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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 (cm^2/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. cm^2/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 (**Mucsi 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**).

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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; Wołosiewicz-Głab, 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

Courtney, 1995; Katubilwa and Moys, 2009; Shin et al., 2013). A faster rotation speed produces ore with smaller particle size and lower cementite (**Kano and Saito, 1998**). When a larger ball size was used, crystallisation decreased faster, while grinding efficiency and ore specific surface area increased. On the contrary, the smaller the ball size was, the smaller the crystallinity decrease. As a result, using a small ball size can result in nanoparticles with greater crystallinity (**Kim et al., 2019**). Hlabangna et al. (2016 and 2018) discussed that the combining impact forces and abrasiveness between ore particles, grinding media, and mill boundary reduce particle size. Particle size reduction (e.g. grinding) operations significantly impact mineral processing plants' energy amount. **Gupta and Yan (2006) and Cho et al. (2013)** mentioned that the variable sizes of grinding balls must be mixed and matched regularly to maintain a steady flow rate of material. Such size-variation of grinding media effectively optimizes the fineness of the product. Currie (1973) said that the options of ball size distributions are, to some extent, determined by experience. The ball charge composition is one of the most critical variables in the grinding circuits.

Austin et al. (1976) and Tarjan (1981) mentioned that choosing the optimal ball loading composition (e.g. mixture) is almost quite challenging. Many authors have examined the kinetics of comminution in tumbling ball mills based on selection and breakage functions. However, few studies recommended composing ball loads of variable sizes where ball number, total surface area, and ball weight are the same for each size fraction. They also suggested another method in which the percentage weight of different ball size groups may be chosen to vary approximately as ball sizes (**Tarjan, 1981; Kotaka et al., 2002; Veniz, 2003; Kotake et al., 2004; Katubilwa and Moys, 2009; Deniz, 2012**). Grinding performance has been investigated with a variety of operating parameters, such as mill speed, charge filling, ball size, and lifter type (**Austin et al., 1984; Powell and Smit, 2001; Cleary, 2001; Dong and Moys, 2003**). However, it is essential to investigate all other possible avenues for a better understanding and improvement of the milling process. Therefore, this article presents an approach to optimize ball loading composition by varying the size of grinding media regarding ball number, total surface area, and ball weight so that the mill charge is the same in all different mixed groups.

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.

$$N = 6W_b / \pi\delta \sum_{i=1}^{n} d_i^3 \quad (1)$$

$$S = 6W_b / \delta \sum_{i=1}^{n} d_i \quad (2)$$

$$W = \frac{W_b}{3} \quad (3)$$

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

Where:

Wb – total weight of balls, kg;

di – ball diameter (e.g. d_1, d_2, d_3), cm;

Ni – number of balls of each size (e.g. N_1, N_2, N_3);

δ – 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

Figure 1. Mastersizer 3000 instrument (Yanbu Cement Company Lab, KSA)

Table 1: Experimental setup and conditions

Mill	Volume	6900 cm^3
	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.

$$E = 10\ Wi\ \left(\frac{1}{\sqrt{P_{80}}} - \frac{1}{\sqrt{F_{80}}}\right) \tag{5}$$

Where:

E – the required energy, kwh/St. (e.g. short ton =2000 lb.);

Wi – Bond work index of quartz, kwh/St;

F80 – size in microns of 80% of head sample passes, µm;

P80 – 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 d1	No. of balls d2	No. of balls d3	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
The 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	00

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

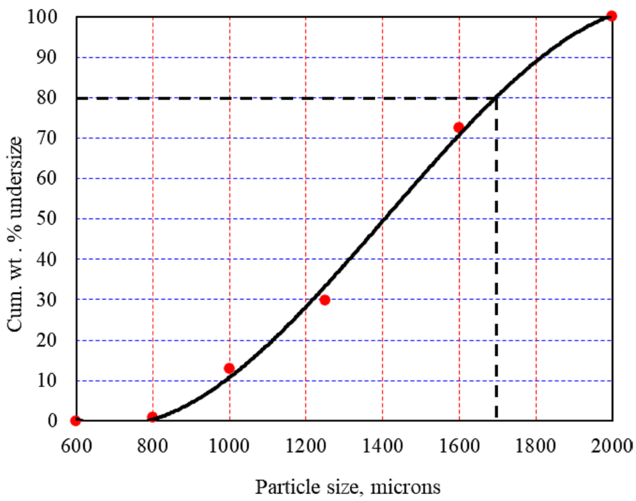

Figure 2. Particle size distribution of the head sample

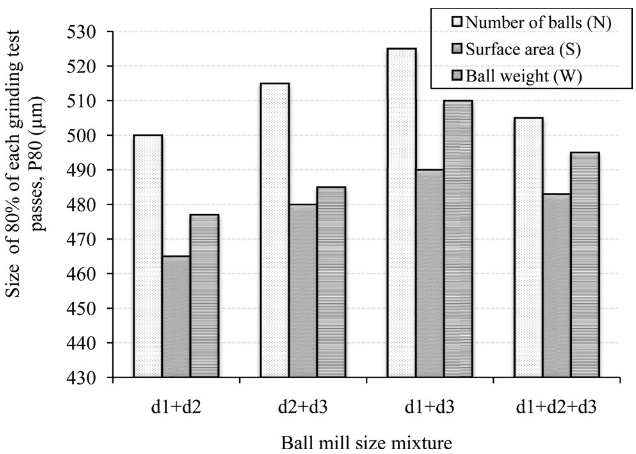

Figure 3. The size of 80% of passed ore at various ball loading composition

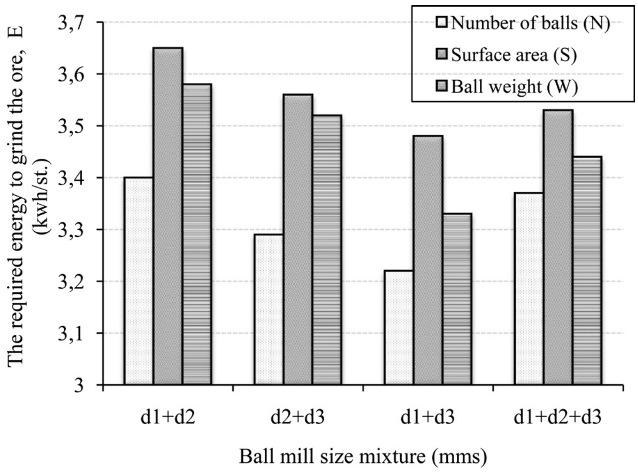

Figure 4. Consumed energy in grinding at various ball size mixtures

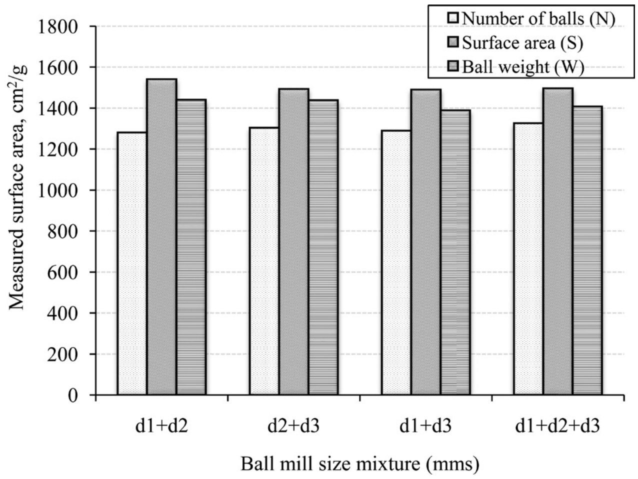

Figure 5. The measured surface area of ore particles inside the mill at variable ball mixed diameters

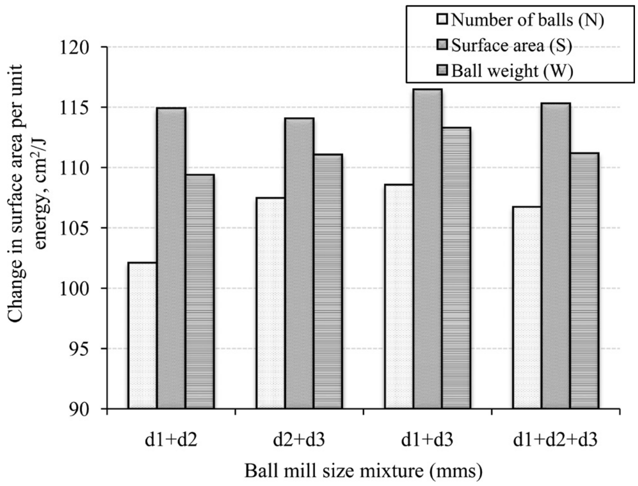

Figure 6. Change in the surface area of ore particles per unit energy at various ball mixed sizes

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

Table 4: Calculation of change in surface area per unit energy

Group No.	Ball mill composition	Characteristic parameter (s)	P80 (μm)	E (Kwh/st.)	Measured surface area (cm²/g)	**Change in surface area per unit energy (cm²/J)
I	d1+d2	N	500	3.40	1280.70	102.10**
		S	468	3.65	1540.89	114.91
		W	477	3.58	1440.66	109.38
II	d2+d3	N	515	3.29	1303.73	107.46
		S	480	3.56	1492.89	114.07
		W	485	3.52	1438.58	111.08
III	d1+d3	N	525	3.22	1289.40	108.56
		S	490	3.48	1490.11	116.47
		W	510	3.33	1389.09	113.29
IV	d1+d2+d3	N	505	3.37	1325.70	106.72
		S	483	3.53	1496.33	115.31
		W	495	3.44	1407.82	111.18
F80=1708 μm (head sample) surface area of head sample = 30.97 cm²/g						

**Change of surface area per unit energy = 1280.70-30.97/ 3.6×3.4 =102.10 cm²/J

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 (cm^2/J). U ovome članku istražen je utjecaj sastava kugli mijenjanjem raspodjele veličine šarže za mljevenje (npr. miješanjem četiriju 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. cm^2/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.