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Grindability of binary ore blends in ball mills

Luís Marcelo Tavares [a,*], Raquel D.C. Kallemback [a,b]

[a] Department of Metallurgical and Materials Engineering, Universidade Federal do Rio de Janeiro – COPPE/UFRJ, Rio de Janeiro, RJ, Brazil
[b] Vale S.A., Porto de Tubrarão, Vitória, ES, Brazil

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ABSTRACT

The understanding of how blends of materials grind is of great relevance in both the minerals and the cement industries. If benefits and challenges associated to it are properly understood, then decisions can be made on blending prior to grinding or grinding additives in separate during cement production, as well as different ores fed to mills in a processing plant. The paper investigates the size reduction of blends of materials with different grindabilities in a Bond ball mill, as well as in a continuous pilot-scale mill. The accumulation of the harder (tougher) component in the mill charge as grinding progresses is analyzed and a simple empirical model that describes this phenomenon has been proposed. It is found that the accumulation of hard component in the mill increases with the decrease in the ratio of Bond work index values of the individual soft and hard components, and with the increase in the circulating load ratio. It is also concluded that the Bond work index of the mixtures is often higher than the weighed-average value of the individual components in the mixture. As such, an expression is proposed for calculating the value for blends based on this modeled accumulation effect and has been found to remove the bias from predictions made on the basis of the weighed-average values from the feed.

1. Introduction

The understanding of how blends of materials grind is of importance in different areas. In cement grinding, size reduction of clinker and additives can be done separately or together. The later, called intergrinding, is beneficial because mills allow not only the size reduction but also the mixture of the components, simplifying the plant flowsheet (Öner, 2000). On the downside, this often leads to an increase in energy demand and in differential grinding of the components, which could have a negative impact on cement usage, since the harder components that are ground to coarser sizes may not react as readily with water during cement curing.

In the minerals industry, it is of relevance to understand how mills will respond to blends of ores with different grindabilities coming from different parts of the deposit. If blending does not prove to be beneficial from the standpoint of energy consumption, it may be possible to feed ores to parallel lines or different plants, whenever available. Further, it is relevant to understand how mineralogical components of different hardness (although 'toughness' would be the most accurate term from a material science standpoint) respond to milling after their liberation has been reached, since their differential grinding response can lead to non-optimal particle sizes in the flotation feed and to increases in slimes generation (Malghan, 1986).

A number of papers have addressed different aspects of the problem, often demonstrating that neither grindability nor the Bond work index obey the simple rule of mixtures (Hosten and Avsar, 1998; Yan and Eaton, 1994; Iglesias et al., 1999; Öner, 2000; Ipek et al., 2005). For instance, Öner (2000) demonstrated that the grindability resulting from mixtures of clinker and blast furnace slag is systematically lower than the weighed-averaged values for the individual components. He also observed that the tougher material (slag) appears in the product with a coarser size distribution than the clinker. Hosten and Avsar (1998) also demonstrated that the Bond ball mill work index of the mixture of clinker and trass is not the weighed-averaged values of the individual components. Indeed, they showed that the work index of the mixtures can be even higher than that of the hardest component. Similar results were found by Iglesias et al. (1999), who demonstrated that small additions of gypsum in a mixture with cement clinker resulted in nearly constant values of work index, in spite of the significantly lower Bond work index values of the gypsum samples. Similar results have been found by a number of researchers, as is illustrated in Fig. 1. Data in the figure has been plotted as a function of the relative Bond ball mill work index of the blend, defined as

$$\text{Relative} \quad BWi_{blend} = \frac{BWi_{blend} - BWi_{soft}}{BWi_{hard} - BWi_{soft}} \tag{1}$$

Yan and Eaton (1994) attributed the higher values of Bond work index of the mixtures in comparison to the weighed-averaged values to the fact that there is often an accumulation of hard

* Corresponding author. Tel.: +55 (21)2562 8538.
E-mail address: tavares@ufrj.br (L.M. Tavares).

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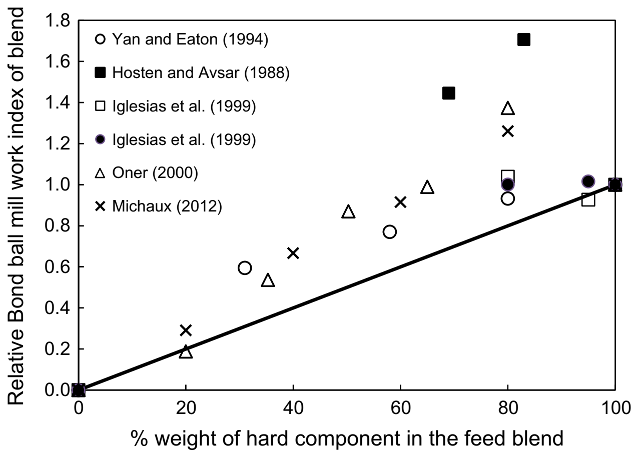

Fig. 1. Variation of the relative Bond ball mill work index of blends as a function of the proportion of hard component in the feed. Line represents the weighed-average values. (See above-mentioned references for further information.)

component in the mill hold-up. Unfortunately, this degree of accumulation is seldom estimated experimentally. Indeed, Fuerstenau and Venkataraman (1988) demonstrated, from a locked-cycled test, that quartz, the hardest component in a binary mixture with calcite, accumulates in the mill as grinding progresses. This accumulation was found to be relatively slow, requiring up to 24 2-min cycles in order to reach equilibrium. They also demonstrated that the breakage rates of individual components were independent of time, but varied with the composition of the mill hold up in each cycle. These findings suggest that a significant part of the literature on grinding of mixtures in mills operating in batch mode is of relatively little relevance to explain what happens in industrial ball mills, which nearly always operate in closed circuit, and will experience an accumulation of the harder component in the charge. It also suggests that simplified methods of measuring the Bond work index, such as the one proposed by Magdalinovic (1989), and that are based on the use of data from batch grinding tests, can lead to unrealistic results when dealing with ores that have components with significantly different grindabilities.

In spite of the important developments in recent decades with improved characterization, modeling and simulation approaches applied to ball mills (Austin et al., 1984; Herbst and Fuerstenau, 1980; Tavares and Carvalho, 2009), the Bond ball mill grindability test retains a significant part of its original importance as a convenient and inexpensive method to assess the response of materials to grinding in tumbling ball mills.

The present paper analyzes the Bond ball mill work index of binary ore mixtures, investigating the accumulation of the hard component in the mill, as well as the different size distributions of the components in the product.

2. Experimental

Samples of six rocks, four of which limestones, from deposits located in Brazil have been collected. They have been prepared for testing by stage crushing, followed by removal of the material finer than 300 μm by screening. Specific gravity of the samples has been determined by pycnometry and a summary of the results is shown in Table 1. It shows that grindabilities as well as single-particle breakage strengths varied significantly for the samples, represented by wide ranging values for both the Bond Work index and $A*b$ values that characterize single-particle breakage by impact.

The Bond ball mill work index of each sample was measured using the standard equipment and procedure (Bergstrom, 1985) using a constant closing sieve of 300 μm. In all tests, material passing the closing sieve was removed from the feed, in an attempt to limit the influence of variations in feed size distribution in the test. Experiments involving mixtures were conducted by first preparing individual longitudinal piles of components that constitute each binary mixture, followed by adding to the mill quartered quantities of each material corresponding to additions of 25%, 50% and 75% in volume (bulk). The Bond work index (BWi, in kW h/t) was calculated using the expression (Bergstrom, 1985)

$$BWi = \frac{1.1 * 4.45}{Am^{0.23} G_{bp}^{0.82} \left(1/\sqrt{P_{80}} - 1/\sqrt{F_{80}}\right)} \qquad (2)$$

where Am is the screen opening used in the test, G_{bp} is the net grams per revolution of the mill in steady-state conditions, F_{80} is the feed 80% passing size, while P_{80} is the 80% passing size of the product of the final locked-cycle. Selected tests were conducted in duplicate and only the averages of the measurements, which had deviations smaller than 1 kW h/t, are reported.

The composition of the hold up and final product from the tests with blends involving mixtures with basalt and copper ore has been analyzed by partially dissolving the limestone phase, leaving an insoluble residue, from which the basalt and copper ore contents were estimated. Details on the experimental procedure used in the analyses, conducted in duplicate, can be found elsewhere (Kallemback, 2012).

Additional tests were conducted with a pilot scale mill working both in open circuit and in closed circuit with an air classifier, and a complete description of the testwork may be found elsewhere (Kallemback, 2012).

Table 1
Summary of the characteristics of the samples.

Sample	Specific gravity (g/cm^3)	$A*b$	F_{80} (μm)	F_{20} (μm)	BWi (kW h/t)
Limestone #1	2.65	61.8	2460	915	9.05
Limestone #2	2.72	609.8	2390	410	6.28
Limestone #3	2.98	Na	2500	640	7.38
Limestone #4	2.88	64.2	2710	1055	6.13
Basalt	3.03	37.2[a]	2610	1265	13.78
Copper ore	3.39	34.2	2730	1090	20.42

Na: not available.
[a] Estimated from testing particle contained in size range 22.4 × 19.0 mm and applying the correction equation proposed by Tavares and Silveira (2008).

3. Results and discussion

3.1. Product size distributions

Upon conclusion of each Bond ball mill grindability test, products have been analyzed in respect to size distribution and composition. Fig. 2 summarizes results from these analyzes for each individual component in a blend of basalt and limestone #1. It suggests that the product size distribution of the hard component (basalt) did not vary if it was ground together or separately from limestone, whereas limestone became only marginally finer in the presence of basalt.

3.2. Accumulation of hard component in the mill

In order to investigate the accumulation of the hard component in the mill hold-up, its proportion in the passing product from each locked-cycle period was measured during standard Bond grindability tests of artificial blends and typical results are shown in Fig. 3. It is evident that the basalt content of the fine product that leaves the mill is initially lower than in the feed, since it is enriched with the