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Effects of mixtures of grinding media of different shapes on milling kinetics

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ABSTRACT

The effect of grinding media on milling kinetics has been generally studied using one media shape. However, very little work has been done on investigating mixtures of media shapes.

Combining different grinding mechanisms in term of contacts, the volume of grinding zones can be efficiently increased when there is an optimal mixture of two or more grinding media with different shapes and, therefore the milling kinetics will be improved.

A series of batch grinding tests was carried out using the same mass of spherical balls, Eclipsoids™ and cubes to break coarse, medium and fine sizes of quartz material. Then, mixtures of the same mass made of spherical balls and cubes, spherical balls and Eclipsoids™ were successively considered. The breakage parameters were determined and used to evaluate the grinding performances of the mixtures of grinding media under the same conditions.

It was found that mixtures of grinding media shapes can increase the breakage rate in a particular milling environment. But, spherical balls remain the most efficient grinding media. Finally, an optimal mixture made of spherical balls and grinding media of different shapes, namely cubes and Eclipsoids that are cheaper to manufacture can be used in the grinding process alternatively to 100% balls.

1. Introduction

For decades milling has been the subject of intensive research. Describing and understanding the process has been challenging because of the tumbling mill environment itself. The problem with tumbling ball mills is that they are extremely wasteful in terms of energy consumed (Wills, 1992). The behaviour of the mill load plays an important role in the overall grinding mechanism. It is directly influenced by some major factors, among them the constitution of the charge, the speed of rotation of the mill, and the type of motion of individual pieces of medium in the mill (Gupta and Yan, 2006). From an industrial point of view, the main operational flexibility is the amount and composition of the charge. Ideally, grinding media should have the largest possible surface area to provide suitable contact with the material being ground and they should be as heavy as possible to have sufficient energy required for breaking the ore particles. Spherical balls or spheres (here referred as "balls") were found to be more efficient than other grinding media shapes (Kelsall et al., 1973). Balls produced the finest products and used the least power for constant batch grinding time (Norris, 1953). Alternative shapes to balls have been suggested to reduce the grinding costs and increase the milling efficiency. However, the spherical balls which are predominantly used in ore grinding change shape through breakage and wear. They can even break during the grinding process. The movement of these irregularly shaped components through the mass of the charge is believed to differ significantly from the behaviour of initial grinding media shapes. Additionally these worn balls experience surface and linear contacts with each other, while spherical ones have only point contact interactions. The breakage is then done with a mixture of grinding media of different shapes rather than with a defined single shape of media.

In this research, we investigate the breakage rate for different grinding media shapes and for the mixtures made of these shapes. This requires a complete breakage characterization of the material being described. The breakage parameters are determined for mixture of grinding media of different shapes, and then compared to the parameters of individual grinding media shapes. The overall impact of the mixture of grinding media shapes is then evaluated in terms of their grinding performances.

The grinding process is satisfactorily described using the population balance model. In this model, milling is expressed in terms

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of the selection function and the breakage function (Austin et al., 1981). On a laboratory scale, the selection and breakage functions are determined by batch grinding tests performed on single particle sizes for a ball charge consisting of a single size.

The selection function is the fractional rate at which a given size of particle is broken into smaller particles. The breakage of a given fraction of material usually obeys a first-order pattern (Austin et al., 1984).

$$\text{Rate of breakage of size } i = S_i w_i W \tag{1}$$

where w_i is the weight fraction of material of size i, W is the total material charge in the mill and S_i is the specific rate of breakage of size i.

Since the total mass W is constant, this equation becomes:

$$-\frac{dw_i(t)W}{dt} = S_1 w_1(t)W \tag{2}$$

S_1 is the specific rate of breakage when the feed is ground for a set of time t_1, with units of time^{-1}. Then, if S_1 does not vary with time, we obtain after integration:

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

where t is the grinding time.

The formula used for the variation of the specific rate of breakage S_i with particle size is:

$$S_i(d) = a(d) \cdot \left[\frac{x_i}{x_0}\right]^{\alpha} \cdot Q(x) \text{ with } Q(x) = \frac{1}{1 + \left[\frac{x_i}{\mu(d)}\right]^{\Lambda}}; \quad \Lambda > 0 \tag{4}$$

where $a(d)$ and α are parameters dependent on the material ground in a particular mill under defined operating conditions; x_i is the particle size in mm; x_0 is a reference size, usually 1 mm; $\mu(d)$ defines the particle size at which $Q(x)$ is 0.5 and Λ is an index of how rapidly the rate of breakage falls away (Austin et al., 1982). The equation relating the value of the size x_m (at which the rate of breakage is a maximum for a given material) to the parameter $\mu(d)$ is as follows:

$$\mu = x_m \cdot \left(\frac{\Lambda}{\alpha} - 1\right)^{1/\Lambda}, \quad \text{on condition that } \Lambda > \alpha. \tag{5}$$

The specific rate of breakage increases steadily with particle size which reflects the decreasing strength of the particles as size increases. This is attributed to the greater density of microflaws in the interior of larger particles and to the greater likelihood that a particular large particle will contain a flaw that will initiate fracture under the prevailing stress conditions in a mill. The decrease in particle strength does not lead to an indefinite increase in the specific rate of breakage. As the particle size becomes significant by comparison to the size of the smallest media particles, the prevailing stress levels in the mill are insufficient to cause fracture and the specific rate of breakage passes through a maximum and decreases with further increase in particle size (King, 2001).

The breakage function describes the size distribution of the products of breakage. The general fitting model of the breakage function is given by:

$$B_{i,j} = \phi_j \left[\frac{x_{i-1}}{x_1}\right]^{\gamma} + (1-\phi_j)\left[\frac{x_{i-1}}{x_1}\right]^{\beta}, \quad 0 \leq \phi_j \leq 1 \tag{6}$$

where γ, β and ϕ_j are all characteristic of the material being ground and x_i is the top size of the size interval indexed by i.

$B_{i,j}$ represents the cumulative weight fraction of material broken from size j which appears in size interval i. The subscript 1 refers to the original material of size 1 at time $t = 0$, the subscript i refers to a smaller size than the size j and the subscript j refers to the size from which material that appears in size i are broken.

$$\phi_j = \phi_1 \left[\frac{x_i}{x_1}\right]^{-\delta} \tag{7}$$

where δ characterizes the degree of non-normalization.

Some materials are subjected to abnormal breakage in laboratory mills where a departure from first-order kinetics occurs particularly for the larger particle sizes in the mill feed (Austin et al., 1973). Several models were proposed to explain it (Austin et al., 1977; Bilgili et al., 2006).

The basic mill power drawn equation described by Hogg and Fuerstenau (1972) is given by:

$$P = \frac{2\pi N\tau}{60} \tag{8}$$

where N is the mill speed in rpm, τ is the torque exerted by the mill minus friction in the bearings.

2. Experimental

The small Wits laboratory mill was used to carry out the batch grinding tests on the quartz sample. This mill was fitted with eight equally spaced lifters. The mill has 0.302 m diameter and 0.282 m length, and driven by a 0.25 kW mono-phased variable speed motor. It was run at 75% of the critical speed with a ball filling J of 20% and a powder filling U of 75%.

2.1. Grinding media and test materials

Balls, cubes and Eclipsoids™ made of cast iron were used for the batch tests. Eclipsoids™ are semi-prolate spheroid (stretched ellipsoid of revolution). Their shape is similar to that of a half rugby football (Fig. 1).

The spherical balls, cubes and one of the mixture used in this study are presented in Fig. 2.

40 mm balls, 40 × 40 mm Eclipsoids and 32 mm cubes were used. The total load mass was kept constant for all grinding media shapes, as well as for the mixtures of grinding media for an average porosity of 0.4 (Austin et al., 1984). The grinding media shapes were used to grind 11 different mono-sized feed fractions of quartz with a specific density of 2.64 g/cm^3. The size fractions chosen for the tests were ranging between −16,000 and 300 µm. These size fractions were picked in order to get the value of the parameter a and the value of x_m, the size at which the maximum value of the breakage rate S occurs.

The physical properties of the grinding media used are presented in Table 1.

2.2. Experimental methods

The one-size-fraction method (Austin et al., 1984) was used to perform our batch grinding tests. Four grinding times were considered: 0.5, 1, 2 and 4 min. For every test, a blank sieving test was done on the prepared feed material. The prepared material was then loaded and ground in the laboratory mill for 30 s. After this grinding period, the mill content was discharged. A full particle size distribution was done on the collected product using nested screens in decreasing order of size from the top screen down to the 75 µm screen at interval of $\sqrt{2}$. After all this, the material was then recombined for batch grinding for 30 s to reach a total grinding time of 1 min. The very same process was performed. Then load was ground for 1 min to reach 2 min, and finally it was ground for 2 min to reach 4 min. Each grinding process was followed by a size analysis and the material was recombined at the end of each process.