Vertical mill simulation applied to iron ores

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A B S T R A C T

The application of vertical mills in regrind circuits is consolidated. This type of mill is now attracting interest in primary grinding applications, due to its higher efficiency when compared to ball mills, which are usually used at this stage. In this study, a coarse sample of iron ore was tested in a pilot scale grinding circuit with a vertical mill. Other three samples of pellet feed had already been tested with the methodology used in this study. The sample of coarse iron ore was characterized in laboratory tests carried out in a small batch ball mill. Selection and breakage function parameters were determined from the laboratory tests. The parameters were then used for simulating the pilot scale tests using Modsim™ software. The model previously implemented in Modsim™ has been successfully applied to represent the vertical mill operated with different ores. The simulations produced particle size distributions that were very close to the actual size distributions, and the predictions were accomplished only by imputing the calibrated parameters from the batch tests, the power draw and the feed size distribution of the pilot tests. The methodology is therefore useful for scale-up and simulation of vertical mills, only requiring laboratory tests that can be carried out in standard laboratory batch mills with small amounts of samples.

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1. Background

The vertical mill was invented in Japan in the 1950s by the Tower Mill Kubota Corporation for applications in fine and ultrafine grinding and was the first vertical mill used in the mining industry [1]. Fig. 1 shows a vertical mill, also called tower mill. The vertical mill is basically composed of a cylinder with an internal screw that promotes the movement of the grinding media and slurry. This movement is provided by a motor installed on the top of the cylinder and connected to the screw via a gear unit. A separator tank directs part of the material exiting the mill via a recirculation pump. The latest Vertimill™ designs, mainly for fine grinding applications, do not include...
the recirculation pump [3]. In this case, the vertical mill is fed through the bottom and the product is overflowed from the top of the mill without a separating tank. Vale S.A. has investigated the use of vertical mills for fine grinding and also for coarse grinding to replace ball mills in new projects or increase the grinding capacity in existing operations.

2. Grinding modelling

The population balance modelling technique has been used to model biological populations in the early 1960s [4] and later it was formulated for chemical engineering purposes [5]. Currently this tool is used to describe and control a wide range of processes such as agglomeration, flocculation, crystallization and polymerization [4]. Eq. (1) represents the population balance model equation for batch grinding [6]

\[
\frac{d m_i(t)}{dt} = -S_i m_i(t) + \sum_{j=1}^{i-1} b_{ij} S_j m_j(t)
\]

where \(m_i(t)\) is the mass fraction of particles contained in size class \(i\) after grinding time \(t\); \(S_i\) represents the specific rate of breakage of particles in size class \(i\) and \(b_{ij}\) represents the size distribution produced by a single impact breakage event of a particle of size \(j\).

The breakage function model is given in Eq. (2) [6]. \(B_{ij}\) is the cumulative breakage function and the parameters \(\phi, \gamma, \beta\) are ore dependent.

\[
B_{ij} = \phi \left( \frac{x_{i-1}}{x_j} \right)^\gamma + (1 - \phi) \left( \frac{x_{i-1}}{x_j} \right)^\beta
\]  

The selection function for each size class, \(S_i\), presents a proportionality relationship with the power consumed by the grinding action according to Eq. (3) [7,8].

\[
S_i = S_i^c \left( \frac{P}{H} \right)
\]

\(S_i\) is the selection function for each size class \(i\) (h⁻¹), \(S_i^c\) is the energy specific selection function (t/kWh), \(H\) is mill holdup (t) and \(P\) is the net grinding power (kW).

The energy specific selection function \(S_i^c\) is independent of the mill dimensions and may be modelled using Eq. (4) [9].

\[
S_i^c = S_1^c \exp \left\{ \zeta_1 \ln \left( \frac{d_i}{d_1} \right) + \zeta_2 \left[ \ln \left( \frac{d_i}{d_1} \right) \right]^2 \right\}
\]  

\(S_1^c, \zeta_1, \zeta_2\) are characteristic parameters of the material and the grinding conditions and \((d_i/d_1)\) is the dimensionless particle size (normalized at \(d_1 = 1\) mm).

For vertical mill simulations the parameter \(S_1^c\), which is measured from tests carried out in tumbling tube ball mills, is multiplied by a factor \(k\) to represent the highest efficiency of this vertical mills, becoming \(S_1^c\) as shown in Eq. (5).

\[
S_i^c = S_1^c \exp \left\{ \zeta_1 \ln \left( \frac{d_i}{d_1} \right) + \zeta_2 \left[ \ln \left( \frac{d_i}{d_1} \right) \right]^2 \right\}
\]

Eq. (5) is used to describe the selection function of a vertical mill of any scale, pilot or industrial [10]. Three samples of iron ore (pellet feed), here named samples A, B and C, were tested in a pilot vertical mill. The samples were also characterized in order to generate parameters for Eqs. (4) and (5). The simulations predictions (product size distributions) were satisfactory for the three samples studied when a scaling factor \(k = 1.35\) is used. All other parameters were either measured in the plant or measured in the lab (ore characterization).

The objective of this work is to verify whether factor \(k\), adopted in previous studies, is applicable for the simulation of a fourth sample (sample D) pilot test. Sample D is considerably coarser in comparison with the three samples tested before (A, B and C). All samples are compared with regard to their selection and breakage functions.

3. Experimental

3.1. Pilot test

Four different samples of iron ore were tested in a pilot-scale grinding circuit with a vertical mill (Metso) and a high frequency screen (Derrick). The tests were performed using a
direct circuit configuration. The closing screen opening was selected according to the desired product specification. The vertical mill was operated at a constant screw speed of 87 rpm.

Fig. 2 shows the particle size distributions of the feed samples that were tested.

Sample D was crushed to 100% <6.3 mm prior to the test. According to the manufacturer (Metso), this would be the limiting particle size for efficient operation of that particular size of mill. Table 1 shows the ball size distributions used in the pilot tests.

The ball size distribution for sample D was prepared with larger balls to accommodate the larger particles relative to samples A, B and C. The mass balances of the tests were calculated from the particle size distributions, solids concentration and flow rates in each stream of the circuit.

### 3.2. Laboratory tests

The characterization tests were carried out in a laboratory batch ball mill with samples of the fresh feed to the pilot, closed circuit grinding tests. All samples were crushed to 100% <3.6 mm in order to keep an appropriate ratio between the make-up ball size and the diameter of the mill used in the tests.

### Table 1 – Ball size distributions.

<table>
<thead>
<tr>
<th>Size (mm)</th>
<th>Sample</th>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>A</td>
<td>B</td>
<td>C</td>
<td>D</td>
</tr>
<tr>
<td></td>
<td>% Ret.</td>
<td>% Ret.</td>
<td>% Ret.</td>
<td></td>
</tr>
<tr>
<td>35</td>
<td>–</td>
<td>–</td>
<td>38.4</td>
<td></td>
</tr>
<tr>
<td>30</td>
<td>–</td>
<td>27.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>25</td>
<td>30.7</td>
<td>–</td>
<td>14.5</td>
<td></td>
</tr>
<tr>
<td>19</td>
<td>34.6</td>
<td>40.7</td>
<td>17.7</td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>29.7</td>
<td>–</td>
<td>–</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>5</td>
<td>42.5</td>
<td>1.9</td>
<td></td>
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<tr>
<td>9</td>
<td>–</td>
<td>16.8</td>
<td>–</td>
<td></td>
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<tr>
<td>Total</td>
<td>100</td>
<td>100</td>
<td>100</td>
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</tbody>
</table>

The samples were milled in four grinding times. After each grinding time, all the material was removed from the mill in order to measure the particle size distribution of the holdup at the corresponding grinding time. The grinding times were designed so that the product size distributions corresponding to each grinding time steadily moved towards a specified 80% passing size in the final grinding time. This was achieved by calculating the next grinding time assuming the rate of disappearance of the fraction larger than the specified size is a first order process. In fact, non-first order grinding cannot be modelled using the system used in this work. A first order breakage rate is a mandatory requirement for this model. Table 2 shows the operating conditions used in the batch ball mill tests.

The batch grinding tests were performed at the same concentrations of solids and the same ball size distributions used in the pilot scale tests.

### 4. Simulations

#### 4.1. Breakage parameters

The breakage parameters were determined from the results obtained in the batch ball mill grinding tests using the software BatchMill™ version 1.6 from MTE – Mineral Technologies International. Software input consists of feed and product size distributions, the corresponding grinding times, mill holdup and grinding power. Table 3 presents the breakage parameters for the four samples tested.

The software minimizes an objective function that relates the measured and calculated product size distributions at the various grinding times of the batch grinding tests. The product size distributions are calculated using a solution for the batch grinding equation, and the models for selection and breakage functions. The parameters in Table 3 represent the minimum of the objective function, the so-called optimized set of parameters. The \( S_1^{15} \) parameter is calculated by multiplying \( S_1^{15} \) from the batch ball grinding tests by 1.35, that is, there is a scaling factor \( k = 1.35 \) to convert from conventional ball mill grinding efficiency to vertical mill grinding efficiency (\( S_1^{15} = k S_1^{15} \)).

It is possible to compare the properties of different ores with respect to the breakage rates by plotting the resulting energy specific selection functions determined in the batch grinding tests as shown in Fig. 3.

The energy specific selection functions for samples B, and C are very similar (pellet feed samples). Sample B has the highest breakage rate and sample D the lowest. The lower rate of breakage observed in sample D is probably due to the larger balls that were used in the test. Sample A was ground using a
slightly smaller ball charge, relative to sample D, and samples B and C were ground with the smallest ball charge so, in principle, all ores probably have similar tenacity, and the differences observed are mainly due to the differences in ball charges that were used in the batch grinding tests. The specific selection function curve presented a profile close to linear, showing that the ball size used has good proportional relationship with the larger particle size of the sample (top size).

\[ S_1 (\text{kWh}) = 100 \times \frac{\text{size}}{\text{top size}} \]

**Fig. 3 – Specific selection function for samples tested.**

Fig. 4 shows a comparison between the breakage functions for the samples tested.

The breakage function for sample D has a gradual slope, indicating high generation of fines when compared to the other samples, which have steep slopes.

**4.2. Model prediction**

The simulations were performed using the model for vertical mills implemented in the software Modsim™ version 3.6.25 from MTI – Mineral Technologies International. The breakage parameters were input into the simulator to predict the particle size distribution of the vertical mill discharge. Fig. 5 shows the results of the simulations (solid lines) and the measured size distributions in the pilot tests (symbols).

The model was able to predict with acceptable accuracy the particle size distribution of the pilot vertical mill discharge. These results indicate that the mechanisms of ball mills and vertical mills are similar, since it was not necessary to include any additional term to describe attrition mechanisms or other breakage mechanisms that are not present in conventional ball milling [3].

The factor k = 1.35 was adequate to correct for the higher efficiency of vertical mills when compared to ball mills. In terms of net power, the vertical mill would be around 35% more efficient than the conventional ball mill. However, attention

<table>
<thead>
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<th>Table 3 – Breakage parameters.</th>
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<td>Sample</td>
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<td></td>
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<tr>
<td>A</td>
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<tr>
<td>C</td>
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<tr>
<td>D</td>
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* Normalized sum of residuals.

**Fig. 4 – Breakage function for samples tested.**
should be paid to the no-load power of the vertical mill. Preliminary studies indicated that the vertical mill has greater no-load power than the conventional mill, when the same gross power is installed. However, more detailed studies on power requirements by the vertical mills are required in order to establish a fair comparison with power requirements of conventional ball mills.

5. Conclusions

The simulations indicated that it is possible to predict the particle size distribution of a vertical mill using population balance modeling techniques. The energy-based model that is used for ball mill simulations [7,8] was modified to include the correction factor $k = 1.35$ applied to the energy specific selection function measured in a conventional batch ball mill [3]. This methodology can be applied to coarse samples.

Conflicts of interest

The authors declare no conflicts of interest.

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REFERENCES