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An energy benchmarking model for mineral comminution

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ABSTRACT

A method for determining the minimum practical energy for comminution was developed and is presented in this paper. An objective of the method was to determine experimentally the energy-breakage relationship for a wide size range in order to evaluate the energy performance of both crushing and grinding processes using one energy benchmarking value.

Single-particle compression breakage, referred to in the field of comminution as one of the more efficient forms of mechanical comminution, was the basis for a test regimen to characterize the energy-breakage properties of ores. Existing models for impact breakage were found to be valid for single-particle compression breakage when used in a modified form. A key parameter of the adopted model, the threshold energy, was also investigated for three ore types and a range of particle sizes.

The energy performance of comminution processes at a Canadian mining operation was determined by comparing the determined minimum practical energy, using the new method, with actual site specific energy requirements. In order to evaluate the energy performance of different crushing and grinding technologies, the proposed energy benchmarking method was used to compare the energy performance of alternative comminution flowsheets.

1. Introduction

The size reduction of ore prior to minerals extraction is a particularly energy intensive process and typically accounts for 30–70% of the overall energy used by mining operations. Showing the variation in comminution requirements across mining operations, a Canadian study on specific energy consumption in base metal underground mines demonstrated that combined crushing and grinding specific energies ranged from 15.2 to 32.1 $\mathrm{kW\,h_e}$ per tonne of crushed and milled gold ores (CIPEC, 2005). The wide range in industry specific energy requirements is mainly due to the hardness of treated ores, range of feed and product sizes, and the efficiency of implemented comminution processes. Therefore, the energy performance of mineral comminution processes cannot be simply assessed by comparing site energy requirements to the results of an industry survey; rather, an energy benchmarking approach that takes the comminution duty into account is required.

Single-particle compression breakage has been the focus of a number of studies in the field of comminution as a method to gauge the comminution efficiency of grinding equipment. Fuerstenau and Abouzeid (2002) proposed that operational ball milling energy be compared against the energy for producing new surface area by the compression or impact loading of single-particles. Tromans (2008) proposed using a relative efficiency ratio, the ratio of actual energy efficiency and the maximum ideal limiting efficiency, as a practical measurement of comminution efficiency. Actual energy efficiency was based on the energy required to create new fracture surface area and the maximum ideal limiting efficiency for compression breakage.

To date, significant work on quantifying energy-breakage has been carried out using impact breakage devices. Through single-particle impact testing, Vogel and Peukert (2003) developed a master curve describing the breakage probability of various materials. A critical component of the model was the threshold energy, representing the impact energy that a particle can elastically absorb without fracture taking place. The model proposed by Vogel and Peukert (2003) has proven to be quite versatile and applicable to other comminution equipment; a modified form of the model was successfully adopted for fitting results from drop weight testing (Shi and Kojovic, 2007) and steel wheel abrasion testing (Chenje et al., 2011). One objective of the presented research was to see whether the model, in original or modified form, is applicable to results of single-particle compression breakage. An advantage of compression breakage testing is the fact that instrumented piston press equipment can be used to directly determine the threshold energy of minerals.

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Incorporating single-particle compression testing and models adopted from impact testing, a methodology is put forward in this paper to determine the minimum practical energy required to reduce the size of an ore to a certain product size. The determined energy value is then compared to the actual energy consumed at the respective mining operation to determine the Benchmark Energy Factor (BEF), an energy performance indicator, of comminution processes at the plant. The BEF term was initially introduced by BC Hydro, an energy utility in British Columbia, Canada. It is applied in cases where site factors such as environmental and material conditions, which are not under control of the operator, influence energy consumption and need to be accounted for during calculation of energy performance.

A key feature of the proposed method is that it is not constrained to one comminution technology, thereby allowing the comminution energy performance of plants comprising different crushing and grinding technologies to be effectively compared. The battery limits of the benchmarking effort were nominated as starting at the muckpile of blasted or caved material, and terminating before the first beneficiation process. Reflecting the battery limits of the energy benchmarking effort, the approach included testing of a wide range of particle sizes for fitting with an energy-breakage model.

2. Single-particle compression testing

An instrumented MTS piston press unit, shown in Fig. 1, was used to carry out single-particle compression tests on mineral particles. Particles were compressed between a hardened steel piston and base. The piston was attached to a load cell that had a rated accuracy of ±325 N. A transparent plastic wall was fixed to the piston to allowed particles to be observed during compression testing while containing projectiles. The specific energy consumed during particle crushing, calculated from the area of the force–displacement curve and weight of rock, was monitored online and the test was stopped once a setpoint energy level had been reached. Vertical displacement rates were chosen according to the size fraction being tested and ranged from 0.1 mm per minute for the finest fraction to 1 mm per minute for the coarsest fractions. Displacement rate setpoints were considered to be low enough to be able to claim that slow compression breakage is taking place while allowing the test regimen to be carried out in a manageable period of time.

Fig. 1. MTS piston press equipment.

Narrowly sized particles, ranging from 1.8 to 63 mm in size, were screened from sampled ore and used for compression testing. Three energy levels were applied to each size fraction resulting in 15 distinct comminution-energy test results. The sizes and energy levels tested for a copper-porphyry ore are shown below in Table 1. In order to account for mineral variations within the ore sample, a number of particles were tested separately for each size and energy combination. The products for each feed and set of test conditions were combined and sieved.

In order to extend the test method to finer size ranges, testing of multiple particles placed in one layer such that inter-particle effects are minimal was considered. Individually testing particles that are less than 12 mm in size would result in an impractical test regimen as a large number of tests would need to be carried out to generate a sufficient quantity of sample for accurate sieving. Schönert (1996) stated that multi-particle compression tests are equivalent to single-particle test conditions as long as the distance between neighboring particles is less than approximately three times the particle size. To confirm whether the assumption holds true, a comparison of energy input and breakage index t_{10}, which is the percentage of product which passes through one tenth of the original feed size, was carried out for single-layer multi-particle tests and single-particle test results. Based on the similarity in energy-breakage results, shown in Fig. 2, the multi-particle test approach was adopted for feed sizes of 12 mm and less.

The previously mentioned energy-breakage model, developed from impact breakage testing by Vogel and Peukert (2003), was adopted for modeling of the compression breakage results. The model is shown in a modified form presented by Shi and Kojovic (2007) below:

$$t_{10} = M(1 - \exp(-f_{\mathrm{mat}} \cdot x \cdot k \cdot (E_{\mathrm{cs}} - E_{\mathrm{min}}))) \tag{1}$$

where t_{10} is the percentage of product which passes through one tenth of the original feed size, M and f_{mat} are material specific parameters which are fitted to experimental results, E_{cs} is the energy in kW h/t consumed, k is the successive number of impacts and E_{min} represents the minimum energy required to overcome the yield strength of the material and achieve breakage, also referred to

Table 1
Comminution test regimen for Huckleberry ore.

Geometric mean (mm)	Upper sieve size (mm)	Lower sieve size (mm)	No. of Tests	Average energy level (kW h/t)
38.7	40.0	37.5	10	0.26
38.7	40.0	37.5	10	0.61
38.7	40.0	37.5	10	0.91
25.9	26.9	25.0	15	0.29
25.9	26.9	25.0	15	1.01
25.9	26.9	25.0	15	1.45
11.8	12.5	11.2	10*	0.41
11.8	12.5	11.2	10*	0.99
11.8	12.5	11.2	10*	1.77
4.36	4.75	4.0	15*	0.69
4.36	4.75	4.0	15*	1.44
4.36	4.75	4.0	15*	1.91
1.83	2.0	1.68	15*	0.66
1.83	2.0	1.68	15*	1.20
1.83	2.0	1.68	15*	1.38

* Tests on these size fractions were carried out using a single layer of multiple particles per test.