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Scale-up of batch grinding data for simulation of industrial milling of platinum group minerals ore

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ABSTRACT

The attainable region analysis of batch grinding is a graphical method of establishing limits of performance of possible outcomes of any defined process. When applied to batch grinding, the results have often come into conflict with traditionally acceptable milling practice under which most concentrators operate (Metzger et al., 2011). This novel technique has not been tested on an industrial scale and thus, application of the scheme to full scale industrial mill is naturally the next step.

This research entailed scaling-up data obtained from laboratory batch milling of a platinum ore using empirical models. Using the parameters obtained in the laboratory tests, the authors applied a scheme developed by Austin et al. (1984) to predict the selection function and breakage function parameters for an operational industrial mill on which some plant survey had been conducted. It was found that the simulated product size distributions based on this scale up-procedure displayed a close match with the actual obtained from an operational industrial mill.

The attainable region plots from the scaled-up data showed that a finer product is achieved by using small balls. This is in agreement with initial findings based on laboratory batch tests only. It is also anticipated that pilot tests, industrial tests or simulations should be the next step in the quest for bridging the gap between the attainable region methodology and industrial experience. It has also been validated on industrial scale that less powder and grinding balls are needed to achieve finer grinding. However, it was interesting to note that the factors that produced a coarser product when analysed from a particle point of view were the same as those that yield the greatest amount of the desired size class when viewed from an attainable region perspective.

1. Introduction

The work described in this paper was part of a Minerals Processing project that has been ongoing in the internationally-recognised Centre of Material Process and Synthesis (COMPS), University of the Witwatersrand, for many years. Many of the innovations suggested by researchers at COMPS as a result of their own investigations have built on the previous contributions of their colleagues in this ever-expanding field, which explains why many of the references to previous publications mention names associated with the Centre[1].

In industrial milling, size reduction is commonly known to be a highly energy-intensive process that accounts for a major proportion of the costs involved in operating processing plants. This explains why engineers designing concentrators strive to operate the grinding systems and circuits in the most energy-efficient way. To identify optimal design configurations, researchers have resorted to laboratory batch tests to establish selection and breakage function parameters that enable them to identify optimal design configurations (Herbst and Fuerstenau, 1980; Herbst et al., 1981; Austin et al., 1984; Rajamani, 1991; King, 2001; Datta and Rajamani, 2002).

The Attainable Region (AR) approach, initially proposed for the analysis of chemical engineering systems, has now been extended to comminution processes and has already been applied successfully to optimise batch milling of different types of ore (Mulenga and Chimwani, 2013). Research carried out on laboratory mills has demonstrated the capacity of the AR technique to determine the set of all the achievable size distributions under different process conditions (Metzger et al., 2011). This information provides the engineer with accurate data on the operating conditions

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[1] The COMPS unit has now relocated to The University of South Africa, where it is continuing its work under the name of Material and Process Synthesis.

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required to achieve a specific objective function, such as those mentioned in the previous paragraph (Khumalo et al., 2006).

As an illustration of the above claim, the investigation carried out by Khumalo et al. (2006, 2007, 2008) used the AR technique to obtain a desired product using a minimum amount of energy. The results from his undertaking showed how the optimisation problem of the level of specific energy to be used in a given equipment, to achieve a certain objective function can be answered. Most importantly, the authors pinpointed the stage at which the energy intensity in a comminution process can be controlled in order to develop an optimal energy regime. On similar lines, Metzger et al. (2009) looked at means of minimizing the total time required for operation. Their results showed how useful AR is in determining optimal policies to reduce milling processing times. Katubilwa et al. (2011) analysed the effect of ball size on milling, and demonstrated clearly the advantage of mixing the sizes of the grinding balls to produce a maximum amount of material in a target size range.

The question being addressed in this work is whether the AR technique can be successfully applied to industrial mills. The present work also seeks to demonstrate how the tool can explore outputs that can assist in choosing optimal operating conditions. It is envisaged that this technique will serve as a complimentary analytical tool for the optimisation of milling circuits.

Initially, standard laboratory batch experiments on a Platinum ore to determine ore breakage characteristics were conducted and an empirical scale-up procedure was carried for full industrial mill application. After validating the scaled-up parameters with industrial survey data, the attainable region scheme was used to investigate the extent to which variations in the selection function parameters (μ, a, α and Λ, as symbolically presented by Austin et al. (1984)) affect the final product distributions in an industrial set-up. The results demonstrate that the AR technique can be used as a good tool for the design and analysis of mineral processing circuits.

2. Literature review

2.1. Population balance models

Population balance modelling has found widespread use in the simulation, control and optimization of various particulate processes. It is one of the most comprehensive tools for analysing and tailoring the particle size distribution (PSD) resulting from a size reduction process; investigating the grinding process; and studying the breakage mechanisms involved. The latter include massive fracture, cleavage and attrition (Bilgili et al., 2005). The population balance modelling approach requires an understanding of two concepts: the selection and the breakage functions. Both of these functions can be applied to predict grinding results once all their parameters are known.

As far as the selection function (S_i) is concerned, Austin et al. (1984) have proposed an empirical relationship that has gained wide acceptance by many researchers (King, 2001; Yekeler, 2007; Tavares and Carvalho, 2013), which is expressed as follows:

$$S_i = a \cdot x_i^{\alpha} \cdot Q_i = a \cdot x_i^{\alpha} \frac{1}{1 + \left(\frac{x_i}{\mu}\right)^{\Lambda}}, \text{ on condition that } \Lambda \geqslant 0 \tag{1}$$

where x_i is the upper limit in the screen size interval i in mm, Λ and α are characteristic constants which are dependent on material properties, a is a characteristic constant dependent on mill conditions and can also dependent on material properties since it implies how fast grinding occurs (Makokha and Moys, 2006), μ is a parameter dependent on mill conditions, Q_i is the correction factor (taken as unity for lower size classes, i.e. $x_i \ll d_{ball}$), d_{ball} is the diameter of the spherical grinding media.

Eq. (1) contains four parameters, two of which are dependent on mill conditions (a and μ) while the other two (Λ and α) are material-dependent.

Austin et al. (1984) also proposed an empirical model relating the cumulative breakage function $B_{i,j}$ to particle size x_i. The model has three parameters (γ, Φ and β) which have been found to depend on the properties of the material being ground. For a normalisable material, that is, a material that breaks following the same pattern regardless of relative size, the cumulative breakage function $B_{i,j}$ is given by:

$$B_{i,j} = \Phi_j \left(\frac{x_{i-1}}{x_j}\right)^{\gamma} + (1 - \Phi_j)\left(\frac{x_{i-1}}{x_j}\right)^{\beta}, \text{on condition that } n \geqslant i \geqslant j \geqslant 1 \tag{2}$$

where β is a parameter characteristic of the material used, the values of which are generally greater than 2.5, γ is a material dependent parameter, the values of which are typically found to be greater than 0.6, Φ_j represents the fraction of fines that are produced in a single fracture step, dependent on the material used and ranges from 0 to 1.

With the selection function and breakage function known, a mass balance in each size interval can be performed. Ultimately, all the amount of material in each individual size class can be calculated using the population balance model (PBM) of milling. In the case of batch milling, the model reduces to the batch grinding equation (Reid, 1965):

$$\frac{dw_i(t)}{dt} = -S_i w_i(t) + \sum_{\substack{j=1 \\ i>1}}^{i-1} b_{i,j} S_j w_j(t), \text{ on condition that } n \geqslant i \geqslant j \geqslant 1 \tag{3}$$

where $w_i(t)$ and $w_j(t)$ are the mass fractions of size i and j material present in a mill at time t respectively, $b_{i,j}$ is the discretized breakage function which gives the proportion of the particles of j that reports to size fraction i after one breakage event: $b_{i,j} = (B_{i-1,j} - Bi, j)$, S_i is the selection function of the material considered of size i.

Eq. (3) describes the evolution of mass fractions within each size class interval as a function of time while taking into account all sub-processes of breakage such as the birth and death of particles (King, 2001).

2.2. Factors affecting the breakage rate

In tumbling ball mills, the rate of breakage (S_i) and overall mill performance are affected by fractional ball filling (J), fraction of the mill volume filled by powder (f_c), powder filling (U), fraction of critical speed (ϕ_c), and ball diameter. These are discussed below.

2.2.1. Ball filling

Fractional ball filling (J) is conventionally expressed as the fraction of the mill volume filled by the ball bed at rest, assuming a formal bed porosity of 0.4. It can be calculated as follows:

$$J = \frac{\left(\frac{\text{mass of balls}}{\text{ball density}}\right)}{\text{mill volume}} \times \frac{1.0}{(1 - 0.4)} \tag{4}$$

The rate of breakage has been found to depend primarily on how much of the mill volume is filled with grinding balls, i.e. ball filling (J). Indeed, as the mill rotates, the grinding media reach a point where the balls will either be thrown off or roll off the liners and the charge separates from the shell, forming the shoulder of the charge. In the former case, the motion is referred to as cataracting whereas the latter as cascading. In general, the mill load will experience a combination of both. Fortsch (2006) reported that