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New approach to ball mill modelling as a piston flow process

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ABSTRACT

Comminution represents one of the most important operations in mineral processing due to the high energy cost and tool wear. This paper presents a new population balance model (PBM) of ball mills that understands the ball mill process as a hybrid of a perfectly mixed mill and piston flow mill. Usually, PBM for grinding is related to a perfectly mixed mill. In this case, the piston flow was introduced for a more realistic process. The ball mill modelling process is described as the point where the feed entering the distribution size is coarse, and where there is an overflow and discharge of the mill, the distribution size is fine and equivalent to the product distribution size. In this work, the evolution of the size of particles along the mill piston flow process was studied. The relationship between the particle size and position in the length of the mill was established. The equation of the balance population model was formulated, and the parameters were determined for a tungsten ore.

1. Introduction

Large amounts of energy are necessary to reduce the particle size in ore processing, usually representing a significant amount of the total expenses of the processing (Datta and Rajamani, 2002). Selection of the optimal parameters to reduce the particle size is a key factor in these operations (Grupta and Sharma, 2014; Zhang et al., 2016). The development of models to predict the comminution behaviour of particles can determine the optimal parameters for reducing the particle dimension. Population balance modelling has been widely and successfully used in ball mills (King, 2001; Hennart et al., 2009); it was initially introduced by Epstein (1947) and used for comminution models (Austin et al., 1984; Venkataraman and Fuerstenau, 1984; Morrell et al., 1993; King and Bourgeois, 1993; King 2001; Wang et al., 2012). The Population Balance Model (PBM) is referred to as a simple mass balance for the size reduction. This model allows the particle size distribution to be controlled and the breakage mechanisms during comminution to be found (Bilgili et al., 2004, 2006). It is based on the determination of particle size distributions and divided into size classes. The fundamental postulate supports the kinetic model which states that the rate of breakage of material out of a size class is proportional to the amount of material of size i in the mill; it is detailed in Eq. (1):

$$Rate\ of\ breakage = k_i\ M\ m_i \tag{1}$$

where k_i is the specific rate of breakage, M is the mass of material in the mill, and m_i is the fraction of the mill contents in size class i. The formulation of PBM for grinding has been developed by different authors (e.g., Austin et al., 1984). In brief, a mass balance for class i in a well-mixed milling process is achieved by Eq. (2) (Austin, 1972; Datta and Rajamani, 2002):

$$\frac{dm_i(t)}{dt} = -k_i\ m_i(t) + \sum_{j=1}^{i-1} b_{ij}k_jm_j(t) \tag{2}$$

where $m_i(t)$ is the mass fraction of particles with size class i at milling time t. The first term after the equal sign is the disappearance or breakage rate at which particles of class i are broken into smaller particles. The second term represents the summed rate at which particles in all classes $j < i$ are broken into class i, where i and j are size class indices extending from size-class 1, containing the coarsest particles, to size-class N, containing the smallest particles. In this equation, b_{ij} is the breakage function. Breakage simulation can be obtained with the use of discrete elements (Cleary and Morrison, 2011; Wang et al., 2012; Weerasekara et al., 2013; Soni et al., 2015).

The equation of the PBM for a perfectly mixed mill derives directly from a simple mass balance for materials in any specific size class. This would be the simplest case, but it is also sufficiently realistic. This case assumes that once the material is inside the mill, it is broken directly to the product particle size. All of the material inside the mill has the same characteristics.

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In practice, there are some restrictions when the material inside the mill moves towards the outlet stream. Larger particles do not pass through the discharge grate, and then they are not released from the mill. In the overflow discharge mills, when the discharge grate is not used, larger particles do not leave the mill because finding a path to rise in the medium bed to the discharge is difficult (King and Schneider, 1993). On the other hand, very small particles move readily with water and are easily discharged. Therefore, the discharge end of the mill behaves as a classifier, which permits the selective discharge of the smallest particles and recycles the larger particles back into the body of the mill. Some authors state that transport is separated from breakage events. To enable a dynamic simulation capability for non-steady-state simulation and control modelling, a new model structure based on dynamic time stepping was proposed by Yu et al. (2014).

The present work aims to study the evolution of particle size along the mill process to establish the relationships between particle size and its position along the mill. The study is based on the population balance models to determine the evolution of the particle size during the grinding process. It can be assumed that the distribution size is coarse at the feed inlet, the distribution size is fine at the overflow and discharge of the mill, and it is the product distribution size. Given this, it is credible that the distribution size changes along the mill; therefore, the real process can also be partly interpreted as a piston flow mill.

2. Materials and methods

2.1. Materials

Approximately 400 kg of a low-grade tungsten ore from the Mittersill Mine, Austria, were used for the experiments. These are calc-silicate metamorphic rocks mainly comprising hornblende, biotite, plagioclase and epidote, with scheelite as the W-bearing mineral. The sample was crushed by a KHD Humblot Wedag jaw crusher, sieved and classified by size classes of −5 +4 mm, −4 +3.15 mm, −3.15 +2 mm and −2 +1 mm to perform the experiments. For the experiments, these size classes were mixed to have a feed particle size distribution.

2.2. Experimental

The methodology can be divided into three different stages: (1) Preparation of the materials and determination of operative parameters, (2) selection of the model and executing experiments, and (3) modelling and back-calculation to find the different parameters of the breakage and selection functions.

Four experiments were performed with a laboratory scale overflow ball mill. Three were conducted to study the process and determine the parameters, and the last was for validation. The internal dimensions of the mill are 48.26 cm in length and 22.86 cm in diameter. The tests were performed at 70% of the critical speed and charged with 300 balls of 26.8 mm in diameter with a residence time between 76 and 85 min. A window in the wall of the mill was built to control the activity inside the mill at a specific time. The tests started with the mill empty of material with only balls charging. The flow was constant during all of the experiments; initially, the mill ran in a non-stationary stage, and the experiment continued until it reached the stationary stage (same flow in the inlet and outlet). At this time, the particle size distribution of the product and three points along the mill were determined for each assay to prove the piston flow process. The mill was stopped to collect the samples, the cover was removed, and three different samples from three places along the mill were taken (Fig. 1). The first sample was taken from the first 5 cm of the mill, the second from the centre, and the last from the last 5 cm of the mill. Each sample was a representative mass, approximately 500 g, from an entire cross-section of the three places described. The charge fraction inside the mill was also determined (Table 1). MATLAB software and the backcalculation *globalsearch* solver were used to adjust the parameters.

Fig. 1. Interior of the mill during an experiment. Coarse particles are fine compacted aggregates dropped from the window.

Table 1
Operative parameters of the different experiments. L is the internal mill length; D is the internal mill diameter; J_R is the fraction of the mill volume occupied by the bulk rock charge; and J_B is the fraction of the mill volume occupied by the bulk ball charge.

Parameters		Unit
L	0.48	m
D	0.23	m
N° balls	300	
J_B	53.14%	
J_R	22.21%	
Flow	80	g/min
Residence time	76.5–85	min
Power	0.75	kW
Feed bulk density	1.8	t/m^3
Critical speed	94.2	rpm
% critical speed	70	%
Total time	106–200	min
Rock porosity	0.52	
Mill conditions	Dry	

3. Modelling

Two main hypotheses have been proposed: (1) Perfectly mixed milling occurs once the material enters into the mill. (2) A percentage of material behaves as a piston flow phenomenon when a selection function discriminates the particle sizes with a certain probability to be influenced by this mechanical breakage. Fig. 2 shows the flux for this proposed model.

The perfectly mixed mill dynamic Eq. (2) for PBM can be solved in a stationary state as a mathematical discretization assuming that the content of the mill is perfectly mixed at a first stage (Eq. (3)), $m_i = p_i^P$:

$$p_i^P = \frac{p_i^F + \sum_{j=1}^{i-1} b_{ij} k_j \tau p_j^P}{1 + k_i \tau} \tag{3}$$

where m_i is the fraction of mill content in size class *i*, p_i^P is the product of the mill in a differential mass, p_i^F is the feed in a differential mass, b_{ij} is the breakage function, k_i is the specific rate of breakage and τ is the residence time. Austin et al. (1987) proposed the variation of the specific rate of breakage with particle size as Eq. (4).

$$k(d_p) = \frac{S_1 d_p^{\alpha}}{1 + (d_p/\mu)^{\Lambda}} \tag{4}$$

where the value of α is a positive number, which is characteristic of the material; although the α value will vary with the mill conditions, μ is the particle size that fixes the maximum position, and Λ is a positive number that is an index of how rapidly the breakage rate declines with increasing size. The standard form presented by Whiten et al. (1979) is