Bond standard test alternative procedures

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grindability comminution Bond work index

1. Introduction

Determining the Bond index using the Fred Bond method [1][2] is considered the state-of-the-art methodology for mill calculations and a critical process parameter in raw materials selection and grinding process control. Although it is usually referred to as a standard test, no ISO (International Organization for Standardization) or ASTM (American Society for Testing and Materials) standard procedure has been established, so the primary reference used worldwide to define the procedure is the original proposal from Bond. Despite this, the knowledge of the Bond standard test is enriched continuously with new research, as is the case of the recently published work by García et al. [3], which presents a deep analysis of the test procedure and evidences the importance of the grindability index (proposing it to be renamed as the Maxson index), or the recent proposal by Nikolić and Trumić [4], which represent a new approach for determination Bond work index on finer samples.

Alternative tests soon arose after Bond's proposal to avoid the need for the standard mill and time-consuming procedure. Therefore, papers dealing with this problem are numerous, aiming to discuss the validity of simpler and quicker methods to determine the Bond work index (w i). Some of them use the standard mill, while others use a non-standard mill or are based on computation techniques. It is worthy to mention the development of other approaches to grindability evaluation based on impact breakage tests. The drop weight test has proven its validity and scaling-up possibilities under certain conditions [5][6][7].

There are not many review papers describing alternative methods of ball mill w i determination. The work of Lvov and Chitalov [8] is probably the most recent one, and it performs a sound analysis of several alternative methodologies.

2. Alternative Procedures to the Bond Ball Mill Standard Test

Berry and Bruce [9] introduced the first alternative procedure to the Bond standard test. The procedure is based on determining the grindability of an unknown ore by comparing it to the grindability behaviour of a reference ore. It can be performed in any laboratory ball mill, but it requires a reference sample ore for which w_i is known. In the Berry and Bruce procedure, 2 kg weight samples of the reference and unknown ores with a particle size under 1.651 mm are wet ground in a laboratory ball mill that is 305 mm in diameter, using active power monitoring.

Differences in sample densities and PSD affect the density and rheological characteristics of the pulp when performing the test wet way. Moreover, it has been proven that w_i is not a constant value for each ore, so the reference sample value would only be valid within a specific grinding size range [3][10]. The main advantage of this procedure is that it is fast and does not require Bond's standard ball mill, but accurate power measurements are needed, and the use of a reference ore as if w_i had a constant value is also a source of inaccuracy.

Smith and Lee [11] determined the Bond work index in a standard mill for eight different materials at different openings of a comparative sieve according to the standard Bond test. They compared the data obtained by the standard Bond test and the data from the open-circuit grinding, i.e., the first grinding cycle of the standard Bond test. The tests showed that the parameter Gz [g/rev] of the last grinding cycle of the standard Bond test and the parameter G0 of the open-circuit grinding under the same conditions are in a direct correlation G0=f(Gz).

A correlation that is established in this way is valid only for the materials on which it is determined. For other materials, it is necessary to establish a new correlation relationship, which requires a Bond mill and sample preparation conducted in the same way as the standard Bond test. A lot of work and grinding cycles are needed to determine the correlation Gz=K·G0. The Bond work index is estimated based on one grinding cycle performed in the standard mill . The Smith–Lee results showed that the differences from the standard Bond test and the wi,SL values do not exceed 15%. Probably one of the main shortcomings of this methodology is the influence of feed particle size on the initial cycles, which could be the main source of deviation.

Karra [12] developed a mathematical algorithm for simulating the Bond test based on the first two grinding cycles from the standard test. It can be considered a modified procedure of the one proposed by Kapur [13]. He considered that the circulating load in the standard Bond test has lower grindability and shows slower grinding behaviour. The Bond test is simulated until a circulating load of 250% is established. The value G (g/rev) is obtained from the last simulated grinding cycle, but P80 (μm) cannot be estimated. Therefore, in this procedure, the Bond formula cannot be used to calculate the work index, but the empirical formula obtained by statistical data processing can be used.

Mwanga et al. [14] developed a Geometallurgical Comminution Test (GCT) that requires a small amount of initial sample and a jar mill (Capco, Ipswich, UK). The grinding test is performed on a sample under 3.35 mm with a starting weight of 220 g and can be performed within 2–3 h. The sample is ground while dry for 2, 5, 10, 17, and 25 min. After each grinding time, the PSD is determined by sieving, and the sample is returned to the mill for further grinding. P_{80} is obtained from the PSD, and the power consumption is measured during the test. When the test is performed at a constant sample mass and mill parameters (number of revolutions, grinding batch), it can be assumed that the energy supplied to the mill per unit time is constant.

Lewis et al. [15] developed a new method of grinding testing based on computer simulation, closely related to the standard Bond method. The simulation is based on a mathematical algorithm that simulates a standard Bond test and is divided into two parts. The first part uses experimental data from the first grinding cycle to obtain the initial parameters of the model. The calculated parameters and raw material characteristics are stored in a database to be used in the second part of the simulation for prediction purposes. The prediction method simulates a standard test. For each grinding cycle, all raw material that is smaller than the opening of the comparative sieve is replaced by a representative mass of the starting sample. The calculation continues using the parameter values set for a given grinding cycle. Four grinding cycles are calculated automatically. A check is performed during the fourth and any subsequent grinding cycles to assess whether the newly formed undersize mass per mill revolution G (g/rev) is constant (within 3%) for the last three grinding cycles. If G (g/rev) is constant, a steady state is reached; otherwise, the computer procedure continues with the next grinding cycle. When a steady state is reached, the Bond work index is calculated using Equation (32). The mean square relative difference between the values of the Bond work index obtained by the standard method and the values obtained by computer simulation is 2.81%.

Gharehgheshlagh [16] presented a method for calculating the Bond work index that tracks the grinding kinetics in a Bond ball mill. The method is fast and practical because it establishes a relationship between the grinding parameters and the parameters of the Bond equation and eliminates specific steps of the laboratory test due to the reduction of the grinding cycle. The test is performed by grinding 700 cm3 of a sample 100% under 3.35 mm in a Bond ball mill for 0.33, 1, 2, 4, and 8 min. After each grinding cycle, the grinding product PSD is determined and returned to the mill for the subsequent grinding cycle. This grinding kinetics analysis is used to determine the functional dependence between the number of mill revolutions and undersize mass passing P100 (mus) as well as the relationship between the number of mill revolutions and P80 (µm) using the least-squares numerical method. The first function determines the number of mill revolutions N250% (revolutions) required to obtain the under-size mass, such that the circulating load is 250%. Based on the values of N250% (revolutions) and the determined functional dependencies, the parameters G (g/rev) and P80 (µm) are estimated, and Equation (32) can be used to estimate the work index. The mean square relative error between the real and estimated wi was 1.23%.

3. Conclusions

Alternative abbreviated and simplified procedures for determining the work index have been proposed through the years.

- Alternative tests that simulate the standard Bond test with an abbreviated procedure;
- Alternative tests based on determining problem sample grindability using a reference sample with wi known.

Alternative tests from the first group are based on the use of a Bond standard ball mill for the reach the steady-state more quickly [28,29,30] or for performing the mathematical simulation of the standard test [13,14,21,22,27]. Alternative tests from the second group can be performed in a different mill, usually needing less sample than the standard procedure. All of the methods aim to give a close estimation of the Bond work index when the standard Bond ball mill is not available and are faster procedures with a reduced number of grinding steps. The longest alternative test requires 3–4 grinding cycles, while the shortest one can be performed with one grinding cycle. It must be considered that the standard procedure compels a minimum of 5 grinding cycles, with 7–10 grinding cycles usually being necessary.

In general, the mean square error data presented cannot be understood as a validity indicator, for in some cases, the reported value was based on just a few tests or with few ores. However, these data indicate that shorter procedures (i.e., with just one grinding cycle) are usually less reliable, yielding a higher mean square error. Nevertheless, due to the advantage in laboratory time, they could be recommended if ore feed is the same, which could be the case of the periodic grindability control in a specific mine.

Finally, after an adequate grinding kinetic behaviour characterisation of the ore, alternative tests based on the simulation of the standard Bond test could be recommended when considering the process digitalisation as part of the global digitalisation strategy in the mining industry.

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