DOI: 10.5937/IOC24121J Original Scientific Paper-Mineral Processing

MODIFIED BOND AND RITTINGER ENERGY-SIZE MODELS FOR THE LABORATORY ISAMILL

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Abstract

The IsaMill is a horizontal high speed stirred mill developed by the Mount Isa Mines and Netzsch-Feinmahltechnik GmbH in the late 1990's to improve the performance of ultrafine grinding for mining industry. The IsaMills are now widely applied all over the world. This paper discusses the interpretation of the IsaMill laboratory test results for assessing material grindability and for industrial scale-up. Previously it was found that the Bond and Rittinger energy-size models do not reproduce the experimental results as well as the "signature plot". However, the modified Bond and Rittinger energy-size models using a variable grindability coefficient offer better accuracy. This, along with the extended functionality for grinding media size assessment, indicates a potential to improve the process for selection the industrial scale IsaMill circuits from the laboratory-scale tests.

***Keywords**: IsaMill, laboratory, fine grinding, comminution, energy, size, modelling.*

1. INTRODUCTION

1.1 History of IsaMill's

In the late 1980s, the Mount Isa Mines (MIM) initiated a fine grinding project to tackle the deteriorating ore conditions observed at the lead/zinc concentrator [5]. Their focus was on improving the liberation of sphalerite within the ore. To address the iron-related issues and enhance the recovery performance, the Mount Isa Mines (MIM) reached out to Netzsch, a renowned player in ultrafine grinding technology [5], [7]. Netzsch had significant experience in fine grinding equipment, particularly in the paint and food processing industry [5]. The required liberation size was in the range of 10 microns which was not possible to economically achieve with the existing ore grinding technology at that time.

In January 1992, the Mount Isa Mines (MIM) installed a small pilot-scale mill called LME100 at their pilot plant [5]. In 1994, the MIM implemented the first full-scale IsaMill prototype (later known as the model M3000) in the lead circuit at the Mount Isa [5]. Subsequently, in 1999, the additional IsaMills were installed in the lead/zinc concentrator to process the George Fisher orebody. These additions increased sphalerite liberation by 5%, zinc recovery by 10%, and concentrate grade by 2%, resulting in an impressive 16% recovery increase at the same concentrate grade [5]. There is now more than 150 IsaMills operating all around the world and it could be considered as the most technologically advanced fine grinding mill [2].

1.2 Overview of IsaMill's

Slurry enters the IsaMill at one end (opposite the shaft end cap) and must pass through each of the agitated grinding chambers in series before it can exit. This sequential arrangement makes it virtually impossible for any material to short circuit the IsaMill [7].

The IsaMills operate by rapidly rotating a central shaft, which in turn drives grinding discs. These discs agitate the grinding media, causing it to move outward along the face of the discs toward the shell liner. As it reaches the shell liner, the media is redirected back toward the mill shaft area. This dynamic process occurs between each disc, where there is sufficient grinding media (typically around 70% filling volume), creating a chamber of agitated grinding media [7].

At the discharge end of the IsaMill, a grinding media separator utilizes a closer spacing between the final disc and rotor disc to centrifuge the grinding media toward the shell [7]. By the use of a rotor that acts like a pump, the grinding media is kept in the mill, while the ground product slurry flows out through the IsaMill's exit.

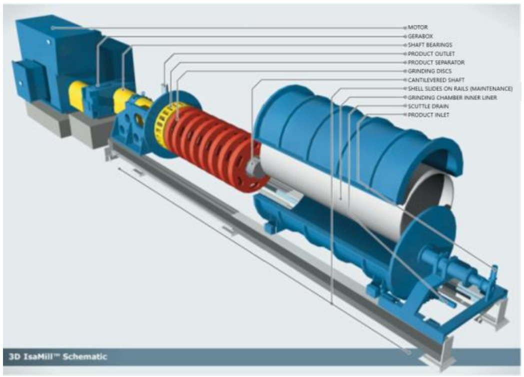

Figure 1-1. *IsaMill Design [6]*

Ceramic beads are mainly used as the grinding media; although in early days, when the ceramic grinding media was not available, the granulated slag, coarse sand and other materials were used. Mill grinding efficiency is strongly dependent on the grinding media size as well as quality and therefore the ceramic grinding media available in various sizes, densities, hardness, and wear properties is used to optimize grinding performance. The IsaMill grinding media consumption is relatively low compared to the conventional mills using the steel grinding media which makes operating cost low despite high price for the ceramic grinding media.

Validation studies over the past two decades have demonstrated that a 1:1 direct scale-up from laboratory-scale to full-scale IsaMill is achievable due to the similarity of operating conditions, feed size distribution, and grinding mechanisms[5],[7].

Over the years, driven by numerous trials and increasing demand for higher throughputs, the IsaMill design has evolved. The current models, sizes, motor specifications, and maximum flow rates are detailed in Table 1. For feeds requiring a reduction ratio greater than eight, it is advisable to implement two stages of size reduction in series, utilizing different grinding media sizes to minimize the energy requirements [5]. Additionally, the IsaMills can be equipped with features like acoustic emission analyzers for further analysis.

Table 1. *Market available IsaMill models [2]*

Model	Volume (L)	Motor Size (kW)	Max Flowrate (m^3/h)
M100	100	75	12
M500	500	200	30
M1000	1,000	500	90
M3000	3,000	800	150
M5000	5,000	1120 or 1500	200
M7500	7,500	2,200	275
M10000	10,000	3,000	350
M15000	15,000	3,800	600
M20000	20,000	5,000	800
M30000	30,000	6,000	1,000
M50000	50,000	8,000	>1,000

2. SIGNATURE PLOT AND TESTING

No general work index formula governing energy use over a range of conditions, like the Bond equation for intermediate grinding, has been used for the fine grinding regime. Instead, the specific energy versus 80% passing product size (P_{80}) is determined in the laboratory for each case. The specific energy consumption usually fits an equation of the form:

$$SE = A \times P_{80}^{k} \tag{1}$$

Where W is the specific grinding energy (kWh/t), P_{80} the product 80 percent passing size (μm), and A and k are the constants.

Taking the logarithm of both sides, one obtains a linear equation:

$$\log(SE) = \log(A) + k \times \log(P_{80}) \tag{2}$$

The specific energy vs P_{80} curve is usually plotted on the log–log axes. This is referred to as a ‘‘Signature Plot’’; an example is given in Figure 2-1. The Signature Plot is widely used for the specific energy versus product size presentation.

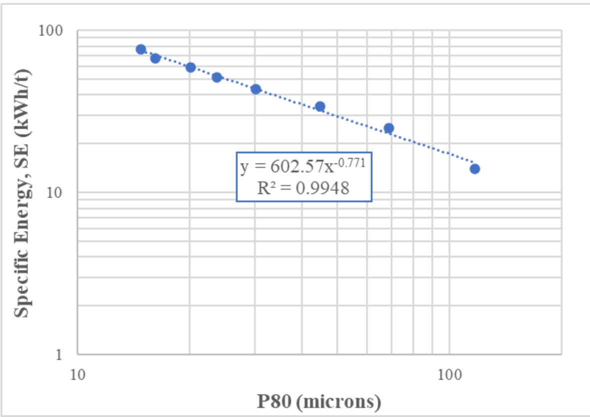

Figure 2-1. *Signature Plot*

Accredited laboratories worldwide use the IsaMill test, known for its 1:1 scale-up [4], [5]. The testing procedure involves loading the standard M4 (4L) IsaMill with 80% grinding media, which is typically 1-3 mm in size — the same as the final application. The mill is then agitated at 1500 RPM [8]. The mill configuration and operation, including factors like disc speed, media type, and media filling, are similar to those of the full-scale operation [8]. Each point on the "signature plot" results from a continuous pass through the mill, during which samples are taken for the particle size measurements and energy consumption is measured directly from the agitator shaft.

Figure 2-2. *Laboratory M4 (4L) IsaMill test rig [1]*

2.1 Alternative to Signature Plot

Recent work using the results from several different fine grinding laboratory tests, including the IsaMill, has found that the modified Bond and Rittinger models can be used to accurately describe the fine grinding energy – size relationship [1]. A closer look in the IsaMill is taken in this paper. As the Bond and Rittinger models are well known and understood by the industry they could provide an alternative to the signature plot which is only a mathematical model happen to fit the results well and has no "visible link" i.e., parameters to the size reduction process. Model that is linked to the comminution theory may provide better understanding and interpretation on the test work results and ultimately improve the equipment selection process.

3. ISAMILL TEST WORK DATA ANALYSIS

Over the 20 laboratory IsaMill test work results with a variety of different materials were analyzed. A summary of the test material, feed and final product size and grinding media size, used for each test, is listed in Table 3-1. It can be observed that 80 percent passing feed size (F80) varies from very fine (25.8 microns) to very coarse (350 microns) and that the grinding media size varied from 1.8 to 6.5mm with larger media, used for the coarser feed.

Table 3-1 *Laboratory IsaMill Tests Summary Information*

Test number	Test material	Grinding media size (mm)	F80 (microns)	Final P80 (microns)
1	Cu concentrate	3	48.4	18.1
2	Cu concentrate	3	45.5	17.2
3	Cu concentrate	3	34.0	18.1
4	Pyrite concentrate	2	117.0	10.2
5	Pyrite concentrate	3.5	117.0	10.7
6	Cu concentrate (coarse)	6	267.0	14.8
7	Magnetite concentrate	5	350.0	19.2
8	Flotation tail	6.5	250.0	34.9
9	Magnetite concentrate	3.5	113.0	14.7
10	Magnetite concentrate	3.5	113.0	12.6
11	Pb/Zn concentrate	1.8	46.0	9.4
12	Nickel concentrate	3	160.9	22.0
13	Pb concentrate	2	25.8	8.7
14	Pb concentrate	2	25.8	6.8
15	Zn concentrate	3.5	40.1	11.4
16	Pb/Zn concentrate	2	60.0	11.3
17	Pb/Zn concentrate	2.8	60.0	19.3
18	Pb/Zn concentrate	3.5	60.0	18.3
19	Magnetite concentrate	5-6	85.0	32.0
20	Magnetite concentrate	5-6	60.0	32.0
21	Magnetite concentrate	5-6	87.7	32.0

In addition to the Signature Plot, the modified Bond and Rittinger models [1] were used to fit the specific energy (SE) versus product size P_{80}.

$$\mathrm{SE} = 10 \times RW_{io}(P_{80}) \times \left(\frac{1}{P_{80}} - \frac{1}{F_{80}}\right) \qquad \text{modified Von Rittinger} \qquad (3)$$

$$\mathrm{SE} = 10 \times BW_{io}(P_{80}) \times \left(\frac{1}{\sqrt{P_{80}}} - \frac{1}{\sqrt{F_{80}}}\right) \qquad \text{modified Bond} \qquad (4)$$

where:

F_{80} and P_{80} are the feed and product particle size respectively, µm.
$RW_{io}(P_{80})$ Rittinger model variable coefficient, function of product size P_{80}.
$BW_{io}(P_{80})$ Bond model variable coefficient, function of product size P_{80}.

The quality of three models were evaluated based on the average model error of the test. The data in Table 3.2 shows that both the modified Rittinger and Bond models can predict the specific energy of the mills with an average error for the analyzed data set of 2.9% and 3.0%, respectively. This is significantly smaller error compared to the signature plot, which had an average error of 7.1%, and may encourage the use of these models for the analysis of the IsaMill test work results. It should be noted that earlier investigations showed that the standard Bond and Rittinger models (with a fixed coefficient) were less accurate for modeling the fine grinding (<100 µm).

Table 3-2 *Laboratory ISA mill test results modelling errors*

Test number	Signature plot R^2	Signature Plot Error (%)	Modified Rittinger model error %	Modified Bond model error %
1	0.9878	3.7%	0.1%	0.0%
2	0.9719	14.5%	3.9%	3.2%
3	0.9911	12.0%	0.2%	1.0%
4	0.9989	1.6%	1.2%	3.3%
5	0.9989	2.4%	1.5%	4.1%
6	0.9948	3.8%	3.2%	2.2%
7	0.9528	8.7%	0.2%	0.3%
8	0.9942	7.9%	6.0%	3.0%
9	0.9971	8.6%	4.6%	6.2%
10	0.9817	16.6%	3.1%	3.5%
11	0.9800	5.8%	5.7%	4.8%
12	0.9412	16.3%	5.8%	5.9%
13	0.9969	2.0%	0.3%	1.1%
14	0.9976	6.1%	5.7%	5.8%
15	0.9724	8.8%	4.7%	4.4%
16	0.9941	4.5%	1.4%	1.4%
17	0.9941	3.6%	1.6%	1.0%
18	0.9932	3.9%	2.4%	1.7%
19	0.9962	4.9%	3.8%	4.3%
20	0.9532	6.1%	3.4%	3.7%
21	0.9371	7.9%	1.4%	1.5%
Average		7.1%	2.9%	3.0%

Close inspection of the variable coefficient provides the useful insights into the test results. Figure 3-1 shows the variable Bond coefficients of tests grouped on the basis of the feed size F_{80}. The first graph has results for the finest feed, F_{80} = 25.8 – 48.5 microns, the second with the medium feed F_{80} = 60.0 – 87.7 microns, the third with coarse feed F_{80} = 113 – 117 microns and the fourth with very coarse feed F_{80} = 161 – 350 microns.

- Fine feeds, F_{80} = 25.8 – 48.5 microns: As the product size P_{80} decreases, the BW_{io} increases sharply in all tests. This trend suggests that the grinding process efficiency deteriorates for the finer product sizes. Finer grinding media would be required for more efficient grinding.
- Medium feeds, F_{80} = 60.0 – 87.7 microns: For tests 16, 17 and 18, the BW_{io} is higher for the coarsest product sizes, due to the low reduction ratios (F_{80}/P_{80} < 1.3), but is relatively consistent for P_{80} < 30 microns. These three tests were testing the media size effect and the lowest BW_{io}, meaning the lowest energy consumption, was obtained for the smallest (2 mm) grinding media. Similar effects are observed for the test T20 which also had the same feed size (F_{80} of 60 microns). The tests T19 and T21 had slightly coarser feed, and therefore, did not have the same issue with a low reduction ratio at coarse product sizes, so all the BW_{io} were in a fairly narrow range (20-26).

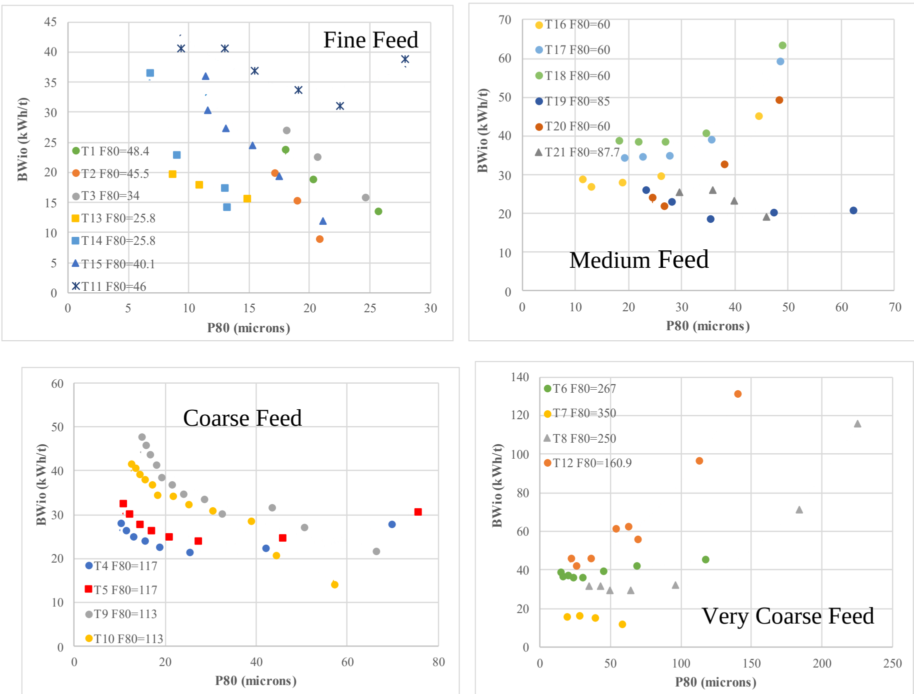

Figure 3-1. *Laboratory ISA mill test modified Bond model variable coefficient trends*

- Coarse feeds, F_{80} = 113.0 – 117 microns: The tests T4 and T5 have higher BW_{io} at coarse product size due to a low reduction ratio, then stabilize for product sizes in the of P_{80} from 20 - 50 microns, then the BW_{io} increases for the fine product sizes with theP_{80} < 20 microns. These two tests were conducted with the same material and different grinding media size (3.5 and 2.0 mm), and the lower BW_{io} for smaller media represents higher grinding efficiency. For the tests T9 and T10, the BW_{io} increased as P_{80} decreased, rapidly for P_{80} < 20 microns, suggesting that 3.5 mm grinding media is not efficient for achieving fine grind sizes.
- Very coarse feeds, F_{80} = 161 – 350 microns: Very high BW_{io} values at the coarse product size are the artifact of low reduction ratio (F_{80}/P_{80}<1.5). The tests T6, T7, T8 used the coarse grinding media (5 - 6.5 mm) and below P_{80} ~ 100 microns the BW_{io} is relatively steady. The test T12 was conducted with smaller 3 mm grinding media and reported lower efficiency for coarser grind (P_{80} > 50 microns) and higher efficiency for smaller product sizes (P_{80} < 50 microns).

The observed trends and differences in BW_{io} provide an additional analysis of the test work data that is not available from the signature plots. These can be used to assess efficiency to optimize the circuit and equipment selection and grinding media size. For example, for a given feed size the efficiency of different grinding media size can be determined across a range of product sizes. However, when assessing these trends, it is important to consider the model limitations when the reduction ratio is low, particularly for F_{80}/P_{80} < 1.5.

The modified Rittinger model has produced the similar results and trends for the variable coefficient and from that it could be concluded that it may not have advantages over the modified Bond model although historical work done by Hukki suggest better suitability of the Rittinger theory in fine grinding area. As the Bond methodology is widely used for comminution use of the modified Bond model for the Isa Mill test work results may be better justified at the moment.

4. CONCLUSION

The IsaMill is a horizontal high speed stirred mill developed for efficient fine and ultrafine grinding in mining industry. Due to its unique engineering design features, it could be considered as the most technologically advanced fine grinding mill in the minerals processing applications.

The IsaMill laboratory test results are used for assessing the material grindability and industrial scale-up. The standard Bond and Rittinger energy-size models cannot be used to model the experimental results and therefore the “signature plot” was adopted. However, the newly proposed modified Bond and Rittinger energy-size models using a variable grindability coefficient has shown to have better accuracy than the signature plot. More importantly, the new model provides the additional analysis of the test work data that is not available from the signature plots as well as better understanding of test results as the Bond methodology is extensively used for the comminution modelling for a long time. All of this indicates potential to improve the process for selection the industrial scale IsaMill circuits from the laboratory-scale tests.

ACKNOWLEDGEMENTS

The authors would like to thank Hatch for providing resources and granting permission to publish this work.

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