of steelmaking and was adopted in steelmaking communities all over the world.

These three processes were the foundation on which the age of steel was erected. Their successful establishment brought many consequent developments which exerted a very wide influence on industry.

Alloy Steels. The steels available to industry in the late 1860s were high-carbon steels of the type made by the crucible process and low-carbon mild steels of the kind produced in the converter and open-hearth furnace. It was known that the hardness of steel depended on its carbon content; tools for instance, which were required to be very hard, being manufactured from high-carbon steels. The general employment, however, of such steel in industry was not possible owing to its brittleness. Thus in order to extend the usefulness of steel further, it was necessary to find other methods than raising the carbon content. The result was achieved by the introduction of certain non-ferrous metals into low-carbon steels, notably tungsten, manganese, nickel and chromium. One of the earliest alloy steels was introduced by R. F. Mushet who by adding tungsten to steel discovered self-hardening steel in 1868. Tools made by this method revolutionized machining processes, and it was also upon Mushet's self-hardening steel that the experiments were based which led to the production of the high-speed steels developed later in America.

In 1883 Robert Hadfield made an important step forward in

this field by incorporating manganese in steel. This alloy was found to possess remarkable tensile strength, elongation and hardness, and became invaluable for all machinery and plant subject to abrasive action such as railway crossings, dredger buckets and the like. These types of steel, however, did not provide a steel suitable for general constructional purposes, a start in this direction being made by J. Riley of Glasgow, who in 1889 by small additions of nickel to steel markedly increased the strength and toughness without decreasing the ductility. By addition of a further alloying element, chromium, H. Brearley in 1913 founded a class of constructional steels which in addition to strength and resistance to wear were also resistant to corrosion.

These alloy steels heralded in the Alloy Steel Age, and so great was their development that at the outbreak of the 1939 war there were no less than 2,000 different specifications dealing solely with alloys having various proportions of nickel chromium and small additions of other elements. With such developments as jet propulsion, nuclear fusion as a source of power and space technology, the acceleration in alloys is likely to continue.

Iron. Immediately prior to the invention of the Bessemer process, production of steel in Great Britain was of the order of 60,000 tons, whereas production of iron was 3 million. Iron was thus the principal metal on which the Industrial Revolution was founded. Iron and yet more iron, both wrought and cast, was the cry, and as the raw materials iron ore and coal were available in great quantity and in close proximity, the supply was adequate to the demand. Abraham Darby, a Shropshire ironmaster in the 18th century, by replacement of charcoal by coke enabled a much greater charge to be sustained in the blast furnace and thus made possible the production of pig and cast iron in much larger tonnages.

Henry Cort and J. Hall did the same for wrought iron, and Benjamin Huntsman produced the tool steel essential to the forming and shaping of castings, forgings, bars, etc. With these materials, and using the facilities which the newly discovered steam engine invented by James Watt in 1762 made available, extensive mechanization of industry took place. Essentially the Industrial Revolution was an engineers' revolution and not a metallurgical one. By the time, however, of the Great Exhibi-

tion of London in 1851, the metallurgical world was to experience a great advance in technical progress. Many factors contributed to this situation, new inventions, techniques and operational improvements, and a better understanding and appreciation of the scientific principle on which these operations are based. In addition the rapid developments in the use of iron and steel during the Industrial Age brought with them greatly increased demand for other metals, particularly copper, tin and lead. Moreover, the demand was not only for greater tonnages but also for a far greater variety of metals. Many of these metals were one hundred years ago little known names in the periodic table, but have now come into prominence and have become marketable commodities. It is accordingly not surprising that there have been more notable advances in metallurgy during the century under review than in the whole history of this ancient art.

Non-Ferrous Metallurgy. The above outline has briefly enumerated some of the features of iron and steel manufacture during the past century. Developments in the non-ferrous field were likewise proceeding on every front.

Production of copper and lead received early impetus following the introduction of the dynamo in the second half of the 19th century; in fact the electrical industry was destined to become the greatest customer for these two metals and to a lesser extent practically all other non-ferrous metals. Later on, the automotive and aviation industries were to constitute the principal outlet for the light metals aluminium and magnesium. The phenomenal rise in the production of aluminium since its first commercial production in 1888 has not been matched by that of any other metal. World production today at 5 million tons is greater than that of any metal other than iron and steel. Its valued properties of lightness, corrosion resistance, electrical conductivity combined with moderate cost have extended its use into a wide variety of commercial and domestic fields.

The methods by which lead, tin and silver were extracted from their ores are among the earliest of the ancient arts. That there was an important trade in these materials in Great Britain is undoubted and it is commonly held that the Phoenicians came to Cornwall for their supplies of tin. We know also that the Romans smelted galena from the Mendip Hills and else-

where for their production of lead. In spite of the fact that our country owed its early development to the exploitation of minerals, it is a surprise to most people that Britain in the mid-19th century was dominant in the production of the non-ferrous metals. For more than 150 years during the 18th and 19th centuries, Swansea was the biggest copper smelting centre in the world. At the height of the boom, Swansea docks were so packed with copper ore ships from all parts of the world, that it was possible to walk from dock to dock by stepping from one ship to another.

Tin, one of the oldest established of British exports, was being mined and smelted on a considerable scale from Cornish ores. In the smelting of lead this country had been pre-eminent since the days of the Roman occupation. Zinc smelting was firmly established in Bristol and Swansea.

During the second half of the 19th century, however, Britain lost her pre-eminence, the copper and tin smelting industries are now fading history; only a few clusters of ruined copper works testify to the former greatness of Swansea. The chief reason was the development of natural mineral resources and progressive industrialization abroad. Britain had never been a richly mineralized country, the domestic mines were being worked out, the copper, lead and zinc smelters being no longer able to purchase supplies of rich ores from overseas mines in competition with smelters on the mine site itself.

America especially was endowed with abundant resources of metal ores, large deposits of copper ore being especially prolific, a large copper smelting industry being built up between 1850 and 1900. Similarly in South America, the porphyry copper ores of the western slopes of the Andes in Chile and Peru were being developed. Australia discovered that she was well endowed with zinc and lead ores, and laid the foundation of a large smelting industry in these metals.

Alluvial tin was found in the East Indies and being much more accessible than the lode tin of Cornwall, eventually sounded the death-knell to British tin mining. As a consequence Britain became an importing country for the non-ferrous metals she required and today there are few non-ferrous smelters of any size in this country. The zinc smelters at Avonmouth and Swansea depend for their raw material on imports from abroad, as does the Mond Nickel Co.'s plant at Clydach, a few miles

from Swansea, which recovers nickel metal from matte imported from Canada. The only other smelting concern of any size is that of the British Aluminium Company in Scotland which imports its raw material—bauxite. There is now no large plant in the U.K. for the production of lead, nor is there a plant for the smelting of copper ore, which must be regretted.

Ore Dressing. Unlike ferrous metallurgy, in which the smelting operations are applied to the crushed, screened and sintered ore, the first step in non-ferrous metallurgy is beneficiation, in which waste is removed, concentrating the valuable minerals into a smaller bulk for the subsequent costly smelting treatment. Today beneficiation is of far greater importance than a century ago, for the rich ores of those days only necessitated a crude hand picking for either selecting the rich ore or rejecting the barren waste. This was sometimes supplemented by gravity methods. Preferential separation, however, is seldom possible with gravity concentration, so the concentrates were usually of only moderate grade and sometimes so complex that they were not amenable to the treatments that were then available. The introduction of new methods was therefore an advance of the greatest importance, for they rendered profitable not only low grade deposits, but a number of rich complex ores that had previously been unworkable.

Of the new beneficiation methods, the flotation process which was introduced at the turn of the century has undoubtedly been of the greatest importance, in fact it has been termed 'one of the greatest process discoveries ever made for the betterment of our standard of living'.

No detailed description will be given here (see page 28); it suffices to say that active research on flotation began just before 1900 and led to the process of bulk froth flotation which resulted in the production of a concentrate containing substantially all the sulphide minerals. This limited the process to the beneficiation of ores in which only one valuable sulphide mineral existed, since bulk flotation was incapable of dealing with complex ores. Later, however, in the early 1920s it was found possible to separate the sulphides of the various metals present in the ore by a selective flotation operation and it is now possible to separate three or four different metal sulphides from the same ore. The process has become very important in the beneficiation

of the major non-ferrous metals, copper, zinc, nickel and lead.

The selective process has also made possible the treatment of complex ores that formerly were of little value due to the costly metallurgical requirements for the extraction of the metals.

The effect on the economy has been an important one, for the flotation process has been a vital factor in increasing the world ore reserves by making it economical to work lower grade ores and to use the leaner portion of the orebodies which were formerly left in the slopes.

Not only in metallic ore beneficiation has flotation become important but also in non-metallic material, for it is now being used in the treatment of phosphate rock, fluorspar, barytes, feldspar, etc.

Flotation and many of the other beneficiation methods produce material in a very fine state of subdivision. The blast furnaces and some other operations are incapable of treating such material, lump ore being required for feed material. Hence such methods as sintering, pelletizing, and briquetting have been developed. Of these, sintering is the most frequent method in use. In this process, air is drawn through a moving layer of the material which has been previously ignited, the air supporting the combustion of sulphur present in the ore (or added carbonaceous material such as coke dust). The high temperature causes the charge to frit or fuse together into compact lumps. This process has become of particular importance in the iron industry where the ores now obtainable have become finer and finer. The sintered iron ore is in a physical condition extremely favourable for reduction in the blast furnace, and nowadays almost all iron plants have sintering installations.

Pyrometallurgy. Smelting usually necessitates a dry coarse feed with a low sulphur content, and in roasting, which is used principally for lowering the sulphur content of ores, progress has mainly been in the improvement of mechanical equipment and not in chemical fundamentals. Reverberatory roasting furnaces with fixed hearths necessitating hand-rabbling, expensive in labour and fuel, which were in use in the mid-19th century, gave way to the mechanical-rabbled type (Edwards, Merton, Ropp, etc.) and finally to the mechanical-rabbled multiple-hearth furnace as exemplified by the Wedge and

Herreshoff. The original 7-hearth water-cooled McDougal wedge multiple-hearth furnace has been gradually developed to 8, 12 and up to 16-hearth, 100 tons of sulphide material per day being roasted with practically no fuel.

During recent years the fluo-solid roaster has been introduced and in certain fields is seriously challenging the multiple-hearth roaster. In this process the finely divided feed is held in suspension by a stream of gas, combustion having been initiated by a burner. It requires simple equipment, does away with rabbling, gives intimate contact between air and solid resulting in high thermal efficiency.

One hundred years ago carbon reduction was prominent in the smelting of lead, tin and zinc and is still the most commonly used procedure. The blast furnace still dominates in iron and lead smelting; but is now used very little in the copper and nickel industry, reverberatory smelting having taken over almost all smelting operations. This furnace has been brought to a high state of perfection and efficiency from the old hand-operated 13 ft. long copper furnaces expensive of fuel and labour. It possesses the advantage over the blast furnace that a variety of fuels can be used, pulverised coal, gas, oil, tar and pitch, most of which are cheaper and more convenient to handle than coke. The blast furnace has, however, recently received a fillip, for a recent publication* states that after 25 years of study and research production of zinc in a blast furnace is now possible. As lead can also be recovered, and as lead and zinc so frequently occur in intimate association in their ores, the importance of this development is evident.

Electrometallurgy. In 1831 Michael Faraday made his vital discovery of the relationship between magnetism and electricity, from which flowed the invention of the dynamo and the electric motor. The benefits resulting from these inventions, however, were obtainable only where electricity was available in bulk, which did not occur until some forty years later—well into the second half of the 19th century. Electricity had a many-sided impact on metallurgy. Copper, for instance, because of its high electrical conductivity and the ease with which it could be drawn into wire became in great demand as an electrical

* S. W. K. Morgan, 'Production of Zinc in a Blast Furnace', *Bulletin I.M.M.*, August 1957.

conductor, and thus copper made possible an enormous expansion in electrical generating and other equipment. On the other hand, the electrical generators made possible the electrolytic refining procedure necessary to produce copper of the required high standard of purity. The electrical industry also became the major customer for lead and a great consumer of other metals.

The commercial utilization of electrolysis in metallurgy had its origin nearly 100 years ago when James Elkington, an English electro plater, invented a process for refining copper electrically; later, about 1890, aluminium was first produced on a commercial scale by electrolysis, by Hall in America and Heroult in France, followed by lead in 1903, nickel about 1910 and zinc in 1915.

In addition to providing a means of obtaining a metal direct from its ore it also serves to purify a metal produced by some other process. At the end of the last century it was limited to the refining of gold, silver and copper, and to the production of a small amount of aluminium. Since that time, most of the copper, nickel and magnesium and a large part of the zinc and lead are produced electrolytically, cathodes of copper, nickel, lead, zinc being made close to 100% pure.

Electrolytic manganese and cobalt have also in recent years been introduced, as have many of the rarer metals such as beryllium, indium, tantalum and tellurium.

Electrolytic methods using fused salts as electrolytes are also of the greatest importance; these are used not only for the production and refining of aluminium, but also for the winning of magnesium, and may in the future be employed for the production of titanium.

Electrolysis also possesses another valuable attribute in that during the refining process precious metals such as gold, silver and platinum associated with the metal being refined are deposited in the cell as a slime, their recovery constituting a valuable by-product.

Electric Smelting. The development of cheap power towards the end of last century enabled the electric current to be utilized for heating purposes. Very high temperatures were attainable by its use which is important in the production of such materials as ferro-alloys. It has also the advantage that the furnace

atmosphere can be made reducing, oxidizing or neutral at the will of the operator; further a product of higher purity can be obtained than by the use of other processes using conventional fuel. Electric pig iron, electric steel and steel alloys generally have the advantage of high quality. The arc furnace was introduced into the steel industry at the beginning of this century and originally used for the manufacture of tool steels. It was extensively used during World War One for the production of alloy steels for ordnance purposes and at present it is commonly used for stainless and manganese steel as well as the whole range of low alloy steels for the automobile and aircraft industry. In countries possessing cheap hydro-electric power such as Italy and Scandinavia the arc furnace has also for many years been used for making ordinary quality carbon steels. This use is now extending to other countries, furnaces having been built in America, Europe and in Britain. It is likely that such furnaces will in the future actively compete with the basic open hearth as an economic producer of ordinary quality steel.

High-Frequency Induction Melting introduced during the 1920s largely replaced the crucible furnace as a melting unit for tool steel and high alloy steels. In connection with the latter the induction furnace was one of the first to be used for vacuum melting, which overcomes the unfavourable effect of the atmospheric gases on the mechanical properties of the steel. A new development in vacuum melting is the melting of such reactive metals as titanium, zirconium and other rare metals in the consumable electrode vacuum arc furnace using a water-cooled copper crucible. It has enabled ingots of the reactive metal to be cast in sizes of up to 5 tons in weight. Consumable electrode vacuum melted steels up to 20 tons weight are also being produced. These steels possess a high degree of cleanliness, decreased gas content, soundness, uniformity of ingot structure, enhanced toughness and ductility at elevated and sub-zero temperatures. These are the properties which provide the engineer with the quality materials of the new technological era.

Hydrometallurgy is in general the process of recovering a metal by a solvent and has found application in the treatment of certain types of ore. Examples of such processes are the leaching of copper ores, the cyanidation of gold and silver

ores and the Bayer process for extraction of alumina from bauxite.

The first large scale application of the method occurred in the 18th century at the property of the Rio Tinto copper mine in Spain. Large heaps of the crushed sulphide copper ores were allowed to oxidize over long periods under the influence of moisture and air, with subsequent leaching out of the copper sulphate that had formed from the oxidation of the sulphides, followed by precipitation of the copper on scrap iron. This simple method has also been applied elsewhere, notably in America. Confined leaching, i.e. treatment in tanks as opposed to heap leaching, has been practised since the beginning of this century, large scale operations having occurred at the plant of the Chile Copper Company at Chuquicamata, Chile (at a rate of 1 million tons per month), New Cornelia Copper Company at Ajo, Arizona, and the Union-Minière in the Congo.

In recent years there has been a marked extension in the application of hydrometallurgical processes to low grade ores due largely to the introduction of new techniques such as ion-exchange, solvent extraction and high temperature and high pressure methods. Ion-exchange used for the softening of water has found employment in the purification and enrichment of the solution resulting from the acid leach of uranium ore. Solvent extraction widely employed in the petroleum industry is now used in the separation and recovery of uranium, tantalum, etc. High pressure and high temperatures have long been utilized in the chemical industry but it is only comparatively recently that their usefulness has been recognized in connection with hydrometallurgical processes. The first plant employing high pressure and temperature was initiated in Canada at Fort Saskatchewan in 1953 for the treatment of nickel-copper-cobalt sulphide ore, and it has since been followed by similar plants in America and Cuba.

Shaping of Metals. The last stage in smelting usually involves the casting of the metal into a mould. This mould may be shaped to the form desired in the finished article, the process being known as founding or casting. On the other hand the metal may be cast into a mould of simple form such as an ingot for subsequent shaping by such mechanical working methods as forging, rolling, extrusion, etc.

Casting. The last hundred years has seen marked improvements and innovations in this ancient art. Pressure die casting involving the injection of metal into metal dies or moulds under pressure has expanded greatly since World War One. It is the fastest of all casting processes, a large tonnage of aluminium and zinc base die-cast alloys being produced for the automotive, aircraft and engineering industries. Investment casting has also been modernized and introduced as a mass production technique.

The application of continuous methods to the casting of ingots has made rapid strides since the last war. This method of casting involves the continuous solidification of the ingot while it is being poured, the length not being determined by mould dimension. Liquid metal enters one end of a mould continuously, solidified metal emerging from the other end in a long length of the required cross-section which can be cut to length for further processing. Casting by this method eliminates the casting bay, ingot moulds, soaking pit and primary rolling mills. In addition to the saving on capital and reheating costs there is usually an improvement in the yield of saleable product as compared with conventional casting and rolling.

As far back as 1856 Henry Bessemer realized the advantages of the technique and in fact produced sheet by pouring molten steel between a pair of water-cooled rolls, but the product was lacking in quality. During the intervening hundred years many different ideas for the direct casting of liquid metal continuously to semi-finished product were suggested and patented.

Continuous casting machines first achieved success in the non-ferrous field particularly for copper, brass and aluminium. Progress with steel was negligible until the last war, when notable developments were made in Germany, Russia, the United States and the U.K.

Forging. The introduction of the steam hammer, invented by J. Nasmyth in 1842, occurred at an appropriate moment, for it enabled the heavy masses of steel produced a few years later by the Bessemer and open-hearth processes to be readily forged and shaped by rapid and repeated blows dealt by the hammer. Formerly, forging was achieved by the tilt hammer, a crude contrivance consisting of an iron hammer head fixed at

the end of a long wooden beam, pivoted at the other end and actuated by a steam driven cam, which raised the hammer, which then fell by its own weight on the mass of hot metal on the anvil. This type of mechanism would have been inadequate to forge the heavy masses of Bessemer metal.

For very large forgings the hydraulic press was developed by Sir Joseph Whitworth in 1856, the ingot being shaped not by impact but by squeezing induced by pressure from a hydraulic ram. All heavy forgings such as boiler drums and big guns are nowadays formed by pressing.

Rolling. For making long and thin sections of metal, such as sheet and plate, reduction in thickness was originally secured by pounding the metal under a water-powered hammer. For soft metals such as gold and silver this was a fairly simple operation, but for hard, tough metals the method was laborious. Rolling mills driven by water wheels were introduced towards the end of the 17th century, John Hanburg in 1697 erecting a rolling mill at Pontypool, S. Wales, for rolling iron for making tinplate. In Sweden bars and sheets of wrought iron were being rolled on a mill invented by C. Polheim (1661–1751). The employment of rolling mills only began extensively late in the 18th century owing largely to the work of Henry Cort in 1783, who introduced and patented the use of grooved rolls for producing bars from wrought iron. The demand for steel in a greater variety of forms led later to the development of differently shaped grooves for the production of complex shapes and sections.

The rolling mill reached a high standard of development towards the end of the 19th century when steel rollers of sufficient size and strength could be cast and when ample power became available. It is now the most widely used of all metal shaping processes, for steel and non-ferrous metals are rolled in some if not in all stages of fabrication. The growth of mills for production of continuous strip and cold reduced sheet in quantity and quality has been the result of an insatiable demand from old and new industries and is clearly reflected in the enormous output of strip, plate, sheet, bars, wire, structural shapes and foil.

It can be stated that in no other phase of the fabrication of metals has mechanical ingenuity and metallurgical knowledge

been so clearly evidenced as in the construction and operation of the modern rolling mill.

Extrusion. The method of producing special sections by forcing heated metal billets through a suitably shaped die was developed early in the last century. It was at first confined to the softer metals such as lead, but was later extended to brass, and then aluminium, magnesium and their alloys. Within the last few years the method has been applied to steel.

Metallography. In 1861 Professor H. C. Sorby of Sheffield initiated the systematic examination of metals through the microscope and laid the foundation of that branch of metallurgy known as metallography. Sorby's work was largely confined to iron and steel and was accomplished during the years 1860–65. He had previously worked on the microscopical structure of rocks which could be examined microscopically by transmitted light. Metals being opaque were not amenable to such a method, but Sorby was successful in devising suitable techniques using reflected light; his publications contain photomicrographs which illustrate the excellence of his technique. His early observations remained almost unnoticed, until 1887, when he first published his findings in a paper to the Iron and Steel Institute.

Further microscopical work was carried out, mostly with the intention of controlling the quality and composition of iron and steel, in 1878 by A. Martens in Germany, in France by F. Osmond in 1880, and in England by Roberts-Austen.

The constituents of the microstructure of a metal are formed during solidification from the liquid; hence the appearance of the structure alone will not reveal information regarding its origin or the relation of one structure to another. For this the microscope has to be supplemented by other instruments, notably the pyrometer. With its aid thermal equilibrium diagrams were constructed that depict the phases present at all temperatures between room temperature and that at which the metal or alloy melts. This type of work was followed up in many countries, notably France, and as a result metallurgists were able to indicate the structure which was likely to occur in any particular composition of alloy, when (*a*) cast, (*b*) quenched from different temperatures, or (*c*) tempered, and further that

the mechanical properties were related to and dependent upon structure.

These diagrams could be put to practical use, for they indicated the nature of the heat treatments that would produce a desired result, and it is through the data contained in the thermal equilibrium diagrams that methods of heat treatment for different metals and alloys were made possible.

Following on the discovery of X-rays by Röntgen in 1895 the commencement of this century saw the application of X-rays to elucidate the internal structure of metals and alloys and the foundation of a new science was laid. From this work many discoveries of the arrangement of the atoms in metallic crystals have emerged, leading to a better understanding of alloy structure. The invention of the electron microscope, with which magnification may be obtained many hundreds of times greater than was possible in Sorby's time, has greatly facilitated the observation of internal structure. Primarily many of these investigations are the work of the physicist and their connection with metallurgy is not easy to recognize.

Mechanical Properties. A century ago structural design of engineering components was based almost entirely on such static properties as tensile strength and hardness. At that time sources of motive power were limited and the design based on static strength properties provided an ample factor of safety.*

With the development of the steam engine and a higher degree of industrial mechanization, rupture of materials began to be increasingly experienced, which could not at that time be accounted for, as the ruptures occurred at stresses well below those which the metal was capable of withstanding under static load conditions. Fracture of the crankshafts of engines and axles of locomotives and wagons were but two examples. Investigation by Sir William Fairbairn in the early 1860s and by August Wöhler a German engineer a few years later showed that if metals are subjected to variation in load, wide fluctuation in stress occurs which if of sufficient magnitude results in fracture at stresses well below the maximum static strength. The term 'fatigue' was applied to such fractures because they occur only after a prolonged period of service. The term was appropriate

* Factor of safety is the ratio allowed in design between the breaking load on a structure and the safe permissible load on it.

in that under repeated stress the capacity of a metal to withstand stress gradually diminishes. It is, however, inapt in that metals do not regain their original properties after a period of rest.

Fatigue has become progressively more prevalent in modern times as technology has given rise to more equipment subject to repeated loading and vibration, such as automobiles, aircraft, steam turbines, etc. All rotating machine parts such as shafts, axles, piston rods, etc., are subject to cyclic stresses. Vibration due to machining is also a frequent cause of failure. It is particularly invidious because fractures occur without any obvious symptoms or warning. The phenomenon was highlighted in modern times by the 1954 disaster to the original British Comet jets produced by fatigue failure at a hatchway as a result of alternating changes in the cabin pressure with altitude.

Today it has been stated that fatigue accounts for at least 90% of all service failure due to mechanical causes. On this account the fatigue strength of a metal is today one of its most important mechanical properties for in all cases of dynamic loading at normal temperature it is directly or indirectly the limiting factor of design.

In many applications materials are subjected not to cyclic (fatigue) stresses but to steady static loads for long periods of time, e.g. steel cables, furnace and steam boiler equipment, blades of turbine and jet engines. Under such conditions the material may gradually elongate until its usefulness is seriously impaired. This mode of deformation is known as 'creep', so-called because the phenomenon occurs at a slow rate over a relatively long period of time.

Creep will take place in every metal or alloy if it is subjected to stress while maintained above a certain minimum temperature. The majority of metals do not, however, exhibit the phenomenon of creep to any noticeable degree except on the application of heat. Initially, interest in the subject centred around those steels used in steam power plants, oil refineries and chemical plants in which the operating temperature seldom exceeded 550° C. In such employments the components were comparatively only lightly stressed, but during and since World War Two, developments in many fields have necessitated materials possessing stability of physical properties and

dimensions at high stresses and temperatures. The high temperatures and pressures encountered in such applications as the super-heating of steam, the cracking of oil, the jet engine, guided missiles, nuclear power plants, space technology, all call for materials with good high temperature and creep-resistant characteristics. In gas and steam turbines the dangerous aspect of creep is in the loss of clearance of the moving blades, for any failure in this respect can lead to disaster.

The changes with temperature of the resistance of metals to fluctuating stresses (fatigue) are not essentially different from the changes of their resistance to constant stresses (creep); hence alloys developed for high creep strength may also be expected to have high fatigue strength.

Much effort has been directed towards the development of new structural metals such as titanium, vanadium and niobium, and their alloys, by reason of their creep strength, but the range of materials available rapidly decreases as the temperature level rises; in fact above 1000° C. existing alloys are in many cases inadequate for the environment and stresses imposed. This fact has prompted research into such unconventional materials as for example the cermets (an abbreviation of the words ceramic and metals) designed to combine the desirable properties of metals with the refractory heat characteristics of the ceramics.

Summary. How short a distance history had advanced along the road towards the present may be gauged by the fact that in the mid-19th century the only metals that were available to industry were cast iron, wrought iron, a small proportion of tool steel, and of the non-ferrous metals, only copper, zinc, lead, tin, and the alloys of these metals—brass, bronze, gun-metal, pewter and solder. Since then progress and advances made in metallurgical technology during the period under review have enabled metal art to be replaced with metal science. Certainly no similar period in the history of metallurgy compares with the progress recorded here.

In production alone, world metal output during the past half-century has been greater than in all preceding history. Not only have old methods been improved and expanded to meet the increased demand for metals that were in use one hundred years ago, but metals that in 1850 were mere laboratory

curiosities are today being produced by the ton and form the basis for alloys and structural materials demanded by the radical new environments in which man is now operating. The advent of nuclear energy, guided missiles, jet engines and space technology has necessarily led to the creation of new tools, techniques and materials.

BIBLIOGRAPHY

1. AITCHISON, L. (*a*) *History of Metals*, MacDonald & Evans, London. (*b*) 'A Hundred years of Metallurgy, 1851–1951', *Sheet Metal Industries Journal*, May and June 1951.
2. 'Seventy-five years of progress in the mineral industries' (1871–1946). American Institute of Mining and Metallurgical Engineers, New York.
3. DANNATT, C. W., 'Fifty Years of Extractive Metallurgy', *Mining Magazine*, January 1960.

CHAPTER TWO

ORE DRESSING

ORE, the product of the mine, consists of mineral or minerals sparsely disseminated through barren rock material known as gangue. Elimination of as much as possible of this rock material is an economic necessity before smelting, for (1) the rejected material is not transported and hence a saving in freight costs is achieved; (2) a mechanical rejection of gangue is much cheaper than elimination of waste material as slag in a smelting process. The operations involved in the elimination of the gangue and the concentration of the mineral(s) into a small bulk is known as mineral dressing. Several other terms are also in common use, namely ore treatment, ore dressing, milling and beneficiation. The valuable product of the operation is known as concentrate and constitutes the feed to the metallurgical plant; the discarded waste is called tailing.

As the mineral(s) occur intimately associated with waste rock, before any separation and concentration can take place the minerals must be liberated from the gangue, and hence severance or comminution constitutes the first step in mineral dressing. After liberation the mineral(s) are separated from the gangue and collected into an enriched concentrate. It may be stated that mineral dressing does not effect 100% separation of the mineral value from the gangue, and in fact in nearly all cases the mineral concentrate obtained usually contains at least 10% barren material.

One hundred years ago the progress in the art can be seen from the accompanying flowsheet (Fig. 1) of the Clausthal mill (Germany) which was one of the largest and most up to date at that time. The ore which was galena and zinc blende associated with copper and iron pyrites was hand-sorted, crushed and sized, the coarse sizes being jigged and the fines subjected to buddles. The flowsheet should be compared to

that on page 39, which shows the modern approach to beneficiation of the same type of ore.

Comminution. The ore as mined comprises lumps up to 4 ft. and hence reduction in size must be effected in order to break down the ore and release the mineral values. Since no single

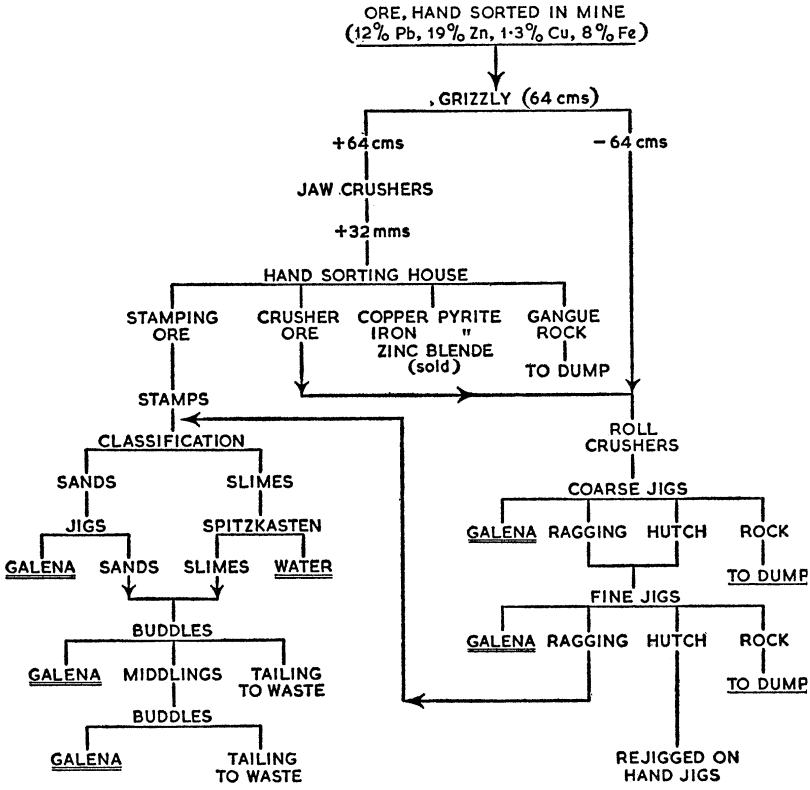


FIG. 1

FLOWSHEET SHOWING LEAD RECOVERY AT CLAUSTHAL MINE (GERMANY) IN 1871 (capacity 500 tons per day)
RANDOLPH, A.I.M.E. 1877, 6, 470

machine is capable of effecting the entire crushing operation, it is customary to conduct the operation in stages, the lump ore being first broken down in primary crushing machines, further reduction being effected in secondary crushers which reduce the ore to $\frac{1}{2}-1$ in. Primary crushing is usually effected by means of jaw crushers or gyratories.

Jaw Breakers. The first successful mechanical rock breaker was invented by Eli. W. Blake (1795–1886) of New Haven, U.S.A., and patented in 1858, being first exhibited in Great Britain in 1862 at the London International Exhibition. Blake adopted the principle of the toggle linkage, the rock being broken between a horizontal fixed jaw plate and a movable jaw plate, hinged at the top and set at a small angle and actuated by a powerful toggle movement communicated to it from a driving pulley through an eccentric shaft and pitman which is made to move up and down. The movable jaw is held up against the toggles by a tension rod and spring, advancing and receding a short distance alternately from the fixed jaw. Rock is fed in at the top between the two jaws and is broken by the pressure exerted by the moving jaw, gradually sliding down until it is finally crushed sufficiently to fall through the opening at the bottom of the jaws. A jaw crusher 30 in. × 15 in. when operating on an average product of say — 8 in. + 2 in. has a duty of about 40 tons per hour. The advantages of simple rugged construction and large capacity are such that today the Blake crusher is still the leading machine for heavy duty primary crushing.

Gyratories. The next major advance in crushing was the utilization of the gyratory principle embodied in the gyratory crusher and its outgrowth the cone crusher. In 1881 P. W. Gates in America was granted a patent for a machine which included in its design all the essential features of the modern gyratory crusher. The machine consists of a central vertical shaft which carries at its upper end a conical crushing head gyrating within a stationary crushing surface in the form of an inverted cone. The central movable crushing head receives impetus via an eccentric from a driving pulley and gyrates around the periphery of the fixed crushing head. Ore is fed in at the top and crushed between the surfaces of the breaking head and that of the fixed crushing face as the former advances towards the latter, the crushed material falling through as it recedes, the same function being performed as the movable jaw in the jaw crusher. The modern gyratory runs at about 500 r.p.m. the capacity depending on the size, a machine capable of dealing with rock up to 8 in. in diameter having a capacity of 60/70 tons per hour, of which about 60% is — 1 in. Large

machines which take up to 12 in. rock have a capacity of 150 tons per hour.

Secondary Crushing. The size of product from primary crushers varies from about 2 in. up to 6 in. or so according to the size of machine, and as concentration processes call for crushing down to $\frac{1}{2}$ in. or finer, the need arose for secondary crushing. This requirement was met for a number of years by the employment of crushing rolls formerly used as hand-operated machines on the small lead mines of Derbyshire, a mechanical type being introduced by John Taylor in 1804 at the Wheal Crowndale mine in Devon. These consisted of two iron cylinders with their axes placed horizontally and so mounted on shafts that they revolved at a distance of about $\frac{1}{4}$–$\frac{1}{2}$ in. apart according to the fineness of the product required. Rock is fed between them and broken by the pinching action produced. The early rolls suffered from many disadvantages, constant attention being required to keep them operating efficiently. Corrugations on the roll surface soon occurred which affected the uniformity of product, repair costs being high. S. R. Kron of Jersey City in 1874 much improved the rolls by making them with hard renewable shells enabling a longer life to be attained. At the present time rolls up to 6 ft. diameter are in use, being specially favoured in the crushing of clayey iron ores for they can handle sticky feeds better than most other forms of crusher.

Cone Crushers. The earliest attempts to adopt the gyratory principle to fine crushing took place at the beginning of this century, but it was not until after World War One that gyratory crushing as exemplified by the cone crusher entered the fine crushing field. In its adoption to fine crushing the gyratory crushing head was made much more obtusely conical, the additional flare resulting in a head of much greater diameter with a consequent large increase in the area of discharge opening. This was essential in order to maintain capacity in face of the reduction in width of discharge opening incidental to finer crushing. In order to overcome the tendency of the material to slow down in speed as a consequence of the increased flare of the crushing head, the eccentric speed was increased, thereby increasing the number of crushing impulses per unit area of crushing surface per unit time. Increase of the move-

ment of the head was also adjusted by giving a longer throw. The result of these modifications was to ensure faster travel through the crushing zone. Originally these machines were fitted with straight face concave crushing surfaces; later the concaves were tapered at both ends to distribute the wear better. Eventually these non-choking concaves became standard equipment. The cone crushers proved popular from the start and are now standard equipment in practically all ore and quarry comminution plants.

Grinding. Grinding is a process of pulverizing ore or other material by a combination of impact and abrasion. Grinding is similar to crushing in that breakage by impact is common to both, but the essential difference is that a much smaller size of particle is secured by intimate contact of the crushing surfaces, reduction thereby being achieved by rubbing or abrasion.

The primary purpose of grinding is to liberate the valuable minerals from the gangue, and hence some form of grinding unit is almost universal. These in modern practice take the form of tumbling mills employing balls, pebbles or rods as the tumbling or grinding media. Grinding in water is usually employed, but in a recent development (Aerofall mill) dry grinding is used.

CYLINDRICAL MILLS

The machines most commonly in use for performing fine grinding are cylindrical-type mills mounted horizontally on their axes. There are several types, differentiation being on the basis of the tumbling media used inside the mill to effect the grinding. Ball mills employ steel balls as the tumbling bodies, rod mills steel rods, and tube mills flint pebbles. A ball mill also differs from a tube mill in that the length is usually not more than 1½ times the diameter, whereas in a tube mill, the length is much greater than the diameter. The approach to the modern grinding mill may be discerned in the invention (by F. W. Mitchell and H. T. Tregoning of Cornwall) of what was termed a barrel pulverizer in 1880. This consisted essentially of a cast iron cylinder mounted on horizontal bearings. Pieces of iron and steel were charged to the mill, which was rotated at 8 r.p.m. Ore was introduced into the mill through one of the

hollow bearings with a stream of water, the ground product flowing out at the other end.

Tube Mill. Following on this early development of the pulverizer came the tube mill first used in the cement industry. The mill consists of a steel cylinder about $5\frac{1}{2}$ ft. diameter by 22 ft. long lined with flint blocks and rotated on hollow trunnions. The mill was loaded with pebbles (10–12 tons) and rotated at a speed of 28 r.p.m., the capacity measured in terms of tonnage of 100 M product being about 150 tons per day. In the early days a peripheral discharge was used, screens being arranged around the periphery at the discharge end of the mill; but excessive wear caused its abandonment in favour of central trunnion discharge. Composite steel and pebble loads are now finding favour, an increase of about 15% in capacity being obtained. The tube mill received a big impetus on its introduction to the Rand goldfields in 1904 by J. R. Williams, for the purpose of grinding the ore leaving the stamp mills to achieve the degree of fineness required for the subsequent cyanide processes which had been introduced some time previously.

Rod Mill. Substitution of steel rods for balls as grinding media characterizes the rod mill introduced from Germany at the turn of the century. Since the action of the rods resembles that of a large number of close-set rolls it is to be expected that the product would be roughly similar, and in fact the size distribution is reasonably so. Like rolls the rod mill is most suitable when a granular product is desired with a minimum of fines, and hence found use in gravity concentration plants, being particularly adapted to tabling.

Ball Mill. A mill with its diameter greater than its length was developed by H. Gruson of Magdeburg in 1885. It was subsequently taken over by Fried. Krupp AG and known as the Krupp mill. It consisted of a steel drum whose circumference was composed of fine screen material. Within these screens were coarse screens made of perforated steel plate so arranged as to protect the outer fine screens. Inside the protecting screens are iron or steel perforated plates, so arranged in helical form as to constitute a series of steps, which has the effect of raising the balls and then dropping them during the rotation of the