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Predicting the product particle size distribution from a laboratory vertical stirred mill

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ABSTRACT

The use of ball mills for fine grinding is inefficient resulting in an increasing use of vertical stirred mills in the mineral processing industry. The difficulty encountered in fine grinding is the increased resistance to comminute small particles compared to coarse particles. Therefore, increased energy inputs are necessary to raise the number of stress events in a mill to contribute to the comminution of the fine material. In this study, a research program was designed and carried out to predict the performance of a laboratory scale vertical stirred mill. An energy-based population balance model was developed to analyze the response in product size by changing operating conditions. The model prediction was compared with the results obtained in the laboratory vertical stirred mill. The grinding results show that changes in feed size, agitator speed, and grinding media size mainly affect the particle breakage rate. The test data also show that a finer product size is obtained when the mill operates at higher stirrer speed and when using smaller grinding media.

1. Introduction

Stirred milling technology has been firmly established in the last 20 years as superior to ball mills for fine and regrinding operations due to its superior energy efficiency (Jankovic, 2000). Stirred mills are now commonly used in many sectors of the mining industry, though they have been used in other industries for many years (Jankovic, 2003). This technology has proven to be more energy efficient with greater opportunities for future optimization in both fine and coarse grinding (Jankovic et al., 2006; Mazzinghy et al., 2013).

The first stirred vertical mill was developed in Japan by the Japan Tower Mill Company Ltd which was later renamed to Kubota Tower Mill Corporation, KTM. The Japanese Tower Mill was the first vertical grinding mill to be used in the mining industry (Stief et al., 1987). The Tower Mill® is now produced by Nippon-Eirich. The Vertimill™ is a modified version of the Tower Mill® and it is developed by Metso, Inc. The Vertimill™ and the Tower Mill® have similar design configurations. Both technologies are gravity-induced mills that use high density grinding media as the charge. The Tower Mill® and the Vertimill™ are typically operated in a closed circuit, where the non-comminuted product material returns to the mill to enhance energy efficiency. The rotating and lifting action generated by the helical agitator is responsible for the movement of the grinding media and the grinding mechanism within the mill (Stief et al., 1987).

The efficient operation of grinding mills requires that parameters such as feed rate, feed size distribution, solids concentrate, slurry density, grinding media size distribution, and grinding power should be constantly monitored and adjusted for better grinding results (Sepulveda, 1981; Mankosa et al., 1989; Morrel et al., 1993; Morrison et al., 2009; Carvalho & Tavares, 2013; Rosa et al., 2014). It has been reported in the literature that the smaller grinding media used in stirred mills increases the contact probability between the media and the particles, and, therefore, the number of stress events inside the mill should also increase (Matter, 1983; Mankosa et al., 1986; Erdem & Ergun, 2009; Katubilwa & Moys, 2009). Unlike traditional ball mills, collisional energy in stirred mills is not lost by high-intensity impacts between the grinding media and the equipment internal walls (Hoyer, 1984; Jankovic & Morrel, 1997). Thus, stirred mills have been preferred for fine, ultra-fine and regrinding operations.

In this study, a laboratory vertical stirred mill equipped with a torque sensor and an agitator speed control was built to analyze the performance of this unit when varying operating conditions. Grinding test work in the vertical mill was carried out by varying speed, grinding media size, feed size, and grinding time. A population balance model originally developed to predict grinding in ball mills by Austin et al. (1984) and Rajamani & Herbst (1984) was used to analyze the test results. The results show the applicability of using population balance modeling in estimating the product particle size distribution from a

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laboratory vertical stirred mill. The use of a Bond ball mill to estimate the breakage parameters in order to predict grinding in a vertical mill was also investigated.

The objective of this work is to simulate grinding in a vertical stirred mill under different operating conditions from parameters obtained in a batch test using a Bond ball mill.

2. Population balance model

Population balance models have found increased use in the design, optimization, and control of grinding circuits due the methods' ability to predict complete product size distribution (Napier-Munn et al., 1996). In these models, the breakage behavior of each particle of a given size class can be calculated.

The population balance equation is a mathematical description of the evolution of the particle size distribution when submitted to grinding processes over time in a batch operation. Eq. (1) illustrates the size-mass balance model (Austin et al., 1984).

$$\frac{dm_i(t)}{dt} = -S_i m_i(t) + \sum_{j=1}^{i-1} b_{ij} S_j m_j(t), \qquad i = 1, 2, \cdots n \tag{1}$$

where $m_i(t)$ is the mass fraction of particles contained in the size interval i after a grinding time t; b_{ij} represents the size distribution of particles in the intervals i after a breakage event of particles in the size interval j; S_i represents the selection function or the specific rate of breakage of particles in the size interval i.

2.1. Breakage function

The breakage function model represents the cumulative weight fraction of the material broken from size j which falls into the smaller size intervals. Eq. (2) illustrates the breakage function model developed by Austin et al. (1984).

$$B_{i,j} = \phi\left(\frac{d_{i-1}}{d_j}\right)^{\gamma} + (1-\phi)\left(\frac{d_{i-1}}{d_j}\right)^{\beta}, \qquad 0 < \phi < 1 \tag{2}$$

where ϕ, a material dependent constant, represents the fraction of fines that are produced in a single fracture event; γ is also a material dependent variable with values typically found to be in between 0.5 and 1.5; and β values generally range from 2.5 to 5 for most ores.

Values of β have been found to exceed 5 as advocated by Austin et al. (1984). So, it should not be considered wrong if β values are reported to vary around 5–15, especially for particles finer than 600 μm in wet milling processes (Yekeler, 2007).

Eq. (2) represents an empirical calculation relating the cumulative breakage function to particle size. A simple assumption made to accurately solve the empirical function is to consider the breakage function to be independent of the initial particle size (Katubilwa, 2008). The breakage function is assumed to be normalized in this case. This means that there is a linear relationship between breakage function and particle size. Therefore, ϕ is considered constant. This assumption has proven to be acceptable for many materials and simulation purposes (Austin et al., 1984; King, 2001).

2.2. Specific selection function

The selection function represents the breakage rate of particles in the size interval i. Herbst and Fuerstenau (1973) developed a selection function equation related to the specific energy consumed by the grinding mill. It is assumed that the selection function, S_i (min^{-1}), has a proportional relationship with the mill power consumption according to Eq. (3).

$$S_i = S_i^E\left(\frac{P_{net}}{M}\right) \tag{3}$$

where S_i^E represents the specific selection function (ton/kWh); M is the total mass of material inside the grinding mill (ton); and P_{net} is the net power draw (kW).

The specific selection function, S_i^E, is independent of the mill dimensions and can be directly determined using an equation developed by Rajamani and Herbst (1984).

$$S_i^E = S1^E \exp\left\{\zeta_1 \ln\left(\frac{d_i}{d_1}\right) + \zeta_2\left[\ln\left(\frac{d_i}{d_1}\right)^2\right]\right\} \tag{4}$$

where $S1^E$, ζ_1, and ζ_2 are material and grinding conditions specific parameters; and d_i/d_1 is the dimensionless particle size, or normalized particle size at interval 1.

The specific selection function is dependent on the grinding media size (Lo & Herbst, 1986), and is usually independent of the mill geometry and operating conditions (Herbst & Fuerstenau, 1980).

3. Experimental

3.1. Samples

Commercial granite local to Colorado/USA was used in the laboratory tests. The as-received aggregate of minus 19-mm in diameter was reduced in size using a jaw crusher, and a roll crusher in two stages. The final product was classified based on its size using standard test method for sieve analysis. Table 1 shows the single-size fractions of the aggregate used in this study.

The material hardness was characterized using a Bond ball mill, and the Bond work index (BWI) was calculated for two different product sieve sizes. The results obtained for the BWI is presented in Table 2.

3.2. Grinding tests

A small size vertical stirred mill was manufactured for this study. The dimensions of the laboratory vertical stirred mill are specified in Table 3. Grinding test work in the vertical mill was carried out by

Table 1
Single-size fractions of an aggregate sample.

Size number	Single-size fraction (μm)
1	−841 + 595
2	−595 + 420
3	−420 + 297
4	−297 + 210
5	−210 + 149
6	−149 + 105

Table 2
Bond work index for two different test-sieve sizes.

Test number	Test-sieve size P_{80} (μm)	BWI (kWh/ton)
1	75	16.25
2	106	12.59

Table 3
Laboratory vertical stirred mill dimensions.

Chamber diameter (mm)	240
Chamber height (mm)	230
Agitator diameter (mm)	163
Agitator length (mm)	187.5
Clearance between agitator and mill floor (mm)	10