ASSESSING COMMINUTION EFFICIENCY

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ABSTRACT

The Bond Operating Work Index is commonly compared with the measured Bond Laboratory Ball Mill Work Index to assess comminution efficiency. However, the Operating WI is based on the $P_{80}$ and $F_{80}$ sizes which only represent the complete size distributions — if their cumulative size distributions are at least approximately parallel when plotted on semi-logarithmic or Rosin-Rammler axes. This requirement is usually satisfied by ball and rod mills but not by AG/SAG mills, crushers and many other devices. Hence, an Operating WI estimate based on these single point parameters can give misleading results for other than ball and rod mills.

In the light of the shortcomings of the Bond equation, several new approaches for assessing comminution efficiency have been developed. This paper outlines the development of and explores the potential of a method to assess comminution efficiency based on the energy required to generate new material which is finer than the size in the product which represents 80% of the surface area of the product size distribution. For typical comminution circuit products, generation of new minus 75 micron (that is, kWh/t of new minus 75μm) is a practical guide. This paper reports on a method to estimate the surface area of comminution progeny and compares the results of energy required to generate new -75 μm with Operating Work Index based calculations for a wide range of processing equipment. The -75 μm marker is suitable for many comminution products. Coarser or finer sizes can be used when appropriate.

KEY-WORDS: Comminution; energy efficiency; Bond Work Index.

1. INTRODUCTION

The aim of any mineral processing operation is to separate valuable minerals from the waste by physical means. Comminution is almost always required to liberate valuable minerals from the waste and is therefore one of the key operations. This size reduction operation consumes a significant amount of energy. It has been stated by many researchers (Fuerstenau and Abouzeid, 2002; Tavares and King, 1998) that the direct energy (which is the electrical energy to run the mill) accounts for about 3.3% of world consumption of electrical energy. Almost every comminution circuit also uses a classification which will consume an additional 5-10% of the direct energy. It is worth noting that comminution circuits also consume substantial quantities of steel as media and mill lifters. Including the energy required to manufacture these consumables might very well double the energy to 6-7% of world consumption.

A common empirical approach for assessing the performance of comminution equipment or circuits has been to develop an energy-size reduction relationship for each type of the equipment. Several researchers have developed more general relationships which are usually referred to as “Laws of Comminution” even though each law is essentially a hypothesis. These “Laws” have been shown to have some severe limitations and can give misleading results when used to assess the energy efficiency of comminution processes. These limitations can be found elsewhere (Hukki, 1962, Morrell, 2004). In the light of these shortcomings of the Bond method, it is worth investigating the development of new methods of assessing the energy efficiency of comminution processes or devices.
2. DEVELOPMENT OF THE - 75 μm METHOD

Surface area and surface energy have been used widely to estimate comminution efficiency. According to Rittinger, the energy required for comminution should be proportional to the new surface area generated. For a full size distribution, the fines fraction which may represent only a small part of the distribution (in terms of mass) will usually contribute significantly to the surface area and surface energy. But the problem with all measures of surface area produced is that the calculated surface area per unit mass increases rapidly with decreasing particle size. This means that the total surface area may never come to a limit. In order to use production of surface area in assessing comminution energy, it is essential that the total surface area contained in the ultrafines region is bounded with decreasing size. Modern size measurement techniques using laser diffraction and computer modelling allow measurement of surface area of all size fractions including the ultrafines to be measured. This capability was not available when the various "laws" were being formulated.

A surface area model developed by Michaux (2005) was used in this study to predict the surface area of particles in each size fraction. The model predicts the surface area of particles from raw sieve mass data. It calculates the number of particles in each size fraction and simulates each individual particle volume to give the surface area. The surface area model is described in Figure 1.

A set of size distribution data ranging from 37.5 to 1.4 microns from Hashim (2004) was used in this study. It was found that the total surface area (m²) in each case reached a well-defined limit with decreasing size as shown in Figure 2.
This limit occurs because the mass in the finer size fractions tends to zero more rapidly than the increase in surface area per unit mass. Hence, we can consider evaluating energy efficiency in terms of production of particles finer than a stated size. From Figure 2, most of the surface area occurs a size finer than the point of inflection which typically occurs between 1mm and 100 microns. Therefore, a potential method to estimate comminution efficiency is to look at the generation of new material in a selected small size fraction (typically minus 75 micron) by any comminution process. This strategy should substantially reduce the problems with different slopes of feed and product size distributions.

To assess whether minus 75 micron can be used as a marker for a dominant proportion of surface area on typical product size distributions, measurements of the surface area were conducted using the surface area model on several samples. The results are shown in Figure 3.

![Figure 3 - Percentage of surface area for materials in minus 75 micron](image)

The use of minus 75 microns as a marker on a size distribution is clearly acceptable when the product contains a large portion of minus 75 micron material. It can be seen that, a product with 50% material in its minus 75 micron has a surface area of about 80%, and a product with 65% and above material in its minus 75 micron, has a surface area of more than 90% of the total surface area. It clearly shows that, material in minus 75 micron represents a large amount of surface area of the whole size distribution. However, in coarse grinding, another size index, say 106 or 150 microns may be more useful. Similarly for a very fine feed and product, a finer marker may be appropriate.

3. CALCULATION OF STANDARD ENERGY OF kWh/t OF - 75 µM MATERIAL FROM A LABORATORY TEST.

In the Bond method, the grinding energy efficiency can be measured by dividing the operating work index with the work index calculated from the grindability test. This approach can be applied to the new method to give a measure of energy efficiency in terms of actual operating performance (kWh/t to produce new material of -75 µm measured from plant data) compared to calculated performance (kWh/t to produce the same amount of new material of -75 µm in the laboratory test). As yet, no specific test for the determination of the standard energy has been devised.

However, the Bond grindability test is widely used in the characterisation of ores. Since the Bond test is conducted in a standard mill with a closing screen selected to target the desired product size, it is reasonable to use the data from this test to calculate the standard energy of kWh/t of minus 75 µm material produced.

The useful information that can be obtained from a standard Bond grindability test is as follows:

- Closing size screen (µm)
- Percent re-circulating load
- Size distribution of feed and product
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- Mass undersize in refill
- Mass undersize from milling
- Mass undersize per revolution

An example of the calculation of a standard kWh/t of minus 75 μm is as follows:

Data from Bond grindability test:

<table>
<thead>
<tr>
<th>Closing screen size</th>
<th>150 μm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Percentage undersize in feed</td>
<td>8.42 %</td>
</tr>
<tr>
<td>Material of - 75 μm in feed</td>
<td>5.0 %</td>
</tr>
<tr>
<td>Material of - 75 μm in product</td>
<td>64.2 %</td>
</tr>
<tr>
<td>Net mass undersize per revolution</td>
<td>1.29 g</td>
</tr>
</tbody>
</table>

Calculation:

Total undersize per revolution:

\[
\text{Total undersize per revolution} = \frac{1.29 \times 100}{100 - 8.42} = 1.418
\]

Revolution required to produce 1 ton of undersize:

\[
\text{Revolution required} = 1.418 \times 10^6
\]

Since the energy consumption per revolution is 60 J/rev (or 1.667 x 10^-5 kWh/rev), the energy to obtain 1 ton of undersize:

\[
\text{Energy} = \frac{1.667 \times 10^{-5} \times 10^6}{1.418} = 11.756 \text{ kWh}
\]

From milling, the material of minus 75 μm was increased from 5% in the feed to 64.2% in the product, which means 0.592 ton of new -75 μm material (64.2% - 5%) was produced. Therefore, to produce 1 ton of minus 75 μm material would require:

\[
\text{Energy} = \frac{11.756}{0.592} = 19.858 \text{ kWh}
\]

4. APPLICATION

Using new minus 75 μm material produced was tested on data from several full scale ball mill circuit tests. The circuit data are tabulated in Table 1. These data come from a wide range of ore types and ore hardness.

| Table 1 - Performance data from several ball mill circuits (Man, 2001) |
|---|---|---|---|---|---|---|---|---|
| Circuit | % -75 μm Feed | % -75 μm Product | kWh/t | kWh/t - 75 μm | F80 (mm) | P80 (mm) | Operating Work Index | Bond Work index |
| Ball mill 1 | 37.53 | 61.44 | 4.10 | 17.15 | 0.625 | 0.128 | 8.47 | 10.7 |
| Ball mill 2 | 37.53 | 57.75 | 4.10 | 20.28 | 0.625 | 0.147 | 9.67 | 10.7 |
| Ball mill 3 | 30.71 | 58.73 | 8.41 | 30.01 | 1.340 | 0.144 | 15.08 | 16.2 |
| Ball mill 4 | 30.71 | 60.87 | 8.41 | 27.88 | 1.340 | 0.132 | 14.13 | 16.2 |
| Ball mill 5 | 45.58 | 86.03 | 10.78 | 26.65 | 0.927 | 0.062 | 11.49 | 11.8 |
The energy required to produce the same amount of material in the -75 μm size in the laboratory was calculated from the Bond grindability test as previously shown. The relationship between lab grindability and full scale grindability is shown in Figure 4.

![Figure 4](image)

**Figure 4** – Comparison of lab grindability against full scale grindability for ball mill

As might be expected, there is a strong degree of correlation between the laboratory grindability and the full scale grindability to produce the new -75 μm material. This suggests that energy efficiency can be assessed based on the energy required to generate the new -75 μm material.

It is interesting to see if this method works the same way as the Bond operating work indices method. The efficiencies of the circuits calculated based on the kWh/t of new -75 μm material was compared to the efficiencies calculated using the two Bond work indices. The results are shown in Table 2.

<table>
<thead>
<tr>
<th>Circuit</th>
<th>kWh/t of -75 μm from Bond grindability test</th>
<th>kWh/t of -75 μm from plant data</th>
<th>Laboratory Bond work index</th>
<th>Operating Bond work index</th>
<th>Energy Efficiency from -75 μm method (%)</th>
<th>Energy Efficiency from the Bond method (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ball mill 1</td>
<td>16.34</td>
<td>17.15</td>
<td>10.7</td>
<td>8.47</td>
<td>95.2</td>
<td>90.4</td>
</tr>
<tr>
<td>Ball mill 2</td>
<td>16.34</td>
<td>20.28</td>
<td>10.7</td>
<td>9.67</td>
<td>80.5</td>
<td>80.0</td>
</tr>
<tr>
<td>Ball mill 3</td>
<td>23.54</td>
<td>30.01</td>
<td>16.2</td>
<td>15.08</td>
<td>79.0</td>
<td>93.1</td>
</tr>
<tr>
<td>Ball mill 4</td>
<td>23.54</td>
<td>27.88</td>
<td>16.2</td>
<td>14.13</td>
<td>84.4</td>
<td>87.2</td>
</tr>
<tr>
<td>Ball mill 5</td>
<td>25.28</td>
<td>26.65</td>
<td>11.8</td>
<td>11.49</td>
<td>94.8</td>
<td>97.4</td>
</tr>
</tbody>
</table>

It can be seen from Table 2 that the efficiencies calculated using the -75 μm method and the Bond work indices method are quite similar. This shows that the new -75 μm method can provide the same information as the Bond work indices and could be used to assess operating efficiency of comminution circuits whether or not ball mill feed and product size distributions are parallel.

One of the main drawbacks of the Bond method is that it assumes a parallel slope of feed and product size distributions. This assumption is usually applied to ball and rod mills, but not to AG/SAG mills. Hence, it has become of interest to assess this method is for comminution circuits other than ball mills or rod mills. The method has been tested on AG/SAG mill, Verti-mill and IsaMill. The results are shown in Figure 5.
As can be seen from Figure 5, there is a strong correlation between the calculated standard lab kWh/t of new -75 μm and the operating full scale kWh/t of new -75 μm measured from plant survey. The correlation could be seen for all types of comminution devices which suggests that the operating efficiency calculated based on standard and operating energy would be valid for all types of devices. However, as observed in Figure 6, there is no correlation between the Bond operating work index and the Bond lab work index for AG/SAG mill, Verti-mill and IsaMill.

As stated previously, the Bond method only works for ball mills and rod mills. The main source of error in the Bond method when applied to other mills is due to the particle size variation in the feed size (as in the case of SAG mill) and product size (as in the case of HPG). One important limitation of this method is that it is dependent on the single value of $F_{80}$ and $P_{80}$ of the size distribution. This suggests that the conventional representation for size distributions by a single value $F_{80}$ and $P_{80}$ (80% passing size) is not an ideal way to describe the energy efficiency of AG/SAG mill, Verti-mill and IsaMill.
The energy efficiency of comminution devices could be assessed by comparing the standard energy calculated in the lab with the operating energy measured during plant survey. Almost by definition, the operating energy (kWh/t) of an optimally designed and operated process should equal the laboratory standard energy (kWh/t) determined on a sample of the same ore. That is, the ratio of the measured operating energy, to the laboratory calculated standard energy, should equal unity. Based on the relationship between standard energy and operating energy for both -75 μm method and the Bond method as portrayed in Figures 4, 5 and 6, the energy efficiency for different types of mills were calculated and the results are shown in Figure 7.

![Energy Efficiency Diagram](image)

**Figure 7 - Comparison of energy efficiency calculated using -75 μm and the Bond method.**

As can be seen from Figure 7, the energy efficiency for ball mills calculated from the -75 μm method are similar to the energy efficiency calculated using the Bond method. However, there is some difference in the energy efficiency calculated from both methods when applied to AG and SAG mills. A huge difference in the energy efficiency calculated can be seen when the methods were applied to Verti-mill.

Based on the definition of energy efficiency, the ratio of the operating energy and standard energy should equal unity. This is true for the energy efficiency calculated using the -75 μm method. However, the Bond method seems to give unrealistic values when applied to mills other than the ball mill. This can be seen especially for Verti-mill and IsaMill data. This is due to the large difference of the laboratory work index and the measured operating work index. For example, in the case of Verti-mill, the operating work index measured was 44.1 kWh/t and the laboratory work index was calculated to be 15.9 kWh/t which gave an energy efficiency of 2.77. On the other hand, when using the -75 μm method to assess the energy efficiency of the Verti-mill, the calculated energy efficiency value was more sensible than the one calculated from the Bond work index method. The operating kWh/t of -75 μm was 64.5 and the standard kWh/t of -75 μm calculated from the Bond grindability test was 60. Therefore the energy efficiency was calculated to be 1.09.

It can be concluded that, the new -75 μm method can be applied to different types of comminution devices, however, the Bond method only works for certain mills (ball and rod mills) because the method fails when the correlation between the P80 and % -75 μm is not the same in feed and product.

Another way to think about this is that the Bond operating work index provides a measure of the efficiency of elimination of the coarse of the feed size distribution while the -75 μm method measures how much new surface area is generated. The devices with high Bond efficiency both utilise some degree of internal classification to ensure comminution of coarser particles.
5. CONCLUSIONS

The development of a method to assess the efficiency of comminution devices has lead to the following conclusions:

1. The use of the Bond operating work index can give misleading results in assessing comminution energy. The calculation of energy based on the P80 and F80 sizes only works for ball and rod mills, but not for AG/SAG mills, crushers and many other devices.

2. Surface area and surface energy can also be used to assess comminution energy. Surface area model used in this study showed that the total surface area (m²) in reached a well-defined limit with decreasing size.

3. The use of minus 75 microns as a marker on a size distribution is clearly acceptable when the product contains a large portion of minus 75 micron material. A product with 50% material in its minus 75 micron has a surface area of about 80% which shows that material in minus 75 micron represents a large amount of surface area of the whole size distribution.

4. The standard Bond grindability test can be used to calculate the standard energy to produce 1 ton of - 75 μm material and when compared with the measured kWh/t of minus 75 μm method from plant survey can give us the energy efficiency. This method can be applied to different types of comminution devices.

5. The energy to produce new material in minus 75 micron (kWh/t of - 75μm) can be used to compare the energy efficiency of comminution circuits and devices. It is a simple and quick method and does not depend on the shape of the size distributions. This method relates the energy required to increase the percentage of material in minus 75μm from the feed to the product, whereas the Bond method deals with the energy required to reduce the material from 80% passing size in the feed to the 80% passing size in the product. This can give misleading results if the feed has a different slope form the product size distribution.

6. The Bond method fails when the correlation between the P80 and the %-75 μm is not the same in feed and product.

7. A broad range of comminution devices produce quite similar efficiency in terms of new surface area produced (Figure 7). However, the Bond method does provide an indication of the efficiency of elimination of the coarser feed particles while the -75 μm method estimates how much new surface is produced.

6. REFERENCES


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