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Effect of ball and feed particle size distribution on the milling efficiency of a ball mill: An attainable region approach

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ABSTRACT

In this article, alternative forms of optimizing the milling efficiency of a laboratory scale ball mill by varying the grinding media size distribution and the feed material particle size distribution were investigated. Silica ore was used as the test material. The experimental parameters that were kept constant in this investigation was the grinding media filling, powder filling and the mill rotational speed. The data obtained from these batch tests was then analyzed using a model free technique called the Attainable Region method. This analysis technique showed that the required product fineness is a function of grinding media and feed material size distributions. It was also observed from the experimental results that in order to increase the milling efficiency of a ball mill, towards optimum production of material in the desired size class, there is a need to correlate the ball size and the feed size distributions.

1. Introduction

The size reduction unit operation is known to be the most inefficient and energy consuming operation in any beneficiation process. With the emergency of stringent environmental protection and industrial waste disposal policies in most countries, any research effort that has the potential to bring about a reduction in energy consumption and operational costs while maximizing the grinding efficiency is most welcome. Mineral processing plants consist of quite a complex array of processing units connected together through a flowsheet. Traditionally each of the unit operations has been optimized separately and unfortunately it has been realized that a set of optimized units does not necessarily lead to an optimum system. In this investigation an integrated approach was taken in order to optimize the process across an entire circuit rather than individual units. This implies that an operator should not apply a rigid specification for the output from one unit for entry to the next unit but rather the output from a unit must be such that it gives result to an optimum system.

In this article the effect of grinding media size distribution and feed material particle size distribution (PSD) on the product fineness requirements were investigated. A model free approach called the Attainable Region method was then applied in order to optimize the product size fineness in terms of the feed size and ball mix. The practical applications of this research are a reduction in the inefficiencies associated with either flotation or leaching processes as an optimized product size would be reporting to these unit processes. Theory states that for the leaching process, a better recovery is obtained coupled with a reduction in reagent consumption and costs if an optimized feed size is employed. To achieve this objective it is necessary to understand the interaction between the feed particle size and the grinding media size match. These play a major role as gradation of media is influenced mostly by particle size and product fineness requirements. A relatively simple scenario will be used here in order to demonstrate how to optimize a ball match for a product that will be fed to a leaching plant.

1.1. Grinding media size specification

A number of researchers (Deniz, 2012; Bwalya et al., 2014; Petrakis et al., 2016) carried out studies about the effect of feed particle size and grinding media size on the grinding kinetics of different ores. Khumalo et al., 2006 postulated that generally larger sized grinding media would break larger particles quicker but a

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finer product would be obtained by use of smaller balls. However, use of smaller grinding media is believed to support abrasion and attrition (Katubilwa et al., 2011) which are energy inefficient breakage mechanisms (King, 2001).

In order to maintain a steady material flow rate, different sized grinding balls are normally mixed and matched. This approach has the added advantage in that different particle sizes can be effectively milled in a ball mill because each media size can effectively break a particular particle size during the size reduction process ensuring that the product fineness is optimized. The same policy is employed for the make-up charge where adding different ball sizes is done in order to optimize the mill performance. Chimwani et al. (2015) developed a simulation program that could predict optimal make-up balls to be added in order to achieve a required product fineness.

Fine grinding is believed to lead to high leaching rates as predicted by the common leaching models because value material gets more liberated hence requires less time to leach. However, this is associated with higher energy consumption and labor costs.

1.2. The attainable region technique

During the grinding process, coarser material (size class 1) break to finer material (size class 2) and (size class 3) which are termed the daughter products, as shown in Fig. 1. A chemical reaction on the other hand can consist of say reactant ‘A’ forming intermediate product ‘B’ then proceeding to final product ‘C’ or a competing reactant ‘A’ to final product ‘D’ can also take place.

The grinding process can therefore be treated as a reaction that involves the conversion of feed material of a particular size distribution to a product of a specified size distribution. It should be evident that the rate of conversion from feed material to a specific chosen size class is dependent on both the feed and the specified PSD. After a relationship was established, based on the similarities between comminution and chemical reaction engineering, a technique traditionally used in choosing optimal reactor configurations in reaction engineering was successfully applied in comminution (Glasser et al., 1987). This technique is termed the Attainable Region (AR) approach.

A number of researchers (Metzger et al., 2009; Katubilwa et al., 2011; Danha et al., 2015; Hlabangana et al., 2016) outlined a detailed procedure of how the AR tool should be used in process optimization paying particular attention to the graphical construction stages involved. In summary, the researchers stipulated the conditions and steps that necessitate use of the AR approach. For the construction, one needs three size classes and these are the feed, the intermediate and fine size class. Depending on the objective function one might require an intermediate size class or a fine size class. In leaching or flotation, an intermediate size class is desirable while in a cement industry the fine size class is preferred. Fig. 2(a–c) shows the plots required to complete the optimization (Hlabangana et al., 2016).

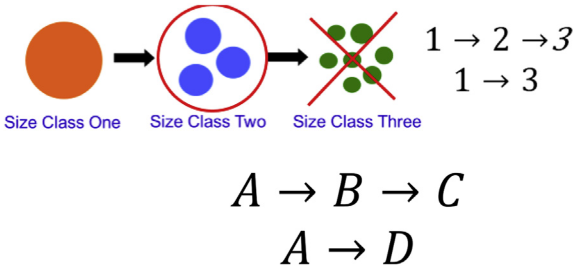


Fig. 1. Comparison of the size reduction process to chemical reaction engineering.

1.3. The objective function

An objective function is a fundamental expression that relates the dependant or output variables to the independent or input variables in a process. The overall aim of the A.R optimization technique is to establish values of the independent variables that will give result to optimum conditions of the output variables (Danha et al., 2016). In order to achieve this, the A.R tool employs a graphical technique that is defined by a set of pre-set conditions. In this investigation, the input variables were the ball and particle size distributions while the output variables were the desired PSD. The objective function was to maximize material in the specified intermediate size class.

2. Experimental approach

Dry batch milling tests were performed in a laboratory scale ball mill measuring 30.2 by 28.2 cm. The mill specifications are given in Table 1. A constant ball load of 20% was maintained in all the tests with a ratio of 0.5 for binary and 0.33 for trinary ball mix.

2.1. Feed material preparation

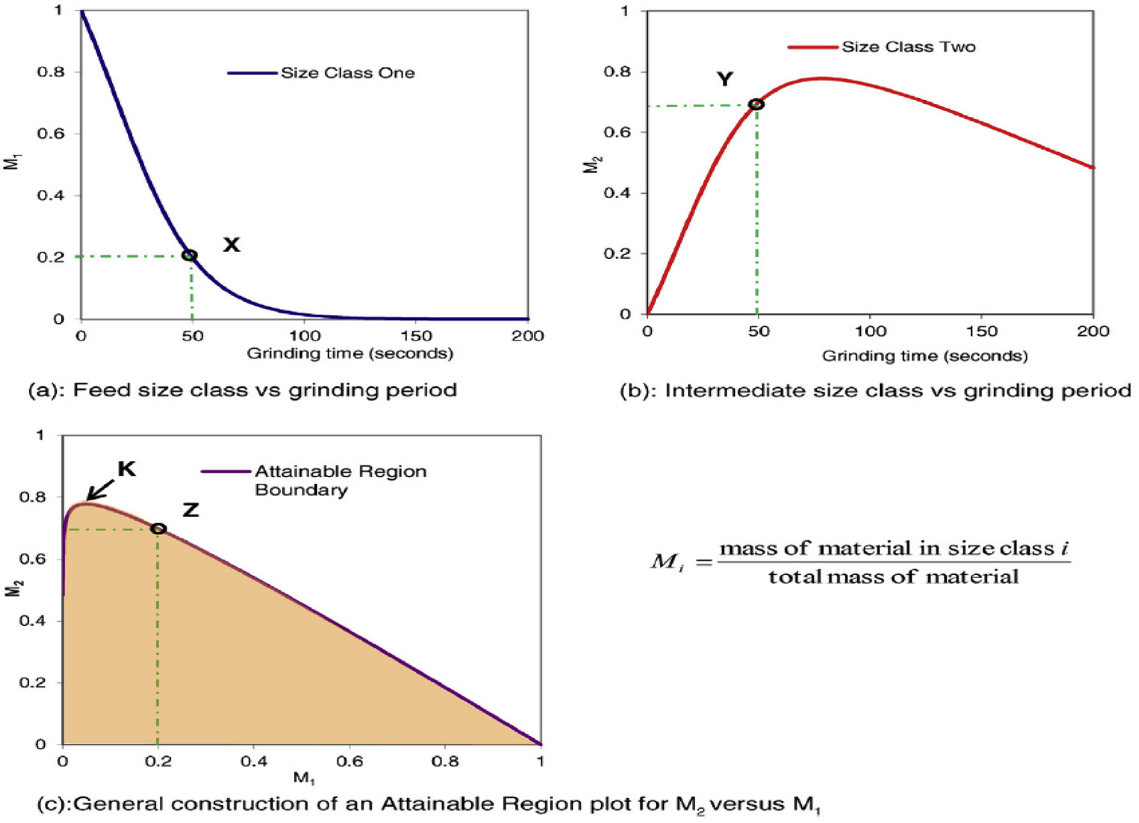
A quartz ore sample was used in the experimental test program. After sample preparation by the cone and quartering method, two feed size classes ($-1700 + 850$ μm and $-850 + 300$ μm) were obtained and used for the subsequent tests. These size classes were arbitrarily chosen for demonstration purposes and any size class of choice could have been used. Grinding media made of stainless steel was prepared as specified in Table 2.

2.2. The grinding test

Using a Jones riffle splitter, material from the two preferred size classes were split and measured into several separate samples weighing 1941g. Starting with the $-1700 + 850$ μm size class, the measured sample together with the specified size of grinding media were then fed into the mill (Table 1) whose operating conditions are specified in Table 2. The feed material was dry batch milled for selected periods ranging from 3; 5; 15; 30–90 min. For all the batch tests, the mill feed was kept constant at 1941g and after each duration the mill was stopped and the contents offloaded. This was then followed by separation of the product from the grinding media on a wire mesh. The mill product was then taken to a jones rifle splitter and homogenously separated into measured 100 g samples for sieve analysis. Using the $-850 + 300$ μm size class material, this procedure was repeated for all the grinding times considered. The standard sieve analysis technique was then repeated three times for each milling duration and the results showed very good reproducibility, within the limits of experimental accuracy. Adequate caution was taken in order to ensure that the sieves were not clogged and the standard sieving time of 20 min used, was enough to break any agglomerates of fines that may have formed. The ball mill, liners and grinding media employed were made from stainless steel. This material of construction is superior over all else because of its durability and resistance to wear and tear. It is due to these reasons that contamination of the material was ruled out. Experimental validation on the absence of contamination through microanalysis (EDX) or chemical (ICP) techniques would have been ideal, but such equipment was not available.

3. Results and discussion

Fig. 3 shows the PSD for silica particles after milling at different times. The milled ore gets finer as more energy is applied to the



(a): Feed size class vs grinding period

(b): Intermediate size class vs grinding period

(c):General construction of an Attainable Region plot for M_2 versus M_1

$$M_i = \frac{\text{mass of material in size class } i}{\text{total mass of material}}$$

Fig. 2. (a): Feed size class vs grinding period, (b): Intermediate size class vs grinding period, (c): General construction of an Attainable Region plot for M2 versus M1 (Hlabangana et al., 2016).

Table 1
Specifications of the mill.

Dimensions	Diameter	0.302 m
	Length	0.282 m
	Volume	19.493 L
Liner configuration	Number	8
	Dimensions	0.013 m height 0.025 m width 0.272 m length

Table 2
Milling conditions for experiments on the ore.

Parameter	Specification
Operational speed (Φ)	75% of critical
Ball loading (J)	20%
Feed sizes (μm)	−1700 + 850 & −1 180 + 850
Grinding media mix	10 mm 20 mm 20 mm followed by 10 mm 20 mm + 10 mm ball mix 50 mm + 20 mm + 10 mm ball mix

material with time. To apply the Attainable Region technique, the ore material is grouped into a number of different size classes in order to monitor how breakage occurs. Initially, six size classes (Table 3) were selected which enabled Fig. 4 to be obtained. In Fig. 4, the initial fractions of size classes 2, 3, 4 and 5 first rise before

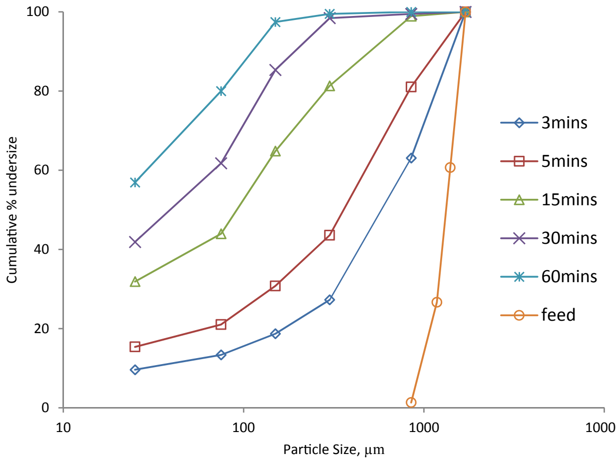


Fig. 3. Cumulative % undersize plot for -1700 + 850 μm silica feed milled at different times.

Table 3
Size class used to monitor the breakage of silica ore.

Size Class	Particle size range μm	
1	−1700 + 850	−1 180 + 850
2	−850 + 300	
3	−300 + 150	
4	−150 + 75	
5	−75 + 25	
6	−25	

Table 4
Size classes used for Attainable Region technique.

Size Class	Particle size range μm	
M1	−1700 + 150	−1 180 + 150
M2	−150 + 75	
M3	−75	

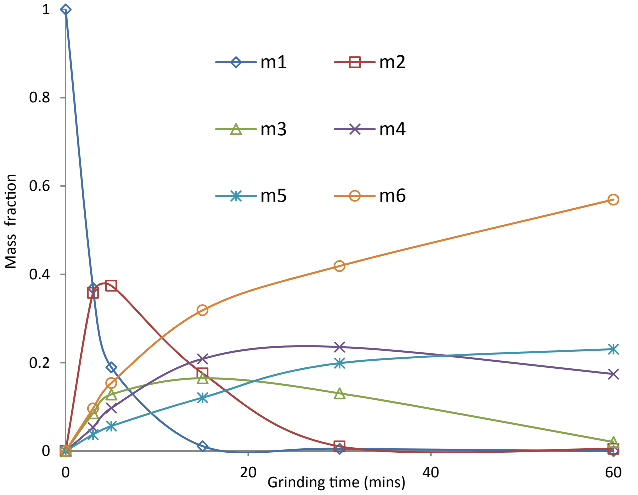


Fig. 4. Mass fraction of each of selected six size classes vs. time for J = 20%, 20 mm ball size and feed size = -1700 + 850 μm.

they start falling again. This is due to the fact that material in these size classes break into smaller size classes. Size class 6 continues to rise until all the material from the other size classes' break into this size range (see Table 4).

In order to find an optimal solution using the Attainable region technique only three size classes need to be used. These are the feed, intermediate and fine size classes. The objective function can be specified using any of these three size classes. In this case a desired product fineness was selected as the objective function.

Fig. 5 shows the variation of size class 1 (M1) with the milling time for the two feed size distributions. For this coarser feed the 50 + 20+10 mm ball diameter mix breaks the material at a faster rate compared to the other ball matches. The availability of a ball size for a particular feed size ensures breakage occurs at a faster rate. The 10 mm ball size is unable to nip the large particle size hence the breakage rate is slower. For a finer feed, the 20 mm + 10 mm binary mix is able to break the feed at a faster rate.

Fig. 6 shows a plot of mass fraction of selected size classes of interest against milling time. The desired size class is selected as the product fineness that is vital for a downstream recovery process. In this case an example size class of -150 + 75 μm can be selected that will maximize the amount of material for a leaching process. The Figure shows that more of the material is obtained for the three ball mixture. It was also observed that a binary mixture resulted in more material reporting to the required product fineness compared to having two mills in series with one having 20 mm and other 10 mm ball size. For the finer feed material, it was also observed that a binary mixture again resulted in more material reporting to the required product specification.

Fig. 7 gives the Attainable Region plot of M2 vs M1. For each curve any point underneath represents all the possible output mass fractions that can be obtained from milling the two size classes under different conditions of ball match. The graphs show that for a courser feed a three ball mixture (50 + 20 + 10 mm) will provide the much required largest amount of size class of interest. For a finer feed a binary mixture i.e. 20 mm + 10 mm will satisfy the objective function which is to get more of the -150 + 75 μm size class material.

Fig. 8 shows that the small 10 mm ball size is superior in generating more material in the fines size class, from both feed sizes used. If an objective function was to maximize the production of fines e.g. in the cement industry, the A.R shows that use of smaller ball sizes would give superior results.

4. Conclusion

The Attainable Region method is a model free tool initially applied in chemical reactor engineering but has been successfully extended to the optimization of size reduction in milling circuits. Using this versatile and simple technique, it is possible to represent milling data and also obtain optimal policies for different objective functions. Experimental results reported in this article showed that the grinding media diameter should be matched according to the

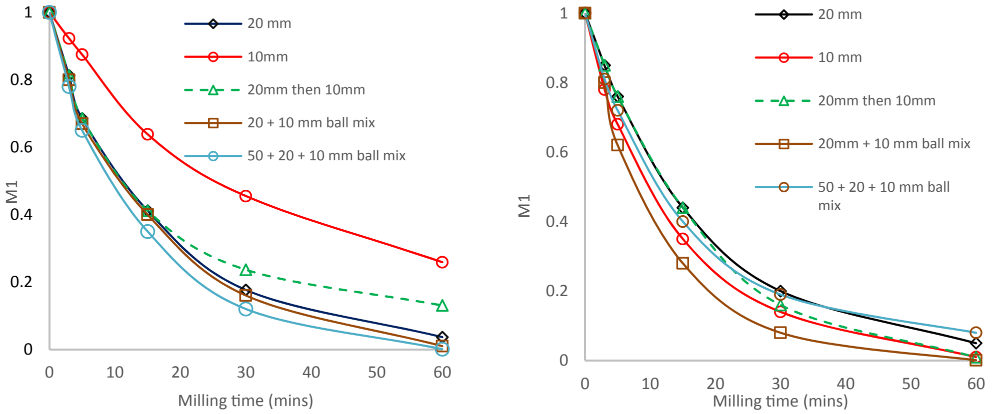


Fig. 5. Mass fraction M1 (size class 1) vs. milling time at a media fill level of J = 20% (a) feed size = -1700 + 850 μm (b) feed size = -1 180 + 850 μm.

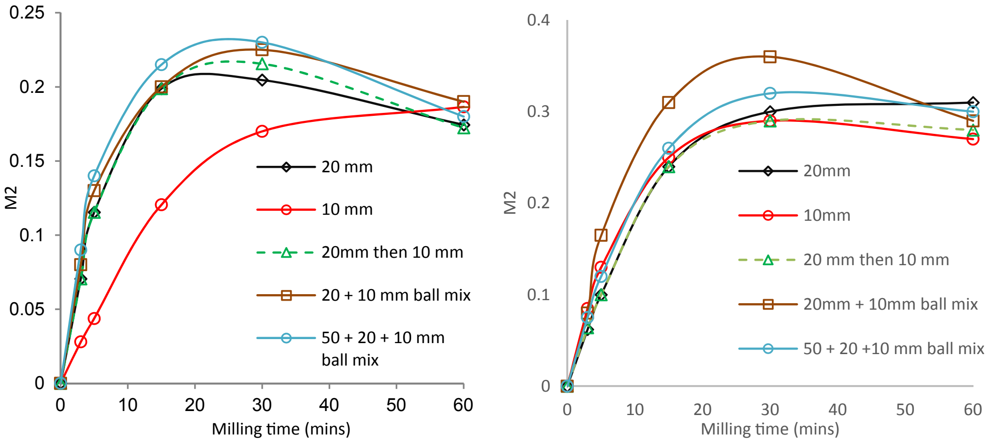


Fig. 6. Mass fraction M2 (size class 2) vs. milling time for various grinding times at a media fill level of J = 20% (a) feed size = -1700 + 850 μm (b) feed size = -1 180 + 850 μm.

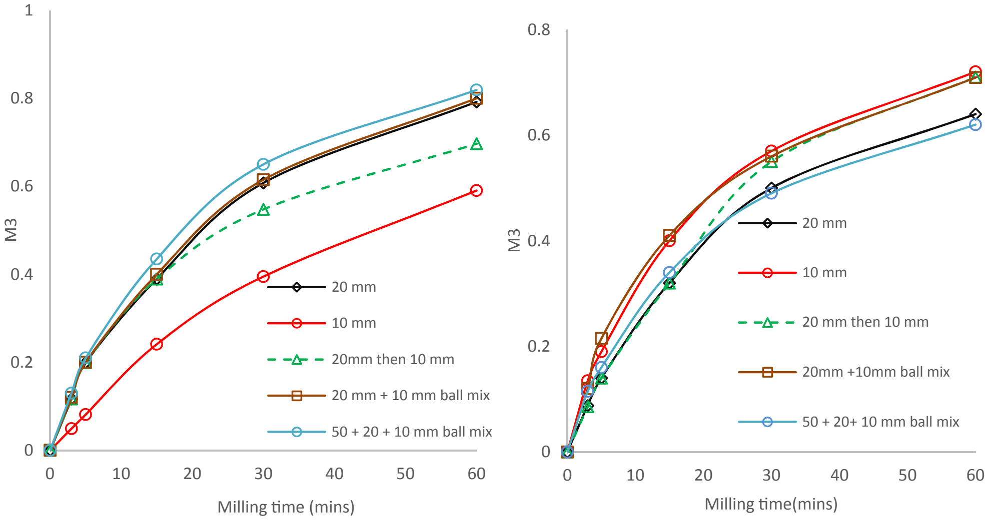


Fig. 7. Mass fraction M3 vs. milling time for various grinding times at a media fill level of J = 20% (a) feed size = -1700 + 850 μm (b) feed size = -1 180 + 850 μm.

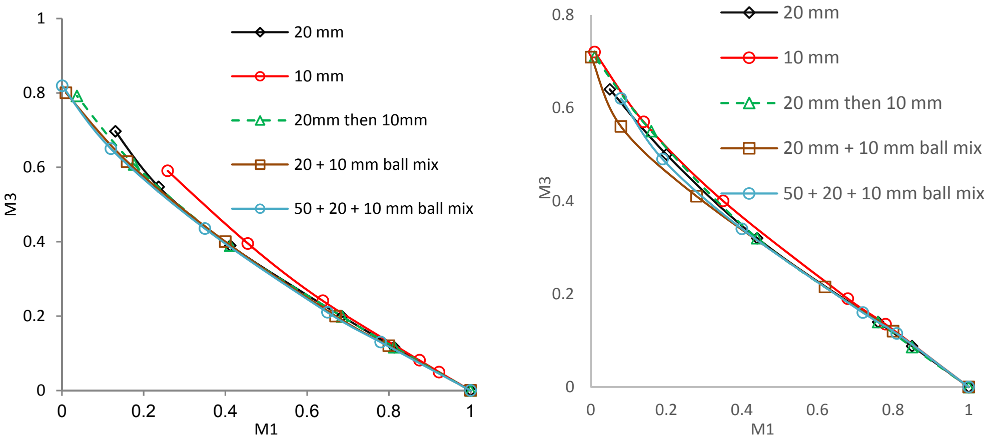


Fig. 8. Mass fraction M3 vs. milling time for various grinding times at a media fill level of J = 20% (a) feed size = -1700 + 850 μm (b) feed size = -1 180 + 850 μm.

feed and desired product size distributions. For the feed sample sizes investigated, the three ball mix was more effective for the coarser feed due to the presence of the 50 mm balls whilst with a finer feed the binary mix gave the optimal amount of size class of interest. These results prove that a close control of feed and ball match is of paramount importance if one is to improve the efficiency of milling circuits.

Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.sajce.2018.02.001.

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