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Evaluating the Effect of Feed Particles Size and Their Hardness on the Particle Size Distribution of Semi-autogenous (SAG) Mill’s Product

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Abstract
The main target of this research was to provide the optimal size of mills’ feed with acceptable accuracy, in order to find the size range of particles to achieve the maximum grinding product. Nowadays, experimental semi-autogenous (SAG) mill and drop weight test are used for evaluation of grinding circuit regarding changes in feed particle size distribution, size of the ball, speed of mill, prediction of energy required and product size distribution for complete grinding in AG and SAG mills. In this study, the effect of initial size ranges of feed (+13.2–315 mm) on the amount of grinding product and its size...
distribution have been evaluated, in order to find the size range of particles to achieve the maximum grinding product. The results showed that the feed size range of 19 to 22.4 mm had the highest amount of grinding product and breakage index number in different energy levels and the validity of results was evaluated with ball drop weight test, as well.

**Keywords:** drop weight test, grinding, product size distribution, SAG mill, size of feed

### 1 INTRODUCTION

The evaluation of grinding and breaking energy is usually criterion for the estimation of ore’s hardness. On the other hand, the mechanism of grinding is different for different grinding mills. Thus, achieving a suitable method to estimate of rock’s hardness and product size distribution is extremely important. A lot of methods have been suggested for the evaluation of rock’s hardness, such as Bond work index, SAG mill power index, standard drop weight test and SAG design test. The provision of a fast and accurate method is important due to the dependence of hardness on the method of grinding. For example, Bond work index is estimated with lower energy level compared to drop weight test, and the obtained results are usable for ball mills, and do not have much application in the designing of a SAG mill circuit. Thus, the results obtained from this test are quite different according to energy level in the estimation of ore’s hardness and product size distribution. The drop weight test is more commonly used compared to other hardness calculation methods, due to its characteristics such as its simplicity within execution of testing, low-cost, requiring less mineral matter and the grinding mechanism being similar to SAG mill. Drop weight test is a simple method for the evaluation of behavior and properties of materials’ breakage. Narayanan (1985) first proposed the $t_{10}$ procedure to analyze the drop-weight experiments. A few laboratory methods were developed to study on the breakage parameters in the mills Bond (1960). Datta (1999), and Datta and Rajamani (2002) applied the model based on
DEM collision spectra in the predicting the product size distribution in mill and proposed directly obtained breakage parameters from drop-weight experiments. Also, they predicted the size distribution. Tavares and Carvalho (2009) used DEM energy spectra to analyze the rates of breakages of the coarsest size fraction and product size distribution in a ball mill. Morrell (2003) presented a rock breakage test which aided in the prediction of autogenous (AG) and semi-autogenous (SAG) mills performance in situations where only limited quantities of rock samples were available. Genc, Ergun, and Benzer (2013) computed the effects of operational and design parameters on specific discharge and breakage rate of particles in geometrically different multi-compartment ball mills. Shi and Zuo (2014) developed an improved method for the characterization of coal breakage at JKMRC, in order to combine hardware for a fine particle breakage characterization test. Magalhaes and Tavares (2014) demonstrated the speed and accuracy of a laboratory cone crusher equipped with a power meter to estimate the A x b breakage parameters. Silva and Casali (2015) introduced two models considering explicitly the effect that the feed particle size has on the mill performance, particularly on the power and its specific energy consumption. The main target of this research work is to provide the optimal size of mills’ feed with acceptable accuracy, in order to find the size range of particles to achieve the maximum grinding product.

2 FEED SAMPLE PREPARATION

Selected samples were chosen from active areas of Sarcheshme’s copper mine which located in Kerman, Iran. After conducting particle size distribution process on the selected feeds, 7 samples in size range of 13.2 to 45 mm were prepared for drop weight test performance (Figure 1). The methods of calculating the grindability and feed hardness were primarily developed on the relationship between particle size and the amount of energy consumption, and include: Bond work
index (BWI), this is used to determine the grindability of ores in ball mills. It is usually carried out in a closed grinding cycle and is determined under standard conditions (Bond 1961). The value of this index is not required for the calculation of the energy required for grinding and designed procedures in SAG and AG mills, because they contain different mechanisms of grinding from those in ball or rod mills. SAG mill power index (SPI), the aim of this test is to develop an equation to determine the power requirements of the SAG mill in industry scale, due to the size of the final product ($P_{80}$) and the ore hardness. Dimension of mill is $302 \times 102$ mm and balls with a diameter of 25 mm are used (Amelunxen, Berrios, and Rodriguez 2014). Initially, bond work index test and SAG power index were conducted on the selected samples and the softest and hardest samples were introduced. The characteristics of selected samples are presented in Table 1.

3 EXPERIMENTAL WORK

In the current work, the experimental effort consists of ball drop weight and laboratory-scale grinding SAG mill experiments. Ball drop-weight tests mimic the high energy impacts occurring in the mill. These tests consist of dropping a ball weight from a prescribed height onto single particles and then sieving the broken particle fragments. Three different size classes, $13.2 \times 16$-mm, $19 \times 22.4$-mm, $26.5 \times 31.5$-mm, were tested at different energy levels. The drop height and weights were predetermined to cover a wide range of mass specific energy. Analysis of the drop-weight experiments were done based on the $t_{10}$ procedure. Narayanan first proposed the $t_{10}$ procedure (Narayanan 1985), and Bourgeois (1993) reformulated the procedure. The main theme of this procedure is that the single particle breakage function can be modeled if the variation of one parameter is known at different impact energy levels. This parameter is called $t_{10}$ which refers to the percent passing value on the particle size distribution curve at 1/10th of the mean size of the original particle. Tracking this parameter alone is enough to describe the entire breakage
distribution. Later, the $t_{10}$ values can be correlated with applied impact energy. Laboratory-scale grinding SAG mill experiments were also carried out, to obtain the size distribution of the ore for different grinding regimes. The used ball drop machine is shown in Figure 2. The batch mill experiments were carried out in a 180 cm diameter and 30 cm length mill shown in Figure 3. All of these defined experiments were carried out in a dry environment. The mill is fitted with 12 square lifters of 1.5 × 1.5 cm cross section. In these experiments, the mass hold-up of ore was 150 kg and the mass of 50 mm grinding balls was around 200 kg.

The maximum speed at which the particles fell on the toe angle in SAG mill with 1.8 meter diameter, was about 4 meters per second (Rezaeizadeh et al. 2010). At this time, a ball with diameter of 50 mm and mass of 880 g has approximately 10 joules of energy. This energy is sufficient to break copper ore with an average hardness and size range less than 2.5 cm (Tavares, Carvalho, and Guerrero 2012). In this experiment, 25% of the mill by volume was initially filled with balls and mill with 75% of critical speed was rotated for 5, 10, 15, 20 minutes. At the end of each period of time, the mill product was graded. The operating conditions of the laboratory mill are given in Table 2.

4 THE EFFECT OF FEED SIZE ON THE SAG MILL’S PRODUCT PARTICLE SIZE DISTRIBUTION

An experimental SAG mill was used, in order to evaluate the effect of initial size of feed on the amount of grinding product and distribution of the product particle size. After performing the test, 75 kilograms of feed of each size range with 60 and 30 mm balls (25% of the mill) were poured in the mill, and the mill run with 75% critical speed for 5, 10, 15 and 20 minutes. At the end of each period, the product of mill was distributed and the effect of feed size on grinding
product was evaluated. Figure 4 illustrates the passing cumulative percentage of an experimental SAG mill’s product for operation times of 10, 15 and 20 minutes for different feed size ranges.

Sieve size of 80% of the product which passed through (P_{80}) can be calculated, using these results. Figure 5 shows the amount of calculated P_{80} in size ranges of 13.2 to 16 mm, 19 to 22.4 mm, and 26.5 to 31.5 mm for operation times of 10, 15 and 20 minutes.

From Figure 5, after 20 minutes of grinding in an experimental SAG mill, P_{80} was reduced from maximum of 15.3 to minimum 5.38 mm for feed size range of 13.2–16 mm, and using 19–22.4 mm feed, it was reduced from 21.55 to 11.46 mm, and for feed size of 26.5–31.5 mm feed, it was reduced from 30.25 to 25.11 mm. Among these size ranges, 19 to 22.4 mm had the highest reduction of P_{80} and had accordingly the highest amount of grinding product. The breakage index number (t_{10}) in different grinding times and for different size ranges is shown in Figure 6.

The breakage index number of the mill for different times was related to the size range of 19 to 22.4 mm. As the grinding time increases, the product particle size distribution has become narrower. For a smaller size range (+13.2–16 mm) across different time ranges, variation of granulation is high, due to the fineness of the initial feed. However, for a coarser feed size range (+19–22.4 mm) within the temporal intervals of 5–15 minutes, the rate of alteration of granulation is higher, due to existing of particles with sharp edges. Over time, as the particles become more homogeneous and uniform, the variations of granulation decline versus grinding time.

5 ANALYSIS OF THE BALL DROP-WEIGHT

The ball drop weight tests were performed, using 570 particles in size range of 13.2 to 65 mm for seven selected samples (totaling 3990 particles), and results were compared with the results of size ranges of 13.2 to 16 mm and 19 to 22.4 mm and 26.5 to 31.5 mm. The reasons of
running these tests were first to evaluate the effect of sample’s particle size on the amount of
grinding product and distribution of the product particle size. And second, evaluation of result’s
validation which was obtained from Experimental SAG mill in different feed size ranges. **Figure 7** shows the size distribution for 7 ball drop-weight experiments. Therefore 7 different energy-size
relationships were used to set up the $t_{10}$ procedure. The range of impact energy was between 0.25
kWh/t (900J/kg) and 2.5 kWh/t (9000J/kg). The particle size varied from 13.2 to 61 mm. The
relationship between $t_{10}$ and applied impact energy may be formulated by alternative ways. In this
study Napier Munn’s formulation (Napier Munn et al. 1993), shown below in Equation (1), was
employed to show $t_{10}$ and the applied energy relationship.

$$ t_{10} = A(1 - e^{-bE_{cs}}) \quad (1) $$

Where $E_{cs}$ (kWh/t) is the specific energy applied, $t_{10}$ indicates the degree of comminution
and the breakage index number, The A and b in equation 1 are parameters which present the ores
breakage. The amount of A defines the energy levels for breaking ores higher than those (levels)
which occurs in SAG mills. Also, b is defined for low levels of ores breakage energies, and is
related to the slope of $E_{cs}$-$t_{10}$ curve. It should be noted that harder ores present less $A \times b$ value
than softer ores. To calculate the values of A and b, according to Equation 1, different levels of
energy ($E_{cs}$) were applied to each sample, and this was accordingly broken. Then, $t_{10}$ was estimated
from the product size distribution, and the $E_{cs}$-$t_{10}$ curves were prepared (**Figure 7**). The A and b
values were achieved from the curves by using the least square method. The obtained results of
product particle size distribution are presented in **Figure 8**.

The $t_{10}$ value of each ore size ranges and energy level was estimated, and then the average
of sum of the obtained seven values was accordingly calculated. The average value for size ranges
of 13.2 to 16 mm, 19 to 22.4 mm and 26.5 to 31.5 mm in low energy level were 8.83%, 10.96%
and 10.72% and in moderate energy level were 21.51%, 24.59% and 24.80% and in high energy level were 27.10%, 33.41% and 26.11%, respectively. It shows that size range of 19 to 22.4 mm had the highest breakage index number in different energy levels in drop weight test, and had the highest amount of grinding product. When the drop weight test which utilizes drops of balls as breakage media is used, the applied stress is approximately focused in a point of the ore sample. Thus the point cannot be not in the center of sample, hence the tested particles sizes are important in products size distribution and hardness, in comparison with the drop weight test using flat media. It implies that if the sample size is finer than a specific size, then due to focused stress and central impact, the product size will be finer, and the sample hardness will be low. One of this research work was to evaluate the effect of feed hardness in SAG milling. To do that, the A × b values for different feed size ranges were compared with A × b ones obtained from drop weight tests which is given in Figure 9.

According to Figure 9, the deviation of A × b values of each feed size ranges with ball drop test was estimated, and then the average of sum of the obtained seven values was calculated. The average value of deviation for size ranges of 13.2 to 16 mm, 19 to 22.4 mm and 26.5 to 31.5 mm were 12.46, 4.78 and 6.6, respectively. It shows that the least deviation belongs to size range of 19 to 22.4 mm which would be an indication of being well matched with the results of ball drop tests, and the results of feed hardness in size range of 19 to 22.4 mm had the most compliance with the results of drop weight test.

6 CONCLUSIONS

In this research work, in order to evaluate the effect of initial size of feed on the amount of grinding product and distribution of the product particle size of SAG mill, experimental SAG mill
test was firstly performed, using the selected samples. Second, to evaluate the validation of results which was obtained from Experimental SAG mill tests in different ranges, ball drop tests were carried out. The obtained results can be summarized as follows:

- Among different size ranges of feed (+13.2–31.5 mm), the 19 to 22.4 mm had the highest amount of grinding product and $P_{80}$ reduction.

- Comparison of breakage index number ($t_{10}$) for an experimental SAG mill with ball drop weight test showed that the highest amount of grinding product was related to the size range of 19 to 22.4 mm.

- The results show the range of ore from 19 to 22.4 has maximum comminution and is common between SAG mill and ball drop test and it can be related to the shape of comminution based on the ball impact condition.

- The deviation of $A \times b$ value of each ore with ball drop test was estimated (Figure 9), and then the average of sum of the obtained seven values was calculated. The average value of deviation for size ranges of 13.2 to 16 mm, 19 to 22.4 mm and 26.5 to 31.5 mm were 11.89, 5 and 6.28, respectively. It shows that the least deviation belongs to size range of 19 to 22.4 mm which would be an indication of being well matched with the results of full ball drop tests.

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**References**


Table 1. Properties of 7 samples

<table>
<thead>
<tr>
<th>SPI (kWh/t)</th>
<th>BWI (kWh/t)</th>
<th>Density (g/cc)</th>
<th>Tonnage (t)</th>
<th>Sample no.</th>
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<tr>
<td>11.31</td>
<td>10.87</td>
<td>2.85</td>
<td>10</td>
<td>Ore1</td>
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<tr>
<td>7.53</td>
<td>14.7</td>
<td>2.78</td>
<td>10</td>
<td>Ore2</td>
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<td>7.13</td>
<td>10.37</td>
<td>2.81</td>
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<td>Ore3</td>
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<td>13.24</td>
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<td>26.09</td>
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<td>2.83</td>
<td>10</td>
<td>Ore6</td>
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<tr>
<td>23.09</td>
<td>15.32</td>
<td>2.91</td>
<td>10</td>
<td>Ore7</td>
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**Table 2. Conditions of SAG mill tests**

<table>
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<th>parameter</th>
<th>value</th>
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</thead>
<tbody>
<tr>
<td>mill diameter, mm</td>
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<tr>
<td>length, mm</td>
<td>300</td>
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<tr>
<td>speed, rad/s</td>
<td>2.4</td>
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<tr>
<td>fraction of critical speed</td>
<td>0.75</td>
</tr>
<tr>
<td>lifters number</td>
<td>12</td>
</tr>
<tr>
<td>shape height, mm face angle, °</td>
<td>Trapezoid 15 0</td>
</tr>
<tr>
<td>grinding media material</td>
<td>Chrome alloy steel</td>
</tr>
<tr>
<td>ball diameter, mm</td>
<td>30, 60</td>
</tr>
<tr>
<td>density, kg/m³</td>
<td>7800</td>
</tr>
<tr>
<td>load levels</td>
<td>0.25 fraction of mill</td>
</tr>
<tr>
<td>feed material size, mm mass, kg</td>
<td>Copper ore 13.2 to 16,</td>
</tr>
<tr>
<td></td>
<td>19 to 22.4, 26.5 to</td>
</tr>
<tr>
<td></td>
<td>31.5 200</td>
</tr>
<tr>
<td>ore density, kg/m³</td>
<td>2780, 2900 moderate</td>
</tr>
<tr>
<td>ore hardness working time, minute</td>
<td>5, 10, 15, 20</td>
</tr>
</tbody>
</table>
Figure 1. Samples used in ball drop weight test.
Figure 2. Ball drop machine.
Figure 3. Laboratory-scale 180 cm SAG mill.
Figure 4. Comparison of passing cumulative percentage for operation time of (A): 10 and (B): 15 and (C): 20 minutes of an experimental SAG mill for different feed size ranges.
Figure 5. Comparison of $P_{80}$ for different feed size ranges in an experimental SAG mill.
Figure 6. Comparison of the breakage index number ($t_{10}$), for different feed size ranges in an experimental SAG mill.
Figure 7. Full ball drop $t_{10}$ values at various energy inputs for different 7 samples.
**Figure 8.** Changes of the breakage index number ($t_{10}$) for different size ranges (A: low B: moderate C: high energy levels).
Figure 9. Comparison $A \times b$ values for different feed size ranges of sample’s particles.