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Technical Note

Why is the Bond Ball Mill Grindability Test done the way it is done?

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ABSTRACT

The Bond Ball Mill Grindability Test is a locked-cycle laboratory grinding test. It provides the Bond Ball Mill Work Index which expresses the resistance of a material to ball milling. This Index is widely used in the mineral industry for comparing the resistance of different materials to ball milling, for estimating the energy required for grinding, and for ball mill scale-up. The test has existed for more than 40 years. However, there is little information which explains why the test is done the way it is done. This paper uses knowledge from past research to attempt to answer this question. It is suspected that the test is done this way because of three reasons. First, to make the test relatively easy and quick to carry out. Second, so that the test requires only a small amount of sample (about 10kg). Finally, the test can give results that are suitable for ball mill scale-up and for comparing different materials' resistance to ball milling.

Keywords: Bond test; Ball milling; Grinding

1. INTRODUCTION

The Bond Ball Mill Grindability Test (Bond, 1952, 1961) gives the Bond Ball Mill Work Index. This Index expresses the resistance of a material to ball milling; the higher the value of the Bond Ball Mill Work Index, the more difficult it is to grind the material using a ball mill. This Index is widely used in the mineral industry for:

- comparing the resistance of difference material to ball milling,
- estimating the energy required for ball milling (Levin, 1989),
- ball mill scale-up.

The appendix gives a brief summary of the test procedure.

The Bond Ball Mill Grindability Test is probably based on a laboratory grindability test first described by Maxson, Cadena and Bond (1934). The two tests are very similar. Both are locked–cycle grinding tests. In both tests, the top size of the feed to the laboratory mill is 3.35mm, and the volume of the mill feed is 700cc. Both tests stop when they have reach equilibrium. The mill used in the Maxson, Cadena and Bond test also has internal dimensions of 304.8mm by 304.8mm, and the mill contains 21.125g of balls. Bond probably used this earlier test, and then developed the Bond Work Index as a way to use the laboratory test results to determine the performance of industrial mills. At the time, the mineral processing industry expressed a need "...to establish an empirical relationship between the performance of a particular type of pulverizer and the laboratory index" (Yancy *et al.*, 1934). Bond appeared to have answered the need of the industry.

Although the Bond Ball Mill Grindability Test has existed for more than 40 years, there is little information which explains why the test is done the way it is done. Questions about the Bond test include:

- Why is the test a locked-cycle grinding test?

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- Why the test should preferably be made at or near the product size required in industrial grinding?
- Given that most industrial ball milling circuits use hydraulic classifiers, eg. hydrocyclones, for classification, why does the test use a dry screen as a classifier?
- Why is it a dry grinding test?
- Why does the Bond mill have smooth liners?
- Why does the Bond mill rotate at 0.91 of the critical speed?
- Why the top size of the feed to a Bond test is 3.35mm?
- Why the test procedure specifies that the mill grinds a constant volume of material rather than a constant mass of material?
- Why does the Bond test aim to achieve a re-circulating load of 250%?

If the Bond test was based on the Maxson, Cadena and Bond test, then Maxson *et al.* (1934) have answered some of the above questions. This paper will summarise these explanations. It will also use the knowledge from more recent research to add to these explanations and to answer some of the questions that have not previously been answered.

2. WHY IS THE BOND TEST DONE THE WAY IT IS DONE?

2.1. Why is the Bond test a locked-cycle test? And why does the aperture size of the limiting screen need to be at or near the cut size required in industrial grinding?

The Bond test is a locked cycle test because it mimics a continuous grinding ball mill in closed circuit with a classifier. The aperture size of the limiting screen, used in the Bond test, needs to be at or near the cut size required in industrial grinding because, for a given material, the value of the Bond Work Index can change with particle size.

Most industrial ball mills are in closed circuit with a classifier. The interaction between the ball mill and the classifier can change the composition of the material in the mill until equilibrium is reached. Maxson *et al.* (1934) stated that the minerals in the ore that offer maximum resistance to grinding would accumulate in the re-circulating load up to an equilibrium value. They further stated that a method of testing that does not consider the re-circulating load might yield results quite different from those to be expected in practice. Additionally, Levin (1989) highlighted that some materials exhibit a variation in hardness with size. Generally, the Bond Work Index increases as the grind size becomes finer, but the opposite does sometimes occur (Levin, 1989). For this reason, Bond (1961) advised that "...laboratory tests should preferably be made at or near the product size required in commercial grinding", ie. the limiting screen used in the Bond test must have an aperture size at, or near the cut size required in industrial circuit.

2.2. Given that most industrial ball milling circuits use hydraulic classifiers, eg. hydrocyclones, for classification, why does the Bond Grindability test uses a dry screen as a classifier? And why is the test done dry?

The Bond test uses a screen as a classifier because a screen simplifies the experimental set up and the procedure. Different screen aperture sizes can be used to obtain different cut sizes and the dimensions of the screen itself can remain the same. Whereas hydraulic classifiers, eg. hydrocyclones, do not easily provide a fixed cut size. Also, classifiers with different dimensions might be needed to obtain different cut sizes.

A screen can classify a small amount of material. This is an advantage over the hydrocyclone because the mill, used in the Bond test, grinds a constant 700cc of material. Such a small amount of material is insufficient for a hydrocyclone to operate properly.

A screen allows the test to be done dry, and a dry locked-cycle grinding test is much more convenient than a wet locked-cycle grinding test. The dry grinding test also avoids problems of varying slurry viscosity. Because the test can be done dry, there is no need for pumps, sumps and pipework which are required to transport slurry to a hydraulic classifier, such as a hydrocyclone. The elimination of pumps, sumps and pipework also makes the capital and operating costs of the test cheaper.

2.3. Why does the Bond laboratory mill have smooth liners?

There are two likely explanations. First, a mill with smooth liners is easier to empty completely after each grinding cycle. Second, with smooth liners, there are no sharp angles in which material can accumulate and thus avoid grinding. In the discussion section of a paper by Yancy *et al.* (1934), Baltzer and Hudson expressed that "...the ribs or "lifters" make the jar (ie. the grinding mill) more difficult to clean than otherwise,...their use is objectable from this standpoint". Also, lifters have to be replaced when they are worn. This adds to the maintenance of the mill.

2.4. Why does the Bond laboratory mill rotate at a fraction critical speed of 0.91?

The Bond laboratory mill has to rotate at such a high speed because this mill has smooth liners. The high rotational speed enables the charge inside the mill to attain a profile similar to the rotating charge inside most industrial ball mills. Most industrial ball mills have lifters. Data from 40 ball mills show that the average critical speed is 0.73 (Morrell, 1996). Research in mill charge motion (eg. Mishra and Rajamani, 1992; Inoue and Okaya, 1994) reveals how the charge motion vary with mill speed and liner/lifter profile. Comparison of the charge motion inside a mill with smooth liners and a mill with lifters, when both mills are rotating at the same fraction of critical mill speed and all other variables being equal, indicates that:

- a mill with smooth liners has more material in the continuum charge,
- a mill with smooth liners has more cascading charge than cateracting charge,
- the shoulder of the charge is lower in a mill with smooth liners,
- the toe of the charge is higher in a mill with smooth liners.

Hence for both mills to have similar charge motion, the mill with smooth liners must rotates faster than the mill with lifters. The movement of the charge brings about the breakage of particles inside the mill. For the laboratory test results to be suitable for ball mill scale-up, the laboratory mill must therefore mimic, as far as practicable, the charge motion inside an industrial mill.

2.5. Why the top size of the feed to a Bond test is 3.35mm?

My experience has shown that the Bond mill, operating at the condition specified by Bond (1961), cannot break particles of a typical hard ore coarser than 3.35mm. Maxson *et al.* (1934) also found that minus 3.35mm is small enough to be broken by a grinding mill with the same dimensions and operating condition as the Bond mill.

2.6. Why does the test procedure specify a constant volume of material rather than a constant mass of material?

The Bond mill, use in the Bond test, grinds a constant 700cc of material. The possible reason for using a constant volume of material is because a constant volume allows a better comparison of different materials' resistance to ball milling. Maxson *et al.* (1934) explained that in parallel grinding of two ores of different specific gravity, the volumes of the ore in the industrial mills would be more similar than their masses. Because of this, they have chosen to use a standard volume rather than a standard mass in the laboratory mill.

The standard volume of 700cc only occupies about 35% of the voids within the ball charge in the Bond mill. This percentage is lower than expected in industrial mills. This is especially true for overflow ball mills, where all the voids within the ball charge are occupied by slurry. It appeared that the Bond test uses 700cc as a standard volume because this volume makes the test quicker. Maxson *et al.* (1934) stated that "...the largest volume that can be conveniently screened at one time in three half-height Tyler sieves in a Ro-Tap is 700cc". Further, Maxson *et al.* stated that the volume of balls, the volume of voids within the ball charge and the volume of ore charge were "...chosen for convenience in operation rather than to obtain the maximum mill efficiency, since the object of the tests is to obtain an accurate comparison of different ores, rather than to arrive at absolute values".

2.7. Why does the Bond test aim to achieve a re-circulating load of 250%?

A 250% re-circulating load was selected probably because it was a typical value at the time. However, it is uncertain whether this re-circulating load is still representative of nowadays ball milling circuits. Table 1 gives the mass-balanced re-circulating load from 19 sets of data. These data came from industrial ball milling circuits. Table 1 shows that four data sets have re-circulating loads that are very close to 250%, half of the data sets have re-circulating loads between 200% and 300%, and seven data sets have re-circulating loads lower than 120%.

Table 1
Mass-balanced re-circulating load of full-scale ball mill circuits

Site	Data set number	Mass-balanced re-circulating load %
Alumbrera	1	248
	2	302
Cadia	3	248
Copper Mines of Tasmania	4	175
	5	107
	6	126
Golden Grove	7	108
	8	116
	9	107
Mount Charlotte	10	183
Mount Isa Copper (secondary grinding)	11	134
	12	277
	13	128
Mount Isa Copper (re-grinding)	14	256
	15	223
	16	199
New Celebration	17	217
	18	128
	19	247

3. CONCLUSIONS

This paper attempted to answer the question "why is the Bond Ball Mill Grindability Test done the way it is done?" Knowledge from past research has been used to answer this question. It is suspected that the Bond test is done this way because this test procedure:

- makes the test relatively easy and quick to carry out,
- requires only a small ore sample (about 10kg),
- gives results that are suitable for ball mill scale-up and for comparing different materials' resistance to ball milling

For these reasons, the test is a locked cycle test, a screen is used as a classifier and the test is done dry. Smooth mill liners make the mill easy to maintain and to empty. It is also believed that the mill rotates at 0.91 of critical speed because of the smooth liners. Most industrial ball mills have lifters and rotate at a lower fraction of critical speed. The Bond mill needs to rotate faster in order to achieve a similar charge profile as most industrial ball mills.

It is clear that Maxson *et al.* (1934) and Bond (1952, 1961) designed the test procedure very carefully. They took into account the needs of a practical test. The fact that the test is still widely used after more than 40 years demonstrates the amount of thought that went into the test design.

Several variations of the Bond grindability test have been suggested in the literature. Levin (1989) proposes a method to deal with feeds finer than the standard 3.35mm. Tüzün (2001) details a wet test procedure suitable for fine grinds where dry screening does not give an accurate size separation. Other authors (eg. Magdalinovic, 1989; Lewis, Pearl and Tucker, 1990; Aksani and Sönmez, 2000) have looked at methods of shortening the test procedure by using mathematical models to predict the performance of the Bond test mill. A detailed examination of these techniques is beyond the scope of this technical note.

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APPENDIX

Summary of the Bond Ball Mill Grindability Test Procedure

Bond (1961) detailed the test procedure. The test uses a specific laboratory grinding mill. Table A.1 gives the dimensions and operating condition of this mill:

Table A.1
Bond ball mill details

Internal diameter (m)	0.3048
Internal length (m)	0.3048
Mill speed (rpm)	70
Mill speed (fraction of critical)	0.91
Ball load (% by volume)	19.27
Total mass of balls (g)	21125
Ball top size (mm)	36.38
Geometry of mill liner	smooth
Is grinding performed wet or dry?	dry

The test involves a series of consecutive batch grinds in the Bond ball mill. After each grind the mill contents are screened to remove the undersize which is replenished with an equal mass of new feed. The length of time to each grind is adjusted until the mass of the oversize fraction is consistently 2.5 times greater than the undersize. Under these conditions, the test approximates the steady state performance of a closed circuit continuous mill with a recycle load of 250%.

The test stops when the net grams of undersize produced per mill revolution reaches equilibrium and reverses its direction of increase or decrease. The final undersize and the new feed are sized to determine their respective 80% passing size. The 80% passing size of the final undersize and the 80% passing size of the new feed, together with the average net gram of undersize produced per revolution for the last three grinds are subsequently used to calculate the Bond Work Index (see equation A.1).

$$W_i = 1.1 \frac{44.5}{P_i^{0.23}\, G_{bp}^{0.822}\left(\frac{10}{\sqrt{F}} - \frac{10}{\sqrt{P}}\right)} \qquad \text{(A.1)}$$

where:

F = 80% passing size of the new feed, µm

G_{bp} =average grams of undersize material produced per revolution for the last three cycles

P = 80% passing size of the final undersize, µm

P_i = aperture size of the limiting screen, µm

W_i = Bond Work Index, kWh/t