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Breakage and liberation characteristics of low grade sulphide gold ore blends

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ABSTRACT

Within the scope of the evaluation and optimization of a grinding circuit, the breakage and mineral liberation characteristics of three low grade sulphide gold ore blends have been investigated by Bond tests, batch grinding tests, and mineral liberation characterization. The tests were conducted in a size range from 0.063 to 2 mm. It was found that the breakage of all blends follows a first-order behaviour for all feed sizes. The work index was correlated with the quartz content and the breakage rate deceleration parameter, which both showed a linear relationship. The correlation between breakage function fineness parameter and first-order rate constant also satisfied a linear relationship .The breakage parameters established from batch grinding and grindability studies indicate differences in the breakage behaviour of the three ore blends. However, the mineral liberation properties of the valuable phase in three blends show minor differences.

1. Introduction

In the minerals industry, it is important to understand how mills will respond to variations in the grindability of ores coming from different parts of a deposit. It is based on the fact that comminution accounts for approximately 65–85% of all energy used for processing ore (Deep level mining consumes the major part in some mines) and that only 1–2% of the supplied energy is translated to the creation of new surface area (Tromans, 2008). Nevertheless, comminution circuits determine the success of overall mineral processing plants; sufficient comminution products are the basis of good results in beneficiation, extraction and recovery stages, and vice versa (Wills and Finch, 2016). The main purpose of comminution is to liberate valuable minerals from the gangue prior to subsequent beneficiation processes such as flotation or leaching. However, the performance of comminution circuits is typically modelled, designed or assessed based on product size reduction rather than liberation. In order to properly design, diagnose, monitor and optimize comminution processes, the liberation characteristics of ore minerals have to be of equal interest and should not be ignored. If such aim is achieved, not only is energy saved by size reduction processes, but also, any subsequent separation stage becomes easier and cheaper to operate.

One of the main challenges in mineral liberation is the changing grinding and liberation behaviour of the material as the mineralogical composition of the feed varies with time. Therefore, the ability to predict how minerals act during grinding will be important for two reasons: (1) the output of processing plant can be projected based on present condition, and (2) further actions can be taken in order to meet the target product size.

The grinding result is determined by two components, the circuit or equipment on one side and the material itself on the other. Studies on the correlation between mineralogical composition of the material and the grinding properties of blends, ores or pure minerals provide information about the integral or individual liberation characteristics. Thus, it becomes possible to estimate and predict the liberation based on mineralogical data of a deposit, even before a mine is in operation.

Another approach in studying the grinding behaviour is by determination of Bond's work index (Bond and Maxson, 1943). This is the comminution parameter which expresses the resistance of material to crushing and grinding. It is derived from the Bond grindability test, which is a dry laboratory simulation of closed circuit grinding. Apart from Bond's work index, selection and breakage functions are used to describe the grinding kinetics. This is based on the theory of comminution that considers the process as being represented by two events (Kelly and Spottiswood, 1990): (1) the *fracture event*, where a particle is selected for breakage (represented by the selection function), and (2)

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the *fracture process*, where a broken particle produces a given distribution of fragment sizes (represented by the breakage function).

The present paper analyses, compares and correlates the grinding and liberation characteristics of three low grade sulphide gold ores. Three properties were investigated from grinding tests: Bond's work index, breakage function, and selection function. The modal mineralogy and liberation characteristics of the ores were also determined in order to provide the correlation between the mineralogical composition and their grinding behaviour. The practical background of this work is to predict key grinding circuit parameters in order to be prepared for future challenges.

2. Theory

It is generally accepted that the rate of disappearance of particles being ground in a mill is proportional to the amount of particles present. This assumption known as the first-order breakage law, results in a similarity between milling and chemical reactions (Reid, 1965). Thus, the rate of breakage of the material that is in the top size interval 1 is expressed as (Austin, 1972):

$$-\frac{dw_1}{dt} = S_1 w_1(t) \tag{1}$$

where S_1 is the specific rate of breakage (time^{-1}). If S_1 does not change with time (i.e. first-order breakage process), Eq. (1) integrates to:

$$w_1(t) = w_{t=0}\exp(-S_1 t) \tag{2}$$

That is,

$$\log[w_1(t)] = \log[w_1(0)] - \frac{S_1 t}{2.3} \tag{3}$$

where w_1 (t) is weight fraction of mill hold up, that is of size 1 at time t. Therefore, a plot of w_1 (t) vs. t should give a straight line on a log-linear scale and S_1 can be determined from the slope of the plot. However, at longer grinding times, S_1 decreases as fine material start accumulating in the mill causing a non-first order breakage, i.e., slowing down breakage (Austin and Luckie, 1972).

The following model was used by Austin et al. (1984) to express the effect of particle size on the specific rate of breakage:

$$S_i = \frac{a x_i^{\alpha}}{1 + \left(\frac{x_i}{\mu}\right)^{\lambda}}, \lambda \geqslant 0 \tag{4}$$

where x_i is the upper limit of the size interval i in mm, and a,α, μ and λ are the model parameters. α and λ are characteristic constants which depend on the material properties. α is a positive number normally in the range 0.5–1.5. λ is also a positive number, an index of how rapidly the rates of breakage fall as particle size increases. a is characteristic constant dependent on mill conditions and can also depend on material properties as it implies how fast grinding occurs. μ is dependent on mill conditions.

The weight fraction of the material broken initially from size interval j down to the size interval i is defined as the primary fragment distribution (breakage function) $B_{i\ j}$. This is conveniently presented in cumulative form as:

$$B_{i,j} = \sum_{k=n}^{i} b_{k,j} \tag{5}$$

The values of $B_{i,\ j}$ can be estimated from size analysis of the grinding product after a short grinding interval and with an initial mill charge. Here, the material is predominantly in size j (Austin et al., 1984) (i.e. one-size fraction BII method). According to BII method:

$$B_{i,1} = \frac{\log[(1-P_i(0))/(1-P_i(t))]}{\log[(1-P_2(0))/(1-P_2(t))]}, i > 1 \tag{6}$$

where $P_i(t)$ is the mass fraction smaller than size i at time t. $B_{i,\ j}$ can also be fitted to an empirical function relating particle size x_i as (Austin & Luckie, 1972):

$$B_{i,j} = \varphi_j\left(\frac{x_{i-1}}{x_j}\right)^{\gamma} + (1-\varphi_j)\cdot\left(\frac{x_{i-1}}{x_j}\right)^{\beta}, i > j \tag{7}$$

$$\varphi_j = \varphi_1\left(\frac{x_j}{x_1}\right)^{-\sigma} \tag{8}$$

where ϕ, β, γ and σ are model parameters dependent on material properties. Thus cumulative breakage functions B are the same for different ball filling ratios, mill diameters, etc. (Austin et al., 1984). Values of β are generally between 2.5 and 5, γ mainly in the range of 0.5–1.5. ϕ represents the fraction of fines produced in a single fracture step, depends on the material and ranges from 0 to 1. If $B_{i,\ j}$ values are independent of the initial size (i.e. dimensionally normalizable), then $\sigma = 0$. This parameter characterizes the degree of non-normalization.

3. Experimental

3.1. Material and initial sample preparation

Samples of the feed to SAG mill at Acacia's Buzwagi Gold Mine, in Tanzania, were taken. The ore had a maximum size of 200 mm and three samples were taken, (S-1, S-2, and S-3), which were representative of the three main ore types. Based on mineralogical reports from the mine, gold and silver occurs as inclusions in pyrite, inclusions in unaltered chalcopyrite, free grains, inclusions in quartz, and inclusions in bornite. Copper occurs primarily in the chalcocite-chalcopyrite replacement grains. It was reported by the mine that the three ores showed different milling behaviour. The mass and assay of the samples are presented in Table 1. For mineral liberation analyser (MLA), Bond, and grinding tests, representative subsamples were prepared by stage crushing (laboratory jaw and cone crushers), followed by splitting (riffle splitter). Each subsample was then treated separately according to recommended protocols (see below).

3.2. Mineral liberation analysis

A ball mill equipped with a screen (1 mm in this case) was used for preparation of samples for mineral liberation studies. The mill discharge was sieved into five fractions, −1 +0.5 mm, −0.5 +0.25 mm, −0.25 +0.125 mm, −0.125 +0.063 mm and −0.063 mm. A broad sample from the mill discharge (i.e. 0–1 mm) was also included. The fractions were handed to automated mineralogical characterization. The measurements were performed at the Department of Mineralogy, TU Bergakademie Freiberg, using FEI MLA 600F system (Fandrich et al., 2007; Gu, 2003; Sandmann, 2015; Sandmann et al., 2014; Sandmann and Gutzmer, 2013). Feed samples to the system were prepared as polished grain mounts (Leißner et al., 2016; Sandmann, 2015; Sandmann and Gutzmer, 2013). Three sample splits were prepared from each fraction and used for MLA measurement. The mounts were carbon-coated prior to measurements in order to obtain an electrically conducting surface. Upon bombardment of an electron beam in a SEM, a mineral phase will backscatter electrons at an intensity defined by its average atomic number as well as releases X-rays characteristic of elements that are present. The measurement of Backscattered Electron (BSE) intensities allow the segmentation of mineral phases within a

Table 1
Mass and assay of the bulk samples.

Item	S-1	S-2	S-3
Mass (kg)	377.50	341.14	314.94
Au (g/t)	1.94	1.75	1.33
Ag (g/t)	2.36	3.0	1.90
Cu (%)	0.07	0.10	0.08