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The comminution energy-size reduction of the Bond Mill and its relation to Vickers Hardness

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ABSTRACT

The results of Bond Work index (BWi) tests of five materials with five closing screen size (P_1) of 63o 500 μm are documented. These are normalized to eliminate the effect of material present finer than the closing screen sizes and test sample apparent densities. Analysis of normalized test results show, with a correlation factor R^2 of 0.9956, that the revolutions required in all the Bond Work index mill tests conducted (29–419 revolutions) corresponds to a specific grinding energy per Bond Mill revolution of 0.0823 kWh/ton for a material corrected to a tapped apparent density of 1 t/m^3 and for material present finer than the closing screen size. Conversion of this value to operation of the mill for the Bond Work index test results in a value of $194 * 10^{-7}$ kWh/mill revolution.

It is demonstrated that the indicated specific grinding energy of the Bond Mill revolution is not a precise value. An exponential function with a perfect correlation is presented relating the final required number of Bond Work index test mill revolutions required with the P_1 values for sample materials tested.

A perfect correlation with an exponential relation to the evolution of the specific grinding energy with change in closing screen size is presented. This relation is interpreted as a measure of the reduction in grinding efficiency with increase in fineness of grinding.

It also shown that there is an exponential relation with a R^2 correlation factor of 0.9900 between experimental specific grinding energy of a mono-mineralogical material normalized for $< P_1$ content and apparent density to the root of its VH at a given P_1. Most if not all the deviations between the calculated specific grinding energy based on P_1 values and the sample Vickers Hardness correlates with the differences between the experimental and corrected mill revolutions applied to compensate for the $< P_1$ fines contents of the test samples.

1. Introduction

Grinding is one of the largest industrial consumers of energy. Some 4% of the total world's electrical energy consumption is consumed in the crushing and grinding of mineral ores (Energy Efficiency Exchange, 2013). Large amounts of energy are also consumed in the production of many commercial products such as cements, fillers, pigments, fritzes, cereal flours and pharmaceuticals. Being energetically very inefficient, the largest portion of this energy consumed is typically in grinding. Effectively accounting for and predicting the energy necessary to fragment a material to a given particle size has been the basis of extensive research by engineers, chemists, physicists and mathematicians into the theoretical and practical aspects of comminution and especially that of energy consumption in particle size reduction by grinding.

To date the theories of Kick (1885), von Rittinger (1987) and Bond (1952) remain the most established. The recommendations of Charles (1957) and Hukki (1962, 1975) that Kicks's is the most applicable for crushing, Bond's for ball mill grinding and von Rittinger's for fine grinding is generally accepted. Of these theories, that of von Rittinger has a theoretical basis founded on the new particle surface area generated whereas that of Kick's is based on the change in volume of particles created. That of Bond is empirical and based on very extensive laboratory test results compared to industrial grinding operations of the same materials tested in the laboratory. However, neither Kick's nor von Rittinger's theories include an established means of determining the energy requirements for grinding on an industrial scale. Only Bond's theory is widely used for effectively designing or controlling ball mill grinding circuits despite it not including a theoretical basis and underestimating energy consumption for production of particles finer than 100 μm (Hukki, 1962, 1975).

The procedure to apply Bond's law requires the laboratory determination of a Bond Work index (BWi). This laboratory procedure has been extensively described in detail by Bond (1952), Deister (1987) and Mosher and Tague (2001). It is conducted in a specified ball mill and

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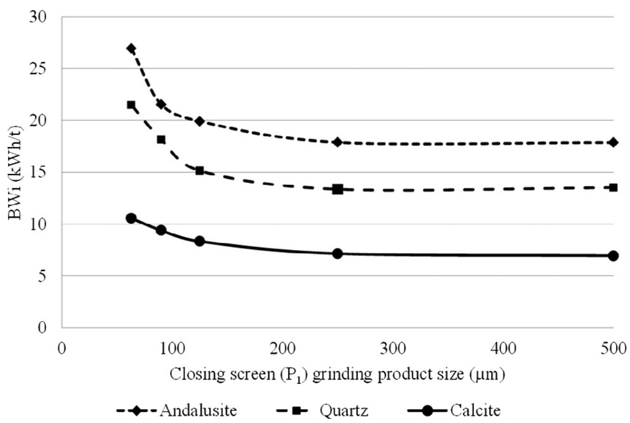

Fig. 1. Examples of the variation in BWi values with closing screen size (P_1).

grinding ball charge. The BWi is calculated using Eq. (1) based on: the cumulative 80 percentile grain undersize (F_{80}) expressed in µm of a minus 3.36 mm mill feed; the test product closing screen cumulative 80 percentile grain undersize (P_{80}) expressed in microns; and the grams per revolution (G) produced finer than the closing screen size (P_1). The test is conducted using a locked cycle with a 250% recirculating 700 cc.mill feed until the values of G produced stabilize. Bond tests at $P_1 \leq 100$ µm are common but can require wet screening of each test cycle product and frequently require more than 10 days to complete.

$$BWi(kWh/tonne) = 49.1/[P_1^{0.23} x G^{0.82} * ((10/P_{80}^{0.5}) - (10/F_{80}^{0.5}))] \quad (1)$$

Ball mills are typically used to grind materials to < 500 µm. Hukki proposed limiting Bond's law to grinding no finer than 100 µm and BWi values tend to be relatively constant for grinding products to between 500 and 200 µm. However, experience has shown that some materials (Fig. 1) have a significant increase in BWi values between 250 and 125 µm and increase exponentially for lower values.

The BWi test is a lengthy process and a certain degree of variation in results always occurs due to equipment wear as well as operator and operational errors or variations between operator and operational procedures. Results for a given sample may vary due to errors or fluctuations in: sampling; particle size analysis; determination of the test sample weight; inefficiency of screening of the mill product (especially for grinding < 250 µm); losses of mill product fines and recirculated load; effects of mill charge and liner wear; mill liner roughness; etcetera. The test grinding efficiency is also affected by variations in mill charge weight and thus the total grinding surface area available. Variations in degree of sample tapping to determine the weight of sample to be used in the BWi test has a direct proportional influence on the grams per revolution obtained. The weights of mill product fines produced for abrasive materials are also influenced as a result of contamination by iron from the mill charge and liner.

To date no rapid method has been developed to predict the energy–size reduction relation of a given material without laboratory testing. A number of different alternative theories of grinding energy to particle size relations have been proposed. Despite the complexity of Bond's test procedure, most of these are based on the use of his specified test mill and its feed specifications. Simplified or alternative methods proposed to determine a comminution work index have been proposed by a number of investigators. Examples of the diverse nature of some of the recent investigations are those of Ahmadi and Shahsavari (2009), Aksani and Sönmez (2000), Deniz and Ozdag (2003), Gharehgheshlagh (2016), Morrell (2004), Namura and Tanaka (2011), Ozkahraman (2005, 2010), and Zambrano (2002). A computer simulation model simulating the Bond grindability test based on cumulative kinetics incorporating parameters derived from batch grinding tests has been proposed by Aksani and Sonmez. Zambrano developed a general power model that predicts energy input for grinding based on a statistical analysis of energy–size reduction relationships in batch tumbling ball mills. He reported an error < 5% for von Rittinger's law, 15–20% error for Bond's law and 20–30% for Kick's law. He also reported that a lab mill behaves like an industrial-size mill. An alternative method of determining the Bond grindability and BWi was developed by Deniz and Ozdag based on material dynamic elastic parameters. Morrell proposed an alternative energy-size relationship for 100 to +0.1 mm particles to that of Bond's based on a particle size exponent that is a function of feed and product particle sizes. Unfortunately, the author did not present a value(s) for the function proposed. Nor is the proposal demonstrated to be applicable to grinding to < 100 µm. Ozkahraman showed that the BWi and the grindability index could be estimated from a materials friability value. Ahmadi and Shahsavari used first-order grinding kinetics based on results of the two Bond grinding cycle tests to develop a rapid method of determining the BWi. Namura and Tanaka presented an empirical power law between energy input and size reduction. The power applied varies according to the material ground and requires knowledge of its strength properties. Gharehgheshlagh found that a kinetic batch grinding test for 5 different grinding internals could be used to calculate the BWi with < 2.60% error. He also observed that the mill product d_{80} is a function of P_1.

This investigation reports the results of BWi tests of five materials of diverse physical characteristics conducted with the objective of determining if the use of corrections for variations in sample characteristics could be applied to determine the equivalent energy consumed per Bond Mill revolution. Vickers hardness tests of the samples were also conducted to determine the extent to which the grams of fines produced at a given closing screen size as a function of the materials hardness values. The determination of the specific grinding energy of the Bond Mill in tests where a complete Bond Work index test may not be practical has potential applications in some instance. This is especially so in the cases of tests where fineness of the grinding to be achieved does not permit effective preparation of recirculated material, the presence of materials extremely resistant to grinding such as metals in slags, time requirements, open circuit grinding, etcetera. Comparative grinding testing methods such as proposed by Berry (1966) to determine the energy consumption for fine materials such as plant middlings and tailings, as well as most commercial products require the use of a reference material with a similar particle size distribution and grinding characteristics. Reference samples with a suitable particle size distribution may not be available. Furthermore, reference samples of ores composed of minerals with large variations in resistance to grinding can be especially difficult to identify. Magdalinović et al. (2011) observed that there might be a material constant which characterises mineral resources grindability. Gent et al. (2012a,b) observed from their BWi tests in addition to published data that there appeared to be a significant polynomial correlation between BWi and Vickers Hardness (VH) values. This relation was interpreted to be due to VH values and BWi values being related to the plasticity of materials and thus their fracture toughness but did not consider whether or not the VH of a material influenced the increase in BWi values with increase in the degree of particle size reduction.

2. Theory

Grinding energy requirements for a given material decrease with abundance of fissures, stress planes or inclusions. As breakage tends to occur at the interface between crystals when particle sizes are greater than the size of crystals composing them and the adherent energy is usually lower than the coherent energy required when the crystal themselves are broken, less energy is required to separate crystals than to break them (Hukki, 1962 and Ozkahraman, 2010). The maximum energy requirement for a particle size reduction occurs when the particles to be fragmented consist of liberated grains (typically individual crystals). It is to be anticipated that BWi values should increase as the degree of grinding fineness and proportion of liberated grain particles