Effect of grinding media on the milling efficiency of a ball mill

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Abstract
The size of grinding media is the primary factor that affects the overall milling efficiency of a ball mill (e.g. power consumption and particle size breakage). This article tackles the lack of a design tool that could help choose the ball loading composition in mills. Such a tool enables the maximization of the exposed surface area per unit energy (cm²/J). The effect of ball load composition, by varying the grinding media size distribution (e.g. alternatively by mixing four groups of 19.5, 38 mm; 19.5, 50 mm; 38, 50 mm and 19.5, 38, 50 mm), on the milling efficiency of a laboratory scale ball mill has been investigated in this article concerning ball number, total surface area, and ball weight. The results reveal that the amount of required energy is close in values, per each ball loading mixture, concerning three characteristic parameters. The amount of required energy varies between 3.22 kWh/st & 3.65 kWh/st. Moreover, the new surface area per unit energy (e.g. cm²/J) significantly influences milling efficiency. In contrast, the ball weight has a minor effect. This study would be helpful in industries in which comminution is part of the process, such as mining and cement industries.

Keywords: ore comminution; grinding media; ball size distribution; Bond Work Index

1. Introduction

Grinding is very significant component of the comminution process. Comminution is a critical operation in mineral processing, and the cement and pharmaceutical industries (Musci et al, 2019). In terms of energy requirements and steel consumption associated with grinding media and liners, it is an expensive and inefficient process (Lameck, 2006). The comminution process ends with a grinding process in which the particle size has resulted in fine particles, e.g. microns (Kabezya and Motjotji, 2015; Abdelhaffez, 2020). The cost of comminution accounts for roughly 60% of the overall investment in a beneficiation plant, and their power consumption is 50-60% (Sadrai et al., 2006). Ore grinding consumes more than 5% of total yearly electricity generation and millions of tonnes of steel each year (Musa and Morrison, 2009). The ore should first go through several stages of comminution, which is the process whereby the particles of the ore are gradually reduced until the mineral particles are detached. Comminution activities, including grinding, consume up to 4% of global electrical energy, and comminution consumes approximately 50% of mine site energy (Kolev et al., 2021).

According to one study, the grinding process alone accounts for approximately 40% of total power consumption in a mine complex (Ballantyne et al., 2012). A ball mill employs steel balls to generate a grinding action, i.e. ore particle comminution via impact and abrasion with steel balls, and is a key component of beneficiation plant production. Even though it has massive benefits, such as a high reduction ratio, effective breakage impact, and a wide application (Fuerstenau and Abouzeid, 2002), it also has shortcomings, such as lower efficiency, higher steel ball consumption, and severe lining degradation (Cleary, 2001). Nevertheless, the ball milling process has an impact on a beneficiation plant’s performance and financial advantage. As a result, improving the milling and selecting grinding media are of real importance in lowering the grinding cost and improving the separation rate (Ma et al., 2021; Si et al., 2021). Also, it is critical to shorten the grinding time in order to reduce the cost of energy usage (Bruckard et al., 2011; Wolosiewicz-Glab, 2018).

The size distribution, shape, and surface characteristics of the material generated can all be influenced by the grinding media used. However, there is a shortage of detailed study on the effect of grinding medium on flotation performance (Cao et al., 2021). The rotation speed, ball size, and ball-to-ore ratio all have a significant impact on ball milling grinding efficiency (Cook and
2. Methodology of Experimental Work

The section that follows explains the experimental work that was done. It demonstrates the quantity and location of where the sample was collected, as well as the testing procedures and devices used in this analysis.

2.1. Materials

A 100-kg of raw quartz (e.g. density is 2.55 g/cm$^3$) has been collected from a quarry in the Red Sea region, Saudi Arabia. The whole amount has been crushed to -3.15 mm, mixed thoroughly, and then divided by riffling into 20 samples (e.g. 5 kg each).

2.2. Experimental Procedures

Magdalinovic (Magdalinovic, 1989) showed that the grinding tests were conducted in a smooth surface cylindrical steel mill of 215 mm diameter and 190 mm long. The grinding media consisted of three different-sized steel balls having a density of 7.68 g/cm$^3$ and diameters of 19.5, 38, and 50 mm. The Bond work index (Wi) of the quartz sample was determined based on two grinding tests. The test was repeated twice, and the Wi’s average was taken as the Bond work index of the quartz sample. After that, 40 kg of size -3.15 mm were again reduced by crushing to -2.0+0.80 mm to carry out the grinding tests. A representative head sample of 150 g from the crushed product was subjected to sieving with a vibrating shaker. From the sieving results, the cumulative % undersize curve was plotted to determine graphically F80 in microns (e.g. F80 is 80% of head sample passes). The surface area in cm$^2$/g of the head sample and the ground samples were measured by Mastersizer 3000 instrument belong to the Yanbu Cement Company, Saudi Arabia, as shown in Figure 1. The instrument measures the surface area of particles from 0.01-3500 µm contained within a sample. The experimental conditions of all tests were summarized in Table 1. Three different ball diameters (e.g. d1=19.5 mm, d2=38 mm, and d3=50 mm) have been mixed into four groups (e.g. d1+d2, d2+d3, d1+d3, and d1+d2+d3) and used as grinding media under the condition that the mixture (e.g. ball loading composition) retains the same charge weight. Equations 1, 2, and 3 give the characteristics parameters of ball distribution in terms of constant number (N), surface area (S), and constant weight (W), respectively. These parameters have been derived from Equation 4.

\[
N = \frac{6W_b}{\pi \delta \sum_{i=1}^{n} d_i^2} \quad (1)
\]

\[
S = \frac{6W_b}{\delta \sum_{i=1}^{n} d_i} \quad (2)
\]

\[
W = \frac{W_b}{3} \quad (3)
\]

\[
W_b = \frac{\pi d_1^3}{6} \times N_1 \times \delta + \frac{\pi d_2^3}{6} \times N_2 \times \delta + \frac{\pi d_3^3}{6} \times N_3 \times \delta \quad (4)
\]

Where:

Wb – total weight of balls, kg;

di – ball diameter (e.g. d1, d2, d3), cm;

Ni – number of balls of each size (e.g. N1, N2, N3);

\delta – density of steel balls (e.g. 7.68 g/cm$^3$).

Table 2 gives the details of each grinding test. After milling for 15 min, a representative sample of 150 g

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Table 1: Experimental setup and conditions

| Mill       | Volume   | 6900 cm³ |
|------------|----------|----------|
|            | Critical speed | 105 rpm |
|            | Operational speed | 84 rpm |

| Ball charge | Diameter of balls | 19.5, 38, 50 mm |
|-------------|-------------------|-----------------|
|             | Void space (measured) | 40% |
|             | Ball filling ratio | 25% |
|             | Weight of ball charge (calculated) | 7.948 kg |

| Ore filling conditions | Void space (measured) | 25% |
|------------------------|-----------------------|-----|
|                        | Interstitial filling | 90% |
|                        | Weight of ore (calculated) | 1.200 kg |
|                        | Duration time of grinding | 15 min. |

from each test was subjected to sieving by vibrating sieve shaker. Mular and Bhappu (1980) and Noaparast et al. (2012) showed that the cumulative % undersize curves were then plotted to obtain P80 of each test graphically. The required energy, E, to produce the new surface area of the twelve tests was calculated using Bond’s law presented in Equation 5.

\[
E = 10 \frac{W_i}{\sqrt{P_{80}}} - \frac{1}{\sqrt{F_{80}}} \quad (5)
\]

Where:
- \(E\) – the required energy, kwh/St. (e.g. short ton =2000 lb.);
- \(W_i\) – Bond work index of quartz, kwh/St;
- \(F_{80}\) – size in microns of 80% of head sample passes, µm;
- \(P_{80}\) – size in microns of 80% of each grinding test to product pass, µm.

3. Results and discussions

From the experimental work, the Bond work index of quartz is calculated 16.6kwh/St. Table 3 gives the sieve analysis numerically, before grinding, of the head sample, while Figure 2 depicts it graphically to obtain F80. The particle size was found to be 1708 µm. Figure 3 shows the size in microns (e.g. P80) of milled ore at variable ball load size mixtures concerning several balls (N), surface area (S), and ball weight (W). It can be seen that each characteristic parameter (e.g. N, S, and W) varies as the ball mixture size changes. The most dominant variable is the number of balls. However, the surface area of ore in the mill is small. Alternatively, the voids between mill and ore particles are increase. Thus, grinding time will increase due to a lower mill charge. Therefore, the number of balls (e.g. N) is not the conservative parameter. The required energy per short ton at various ball-sized mixtures is depicted in Figure 4 concerning the three characteristic parameters (e.g. N, S, and W).

Table 2: Details of studied grinding tests

| Group No. | Test No. | Composition of ball charge | Characteristic parameter | No. of balls | Actual wt. of ball charge, kg |
|-----------|---------|----------------------------|--------------------------|--------------|-------------------------------|
| I         | 1       | d1+d2                      | N*                       | 30 32 -      | 7.955                         |
|           | 2       |                              | S                        | 89 24 -      | 7.950                         |
|           | 3       |                              | W                        | 133 18 -     | 7.938                         |
| II        | 4       | d2+d3                      | N                        | - 11 11      | 7.956                         |
|           | 5       |                              | S                        | - 18 8       | 7.993                         |
|           | 6       |                              | W                        | - 18 8       | 7.993                         |
| III       | 7       | d1+d3                      | N*                       | 14 - 15      | 7.957                         |
|           | 8       |                              | S                        | 81 - 11      | 7.945                         |
|           | 9       |                              | W                        | 132 - 8      | 7.958                         |
| IV        | 10      | d1+d2+d3                  | N*                       | 10 12 10     | 7.973                         |
|           | 11      |                              | S                        | 52 13 7      | 7.938                         |
|           | 12      |                              | W                        | 93 12 5      | 7.934                         |

*The non-equalization of ball numbers is necessary to make the actual weight of the ball charge matches the calculated weight of the ball charge (7.948 kg).
Table 3: Results of sieve analysis of the head sample

| Screen size μm | Wt.% | Cum. wt.% passing |
|----------------|------|------------------|
| 2000           | 0    | 100              |
| 1600           | 27.39| 72.61            |
| 1250           | 42.62| 29.99            |
| 1000           | 17.07| 12.92            |
| 800            | 12.12| 0.80             |
| Pan*           | 0.80 | 0.00             |

*The pan displays the amount of weight that has been retained (e.g. screen opening size for pan is zero)

The amount of required energy is close in values, per each ball loading mixture, concerning three characteristic parameters. The amount of required energy varies between 3.22 kWh/st & 3.65 kWh/st. Figure 5 shows the measured surface area in square centimetres per gram of ore particle at different ball size compositions. The ore particle occupies a large surface area in the ball mill. This means there is a decrease in voids between balls

and ore particles. Consequently, the efficiency of milling increases, and the time of grinding decreases. Figure 6 illustrates the effect of change in the surface area on the amount of energy consumed. Different ball loading
composition enhances the surface area, which is occupied by ore particles per each energy unit. Thus, it increases the amount of ore in the mill, reduces the grinding time, and increases the overall milling efficiency.

The P80, the power (E), the measured surface area, and the change in the surface area per unit energy (cm²/J) for each test are listed in Table 4. The constant surface area (S) is the most dominant parameter than the other two parameters (e.g. ball weight and ball number). Alternatively, the constant surface area gives the best results in the change of surface area per unit energy (cm²/J). This might be related to grinding mechanisms, which depend on the total surface area of the balls’ loading charge and their distribution in the mill. Therefore, it gives adequate impact energy to break the bonds between particles. Wills (2006) and Ebadnejad et al. (2013) and Bwalya et al. (2014) showed that the obtained results are consistent with the qualitative information of some authors. On the other hand, the ball weight parameter (W) has the most negligible impact.

4. Conclusions

This research provides a simple procedure and serves as the foundation for the ball loading composition in grinding ball mills. The following conclusions are drawn from the experimental results:

- A mixture of balls of varying sizes would eventually be required to improve grinding efficiency.
- Surface area is an excellent tool to measure and predict grinding operation efficiency in terms of duration time, amount of ore per charge and consumed energy. For example, an increase in the ore’s surface area will decrease the voids between balls and ore in the mill—accordingly, higher amounts of ore are milled with less time and consumed energy.
- For each ball charge composition, the values of grinding energy were close.
- The required milling energy varies between 3.22 kWh/st. and 3.65 kWh/st.
- The ball weight has a small effect on the milling efficiency.
- This research would be useful in industries where comminution is a part of the process, such as mining and cement.

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SAŽETAK
Utjecaj raspodjele veličine šarže za mljevenje na učinkovitost mljevenja kugličnoga mlina

Veličina šarže za mljevenje primarni je čimbenik koji utječe na ukupnu učinkovitost mljevenja kugličnoga mlina (npr. potrošnja energije i veličina usitnjenih čestica). Ovaj članak bavi se nedostatkom alata za dizajn koji bi mogao pomoći u odabiru sastava kugli za punjenje mlinova. Takav alat omogućuje maksimiziranje izložene površine po jedinici energije (cm²/J). U ovome članku istražen je utjecaj sastava kugli mijenjanjem raspodjele veličine šarže za mljevenje (npr. miješanjem četiri grupa od 19,5, 38 mm; 19,5, 50 mm; 38, 50 mm i 19,5, 38, 50 mm) na učinkovitost mljevenja laboratorijskoga kugličnog mlina analizirajući broj kugli, ukupnu površinu i masu kugli. Rezultati upućuju na to da nova površina po jedinici energije (npr. cm²/J) znatno utječe na učinkovitost mljevenja. Nasuprot tome masa kugli ima manji učinak. Stoga bi rezultati ove studije mogli bili korisni za primjenu u cementnoj, kemijskoj i industriji plastike.

Ključne riječi:
sitnjenje rude, šarža za mljevenje, raspodjela veličine kugli, indeks Bond Work

Author(s) contribution
Gamal Abdelhaffez (Associate professor of Mineral Processing) gathered rock samples, collaborated on all experimental work with Haitham M. A. Ahmed (Assistant professor of mining engineering at King Abdulaziz University in Saudi Arabia), and evaluated the results. Ahmed Abd Elmajeed Ahmed (an Emeritus professor of Mineral Processing at the University of Assiut’s Mining Engineering Department) reviewed the draft manuscript and provided technical suggestions. The entire work was written collaboratively by all of the authors.