Crushing characteristics of different minerals by cylindrical ball mill in cascading motion state

Xiaojing Yang¹,², Shaojian Ma¹,² *, Jinlin Yang² and Pengyan Zhu²

¹School of Chemistry and Chemical Engineering, Guangxi University, Nanning 530004, China
²Guangxi Key Laboratory of Processing for Nonferrous Metallic and Featured Materials, Guangxi University, Nanning 530004, China

*Correspondence: xjyang@st.gxu.edu.cn; Tel.: +86-0771-3232200

Abstract: During the grinding process of the impact and abrasion actions synchronously coexist and continuously occur, the two actions may exert forces in different areas and transform to each other periodically. So it is difficult to characterize the respective crushing characteristics of the impact and abrasion actions. Based on the kinematics theory of grinding media, to ensure the grinding medium to be in cascading motion state in which minerals are crushed by only abrasion action of medium, to investigate the crushing characteristics of three kinds of minerals of quartz, pyrrhotite, and pyrite. Moreover, the difference in the ability to resist the crushing in the grinding process and the influence of feed sizes on the crushing were investigated by analyzing and comparing the breakage rate of the different minerals and the yield of specific product size - \( t_{10} \) value under different test conditions. The research results indicated that the grinding resistance of quartz is the strongest, followed by pyrite and pyrrhotite. Besides, a smaller feed size resulted in a more grinding and crushing effect on the minerals. Therefore, during production, the grinding system should be adjusted according to the change in the material property to prevent over-grinding.

1. Introduction

The grinding process plays an important role in mining, metallurgy, building materials, chemical industry and other industries, it is the preparative operation before separation, and its product particle size characteristics significantly affect the efficiency and product quality of the subsequent process [1-4]. Therefore, the grinding operation occupies a very important position in mineral processing plants. Ball milling is the most widely applied method in grinding process, which crushes ores by the influence of medium in a cylindrical mill facilitated by continuous rotation. Generally, grinding medium has three types of motion states in the ball mill such as cascading, cataracting, and centrifuging. The action of grinding media varies with the experienced motion states. Specifically, the action mode of cataracting motion is impact crushing, and that of cascading motion is abrasion. The existing theoretical equations are merely applicable to the cataracting motion. However, there are obvious differences in the motion patterns of medium between other states and cataracting motion state, and the mechanism of impact crushing is completely different from that of abrasion. Hence, the current grinding models can only provide definite theoretical references for practice, with certain conditionality and limitation [5-8].

Based on the above research status and related previous studies, three kinds of minerals that are widely distributed in metallic ores such as quartz, pyrrhotite, and pyrite are selected as the subjected in this paper. Firstly, the critical rotational speed of the ball mill in a cascading motion state is calculated
using theoretical equations. Secondly, on this basis, grinding tests are conducted for the three kinds of minerals by the cylindrical mill. Finally, the breakage rate of feed materials in the cascading motion state and the particle size distribution characteristics of grinding products for the samples are analyzed and compared. The differences in the crushing effect by the abrasion action of the cascading motion state on the three kinds of minerals are discussed for exploring the crushing characteristics of the cylindrical ball mill and to provide experimental and theoretical bases for subsequent studies on the grinding behavior characteristics.

2. Materials and methods

2.1. Calculation of rotational speed of mill in the cascading motion state

Studies have shown that the motion state of medium in the mill is mainly affected by factors such as rotational speed of the mill, filling rate of medium, grinding concentration, and shape and material of lining board, among which the filling rate of media and rotational speed of mill are the most influential parameters [1-3]. With other factors determined, the motion state of medium changes with the variation in the rotational speed of the mill provided the filling rate of the medium in the mill is kept constant. Therefore, to ensure the occurrence of cascading motion state during the analysis, a mathematical analysis is performed to find out the appropriate rotational speed of the mill.

Since the medium in the outermost layer of the mill are located farthest from the center of the mill, the rotational speed necessary for lifting and cataracting is the lowest. On the contrary, the rotational speed needed by the medium in the innermost layer for lifting and cataracting is the highest because they are located closest to the center of the mill. To ensure that the medium in each layer are in the cascading motion state, it is necessary to confirm that all the medium in the outermost layer are in the same state. The motion trajectory of the medium in the outermost layer is displayed in Figure 1.

In this paper, the coordinate system of the ball mill with radius $R$ is established with the detachment point as the origin of the coordinate. The detachment velocity $v \cos \alpha$ could be illustrated by the landing point coordinate $X_C$ of the media in the outermost layer according to the equation below:

$$x_c = 4R_x \sin \alpha \cos^2 \alpha_x \quad , \quad y_c = -4R_x \sin^2 \alpha_x \cos \alpha_x$$

(1)

Fig. 1 The motion trajectory of the medium

At $\alpha_x = 73.73^\circ$, detachment point A overlapped the landing point C of the media in the outermost layer, and the media in the outermost layer are confirmed to be in the cascading motion. Thereafter, based on the relationship between the detachment angle $\alpha$ and rotation rate $\varphi$ of the media in the outermost layer (Equations 2-3), with the filling rate of 40 %, the rotation rate of the grinding media to facilitate the cascading motion is calculated as follows: $\varphi = 10.5 \%$.

$$\cos \alpha_x = \varphi^n$$

(2)
Where $\Psi$ is the filling rate expressed in decimal, $\varepsilon$ is the repose angle of medium stacking ($\varepsilon \approx 40$ for ball media), and $b$ is the coefficient which is equal to 0.015 when $\varepsilon$ is expressed in degree. According to the equations of the critical rotational speed and rotation rate of the media in the mill, when the diameter of the grinding ball media in the mill is $D=25$ mm, the critical rotational speed can be calculated via the equation $n_c = 94.8$ r/min. Meanwhile, from the rotation rate of $\varphi = 10.5\%$, the rotational speed of the media in the cascading motion can be calculated using the following equations ($n = 12.43$ r/min),

$$n_c = \frac{30}{\sqrt{R-r}} = \frac{42.4}{\sqrt{D-d}}$$

(4)

$$\Psi = \frac{n}{n_c} \times 100\%$$

(5)

Where, $R$ stands for the radius of mill, and $r$ refers to the radius of media. $D$ stands for the diameter of mill, and $d$ refers to the diameter of media.

As a result, when the rotational speed of the mill is $n \leq 12.43$ r/min, the grinding medium in the cylindrical mill achieves cascading motion state, so the abrasion action is the dominant grinding effect.

The crushing degree of mineral can be represented as the breakage rate of minerals and the yield of specific product size - $t_{10}$ value. In the two regards, the grinding resistance of the minerals under different conditions is evaluated and compared. Moreover, the generation rate of each product size also were investigated, obtained the differences of minerals under cascading motion state.

2.2. Materials and grinding process

A cylindrical ball mill altered from a cylindrical rod mill is used as the test equipment, and its rotational speed is adjusted to 10 r/min employing a frequency converter to ensure that all the media in the mill are in the cascading motion state during grinding.

The materials used in this test include natural pure quartz, pyrite, and pyrrhotite, which are washed, dried, crushed, screened, and bagged. Then, three samples having particle sizes -3.35+2.36 mm, -2.36+1.7 mm, and -1.7+1.18 mm are prepared and bagged for later use (500 g per bag). The test conditions are fixed as follows: rotational speed of mill as 10 r/min, grinding concentration as 75%, filling rate of media as 40%, and medium diameter as 25 mm.

3. Results and discussion

In this paper, only three influencing factors are considered about grinding time, grinding feed size, and mineral type. After processing the data from the test results as per the above test design, the breakage rate, $t_{10}$ values, and the generation rate of the three kinds of minerals under different grinding conditions were obtained. Then, the three characterization indexes are compared to investigate the difference in the ability of different minerals to resist abrasion action, and the crushing characteristics of the cylindrical ball mill in the cascading motion state are examined.

3.1. Comparative analysis of breakage rate

The breakage rate of the three kinds of minerals under different feed sizes and grinding time is shown in Figure 2.
It is manifested that as the grinding time is prolonged, the materials are broken more effectively under the abrasion action, and the breakage rate for each feed size of the three kinds of minerals is increased. In addition, the smaller feed size results in more changes of breakage rate with the grinding time. Therefore, with other grinding conditions kept constant, the smaller feed size leads to a greater abrasion action on the material. When the medium in the ball mill are in the cascading motion state, the medium move upward along with the cylinder wall, deflecting to a certain angle, and then they tend to roll down along the slope formed by it after reaching a certain height. During the upward and downward rolling of medium along the cylinder wall, the medium grinds with each other, and the mineral particles between the medium and the cylinder wall are also ground. With other conditions determined, the grinding resistance and surface area of materials are the leading influential factors for the grinding efficiency. Therefore, for the same mineral, the change in the breakage rate of fine grade with grinding time is more prominent than that of coarse grade.

3.2. Comparative analysis of $t_{10}$ of minerals

While calculating the parameter $t_{10}$, the feed particle size is considered based on the average value of the upper and lower particle size limits \[9-14\]. The $t_{10}$ value represents the coarseness or fineness of the grinding products, \textit{i.e.}, the particle size distribution of the grinding products. The results of $t_{10}$ value in the cascading motion state is ranked as follows: pyrrhotite $>$ pyrite $>$ quartz.

(a) -3.35+2.36 mm feed size  \hspace{2cm}  (b) -2.36+1.70 mm feed size  \hspace{2cm}  (c) -1.70+1.18 mm feed size

The changes in the breakage rate of different minerals with respect to grinding time for the same feed size are displayed in Figure 3. It is demonstrated that as the grinding time is extended, the breakage rate of three kinds of minerals rises gradually, and which of pyrrhotite increased prominently. When the grinding time remains constant, the breakage rate of pyrrhotite is the highest, followed by pyrite and quartz. Thus, the crushing effect of the abrasion action on the three kinds of minerals in cascading motion state is ranked as follows: pyrrhotite $>$ pyrite $>$ quartz.
From Figure 4, it is inferred that when the rotational speed of the mill, filling rate, and grinding concentration are kept constant, the relationship of $t_{10}$ value with the feed size and grinding time varies between three kinds of minerals. The $t_{10}$ value of quartz at three feed sizes, and pyrite and pyrrhotite at the smallest feed size show a linear increase with the grinding time. It is manifested from Figure 4 that in the case of a smaller feed size, the $t_{10}$ value changes faster with grinding time. This implies that a smaller feed size results in better grinding effect. According to the change in $t_{10}$ value of minerals considering the same feed size and the grinding time, the $t_{10}$ value of pyrrhotite is the largest, followed by pyrite and quartz. Hence, it can be inferred that the grinding resistance of the three kinds of minerals is ranked as follows: quartz > pyrite > pyrrhotite. Also, the range of $t_{10}$ value changes over time is the largest for pyrrhotite, followed by pyrite and quartz. These results are consistent with the results of the aforementioned breakage rate analysis of different minerals.

3.3. Comparative analysis of generation rate of grinding product

The generation rate of the three kinds of minerals under different feed particle sizes and grinding time is shown in Figure 5.

It is shown that the generation rate of each product particle size are relatively small under the abrasion action of grinding media from Figure 5, except that the smallest fine size -0.038 mm fractions is larger than else, the generation rate of the rest of the particle size decreases with the product particle size decreasing. This means that the product particle size tends to distribute in the second coarse fractions near the original particle size of the feed itself and the fine fractions of -0.038 mm, which indicated that there were obvious abrasion behavior characteristics under cascading motion state grinding process. The abrasion behaviors were affected by feeding particle size and mineral types. From the perspective of the generation rate of the fine fractions of grinding products, the smaller the mineral hardness or the feed size, the greater the generation rate of the same fine fractions. In a word, the feed particle size and the hardness of the mineral affect the abrasion grinding behavior: from the comparison of hardness effects, the generation rate of fine particle grades from large to small is: pyrrhotite > pyrite > quartz; from the comparison of particle size effects, the generation rate of fine particle grades from large to small is: -1.70+1.18 mm > -2.36+1.7 mm > -3.35+2.36 mm.
In a word, the abrasion action under different grinding conditions exerts different effects on quartz, pyrrhotite and pyrite. In other words, the grinding effects of the three kinds of minerals under the abrasion action are different in the cascading motion state.

4. Conclusions
At different grinding feed sizes, a single mineral of fine grade has a higher degree of breakage and crushing speed as the grinding time increases. Besides, at different grinding particle sizes, when the feed size of a mineral is smaller, the particle size distribution of products changes more significantly with the variation of grinding time. Under the same grinding conditions in the cascading motion state, the grinding effect on the three kinds of minerals is ranked as follows: pyrrhotite > pyrite > quartz; and the generation rate of fine particle grades is also ranked as follows: pyrrhotite > pyrite > quartz; feed size influences the generation rate, the rank is: -1.70+1.18 mm > -2.36+1.7 mm > -3.35+2.36 mm. The present research results can provide a reference for the theoretical study on the law of cascading motion of mills.

Acknowledgements
This research was funded by the Natural Science Foundation of China (No.51874105) and Guangxi Natural Science Foundation (No.2018GXNSFAA281204).

References
[1] D. Gwiranai, H. Diane, G. David, B. Clayton, Application of basic process modeling in investigating the breakage behavior of UG2 ore in wet milling, Powder Technol. 279 (2015) 42-48.
[2] Yang Jinlin, Zhou Wentao, Ma Shaojian, et al. Study on the prediction model for production rate of target grinding size in cassiterite polymetallic sulfide ore [J]. Mining Research and Development, 2016, 36(7): 22-25.
[3] Zhang Guowang. Status and development of crushing and grinding equipment [J]. China Powder Science and Technology, 1998(3): 37-42.
[4] D. W. Fuerstenau, P. B. Phatak, P. C. Kapur, et al. Simulation of the grinding of coarse/fine (heterogeneous) systems in a ball mill [J]. International Journal of Mineral Processing, 2011(99): 32-38.
[5] C. Bazin, P. Obiang. Should the slurry density in a grinding mill be adjusted as a function of grinding media size? [J]. Minerals Engineering, 2007, 20(8): 810-815.
[6] N. Chimwani, D. Glasser, D. Hildebrandt, M.J. Metzger, F.K. Mulenga, Determination of the milling parameters of a platinum group minerals ore to optimize product size distribution for flotation purposes, Miner. Eng. 43-44 (2013) 67-78.
[7] X.X. Duan, Crushing and grinding, Beijing: Metallurgical Industry Press. (2012) 134-152.
[8] Chen Bingchen. Grinding Principle [M]. Beijing: Metallurgical Industry Press, 1989: 35-83.
[9] Z.W. Shi, Experiment study on grinding law with ball medium of Cassiterite-polymetallic sulfide ore (MS Thesis), Guangxi University, Nanning, China, 2009.
[10] Z. Hu, C.H. Wang, X. Tong, Experimental study on beneficiation of fine cassiterite from polymetallic sulphide ore, Mining Machinery. 40(1) (2012) 81−85.
[11] B. Epstein, The mathematical description of certain breakage mechanisms leading to the logarithmic-normal distribution, Journal of the Franklin Institute. 244(6) (1947) 471-477.
[12] K. Siedlatschek, L. Bass. Contribution to the theory of milling processes [J]. Powder Metal. Bull., 1953, 6: 148-153.
[13] R. Gardner, L. Austin. A chemical engineering treatment of batch grinding. 1962, 1: 21-38.
[14] Xue Tianli. Study on selective grinding behavior of cassiterite-polymetallic sulfide ore [D]. Nanning: Guangxi University, 2014.