Development of ball mill test for simulation of industrial circuit

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Abstract

The Bond method for ball mil designing has been used for 60 years. Based on the Work Index test, such method is applied mostly in traditional circuit configuration, which includes multi-staged crushing, followed by rod and ball milling. On the other hand, simulation is a widespread and used technique for comminution, classification modeling, and simulation. Even though both methods are complementary, there is no effective integration between them. This work shows a technique designed to integrate both energy and modeling approaches for estimating and improving ball mill grinding performance. The work is based on industrial data survey results, as well as on laboratory testing, the latter developed specifically for such a purpose. The technique was validated under an industrial environment for assessing the obtained results.

keywords: grinding; modeling; simulation.

1. Introduction

The main method used for designing ball mills was proposed by Bond (1952). Despite the wide application in traditional comminution circuits, this method shows limitations for its application.

Due to the limitations of the Bond method for designing industrial grinding circuits, simulation using phenomenological mathematical models has been increasingly used for projects destined to design and to improve the ball mill performance. The simulation method also allows assessing the integrated performance of comminution circuits. By determining the interaction among different circuit units, simulation is widely used for enhancing performances, as well as carrying out full circuit mass balances, which is not possible with the Bond method.

The Perfect Mixing Model (PMM) as proposed by Whiten (1976) is a widespread method for grinding modelling and simulation. It followed the Population Balance Model (PBM) developed by Epstein (1947). PMM is based on a steady-state balance among particle size fractions within the mill load, the latter considered as perfectly mixed.

Even though very flexible, PMM depends upon retro-fitting for creating realistic simulation scenarios. The situation is particularly difficult in greenfield projects where virtually no specific data is available. In this case, a pilot plant may be an option, even though it normally requires a relatively large number of ore samples, which may not be available. Moreover, a scale-up procedure has to be established for predicting industrial ball mill performance as compared with corresponding pilot plant units. In such circumstances, bench scale testing significantly reduces the amount of required material for testing but does not solve the scale-up limitation.

This study aimed at developing a method from a laboratory grinding test that allows direct usage of mathematical modelling and simulation with no scale-up procedures to estimate and to improve the performance of industrial ball milling circuits.

2. Method and materials

Three different industrial grinding circuits were surveyed for developing the present method. The first included a traditional multi-staged crushing circuit followed by ball milling at Mineração Serra Grande (MSG). The second was comprised of multi-staged crushing, followed by rod milling and ball milling at VALE Fertilizantes – Araxá (VALE), while the third involved semi-autogenous grinding (SAG) milling, followed by ball milling at Mineração Mirabela (Mirabela).

In each case, the corresponding industrial grinding circuit was surveyed for obtaining size distributions and percent of solids in individual streams, as well as operating data and ore characterization indices. Based on such data, full mass balancing was carried out for obtaining consistent flowrates and size distributions around the circuit.

Samples obtained in survey campaigns were then used to perform bench-scale grinding tests. The sample preparation started with staged crushing and screening to obtain a -3.35 mm (6# Tyler) product. It was followed by homogenization and quartering procedures. Head samples were used for determining size distribution and specific gravity, the former by wet screening and the latter by pycnometry.

The mill used for carrying out the grinding tests was assembled with 1020 carbon steel, diameter and length equal to 254 mm (10"). Tests were conducted at 70% solids and 33% ball load, according to three different ball top sizes, as well as three different mill rotation speeds. Tests included mill shells with lifters and a smooth one. Table 1 shows the operating conditions for each grinding test performed.

Variable	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6
Ball mill type	Lifters	Lifters	Lifters	Lifters	Lifters	Non-lifters
% Critical speed	72	75	69	72	72	72
Ball top size (mm)	38	38	38	30	25	38

Table 1
Laboratory tests
grinding ball mill operating conditions.

Samples obtained in each one of the three surveys were used for six bench-scale tests, undergoing different operations as described in Table 1. In each case the individual test included three grinding periods ie. 15, 30 and 45 minutes, summing up 54 tests. Figure 1 illustrates the procedures adopted for grind tests.

Figure 1
Test grinding ball mill
sequential procedure.

Testing results were used to calibrate the PMM, according to different operating conditions. Simulations were then carried out for predicting the respective industrial grinding circuit based on the corresponding test. In this case the simulations took into account grinding circuit fresh feed and product, the latter being comprised of hydrocyclone overflow.

Additional studies were conducted for adapting both industrial feed size distributions and ball top size to bench-scale tests, the latter included the procedures developed by Morrell and Man (1997).

The results were also compared to the specific energy requirement by using the kWh/t$_{\#}$ index, which represents the energy required to generate mass (t) at specific size (mesh). Bench-scale mill power was estimated by Morrell model (Morrell, 1996a, 1996b).

Table 2 shows ball top sizes for surveyed industrial circuits, as well as respective ball mill power that was measured during the sampling period, as compared with bench-scale tests.

Variable	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	MSG	VALE	Mirabela
Power (kW)	0,0808	0,085	0,0767	0,0808	0,0808	0,0808	936	2.765	11.447
Ball top size (mm)	38	38	38	30	25	38	60	60	63

Table 2
Power and ball top size.

Figure 2 shows a detailed flowchart for procedures adopted throughout the described testing.
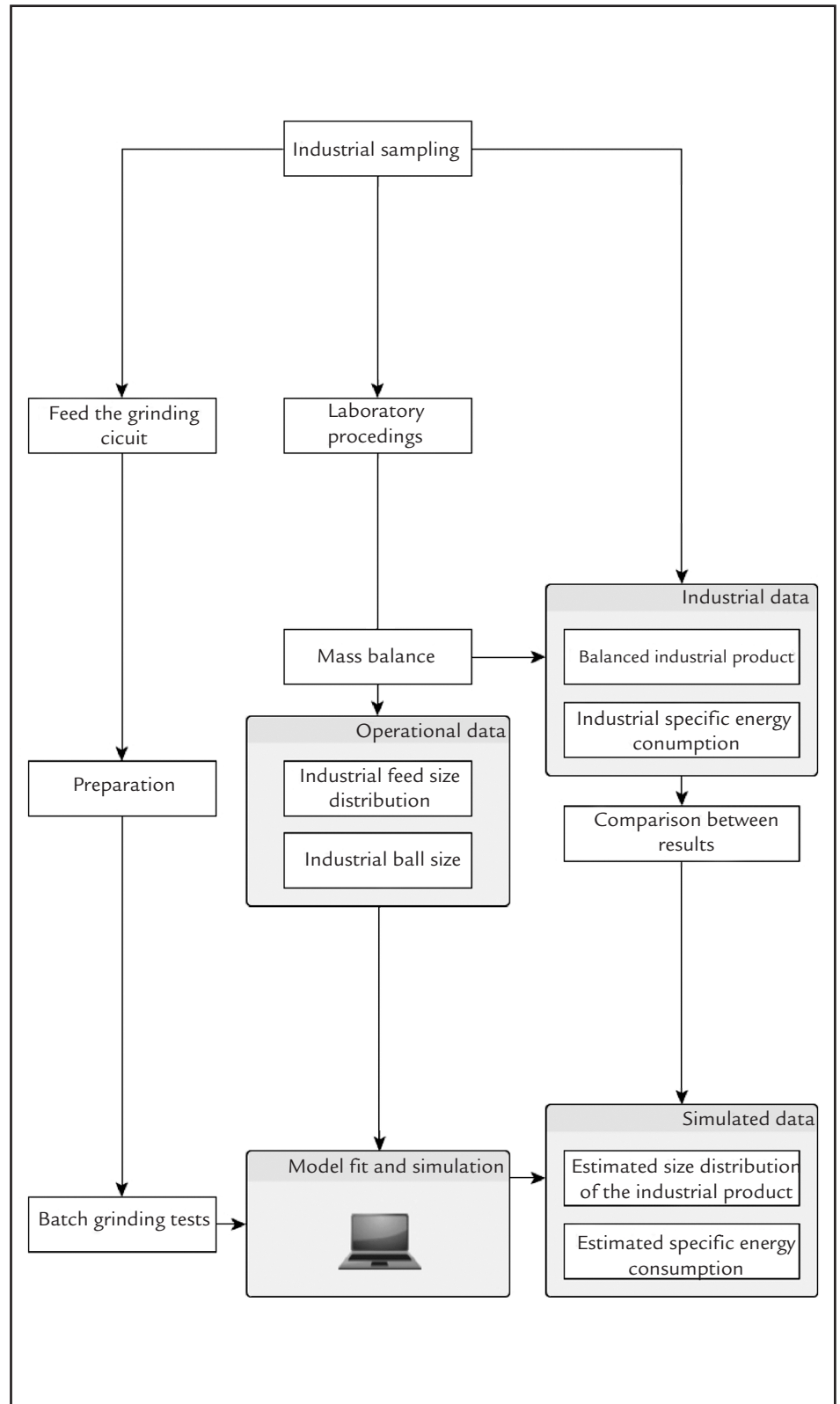

Figure 2
Sequential activities flowchart.

3. Results

Bench-scale tests carried out with all MSG, VALE and Mirabela samples indicated that the 15-minute grinding period was the most adequate for predicting the respective product size distributions (hydrocyclone overflow).

Prediction of industrial circuit product size distribution

Figure 3 shows graphs for comparing simulated and bench-scale testing particle size distributions.
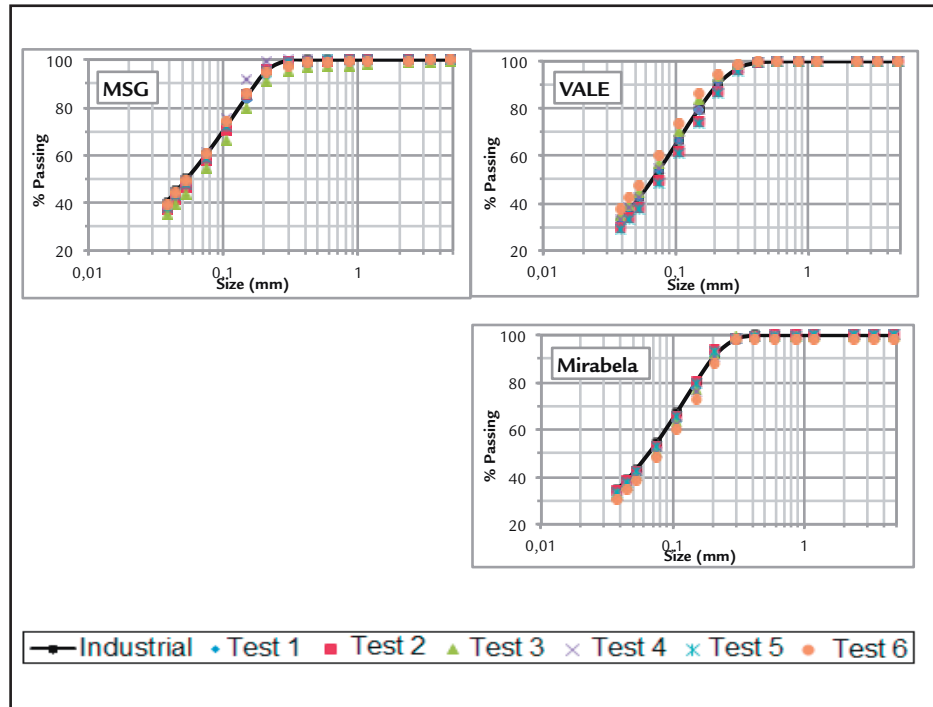

Figure 3
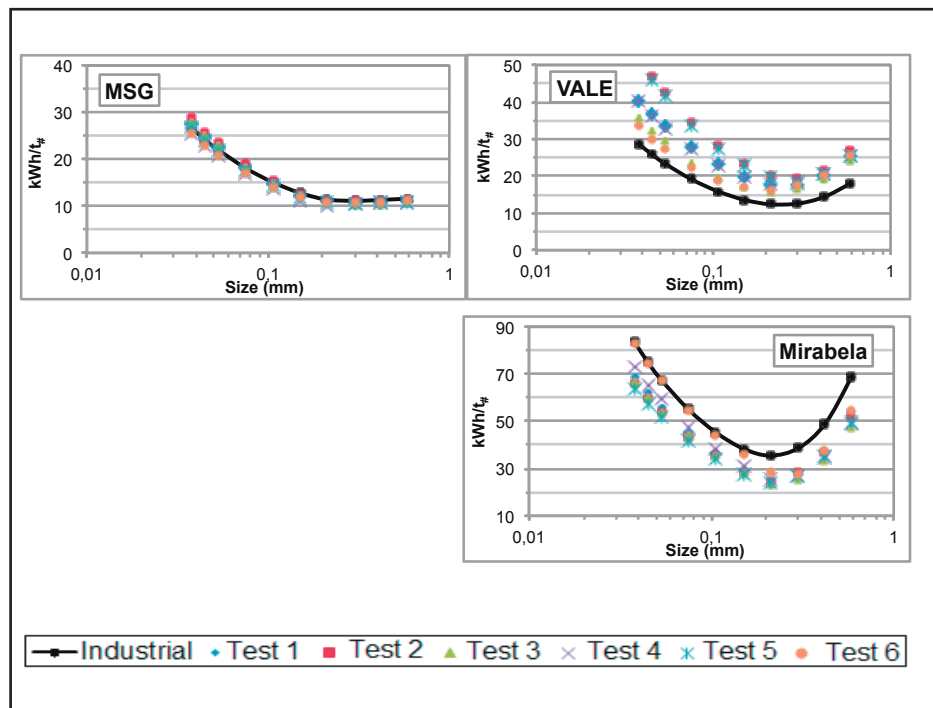Comparing simulated and bench-scale testing particle size distributions.

Figure 4
Comparing simulated and bench-scale specific energy predictions.

4. Discussion

Dissimilarity matrices were used to analyse obtained results, according to which Euclidian distances between simulated and bench-scale results were calculated for all three studied industrial circuits. The index represents the square root of the sum of differences among the values to be compared, ie. size distributions and specific energy consumption at a specific size fraction.

Table 3 shows dissimilarity matrices with respective Euclidian distances comparing simulated and bench-scale testing particle size distributions.

Industrial Circuit	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6
MSG	10,0	6,57	16,5	8,42	4,39	3,98
VALE	2,12	11,3	7,63	1,16	13,1	15,3
Mirabela	7,87	3,24	7,42	8,87	3,18	15,5
Total	20,0	21,1	31,5	18,4	20,7	34,8

Table 3
Dissimilarity matrix with
Euclidian distances – Size distribution.

Table 3 indicates that Test 4 showed the best estimations for size distributions, with 18.4 total Euclidian distance, whereas Test 6 showed the worst estimation, the latter with 34.8 total Euclidian distance. Tests 1, 2 and 5 also showed good estimates, as indicated by total Euclidian distances of 20.0; 21.1 and 20.7 respectively.

Mill rotating speed, ball top size and lifter aspects were also used for comparing size distribution test results. Test 1 indicated that 72% of the critical speed resulted in the best results, while Test 4 indicated that 30 mm ball top size resulted in the best results for such an aspect. Tests with charge lifters resulted in better results when compared with corresponding tests with a smooth mill shell.

Therefore, the best combination for predicting size distributions included bench-scale testing at 72% critical speed, 30 mm optimum ball size and mill shell provided with lifters.

Table 4 shows a dissimilarity matrix with comparative Euclidian distances between specific energy consumption estimated by simulated and bench-scale testing.

Industrial Circuit	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6
MSG	1,74	3,27	2,43	3,85	1,96	3,02
VALE	25,7	45,6	16,5	25,1	43,1	14,9
Mirabela	36,7	41,7	45,2	35,2	47,0	22,5
Total	64,1	90,5	64,2	64,1	92,0	40,4

Table 4
Dissimilarity matrix with Euclidian
distances – Specific energy consumption.

Table 4 indicates that Test 6 showed the best results, with a total Euclidian distance of 40.4.

Here too, the specific energy consumption estimative was separately investigated for the optimum ball size, mill rotating speed and lifted/smooth mill shell.

Tests 1 and 3 indicated that 72% and 69% of the critical speed resulted in best results, as well as Tests 1 and 4 indicated that 38 mm and 30 mm optimum ball size resulted in the best results for such an aspect. Test with no charge lifters resulted in better results when compared with corresponding tests with a smooth mill shell.

Therefore, the best combination for predicting specific energy included bench-scale testing at 72% critical speed, 30 mm optimum ball size and mill shell with no lifters.

5. Method Developed

As described in the previous section, Tests 4 and 6 were selected for predicting respectively particle size distribution and specific energy consumption. However, a more robust approach would include single test conditions for industrial ball milling performance predictions. In this regard, Test 6 was the selected one.

Standard conditions thus include approximately 3 kg of the ore for testing. Initial preparation consists in staged crushing in a roll crusher and screening, for obtaining a -3.35 mm (6# Tyler) product. The test should be conducted on a 10" in length and diameter 1020 steel carbon mill shell at 70% solids, 33% load fraction, 72% critical speed and 38 mm optimum ball size. Grinding time is set at 15 minutes.

The resulting feed and product size distributions are used to calibrate the PMM by varying optimum ball size. Actual fresh feed should be used in the calibrated model for simulating the calibrated industrial ball mill model and should include product simulation to provide an estimation of the industrial product. Specific energy consumption is based on simulation results, as well as on the power model.

6. Conclusions

Based on bench-scale tests, a method for predicting industrial ball milling was developed. The model was based on three different industrial grinding operations including traditional multi-staged crushing followed by ball milling, traditional multi-staged crushing followed by rod milling and ball milling, as well as SAG and ball milling circuit configuration.

Based on bench-scale standard testing, the PMM is calibrated for representing selected test conditions. Such model is also calibrated for predicting industrial ball milling performance in terms of both product size distribution and specific energy consumption. Although the specific energy consumption estimated by batch grinding tests was significantly different for VALE (traditional multi-staged crushing followed by rod milling and ball milling) and Mirabela (SAG and ball milling circuit), detailed investigation is being conducted to better understand this question.

7. Acknowledgements

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