Recovery of Values from Low-Grade and Complex Minerals

Development of Sustainable Processes

Edited by

Elvis Fosso-Kankeu

Bhekie B. Mamba

Antoine F. Mulaba-Bafubiandi

Scrivener Publishing

WILEY

Recovery of Values from Low-Grade and Complex Minerals

Scrivener Publishing
100 Cummings Center, Suite 541J
Beverly, MA 01915-6106

Publishers at Scrivener
Martin Scrivener (martin@scrivenerpublishing.com)
Phillip Carmical (pcarmical@scrivenerpublishing.com)

Recovery of Values from Low-Grade and Complex Minerals

Development of Sustainable Processes

Edited by

Elvis Fosso-Kankeu

Department of Metallurgy, University of Johannesburg, South Africa

Bhekie B. Mamba

College of Science, Engineering and Technology, University of South Africa, Pretoria, South Africa

and

Antoine F. Mulaba-Bafubiandi

Emeritus Professor at the University of Johannesburg, South Africa

Scrivener Publishing

WILEY

This edition first published 2024 by John Wiley & Sons, Inc., 111 River Street, Hoboken, NJ 07030, USA and Scrivener Publishing LLC, 100 Cummings Center, Suite 541J, Beverly, MA 01915, USA

For more information about Scrivener publications please visit www.scrivenerpublishing.com.

Wiley Global Headquarters
111 River Street, Hoboken, NJ 07030, USA

For details of our global editorial offices, customer services, and more information about Wiley products visit us at www.wiley.com.

Library of Congress Cataloging-in-Publication Data

ISBN 978-1-119-89641-8

Cover image: Pixabay.Com
Cover design by Russell Richardson

Set in size of 11pt and Minion Pro by Manila Typesetting Company, Makati, Philippines

Printed in the USA

10 9 8 7 6 5 4 3 2 1

Contents

Preface

The mineral industry is undergoing significant cultural, organizational, and technological transformations to address some of the major limitations and challenges related to the environmental and productivity domains. As far as productivity is concerned, the decrease of high-grade ores has been one of the stumbling blocks toward the achievement of maximum recovery of metals while, on the other hand, the complexity of minerals therein makes it difficult to profitably extract metals using only conventional methods. Recent developments in comminution, froth flotation, and leaching processes have focused mainly on the improvement of technologies to minimize the impact of gangue materials on the recovery of values and therefore increase the grade of minerals or the recovery rate of metals, as well as minimizing the environmental impact of extractive metallurgy activities. In fact, a sustainable recovery of values from minerals implies a cost-effective process, but also a cleaner and responsible production that suggests an ethical and preventative strategy that reduces the risk of environmental pollution.

The refractoriness of metal sources including ore, flotation concentrates, mill tailings and others that could affect mineral/metal processing could be due either to the fine dissemination of the metal in minerals or gangue matrixes that can react with metal host minerals, increasing the consumption of lixiviant and decreasing the rate of leaching reactions. On the other hand, the formation of intermediate phases or species may occur during the leaching process and form passivation layers, or consume important lixiviation reagents, and both will negatively affect the extraction of metal. There are also challenges associated with the greater mineralogical complexity of low-grade minerals from which metals can be extracted.

After the comminution, froth flotation constitutes an important segment of the separation process in the mineral processing industry and was introduced several decades ago to effectively separate gangue materials from valuable minerals. Despite being a matured process, the complexity of minerals can make froth flotation suffer from a relative inefficiency that could be attributed to poor insight regarding the physical and chemical phenomena that underpin the relationship between surface wettability and floatability. For instance, with the decrease of high-grade minerals coupled with the increased complexity of mineral composition and dissemination, the mineral industry has devoted its attention to low-grade and complex ores with high clay contents. However, to liberate values from such ores requires that they are ground to very fine sizes, which also contributes to the liberation of large quantities of fine gangue that are likely to cause problems related to slime coating, rheology, and entrainment during the flotation process. These issues mainly result in overconsumption of reagents, reduction of direct contact between the targeted mineral and collectors, and the reduction of the grade of flotation concentrations that contribute to minimizing the efficiency of the flotation process.

For all these cases, a pre-treatment of the mineral is needed to reduce the amount of the gangue upfront or adapt an adequate technique that will effectively control the formation of unwanted transition phases that can negatively affect the recovery of values.

The technological imperative will be therefore to improve the efficiency and reliability of the processes considered for metal extraction from the source. This technology should additionally be cost-effective and ensure the minimal negative impact on the environment. The various challenges encountered in the industry regarding the processing of complex minerals, research questions raised from unsolved technological mysteries, as well as the research illustrations presented are the various research benefits the readers will find in this book.

This book presents eight specialized chapters that focus on the exploration of the complexity of minerals that are likely to negatively influence the recovery of values, as well as the development of adequate technologies capable of improving the process of mineral concentration and/or metal recovery from complex minerals in a sustainable manner.

This book reviews the various physicochemical properties of minerals that are likely to pose a challenge during the attempt to recover values using conventional methods. It also elaborates on the recent technological development that has been considered by researchers to improve the recovery of metals from gangue-dominated minerals while ensuring cost-effectiveness and minimal adverse environmental impact.

The editors and the publisher are grateful to the reviewers who have contributed to improving the quality of the book through their constructive comments. The editors also thank the publisher for including this book in their series.

This book will be of interest to academic researchers in the fields of mineral processing, hydrometallurgy, geochemistry, environment, chemistry, engineering, and professionals, including mining plant operators, environmental managers in the industries, government regulatory officers, and environmentalists.

Elvis Fosso-Kankeu
Bhekie B. Mamba
Antoine F. Mulaba-Bafubiandi
January 2024

1

Optimization of the Mechanical Comminution – The Crushing Stage

Ngonidzashe Chimwani

Department of Mining Engineering, University of South Africa (UNISA), Florida Campus, Johannesburg, South Africa

Abstract

The mineral processing industry is faced with various challenges that hinder the efficient extraction as well as the marketing of metals. Among those challenges are the depletion of high-grade ores, rise in energy costs, and reduction of metal prices. In view of that, the need to improve efficiency becomes eminent in the mining and mineral processing industry. Improving efficiency can be achieved through carefully reviewing all the mining and mineral processing stages to identify technical innovations that enable the establishment of high-efficiency and low-energy consumption processes. This chapter thus reviews different crushers and the parameters that influence their potential to process low-grade ores efficiently. The review unveiled that downstream processes-oriented research should be preferred to those that focus on the optimization of a particular unit to improve efficiency. Other initiatives, such as managing the demand side of power and optimizing the idling time of the crushers, have shown great potential to reduce the energy consumption of impact crushers. This is because the energy expenditure of a gyratory crusher during idling is 30% of the full load power consumption, and jaw crushers not only lose a significant portion of energy into noise and heat, but have no-load power ranging from 40% to 50%.

***Keywords*:** Comminution, jaw crusher, gyratory crusher, cone crusher, impact crusher, HPGR crusher, low-grade ore, optimization

Email: ngodzazw@gmail.com

Elvis Fosso-Kankeu, Bhekie B. Mamba and Antoine F. Mulaba-Bafubiandi (eds.) Recovery of Values from Low-Grade and Complex Minerals: Development of Sustainable Processes, (1–40) © 2024 Scrivener Publishing LLC

1.1 Introduction

Comminution involves processes that reduce rocks from the infinite size of the half-space to sizes that allow valuable minerals to be separated from the gangue [1] using different separation methods. Rock blasting is the first process of comminution followed by crushing and then grinding, and the efficiency of each process is dependent on the preceding process. The blasting being on the utmost upstream has to provide not only the desired particle sizes for the crushers and mills but particle grains with reduced internal resistance owing to the existence of macro and microfissures within the particle. Although the presence of flaws within the blasted particles enhances productivity and lowers the grinding energy during mechanical comminution generally, they cause a reduction in productivity in autogenous mills that use the blasted particles as the grinding media. Thus, the control of the blasting stage should be guided by the requirements of the downstream process.

Requirements of the downstream processes are further complicated by the challenges exacerbated by the processing of low-grade ores resulting from the depletion of high-grade ores. Low-grade ores contain small grain-sized minerals dispersed through the rock, which require high energy as well as the knowledge of the ore texture to free the minerals from the host, and worse still, high fine losses are unavoidable in the process. The high energy requirements of low-grade ore processing add to the headache that the mineral processing industry has had since its inception. The comminution stage has, over the years, been widely known to be characterized by low efficiency [2] and high energy consumption, among other things. The continuous rise in energy costs and the increased concerns over global warming have sparked efforts to minimize CO_2 emissions, albeit with costs. Thus, it is imperative to be proactive than reactive, that is, to address the problems at the design and process stages.

To that end, several efforts have been made in that direction, at the crushing and milling stages including the development of comminution tests. The tests conducted are the drop weight tests, which provide the abrasion properties of rocks; the bond crushability work index, which determines the energy requirements of a crusher; the bond abrasion tests, which estimate mill/crusher liners; and the point load tests, which measure crushability by correlating the mechanical strength of the rock and the crusher reduction ratio. All these tests play an important role in the simulation and design of crushers and mills. The information drawn from these tests is used by the designers and manufacturers of comminution equipment to determine the load and non-load power requirements of each crusher/mill. From the wealth of research also emerged that the random application of forces inside the crushing and grinding machines between particles themselves or particles and the machine parts is fundamental to the disruptive nature of the comminution process [3]. These random forces make it impossible to achieve 100% efficiency in the comminution machines. Variations of the interactions of those particles and the products obtained are influenced by the equipment and operational parameters, such as the shaft velocities, equipment geometry and material properties, which ultimately affect the process efficiency in general, and the equipment in particular. Some equipment effect single impact, while others apply multiple impacts until particle sizes are disintegrated and reduced to acceptable values. The challenge, however, is that those processes are not efficient as mentioned in the foregoing, worse still with the processing of low-grade ores. This is especially considering that the biggest fraction of the input energy is dissipated as noise and heat with the other fraction channeled towards disrupting the forces that bind particles constituting the ore [4]. Richardson and Harker [5] compiled a list of the breakdown of the energy expenditure in comminution processes, and in that list, energy was observed to be consumed through the production of elastic deformation of the particles before fracture occurrence, inelastic deformation that leads to size reduction, elastic equipment distortion, friction between particles and between particles and the machine, and in the vibration, heat, and noise in the plant.

The proper definition of energy expenditure has been the subject of research over the years, and the need to deepen the enquiry cannot be overemphasized especially with the current dominance of low-grade ore processing. It is important to mention that the widely accepted theory used to determine the actual amount of energy used in comminution is derived from the inverse proportionality relationship between the mean particle size of the particles and the newly produced surface area, as the milling progresses. This thus means that the determination of surface areas at different stages of milling provides a reliable inquiry into the energy expenditure of the comminution process. In that vein, the Bond work index has been widely used and found to be reliable [6]. From comparing the total ideal fracture surface energy needed to generate new surfaces during the comminution of covalent materials and the standard Bond work index, Tromans [7] observed that crushing and grinding operations have 1% energy efficiency or even less.

Modeling energy consumption of a comminution equipment requires the knowledge of the design and operational parameters of the equipment [6]. The parameters range from that of the feed material to those of the equipment comminuting the materials. Some researchers have suggested altering the parameters of the feed through pre-treatment of the material to be comminuted to reduce Bond index values [3]. Although the pre-treatment increases cracks in the particles, it has the possibility of consuming more energy than the comminution process itself [6]. The most followed procedure, however, is to optimize the comminution process through fine-tuning the equipment parameters in a manner that redirects energy to be spent through vibration, heat, and noise into strain energy, which alters the internal forces of particles, hence creating new surface areas. But optimizing the process undoubtedly requires an understanding of Tromans' [7] detailed account of the energy expenditure. The author observed energy as utilized through the elastic deformation of particles before fracturing occurs, the inelastic deformation that results in the breakage of particles, elastic distortion of the equipment, friction between particles and between particles and the machine, and in noise, heat, and vibration of the equipment. It is also important to note that energy efficiency during comminution, as noted by Tromans [7] depends on impact efficiency, which, in turn, is influenced by the particle loading force, size, and orientation of inherent fissures in the particle with respect to the loading axis.

Over the years, the design and optimization of comminution equipment were achieved through experimental work and important milestones were reached. However, the experimental approach could not show how the particles flow and interact among themselves and with the equipment parts. Researchers thus found computer modeling applicable to unpack the internal dynamics of the particles that cause breakage. Advanced tools that allow particle flows to be simulated and the breakage process to be predicted, such as the discrete element modeling (DEM), were utilized. The tool found use in soil mechanics [8], and then later applied to milling and mineral processing [9]. Its ability to address a wide range of particle-related problems is well-documented in the literature [10–12]. Recently, it was used to simulate solid flows and energy transfer in the vertical impact crusher [13], configure ball mill liners to induce ball segregation in a ball mill [14], explore end liners of a ball mill [14], and simulate an impact crusher [15]. Its extensive usage in modeling particulate systems makes it useful to optimize comminution processes, which reduce particle sizes of low-grade ores.

The population balance model (PBM) was also used widely in the optimization of comminution circuits. The model, which found more use on the milling side than the crusher side to model size reduction kinetics, has been successfully applied to modeling hammer mills [16]. The PBM concept is used in the formulation of grinding equations derived from mathematically relating feed size and product size through applying size-mass balance. It is thus defined by the selection of particles for breakage (selection function) and the breakage distribution of 'children' fragments as a result of broken 'parent' particles (breakage function) [6] commonly known as the specific rate of breakage and the primary breakage distribution functions, respectively. These two kinetic functions form the basis for the modeling of the breakage kinetics in comminution devices when combined with the mass transportation of particles [17]. In this scheme, size-class mass balance calculations are used to predict the mass change of size classes at any given time interval from the milling of a narrow size class with set boundaries. From the crushing side of comminution, Chimwani and Bwalya [18] modeled the kinetics of an impact crusher using the PBM while for milling, some researchers have coupled it with other graphical analysis tools, such as the attainable region (AR) to optimize comminution circuits [19], with insightful information obtained from their findings.

All the efforts done so far to lower energy consumption through the optimization of the mechanical comminution stage are impressive. However, the problem is still very far from being contained since high-grade ore is depleting, resulting in the use of low-grade ore, which further complicates the optimization scheme. Furthermore, achieving 100% efficiency in comminution is something next to impossible, as observed by Legendre [20]. In the subsequent sections, different crushers are reviewed with the idea of bringing to light different efforts put by different researchers to understand their mode of operation in an attempt to achieve optimum operation of those size-reduction machines. This would consequently enable feasible processing of low-grade ore and the required crushing proportion of the comminution process.

1.2 The Role of Crushers

Crushers are at the initial stage of the mechanical comminution in the mineral processing chain. They compress or impact blasted particles in dry form against a rigid surface in a constrained motion path into different sizes and shapes for further downstream processing. The run of mine (ROM) ore is crushed in the succession of the primary, secondary, and tertiary crushers, and the particle size and shape requirements of the final product determine the ultimate choice of each crusher in a comminution circuit [21]. The crushing mechanism that dominates the breakage of particles in the crusher also plays a very crucial role in its selection for a given task. This is because some crushers consist of single-pass events that have been associated with the production of angular particles, while those with retention systems have been linked to the production of more rounded particles [22]. Particles that are angular and irregular, with sharp edges, possibly caused by the intersection of the propagated cracks, also result from the massive fracture of particles as effected by some crushers, while the rounded particles result from the chipping of edges and the erosion of surfaces as effected by other types of crushers. How the particles are fed into the crushers also influences the particle shape of the product, as observed by Durney and Meloy [23].

1.2.1 Types of Crushers and Their Effect

1.2.1.1 Jaw Crusher

A heavy-duty machine classified as a primary crusher, a jaw crusher reduces the particle size of the ROM ore in the order of 1.5-m size down to the product of 0.1 – 0.2 m dimensions by compressive force. It is a widely used comminution process equipment characterized by the V-shaped mouth at the top of the crushing chamber. The crushing chamber consists of a flat fixed rigid jaw and the flat or convex pivoting jaw, with hardened steel faces, which swing and thus effect compression between the swinging and stationary plates. The jaws are set at acute angles to each other, and the product size is determined by the setting at the bottom of the plates. Parameters, such as the strength, feed and product size, cost, and volume of operation, among other operational parameters, determine the optimal operation of the machines [24]. It is important to mention that the type of ores to be processed determines which jaw crusher to select for a given task. The swing jaw pivoting position classifies jaw crushers into Blake, Dodge, and Universal crushers, which in turn determines which types of ores the crusher can process.

The Blake crusher, which can be further classified into the single- and double-toggle jaw crusher, has a lower position fixed swing jaw with a variable discharge and fixed feed areas. In a single-toggle crusher, the swing jaw undergoes an elliptical jaw motion characterized by the swing motion and vertical movement caused by the toggle plate and the rotation of the eccentric angle, respectively. Whereas, in a double toggle as shown in Figure 1.1, the vertical motion of the pitman effects the swing jaw oscillating motion. This makes the single toggle suitable for softer materials, while the double toggle efficiently crushes the tough and abrasive materials. Therefore, double-toggle crushers are commonly used in mineral industries as primary crushers [6].

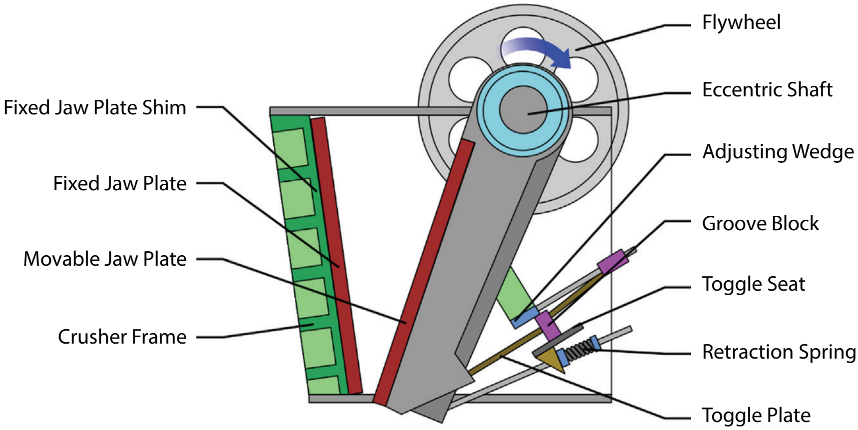

Figure 1.1 Illustration of a double jaw crusher [37].

In that light, all the factors have to be borne in mind when selecting crushers, especially when processing low-grade ores, which are more expensive to process. Important design factors are as follows [6]:

$$\text{Crusher vertical height} \approx 2 \text{ x Gape}$$

$$\text{Jaw width} > 1.3 \text{ x Gape}$$

$$< 3.0 \text{ x Gape}$$

$$\text{Throw} = 0.0502\ (\text{Gape})^{0.85} \tag{1.1}$$

where the crusher gape is in meters.

To size the gape, the following relationship between the gape and the largest particle is used [6]:

$$\text{Largest particle size} = 0.9 \text{ x Gape} \tag{1.2}$$

The swing jaw of the Dodge crusher is fixed at the upper position, and that fixes its discharge area while the feed area is variable. The crusher operates under choking conditions with particles broken smaller and smaller progressively as they approach the bottom end and eventually escape. This makes the crusher unsuitable for handling heavy-duty crushing and hence limited to laboratory use. It is important to note that operating crushers under choking conditions have a bearing on the product particle shape.

In addition to that, choke feeding makes particles break because of compressive forces between the jaws and inter-particle compression with the consequence of a generally fine product [6]. The universal crusher has the swing jaw fixed at an intermediate position.

Jaw crushers, being usually at the initial stages of the mechanical comminution, must operate efficiently so that the efficient operation culture can be transmitted across all the size reduction stages. In that vein, considerable effort has been made to model the crushing machines and optimize their operations [25]. The performance studies include optimizing the jaw crusher in terms of the speed and closed side setting [25, 26], kinematics [27], and the energy consumption of the crusher [3, 28–30]. Some of the researchers enlisted the services of modeling techniques, such as the DEM, to assess the variation of the crusher product with ore body strength [31], response surface method and gene expression programming [32], variable load-based optimal control [29] while others optimized the crusher, in terms of particles using the population balance model [33].

Parameters of jaw crushers that determine their optimal operation are the crusher speed, closed side setting (CSS), feed rate, and gradation. The CSS, determined by the smallest gap between the moving and fixed jaws, is the main parameter for jaw crusher optimization and has implications for the energy consumption and capacity of the jaw crusher. It is also known as the aperture of discharge in the crushing medium [32] that controls the extent of rock crushability of compressive crushers [34]. From the work of Barrios *et al.* [35], CSS was found to be central to the estimation of the product achievement, throughout, compressive forces acting on jaw plates, specific energy consumption and the size reduction ratio. An inverse proportionality relationship occurs between the CSS and the power draw of the crusher, while between the crusher capacity and the CSS, it is the direct proportionality relationship [25]. The jaw speed controls the capacity, as well as the fineness of the product at any given CSS, since it determines the number of compressions a particle gets in its journey between the jaws until it exits the crushing chamber. The distance traveled and time taken while subjected to repeated crushing forces in the crushing chamber were used by Rose and English as the basis for determining the capacity of the jaw crusher [3]. Higher speeds of the jaws reduce the capacity of the crusher since it causes the particle to stay longer in the crushing chamber at the cost of high energy expenditure. Although the result is generally a finer product, the high energy consumed in the process diminishes the returns, especially considering the ever-escalating energy costs and the efforts to reduce the emission of CO_2.

Energy loss through the dissipation of the input energy into noise and heat characterize most comminution process, and thus forms a basic approach on which the modeling of the jaw crushers is based [7]. The processes are optimized numerically with machines that have large computational power, which allows the manipulation of the jaw crusher design parameters to determine efficiency values. Some researchers have also developed an optimal switching control technique that reduces the energy consumption of the jaw crusher, hence the crushing process [36]. This was developed after realizing that compressive crushers such as jaw crushers consume 40% to 50% of rated power when idling without a load, hence filling the energy improvement gaps in literature.

In a study aimed at providing information about the single-stage crushing optimization, Fladvad and Onnela [30] conducted a study that investigated the effect of feed rate and gradation, crusher setting and speed on the crusher operation, and quality of the product. The quality of the aggregates produced was determined by the shape, gradation, and the mechanical strength of the feed particles. From that work emerged that the specific energy consumption during crushing is influenced by the feed gradation, crusher setting, and crusher speed. Interesting to note though is that the authors found that crusher speed was inversely proportional to the specific energy consumption of the crushing process. It was also concluded in this work that products from a specific rock deposit should not be assumed to have constant mechanical strength, and that product quality and crushing efficiency can be controlled in a jaw crusher set-up. Mechanical strength depends on the interaction between crystals, particles, and the cementation material forming it [38].

In a study that focused on the effects of rock strength properties on the performance of a jaw crusher, Olaleye [31] concluded that the stronger the rock, the longer the crushing time required to obtain a given grain-size distribution of particles, hence the higher wear and energy consumption. In another study, Köken and Lawal [32] used the response surface methodology to investigate the choke-feeding intensity of feed sizes ranging from 9.5 to 19 mm during crushing actions. Their findings revealed that the characterized feed size distribution controls the general size reduction, while the amount of the feed in terms of mass affects the energy consumed in the crushing process and the product flakiness. Both the feed size distribution and mass parameters were found to be influential in regulating the choke-feed intensity. The authors acknowledged the importance of the choke-feeding intensity parameter in compressive crushers, hence its important role in the optimization of jaw-crushing operations. They suggested that relatively low choke-feeding intensity results in insufficient