Determination and scale-up of the milling parameters of a high talc containing oxidised copper-cobalt ore using a pear-shaped ball mill

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Abstract

The study reports on the grinding test conducted on an oxidised copper-cobalt ore in order to determine the milling parameters using pear-shaped ball mill. Twelve mono sized fractions of an oxidised copper-cobalt ore sample were prepared and wet ground batch wise using a laboratory-scale ball mill at the University of Lubumbashi: -6700 + 4750, -4750 + 3350, -3350 + 2360, -2360 + 2000, -2000 + 1700, -1700 + 1400, -1400 + 1000, -1000 + 850, -850 + 500, -500 + 250, -250 + 125 and -125 + 75 microns. After the sample and the balls were loaded to the ball mill, it was run for seven different time intervals (½, 1, 2, 4, 8, 15 and 30 minutes). The short time (½ minute) provided data more closely related to the Breakage Function (B) since less secondary breakage was hypothesised.

The data collected was used to determine some of the selection (S) and B Function parameters. The remaining parameters were estimated using a population balance model simulator that seeks the best combination of these parameters in order to minimize the residual error between the experimental and predicted product size distributions (PSDs). To evaluate the kinetics model developed, an un-sized oxidised copper-cobalt ore sample was also milled for ½, 1, 2, 4, 8, 15 and 30 minutes. The measured (PSDs) obtained fairly agreed

with the predicted ones. This suggested that the S and B Functions parameters obtained can be used for continuous operation mass balances.

Keywords: Pear-shaped ball mill, Population Balance Modelling, Selection Function, Scale-up, Breakage Function, oxidised copper-cobalt ore, high talc content

1. Introduction

Size reduction of solids is a very energy intensive and highly inefficient process. It consumes about 5 % of the electricity produced worldwide **[1]**, and about over 50 % of the total energy used in mineral processing plants **[2]**. It is therefore a moral requirement for minerals processing engineers to seek ways of improving the efficiency of size reduction processes in order to save energy. This often amounts to determining the optimal design configurations for the milling of an ore sample in a laboratory mill under standard conditions. Prior to optimising the milling stage, requirements for downstream processes in terms of particle size distribution need to be first understood as low liberation and over-grinding will cause other obstacles further. Once this is done, it is also important to clear understand the breakage properties of the ore to be used. The kinetics of size reduction in tumbling mills is often determined using two probabilistic functions: selection and breakage functions **[3]**. The knowledge of the Selection and Breakage functions also enables the prediction of particle size distribution for a given ore sample.

Oxidised copper-cobalt ores are often treated by hydrometallurgical methods and in some case by flotation. Hydrometallurgical methods typically entail selectively dissolving the metals (Cu and Co) in an acid aqueous solution (leaching) and transferring the dissolved metals to an organic solution and re-transferring these to a second aqueous solution (solvent extraction). The leaching kinetics of oxidised copper-cobalt ores strongly depends on the feed particle size distribution **[4]**. Leaching processes of oxidised copper-cobalt ores are highly favoured by a fine grinding, usually 65 - 70 % less than 75 microns. For a high talc-containing copper-cobalt-bearing ore, it is essential to reduce the ore to talcum powder fineness in order to liberate the copper and cobalt minerals. In fact during the milling, comminution breakage will preferentially occur along the soft and friable talc, and thus leaving the grains of copper and cobalt enclosed in the gangue materials. This will obviously slow down the leaching process. Oxidised copper-cobalt ores have also been successfully floated, by use of sulphidisation agents that enhance adsorption susceptibility of collectors onto the mineral grain surfaces **[5 – 8]**. Flotation of a copper cobaltiferous ore such as that of the Etoile mine in the Democratic Republic of Congo would be a challenge. This is explained by the presence of large amount of talc in the gangue minerals that predisposes the copper-cobalt minerals to an inefficient froth flotation. In fact, entrainment of fine talc in the flotation concentrates is the real threat. Talc is by nature hydrophobic and brittle **[9]**. It floats naturally and can also be successfully depressed during flotation by the addition of polymeric depressants **[10]**. However, if the copper-cobalt ore is over-ground and large amount of fine talc particles (-38 µm) is produced, they will unavoidably be recovered in the water stream and therefore contaminate the concentrate. The understanding of the milling kinetics of copper-cobalt ore can help determining the optimum milling conditions, so as to obtain good leaching kinetics or to prevent over production of fine talc particles that is detrimental for flotation. In this study, an endeavour to optimise the milling conditions of a copper-cobalt ore was conducted using a laboratory pear-shaped ball.

1.1 Modelling the grinding process

The modern theory of comminution relies on two probabilistic sets of parameters: the Selection Function **S** and the Breakage Function **B**.

1.1.1 Selection Function

The Selection Function refers to the milling kinetics and it is given in **Eq. (1)**:

$$S = \frac{a x_i^{\alpha}}{1 + \left(\frac{x_i}{\mu} \right)^{\Lambda}} \qquad \textbf{(1)}$$

where x_i is the upper limit of the particle size interval under consideration; the model parameters a and μ are mainly functions of the grinding conditions while α and Λ are material properties.

Fig. 1 hereunder shows the first-order breakage law for a given material. The initial straight line portion of the curve which shows the normal breakage behaviour is the area where S has not passed through the maximum. The second portion, area where S has passed the maximum, shows the abnormal breakage behaviour. According to Griffith theory of breakage **[11]**, this trend can be attributed to the fact that very fine particles are hard to break. The breakage rate is also affected by the reduced capture probabilities of fine particles in mills **[12].** This suggests that the breakage rate increases with increase in particle size. However, for too large particles that cannot be correctly nipped and fractured by the balls, the rate of breakage steadily drops and tends to zero.

Scale-up of the Selection Function

The Selection Function values (Si) vary with mill design and operating variables. Therefore, the Si determined from laboratory test works need to be scaled to large-scale mills. Austin *et al*. (1984) suggested the following **Eq. (2)** for the Selection Function scale-up.

$$S = \frac{a x_i^{\alpha}}{1 + \left(\frac{x_i}{C_1 \mu} \right)^{\Lambda}} C_2 C_3 C_4 C_5 \qquad \textbf{(2)}$$

The multipliers C_1, C_2, C_3, C_4 and C_5 are given by

$$C_1 = \left(\frac{D}{D_T}\right)^{N_2}\left(\frac{d}{d_T}\right)^2 \quad \textbf{(3)}$$

$$C_2 = \left(\frac{d_T}{d}\right)^{N_0} \quad \textbf{(4)}$$

$$C_3 = \left(\frac{D}{D_T}\right)^{N_1} \quad \text{for } D < 3.81 \text{ and} \quad \textbf{(5)}$$

$$C_3 = \left(\frac{D}{D_T}\right)^{N_1}\left(\frac{D}{3.81}\right)^{N_1-\Delta} \quad \text{for } D >= 3.81 \quad \textbf{(6)}$$

$$C_4 = \left(\frac{1+6.6J^{2.3}}{1+6.6J_T^{2.3}}\right)e^{-c(U-U_T)} \quad \textbf{(7)}$$

(2.9)

$$C_5 = \left(\frac{f_c-0.1}{f_{cT}-0.1}\right)\cdot\left(\frac{1+e^{15.7(f_{cT}-0.94)}}{1+e^{15.7(f_c-0.94)}}\right) \quad \textbf{(8)}$$

where D is the mill diameter (m), d is the ball diameter (m), J is fractional load volume, U is the fractional void filling and Φ is the mill speed fraction of critical speed. The Subscript T refers to laboratory test mill conditions. N_0, N_1, N_2 and Δ are constants ($N_0 \approx 1$, $N_1 \approx 0.5$, $N_2 \approx$ 0.1 to 0.2, c = 1.3 and Δ = 0.2 for larger mills).

1.1.2 Breakage Function

The Breakage Function refers to the distribution of mass fractions after a breakage event. It is given by

$$B_{ij} = \Phi_j\left(\frac{x_{i-1}}{x_j}\right)^{\gamma} + (1-\Phi_j)\left(\frac{x_{i-1}}{x_j}\right)^{\beta} \quad \textbf{(9)}$$

where **Φ**, **γ** and **β** are the model parameters that depend on the ore properties. x_i is the particle size in the i^{th} class of breakage progeny and x_j the particle size of the size being broken.

The B_{ij} values are said to be normalisable if the breakage distribution function is independent of the initial particle size (Austin et al., 1984). In other words, the fraction which appears at sizes less than the starting size is independent of the starting size. For normalized B values, δ=0 and the B_{ij} *are* superimposed upon each other.

A graphical illustration of the cumulative breakage distribution function based on **Eq. (9)** is given in **Fig. 2.** The distribution is in fact a simple weighted sum of two Schuhmann distributions (straight line plots on a log-log scale). The slope of the lower portion of the curve gives the value of γ , the slope of the upper portion of the curve gives the value of β , and ϕ_j is the intercept of the lower portion of the curve at x_j **[11]**.

1.1.3 Batch Grinding Equation

The knowledge of the Selection and Breakage functions enables the prediction of particle size distribution for a given ore sample. **[11]** procedure which consists in a series of laboratory tests in a small mill using a one-size-fraction method is often used. The material is loaded in the mill together with the ball media. Then the grinding is performed for several suitable grinding time intervals. After each interval, the product is sieved. Thus the disappearance rate of feed size material is calculated for the different grinding time intervals. By performing a population balance at size class i in which the selection and breakage functions are incorporated, one gets

$$\frac{dw_i(t)}{dt} = -S_i w_i(t) + \sum_{\substack{j=1 \\ i \succ 1}}^{i-1} b_{i,j} S_j w_j(t), \; n \geq i \geq j \geq 1 \qquad \textbf{(10)}$$

2. Experimental

2.1 Description of the experimental laboratory mill

An experimental laboratory scale ball mill available at the University of Lubumbashi was used in this research work. The ball mill measured 0.305 m in diameter and 0.127 in length. It was driven by an asynchronous motor rated with power close to 10 kW. A schematic of the experimental laboratory ball mill used is shown in **Fig. 3**.

2.2 Sample preparation

The copper-cobalt ore used in the actual test work was obtained from the feed to the primary mill (run of mine) at the Etoile mine of Rwashi mining, a subsidiary of the Metorex group. The ball mill feed content mass was calculated using following

.

$$M_{feed} = V_{mill} \times r_{bulk} \times f_c \qquad (11)$$

The f_c value was calculated from **Eq. (12)** by first setting the slurry filling U, given by **Eq. (13)** and the ball filling J, given by **Eq. (14)**.

$$f_c = \left[\frac{\dfrac{\text{mass of powder}}{\text{powder density}}}{\text{mill volume}} \right] \times \frac{1.0}{1-\varepsilon'} \qquad (12)$$

$$U = \frac{f_c}{\varepsilon \times J} \qquad (13)$$

$$J = \left[\frac{\dfrac{\text{mass of ball}}{\text{ball density}}}{\text{mill volume}} \right] \times \frac{1.0}{1-\varepsilon} \qquad (14)$$

where

Slurry filling (U) is the fraction of the spaces between the balls at rest which is filled with slurry. Mill filling (fc) is expressed as the fraction of the mill volume filled by slurry bed using a slurry bed porosity **ε**. Ball filling (J) is expressed as the fraction of the mill volume filled by the ball bed at rest, assuming a bed porosity **ε'**. In this work, the slurry bed porosity and ball bed porosity were chosen equal to 0.4 that is the conventionally formal bed porosity.

2.3 Laboratory operating conditions

Table 1 gives the laboratory and industrial operating conditions.

2.4 Milling Kinetics tests

The one-size fraction method by Austin *et al.* (1984) for measuring the Selection and Breakage Functions was used to determine the breakage and selection function parameters. Twelve mono sized fractions were prepared and wet ground batch wise using a laboratory-scale ball mill at the University of Lubumbashi: -6700 + 4750 µm, -4750 + 3350 µm, -3350 + 2360 µm, -2360 + 2000 µm, -2000 + 1700 µm, -1700 + 1400 µm, -1400 + 1000 µm, -1000 + 850 µm, -850 + 500 µm, -500 + 250 µm, -250 + 125 µm and -125 + 75 µm. After the sample and the balls were loaded to the ball mill, it was run for seven different time intervals (½, 1, 2, 4, 8, 15 and 30 minutes). The total individual composite samples for each test were carefully removed from the mill. They were weighed in the collection bucket while wet; then pressure filtered, using tared filter paper before being placed on a pan and finally in an oven for drying over night at a temperature of about 65°C. The dried samples were then re-weighed and a representative sample was taken for particle size distribution determination. Then, the feed for the next grinding period was the material retained on the screens, combined with the rest of the mill contents.

2.5 Simulation of the grinding process

The Matlab simulator code by **[13]** that directly translates the population balance model **(Eq. (10))** was used to generate the simulated product size distributions. Details on the Matlab code used can be found in **Appendices A.1-A.3**.The flowchart of the calculation procedure is shown in **Fig. 4**. In order to tune this simulator with the actual grinding process, the breakage function parameters (**β, γ and Φ**) and selection function parameters **(α)**, determined from the experimental tests according to the one-size method by **[11]**, were pre-entered into the code. The remaining selection Function parameters (**a, Λ and μ)** were then estimated by the simulator by minimising the sum of squared errors (SSEs) between the predicted and experimental product size distributions. Finally, the $\mathbf{b_{i,j}}$ functions were then back-calculated by the simulator.

3. Results and discussions

3.1 Determination of the Selection Function parameters

The size-dependence of the Selection Function parameters **Eq. (1)** was used to derive numerically the rate of breakage of the copper-cobalt ore. Experimental mass percents retained on the top screen were plotted against the grinding time t on a log-linear scale for all feed sizes. To illustrate this, the first order grinding plots of the copper-cobalt for selected mono sized fractions (-250 + 125 µm, -3350 + 2360 µm and -6700 + 4750 µm) are shown in **Figs. 5-7.** The results in **Table 2** indicate that the magnitudes of the Selection Function increased with the increase in the size of particles; but quickly decreased beyond 1700 µm.

The Selection Function values were plotted in **Fig. 8**. It can be seen that the Selection Function curve presents two regions: a low-particle-size linear region and an upper non-linear region. The graphical procedure of the full determination of all parameters associated with the Selection Function is given in **Fig. 1 [11]**. With respect to the data outlined in this article, the Selection Function curve was assumed to be linear up to 1700 µm, where the maximum value of S occurred. In other words, the media were large enough to break efficiently the particles in this region. With a further increase in the particle size, the ore sample was too big and strong to be properly nipped and fractured by the actual ball distribution. Hence, the breakage took place in the abnormal breakage region. As a result, the specific rates of breakage decreased. The value of alpha (α) was then determined from the linear region in **Fig. 8**, by using a power function. This value was fed into the population balance model for the computer simulations.

The Selection Function parameters are summarized in **Table 3**.

The specific rates of breakage determined in the laboratory ball milling tests were scaled-up to the industrial scale mill using **Eq. (2).** The multipliers used to scale-up the selection functions were calculated by using **Eqs. (3) - (8)**. The multipliers obtained are C_1=18.343, C_2=0.275, C_3=2.999, C_4=1.016 and C_5=1.563. Only the model parameters *a* and *μ* are affected by the multipliers (a for Si scaled-up: $a_{sup} = a.C_2.C_3.C_4.C_5$,μ for Si scaled-up: $\mu_{sup} = \frac{\mu}{C_1}$), since they depend on the grinding conditions. The remaining Selection Function parameters (α and *Λ)* are material properties. The scaled-up Selection Function parameters are presented in **Table 4**.

3.2 Determination of the Breakage Function parameters

The B-II calculation procedure of the primary breakage function as proposed by **[11]** was used to generate the Breakage Function parameters. This method suggests the use of shorter grinding times, which result in 20–30% broken materials out of the top size before re-breakage. **[3]** further stated that up to 65% broken material will still provide accurate data to be used with this procedure. All the feed materials were considered to be normalizable (δ = 0) for simulation purposes. This means that the fraction appearing at sizes less than the initial feed size was independent of the initial feed size. The cumulative breakage distribution functions of the copper-cobalt ore at different initial feed sizes are shown in **Fig. 9.**

The B_{ij} values obtained were fitted to the empirical model in **Eq. (9) [11]**, and the model parameters: β, γ and ϕ for the UG2 ore were evaluated. The Breakage Function parameters are listed in **Table 5**. The average Breakage Function values obtained are β = 5.20, γ = 1.01 and Φ = 0.86. These values parameters are a little different with those obtained by **[14]** for a copper ore in a Vertimill™ pilot test, which were: β = 3.33, γ = 0.615 and Φ = 0.463. This was believed to be due to the presence of high talc content in the copper-cobalt ore sample treated. **[15]** also found values of β = 4.0, γ = 0.60 and Φ = 0.45; based on their ball milling experiment on copper ore sample from the Los Broncos mine.

3.3 Particle size distributions

The parameters (α, Λ, γ and μ) were estimated by the optimization model that seeks the best combination of these parameters in order to minimize the residual error between the experimental and predicted product size distributions. The parameters of the Selection and Breakage Functions evaluated from the experimental data were used as initial guesses to the model in the parameter search process. The average Breakage and Selection Functions parameters were then used to obtain the product size distribution (PSD) of a normal copper-cobalt ore (un-sized) that was milled for ½, 1, 2, 4, 8, 15 and 30 minutes. The measured and predicted size distributions for all the milling products are given in **Fig. 10**. It can be seen that there is a fair agreement between the measured size distributions, shown as markers in the plotted graphs, and the simulated size distributions, shown as solids lines. This allowed validating the kinetics model and suggested that the Selection and Breakage Functions parameters obtained can be used for continuous operation mass balance.

4. Conclusion

An understanding of the milling kinetics of the Etoile mine copper-cobalt ore is being improved. The simulations indicated that is possible to predict the particle size of a pear-shaped ball mill using the population balance model. The milling kinetics model developed can be useful to provide insight into the copper-cobalt ore behaviour in milling circuits by using routine laboratory batch milling test results. Such information can also be implemented on the grinding circuit models in order to improve actual industrial copper-cobalt ore flowsheets.

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6. References

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7. Appendices