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# Research on the characteristics of particles size for grinding products with a ball mill at low speed

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Abstract: Grinding is a process where the particle size of the material is reduced under the combined effects of the impact action and the abrasion action of steel balls (grinding medium). Even though there are studies related to the grinding process, only a few studies systematically reported the low-speed grinding process. In this paper, the two common minerals: pyrite and quartz are subjected to low-speed grinding using the ball mill technique where the mill rotation is optimized to facilitate the grinding medium to be in the state of cascading. In addition, the relative grindability and grinding kinetic analysis are used to elucidate the particle size distribution characteristics, and rules for achieving the ground product's particle size at lowspeed grinding. Further, discussions are made on the grinding characteristics of the mill when the grinding medium is in the cascading motion. The results show that i) finer feed size induces a significant change in the particle size of the ground products; ii) the grinding fineness of pyrite is higher given the same grinding time, whereas the grinding fineness of quartz increases sharply when the grinding time is prolonged; and iii) the grinding processes of the two minerals follow first-order linear kinetic model at low-speed grinding. These findings provide a theoretical foundation to carry out further research on the motion law and grinding characteristics at lowspeed grinding.

# 1. Introduction

The grinding process is widely utilized in industries like mining, metallurgy, chemical, and other basic industries that build the nation's economy. During the mineral separation process, most of the ores are subjected to the grinding process to liberate useful minerals, except for a few ores where the minerals have been already liberated or they are rich high-grade ores for which the grinding is redundant. The cost of the grinding process accounts for about 50% of the total production cost since the final product quality is directly influenced by the separating indices and the quality of subsequent operations performed at the plant <sup>[1,2]</sup>. Therefore, global experts focus more on the research related to grinding operations and have jointly promoted the development and establishment of the theoretical system for grinding. However, due to the motion of the grinding medium in the mill is affected by multiple factors and thus, cannot be monitored in practice. Even though there are a lot of scientific reports providing positive insights about the working of the mill is formulated based on the concept that the grinding medium is in the state of throwing which is the basis for ball motion theory proposed by Davis and Levinson. This finding serves as the foundation for other scientists to carry out research which leads to

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constant revision and improvement in the theoretical analysis <sup>[3-7]</sup>. At present, the law of throwing motion of the grinding medium in the mill can be quantitatively described through mathematical formulae, but the cascading motion of the grinding medium can only be qualitatively described in a simple manner. In the process of grinding, different motions of the grinding medium follow different grinding medium facilitates the grinding effect. Hence, the grinding mechanisms for the throwing medium and cascading medium are very different. The existing theoretical formulae for the grinding mechanism are only applicable to the throwing motion, and thus, the theoretical guidance for the actual grinding operations in practice is limited.

Based on the status quo of the above-mentioned grinding theory, the grinding characteristics of two common minerals such as pyrite and quartz are studied. The particle size distribution of the two minerals achieved through low-speed grinding, relative grindability at different feed sizes, and the grinding kinetics analysis of low-speed grinding are compared in this paper. The difference in grinding characteristics between the two minerals is studied, and the grinding mechanism of the mill by considering the cascading of the grinding medium is discussed preliminarily. Moreover, the current findings provide theoretical proof to carry out further studies on the motion law while the grinding medium in the state of cascading.

# 2. Materials and methods

Natural minerals of pyrite and quartz are chosen as the test specimens, that are crushed, sieved, mixed, shrunk, and packed separately for use. The mill used to grind test specimen is XMB- $\phi$ 200×240 cylindrical mill which is altered into a cylindric ball mill by replacing the inner steel rod with steel balls.

As per designed, the material is ground when the medium are in cascading motion state. To elucidate the crushing behavior of pyrite and quartz under abrasion action alone, the mill rotation speed is adjusted by a frequency converter in such a way that the medium is in cascading motion while running the mill.

As the steel balls at the outer walls of the mill are the farthest from the center of the mill, the speed of rotation should be minimized to reduce the throwing motion of the grinding medium <sup>[6-8]</sup>. Therefore, to set all the layers of the medium inside the mill in cascading motion, it is only required to make sure that the outermost medium attains a cascading state, whose motion curve is represented in Figure 1.



Figure 1 Motion curve of outermost medium in the mill

The calculation <sup>[8-10]</sup> reveals that when D (size of steel ball) = 25 mm and n (rotation speed of mill)  $\leq 12.34$  rpm, the steel balls inside the mill attain the state of cascading, and the reduction in particle size is induced by the abrasion action. Low-speed grinding tests are performed for pyrite and quartz at three different feed sizes (-3.35+2.36 mm, -2.36+1.7 mm, and -1.7+1.18 mm). The test conditions such as mill rotation speed of 10 rpm, grinding concentration of 75%, the medium filling rate of 40%, medium size D = 25 mm, and grinding time of 0.5 min, 1 min, 2 min, 4 min, and 8 min are employed while performing the experiments.

# 3. Results and discussion

#### 3.1. Particle size distribution of ground products from different feed sizes

In the low-speed grinding test, the particle size distribution results and abrasion behavior characteristics of the ground products were investigated by changing the influence factors such as the feed size, sample type and grinding time. The variations in yield of pyrite and quartz are shown in Figure 2, respectively.

From Figure 2, the results showed that low-speed grinding was a low-energy grinding process, and the distribution of product particle size was uneven, and it tended 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 in the low-speed grinding process. Moreover, it is inferred that as the grinding time is prolonged, the curves of yield for both the feed sizes shift upward for all the feed sizes. At a fixed relative particle size, the yield increased continuously, validating the crushing of minerals passes through low-speed grinding as time. Further, finer the size of feed material, a more evident upward deviation of the yield curve is achieved. As the feed particle size becomes finer, the total surface area of the minerals is increased, allowing a larger effective contact area with the medium and the inner wall. Therefore, for the same mineral, the yield curves of ground products when feed size finer display significant improvement.

Comparing Figure 2 (a) and (b), it can be seen that under the same grinding conditions, the variation in the yield curve of quartz with respect to grinding time is more distinct than the pyrite substantiating that the quartz is more affected by grinding time at low-speed grinding.



Figure 2 The yield curve of grinding product at different grinding time

#### 3.2. Relative grindability of minerals

The concept of relative grindability of the material is evaluated and compared for pyrite and quartz at low-speed grinding. The relative grindability  $^{[12]}(K)$  of the two minerals is defined as the ratio between the new yields of two minerals at the -0.074 mm size per unit time and unit volume, expressed as,

$$K = \frac{q_a}{q_b} = \frac{Q_a (\beta_{a2} - \beta_{a1}) / (V \cdot t_a)}{Q_b (\beta_{b2} - \beta_{b1}) / (V \cdot t_b)}$$
(1)

where,  $q_a$  and  $q_b$  represent the new yields of minerals a and b, respectively, at the -0.075 mm particle size per unit time and per unit volume, measured in kg/(L·min).  $Q_a$  and  $Q_b$  denote the weight of minerals a and b, respectively, to be ground, measured in kg.  $\beta_{a1}$  and  $\beta_{b1}$  represent the content of minerals a and b, at the -0.075 mm particle size, to be ground, measured in %.  $\beta_{a2}$  and  $\beta_{b2}$  represent the content of minerals a and b, respectively, at the -0.075 mm particle size (%). V is the volume of the test mill, measured in L.  $t_a$  and  $t_b$  represent the grinding time of minerals a and b, respectively, measured in min.

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Figure 3 The yield curve of fine fraction of two minerals at different grinding time For the experiment,  $Q_a$  and  $Q_b$  is equal,  $\beta_{a1}$  and  $\beta_{b1}$  is equal,  $\beta_{a2}$  and  $\beta_{b2}$  is equal, therefore, the relative grindability K of mineral a and b can be expressed as:  $K=q_a/q_b=t_a/t_b$ . So, it is evident that the relative grindability of the tested minerals have a correlation with the grinding time. The relationship between the fineness of ground products for different feed sizes and the grinding time is shown in Figure 3. And non-linear fitting analysis results for the relationship curve are shown in Table 1. Table 1 The fitting results of product fineness and grinding time

Tuble 1 The fitting results of product filteness and grinding time				
Feed size	Mineral sample	Fitting equation	Degree of fit R <sup>2</sup>	
-1.17+1.18 mm	Quartz	y=2.7794*x^0.3238	0.9725	
	Pyrite	y=4.4647*x^0.2169	0.9952	
-2.36+1.7 mm	Quartz	y=2.3647*x^0.2769	0.9841	
	Pyrite	y=3.6342*x^0.1574	0.9907	
-3.35+2.36 mm	Quartz	y=2.1514*x^0.2874	0.9876	
	Pyrite	y=3.4868*x^0.1494	0.9735	

According to Figure 3 and Table 1, there is a good convergence between the fineness of the ground product and the grinding time, representing a sound-fitting effect. As shown in Table 2, the required grinding time for ground products, in which particles with a fineness of 0.074 mm in size accounted for 5 %, 6 %, and 7 % while different feed sizes are used. The results are evaluated by combining the fitting equation (Table 1) and the new yields of the -0.074 mm ground products.

Feed size/mm	Mineral – sample	Grinding time/min		
		-0.074 mm	-0.074 mm	-0.074 mm
		accounting for 5%	accounting for 6%	accounting for 7%
-1.17+1.18	Quartz	3.08	6.13	10.77
	Pyrite	0.60	1.69	6.33
-2.36+1.7	Quartz	6.67	14.94	19.58
	Pyrite	1.84	7.59	12.23
-3.35+2.36	Quartz	8.65	18.81	23.45
	Pyrite	2.51	11.16	15.80

|--|

able 5 The Relative grindability of pyrite and quartz
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		Relative grindability	
Feed size/mm	-0.074 mm	-0.074 mm	-0.074 mm
	accounting for 5%	accounting for 6%	accounting for 7%
-1.17+1.18	5.11	3.64	1.70
-2.36+1.7	3.63	1.97	1.60
-3.35+2.36	3.45	1.68	1.48

As per formula 1, the relative grindability for pyrite and quartz to different fineness under different feed sizes are calculated and shown in Table 3. The results revealed that under the condition where - 0.074 mm ground products accounted for 5 % of the content, the *K* value is 3.45 when the feed size is -

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3.35+2.36 mm; when the feed size is -2.36+1.7 mm, *K* is calculated as 3.63; when the feed size is -1.7+1.18 mm, *K* is evaluated as 5.11. All the *K* values are greater than 1 for all feed sizes. The results also imply that when the grinding fineness is same, the required grinding time of pyrite is shorter.

#### 3.3. Analysis of grinding kinetics under different conditions

The grinding kinetic fitting analysis is carried out for the ground products of pyrite and quartz. Sedlatschek and Bass <sup>[11-12]</sup> deduced the theoretical formula for the coarse-grained grinding kinetics following statistical principles which is expressed as,

$$Y_t = Y_0 \cdot e^{-kt} \tag{2}$$

In the equation,  $Y_0$  represents the weight of coarse particles in the feed (measured in g), t is the grinding time (measured in min), and  $Y_t$  is the weight of coarse particles in the grinding product after being ground for t min (measured in g).

In general, the degree of fineness or the cumulative undersize yield is used to determine whether the particle size of a ground product is qualified or not. Therefore, the fine-grained grinding kinetic formula is deduced based on the grinding kinetic theory and is expressed as follows,

$$\ln[1 - X_t / (1 - X_0)] = -k \cdot t \tag{3}$$

Formula 3 can be transformed into a linear relation as shown below,

$$y = k \cdot t + b \tag{4}$$

Based on the aforementioned theoretical analysis and combining formula 3 and 4, fitting regression analysis of test data was performed using Origin software. Results are shown in Figure 4 and Table 4.



Figure 4 The kinetic fitting of ground products of two mineral samples

Table 4 The linear fitting results of kinetic equations				
Feed size	Mineral sample	Fitting equation	Degree of fit $R^2$	
-1.17+1.18 mm	Quartz	<i>y</i> =0.02429+0.00178* <i>x</i>	0.9831	
	Pyrite	y=0.03496+0.00227*x	0.9959	
-2.36+1.7 mm	Quartz	<i>y</i> =0.01621+0.00297* <i>x</i>	0.9994	
	Pyrite	y=0.02338+0.00291*x	0.9920	
-3.35+2.36 mm	Quartz	<i>y</i> =0.01979+0.00239* <i>x</i>	0.9978	
	Pyrite	y=0.02846+0.00211*x	0.9859	

According to Figure 4 and Table 4, the formula for grinding kinetic linear model demonstrated the particle size distribution characteristics and the ground products display good agreement with the theoretical fitting at different grinding time. These findings provide proof for the theoretical study of grinding kinetics at low-speed grinding conditions.

#### 4. Conclusions

After studying the particle size characteristics of ground products of pyrite and quartz achieved through low-speed grinding, the conclusions are drawn as follows:

For the same mineral, finer feed size leads to a significant change in the particle size distribution of the ground product with respect to varying grinding time. Under the same grinding conditions, pyrite is

more susceptible to the influence of grinding time. When the particles with a fineness of -0.074 mm account for 5%, 6% and 7% content, the relative grindability of both pyrite and quartz at different feed sizes is greater than 1. At low-speed grinding, the grinding fineness of pyrite is higher than that of quartz at the same grinding time, but the grinding fineness of quartz increases dramatically when the grinding time is prolonged. Therefore, in practice, grinding time should be reasonably fixed by knowing the mineral properties to prevent over-grinding. At low-speed grinding, the grinding processes of the two minerals are in line with the first-order linear kinetic model of grinding, and thus, provide theoretical proof for the study and analysis of low-speed grinding.

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