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GMSG GUIDELINE: DETERMINING THE BOND EFFICIENCY OF INDUSTRIAL GRINDING CIRCUITS

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ABSTRACT

Use of the Bond Work Index to size industrial grinding equipment was widely known. Bond also described its application for measuring grinding circuit efficiency. Bond Work Index efficiency has been widely used by industry, but until now without concise standard methods, or a formal guideline, for doing so. The Bond Efficiency Sub-Committee of the Industrial Comminution Efficiency work group of GMSG has produced such a guideline, which follows. It covers the methods and provides examples of how to calculate the Bond Work Index Efficiency of most industrial grinding circuits. Bond Work Index testing equipment and methods are also provided.

The next steps are: (1) to establish standard reference testing materials and one or more laboratories to serve as bases for reference testing; (2) to establish the accuracy of relative circuit Work Index Efficiency determinations; and (3), to develop and provide a public data base of industrial comminution circuit Bond Work Index Efficiencies.

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- A1. The Bond Crushing WI Test Equipment and Procedure for Bond Efficiency Determinations (Revised March 26, 2015)
- B1. The Bond Rod Mill WI Test Equipment and Procedure (Revised March 26, 2015)
- C1. The Bond Ball Mill WI Test Equipment and Procedure (Revised March 26, 2015)

Introduction and Background

Please see the references and slide presentation "Bond Efficiency SLC (rev3)-print.pdf." This efficiency determination applies to most brittle materials in their naturally occurring (un-scalped) size distributions being treated in size reduction circuits down to a product sizing of approximately eighty percent passing 70 µm (see below). Unusually shaped materials (e.g. mica) should be regarded with caution.

Part 1. Determining the Bond Efficiency of a Grinding Circuit

Method

In the plant:

- Define the circuit for which the WI efficiency is to be determined
- Procure samples of the circuit feed and product
- Obtain the power draw of the size reduction equipment at the drive pinion(s)
- Obtain the circuit throughput rate (dry tonnage)

In the laboratory:

- Conduct screen analyses of the circuit feed and product samples
- Conduct Bond WI test(s) on the circuit feed (Please see Annexes A, B and C). Use a 1,190 µm screen to close the rod mill Work Index test for these purposes. Choose a closing screen for the ball mill test one (standard square root of 2 series) mesh size coarser than the plant ball mill circuit P80. If between standard mesh sizes, chose the finer of the two. Results of Bond ball mill tests conducted with closing screens of 75 µm or finer are to be treated with caution. The Bond Work Index relationship has been noted to apply down to approximately 70 µm, and perhaps no finer, without making qualifications.

Calculations:

First, calculate the actual Operating Work Index, WIo-ACT, of the grinding circuit.

- Estimate the 80% passing sizes of circuit feed and product, F80 and P80, in microns
- Calculate W, the specific work or energy input, from the size reduction equipment power (kW) and circuit tonnage (t/h). (Auxiliary equipment power is excluded.)

W = Power/Tonnage (kWh/t)

- Calculate the Circuit WIo-ACT, from $WIo = W / (10/\sqrt{P80} - 10/\sqrt{F80})$

Second, calculate the Bond Standard Circuit Work Index (WISTD) for the material being processed, which is equal to its combined laboratory Work Index (Lab WICOMB). The Bond Standard Circuit is the 'conventional' crushing-rod-ball milling circuit of his day, designed so that no correction factors apply to the Bond laboratory test Work Indices. (It is also the Bond 'design' Work Index for this circuit.) To avoid the introduction of any design inefficiency factors in the Bond reference standard circuit, assume 8 foot (2.44 m) diameter, overflow mills, and use a rod mill feed size (F80) of 16,000 µm and a rod mill product size of 1,000 µm . Also note that in order for no correction factor for ball mill product fineness to apply, the ball mill circuit P80 should be no less than approximately 70 µm (See reference by Bond, 1962). This (Bond) efficiency determination should not be applied to circuits with a P80 finer than approximately 70 µm , without making qualifications.

Please refer to the example(s) that follow.

Third, calculate the circuit's ***Bond WI Ratio Efficiency = WISTD / WIo-ACT***

- If the WI Ratio Eff. = 1.0, or 100%, the circuit is performing with the same efficiency as the standard Bond circuit (and the ore WI equals the circuit operating WI), in accordance with the correlation Bond established between plant operating data and test data from his lab test equipment. That is, the circuit is using the same as the (design) amount of energy (per ton) predicted by the Bond design/scale-up method for the standard (conventional crushing-rod-ball milling) circuit, with no correction factors.

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- If the WI Ratio Eff. > 1.0, or >100%, the circuit is performing at an energy efficiency that is higher than the Bond standard circuit (by the stated ratio).
- If the WI Ratio Eff. < 1.0, or <100%, the circuit is performing at an energy efficiency that is lower than the Bond standard circuit.

The inverse of this ratio is the factor that must be applied to the Bond standard circuit energy to make it equal the actual circuit energy usage, the circuit's ***Bond Standard Circuit Energy Factor***. This is the circuit efficiency parameter used by C.A. Rowland, Jr. (Please see references by Rowland, 1976 and 1998).

Demonstration/Example Calculations

"Black Box" (Generic) Circuit Calculation:

Circuit dry tonnage = 450 t/h
Power draw of mill(s) (@ pinion(s)) = 3,150 kW
Circuit Feed F80 =2,500 µm
Circuit Product P80 = 212 µm

Test WI of circuit feed ore = 16.1 kWh/t (The Bond ball mill test Work Index of the ore, which applies over the size reduction range of this circuit)

W = 3,150 kW / 450 t/h = 7.0 kWh/t
WIo-ACT = 7.0 / (10/√ 212 – 10/√ 2,500) = 14.4 kWh/t
The circuit's Bond WI Ratio Eff. = 16.1 / 14.4 = 1.12, or 112%

This circuit is performing approximately 12% better than predicted by Bond, based on the average performance of the plant circuits that Bond correlated with his laboratory testing.

Bond Standard Circuit Energy Factor = 14.4 / 16.1 = 0.89. This circuit is consuming 89% of the Bond specified (design) circuit energy.

Common Plant Grinding Circuit Calculations:

1. Rod-Ball Mill Circuit (or Single-Stage Ball Mill(s), or Multi-Stage Ball Mills, or HPGr-Ball Mill(s))

   Circuit F80 = 19,300 µm P80 = 155 µm W Total = 8.56 kWh/t
   WIO-ACT = 8.56 / [(10 / √ 155) – (10 / √ 19,300) = 11.7 kWh/t
   Bond Test WI's (kWh/t): Rod Mill: 9.5 kWh/t Ball Mill: 9.8 kWh/t
   Bond Standard Circuit Work Index:

Assume the rod mill Work Index of 9.5 applies from the actual rod mill feed size of 19,300 µm (although some of this work might ideally be done by crushers to achieve a rod mill F80 of 16,000 µm) to a rod mill (circuit) product size of 1,000 µm.

W1 = 9.5 x [(10 / √ 1,000) – (10 / √ 19,300)] = 2.32 kWh/t
W2 = 9.8 x [(10 / √ 155) – (10 / √ 1,000)] = 4.77 kWh/t
W Total = 2.32 + 4.77 = 7.09 kWh/t
WI Standard Circuit = 7.09 / [(10 / √ 155) – (10 / √ 19,300)] = 9.70 kWh/t
WISTD = Lab WICOMB = 9.70 kWh/t

Circuit Bond WI Ratio Efficiency and Bond Standard Circuit Energy Factor

This circuit's Bond WI Ratio Efficiency = WISTD / WIO-ACT = 9.70 / 11.7 = 83%

Bond Standard Circuit Energy Factor = 11.7 / 9.70 = 1.21. This circuit is using 1.21 times the Bond standard circuit energy.

2. SAG-Ball Mill Circuit
   SAG-ball mill circuit F80 = 165,000 µm P80 = 125 µm W = 14.6 kWh/t
   Wlo-ACT = 14.6 / [(10 / √ 125) – (10 / √ 165,000)] = 16.8 kWh/t
   Bond Test WI's (kWh/t): Crushing:16.0 Rod Mill: 14.5 Ball Mill: 13.8
   Bond Standard Circuit Work Index:
   W1 = 16.0 x [(10 / √ 16,000) – (10 / √ 165,000)] = 0.9 kWh/t
   W2 = 14.5 x [(10 / √ 1,000) – (10 / √ 16,000)] = 3.4 kWh/t
   W3 = 13.8 x [(10 / √ 125) – (10 / √ 1,000)] = 8.0 kWh/t
   W Total = 0.9 + 3.4 + 8.0 = 12.3 kWh/t
   WI Standard Circuit = 12.3 / [(10 / √ 125) – (10 / √ 165,000)] = 14.1 kWh/t

Note, 14.1 kWh/t is also the combined Cr-Rod-Ball test WI of the ore.

This is also the expected Operating WI of the Standard Circuit, according to Bond.

WISTD = Lab WICOMB = 14.1 kWh/t.

- SAG-Ball Circuit Bond WI Ratio Efficiency and Bond Standard Energy Factor:

Bond WI Ratio Eff. = WISTD / WIO-ACT of this SAG-ball circuit = 14.1 / 16.8 = 0.84, or 84%

(Also note, W Standard/W of this SAG-ball circuit) = 12.3 / 14.6 = 0.84)

Bond Standard Energy Factor = 14.6 / 12.3 = 1.19. This circuit is using approximately 1.19 times the Bond standard circuit energy.

Bond Work Index Testing Equipment and Procedures

See Annexes A, B and C for Bond crushing, rod mill and ball mill test equipment and procedures.

Accuracy of Comparative Circuit Work Index Efficiency Determinations

This will follow in an addendum to this guideline. Sub-topics will include the following.

- Accuracy/sources of error in determining plant circuit WIo-ACT
- Reproducibility of laboratory tests (in the same lab)
- Comparing efficiencies measured on the same circuit and parallel circuits
- Comparing efficiencies of different circuits
- Development and use of reference/calibration sample(s) and laboratories

List of Symbols

F_{80} 80% passing size, in microns (µm), of the circuit feed.

P_{80} 80% passing size, in microns (µm), of the circuit product.

W Specific energy (work) input, kWh/t.

WI Bond's Work Index, the specific energy associated with a standard amount of size reduction, namely from a very large size (F_{80} = approximately infinity) to a P_{80} of 100 µm.

WIo-ACT Actual circuit (Bond) Operating Work Index, kWh/t, determined from measurements taken on the circuit.

WISTD and **Lab WICOMB** The Bond Standard Circuit Work Index used for circuit design (specific energy requirement, at the drive pinions), which is equal to the ore's combined laboratory test Work Index. These are equal to the (expected or design) Work Index of the Bond Standard Circuit, which is the 'conventional' crushing-rod-ball milling circuit of his day, designed so that none of Bond/Rowland's correction factors for non-standard circuit design conditions apply.

Part 2: Data Base of Bond Grinding Circuit Efficiencies

This is being developed and will follow in an addendum to this guideline. See slide no. 13 in presentation "Bond Efficiency SLC (rev3)-print.pdf" for preliminary "Examples from Data Base".

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REFERENCES

For early analyses of plant grinding efficiency issues by F.C. Bond using Work Index see "Non-Cataracting Ball Mill Study", Engineering and Mining Journal, V. 158, No. 3, March, 1957, pp. 98-105, and "Action in a Rod Mill", Engineering and Mining Journal, V. 161, No. 3, March, 1960, pp. 82-85.

"Crushing and Grinding Calculations", Bond, F.C., Allis-Chalmers Publication No. 07R9235D, reprinted from British Chemical Engineering, Part l, June, 1961, and Part ll, August 1961, with additions and revisions, April, 1962.

"The Tools of Power Power: The Bond Work Index, A Tool to Measure Grinding Efficiency", Rowland, C.A., Jr., AIME Fall Meeting, Denver, 1976.

"Using the Bond Work Index to Measure Operating Comminution Efficiency", Rowland, C.A., Jr., Minerals and Metallurgical Processing, V. 15, No. 4, November, 1998, pp. 32-36.

"The Bond Standard for Comminution Efficiency", Rowland, C.A., Jr., and R.E. McIvor, Recent Advances in Mineral Processing Plant Design, SME, 2009, pp.328-331.

Annexes

A1. The Bond Impact Crushing WI Test Equipment and Procedure (Revised March 26, 2015)

B1. The Bond Rod Mill WI Test Equipment and Procedure (Revised March 26, 2015)

C1. The Bond Ball Mill WI Test Equipment and Procedure (Revised March 26, 2015)

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ANNEX A1: THE BOND IMPACT CRUSHING WI TEST EQUIPMENT AND PROCEDURE FOR BOND EFFICIENCY DETERMINATIONS

Rev. 6, March 26, 2015

Introduction and Background

This description of the Bond Impact Crushing WI Test was first developed from the listed references and discussions with the current inheritors of the original equipment and procedure, the staff at the testing laboratories of Metso in York and Danville, PA, and Milwaukee, WI, USA. It was further vetted with the members of the Bond Efficiency Sub-Committee of the Industrial Comminution Efficiency Working Group of the Global Mining Standards and Guidelines body. There are numerous other references which describe or mention this test, but it is believed those listed capture both its essence and sufficient details. This "guide" is aimed at reflecting the historic accuracy of the test as described in the references, while also intending that it meets the functional intentions of the developers. It is recognized that deviations from the equipment and procedure may be acceptable as long as the functional requirement of the test is achieved, that is, it is able to reproduce the Work Index value for the material being tested. Ultimately, calibration against accepted "standard" test equipment and procedures using reference samples will verify the acceptability of any particular variation(s) from this guideline.

Discussion of test result variability (due to the nature of the ore, nature of specimens tested, and test equipment and procedures) will come later.

The developers used a mix of British and metric units, and either or both are used here, as convenient.

Apparatus

Two hammers weighing 30 lbs. (13.6 kg) each are pendulum mounted such that when released they track back on the same line they were raised and impact simultaneously on opposite sides of each rock specimen. The hammer faces are 2 inches by two inches (51 mm x 51 mm) by one inch thick. They swing on a 16.25 inch (0.413 m) radius arc. When at rest the two hammers are separated by a 2 inch (51 mm) gap, the thickness of the two hammer faces. When the hammers are released after being equally raised angle 'α' from the vertical, the impact energy, in ft-lbs, is calculated as 82 (1 – cos α).

Ideally, the spacing between the two hammer axes should be adjustable to allow for suitable (horizontal) impacts of the hammer faces on particles of different widths.

Sample

For the purposes of Bond Efficiency calculations, the entire sample is crushed so that all particles pass through a 3 inch (76 mm) square opening. It uses particles which are then retained on a 2 inch (51 mm) square opening. (Note, for other purposes, such as crusher selection, Metso, and others, now specify feed particles differently, namely that they should be naturally occurring (crushed) pieces of broken rock, taken from a more broadly sized sample source, and have two near parallel faces that are between 2 and 3 inches (51-76 mm) in thickness. It should be noted if this is the case, but the so determined crushing Work Index nevertheless can be used in Bond Efficiency calculations. A minimum of ten, but preferably twenty, pieces are tested.

Procedure

1. Weigh the specimen (piece) to the nearest gram.
2. Mount the specimen between the hammers (using modeling clay, for example, on the pedestal below) such that its smallest dimension is between the hammer faces.
3. Measure its thickness, ***d***, at that point (i.e. the distance between the hammer faces as they are touching the specimen) to the nearest 1/10th (or 1/8th) of an inch (2.5 to 3 mm).
4. Implement suitable safety measures.
5. Initially raise the hammers as deemed suitable, e.g. 10 degrees (or more if the known material characteristics warrant), and release them to impact simultaneously on either side of the specimen.
6. Check the specimen for cracking or breaking. It is considered fractured if 1/3 or more of the original weight is broken off. If still whole, re-measure its thickness, if necessary, and increase the hammer angle by a suitable increment (e.g. 5 degrees, or more if the known material characteristic warrants) and return to same orientation. (Machines may also be marked off in impact energy units.) Repeat steps 4 and 5 until the specimen is broken. Record the last release angle used. If the particle continually chips away but does not break cleanly, note same and disregard in calculations.
7. Note the number of major fragments from the broken specimen. It is noted that this number and the particle weight do not enter the WI calculations.
8. Repeat the above steps for all specimens.
9. Determine the specific gravity, ***s***, of the specimens tested.

Calculations

1. Tabulate for each specimen the weight, ***w*** (grams); thickness, ***d*** (inches); hammer release angle, α (degrees); and number of major fragments, ***n***.
2. Calculate the energy per inch of thickness used to break each specimen. $C = 82\,(1 - \cos\alpha)/d$
3. Average the value of ***C*** for all specimens and calculate the Crushing Work Index, **WIc**:

WIc = 2.59 x ***Cave / s*** (kWh/st) Multiply by 1.1025 for kWh/mt.

See attached example test report and calculations. Other test statistics may be calculated and reported.

List of Symbols

- α The angle 'alpha' which the two hammers are raised from the vertical (e.g. degrees)
- ***d*** The particle thickness between the points it is contacted by the two hammers (inches or mm)
- ***s*** The particle specific gravity (unitless)
- ***w*** The particle weight (gms) (Not used in calculations)
- ***n*** The number of fragments of a broken particle (Not used in calculations)
- ***C*** Energy per unit of thickness to break a particle (in following example, ft-lb per inch)
- ***Cave*** Average energy per unit of thickness to break the particles
- **WIc** The Bond impact crushing test Work Index, kWh/t

References

"Crushing Tests by Pressure and Impact", Bond, F.C., T.P. No. 1895 in *Mining Technology*, January, 1946, and AIME Transactions, v. 169, 1947, pp. 58-66.

"Crushing and Grinding Calculations", Bond, F.C., Allis-Chalmers Publication No. 07R9235D, reprinted from British Chemical Engineering, Part I, June 1961 and Part II, Aug. 1961, with additions and revisions, Apr. 1962.

"Crushability Test", B.H. Bergstrom, Mineral Processing Handbook, SME, 1985, pp. 30-65 to 30-67.

Example Test Report

See following.

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ALLIS-CHALMERS
BOND TWIN PENDULUMS IMPACT CRUSHING TEST

MATERIAL [redacted]
SUBMITTED BY [redacted]

TEST NO. [redacted] DATE [redacted] 1983

SPECIMEN NO.	RANK	THICKNESS MM	THICKNESS INCH	WEIGHT GRAMS	PRODUCT PIECES	ANGLE AT BREAKAGE	FT*LB PER INCH	WORK INDEX
1	6	56	2.20	692	2	60	18.6	15.7
2	22	60	2.36	926	7	130	57.0	48.3
3	7	65	2.56	1074	2	75	23.7	20.1
4	9	62	2.44	824	5	75	24.9	21.1
5	5	58	2.28	576	3	60	18.0	15.2
6	8	57	2.24	1046	2	70	24.0	20.3
7	4	50	1.97	786	2	55	17.8	15.0
8	11	47	1.85	600	3	65	25.6	21.7
9	2	48	1.89	676	6	45	12.7	10.8
10	12	60	2.36	766	3	75	25.7	21.8
11	1	55	2.17	754	2	45	11.1	9.4
12	19	65	2.56	1247	2	120	48.1	40.7
13	10	54	2.13	472	4	70	25.4	21.5
14	23	50	1.97	1050	2	115	59.3	50.2
15	24	50	1.97	666	4	130	68.4	57.9
16	21	58	2.28	1150	4	125	56.5	47.8
17	18	60	2.36	1160	2	110	46.6	39.4
18	16	63	2.48	706	2	100	38.8	32.8
19	17	55	2.17	1010	3	100	44.4	37.6
20	20	55	2.17	1222	4	110	50.8	43.0
21	13	48	1.89	426	3	70	28.6	24.2
22	15	55	2.17	510	2	90	37.9	32.1
23	3	63	2.48	658	2	55	14.1	11.9
24	14	56	2.20	1156	3	85	34.0	28.7
AVERAGE			2.21	839.71	3.1		33.83	28.6

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ANNEX B1: THE BOND ROD MILL WI TEST EQUIPMENT AND PROCEDURE

Rev. 4, March 26, 2015

Introduction and Background

This description of the Bond Rod Mill WI Test was developed from the listed references, a report from a visit to the Allis-Chalmers manufacturing facilities in Milwaukee, Wisconsin, and lab facilities in Oak Creek, Wisconsin, by the writer in 1986, and discussions with the current inheritors of the original equipment and procedure, the staff at the testing laboratories of Metso in York, PA. There are numerous other references which describe or mention this test, but it is believed those listed capture both its essence and sufficient details. This "guide" is aimed at accurately reflecting the test procedure as described in the references, while also intending that it meets the functional intentions of the developers. It is recognized that deviations from the equipment and procedure may be perfectly acceptable as long as the functional requirement of the test is met, that is, it is able to reproduce the Work Index value for the material being tested. Ultimately, calibration against accepted "standard" test equipment and procedures using reference samples will verify the acceptability of any particular variation(s) from this guideline.

It is also recognized that different laboratories will apply extensively greater detail in the sub-procedures for this test (e.g. s, packing density determination, screening load and times, use (or not) of calibrated screens, determination of feed and product 80% passing sizes, etc.). This will greatly increase the reproducibility and comparability of test results from the same, versus different, laboratories. Once again, calibration against a "reference" laboratory will aid in making more accurate comparisons of test Work Index values between laboratories.

Discussion of test result variability (due to the nature of the ore, nature of samples tested, and test equipment and procedures) will come later.

The developers used a mix of British and metric units, and either or both are used here where convenient.

Apparatus

The Bond rod mill is made of metal, 12 inches (305 mm) maximum inside diameter, with a wave type lining. The internal mill length is 24 inches (610 mm).

The grinding charge consists of six 1.25 inch (31.8 mm) and two 1.75 inch (44.5 mm) diameter steel rods, all 21 inches (533.4 mm) in length, and weighing a total of 33,380 grams.

It runs at 46 rpm, and has a revolution counter. In order to deal with material segregation at the ends, it is run in a level position for eight revolutions, tilted 5 degrees up for one revolution, and then tilted 5 degrees down for one revolution, repeatedly during each grinding period.

Below the test feed control size of 0.5 inch (12.7 mm), the normal root of 2 series sieve analysis equipment is used for test feed, test product, and circulating load (screen oversize) material dry size analyses. Dry screening on one or more sieves is done between grinding cycles with the size of opening ("closing screen size") chosen to close-circuit the test. Dry screening is suitable for rod mill test requirements, except final product size analysis, which may require wet and dry sieving.

Sample

Ensure the material is dry. The rod mill test feed is all stage crushed and screened through a 0.5 inch (12.7 mm) screen. Avoid over crushing by screening, then crushing the oversize, successively, until it all passes the ½ inch (12.7 mm) screen.

It is best to start with approximately 14 kg of material with SG 2.7, proportionally more with higher material SG. This will allow for up to 10 grinding cycles. The material used for the feed size analysis can be re-used for the grind test.

Procedure

Summary:

The test feed is crushed to minus 0.5 inch (12.7 mm), and 1250 packed cubic centimeters are weighed, screen analyzed, and ground dry in closed circuit with 100 percent circulating load.

Tests can be made at mesh (closing screen) sizes from 4 mesh (4.76 mm) to 65 mesh (212 µm), but normally 8 mesh (2.38 mm) to 28 mesh (300 µm). The test control size to be chosen for the test is for these efficiency calculations is generally 1,190 µm.

At the end of each grinding period the mill is discharged, and the ground material is screened at the designated closing screen size. The undersize is weighed, and an equal amount of fresh feed is added to the oversize to make up the total weight of the 1250 cc originally charged to the mill. This is returned to the mill and ground for the number of revolutions calculated to give a circulating load of 100%. The grinding cycles are continued until the grams of undersize produced per revolution reaches equilibrium, and/or reverses its direction of increase or decrease. Then the final circulating load and the undersize from the last three cycles are screen analyzed.

Steps:

1. Ensure the sample is dry. Crush and screen the sample through 0.5 inch (12.7 mm).
2. Conduct a screen analysis of the test feed through the test closing screen size.
3. Determine the packed bulk density of the test material using a suitably sized container.
4. Determine the weight of 1250 cc of the material when packed. This is the material charge weight to be present in the rod mill.
5. Calculate the IPP (Ideal potential Product) for 100% circulating load, which is the material charge weight divided by two.
6. Rotary split the sample into suitably small batches, slightly smaller than the IPP. Further rotary split one or two of these batches into smaller sub-batches.
7. Make up the initial 1250 cc mill material charge from its calculated weight using the batches and sub-batches. Place the material and ball charge in the mill and run for, say, 50 revolutions. (This number can vary, chosen according to the closing screen size and experience of the lab.) If the test feed contains 50% or more minus the closing screen opening, assign zero as the first number of revolutions, screen the material at the closing screen, and make up the material to be ground to the desired weight with fresh feed.
8. Dump the material charge, screen it with the closing screen(s), and weigh screen oversize and undersize product.
9. Determine the weight of Net Product = Undersize Product – Undersize in Mill Feed
10. Determine the Net Grams (of product) per Revolution = Net Product / No. of Revs.
11. Add new feed to oversize (circulating load) to bring it up to the desired material load in the mill.
12. Calculate the number of mill revolutions to use for the next cycle. No. Revs. = (IPP – Weight of Undersize in newly add fresh feed) / Previous Net Grams per Rev.
13. Repeat steps 8 – 12 a minimum of five grind cycles, or until the Net Grams per Revolution (Gpr) reaches equilibrium, and/or reverses its direction of increase or decrease.
14. Determine the circulating load ratio for the last 3 cycles, equal to the material charge less the average product weight, then divided by the average product weight.
15. Conduct screen analyses of the combined undersize (product) of the last three cycles and the oversize (circulating load) from the last cycle.

Calculations

The average grams per revolution of the last three grind cycles is the rod mill grindability (Gpr).

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The Bond Rod Mill Work Index (kWh/st) is then calculated:

WIRM = 62 / [(P1) ^0.23 x (Gpr)^0.625 x (10/√P80 – 10/√ F80)]
Multiply by 1.1025 for kWh/mt.

P1 is the closing screen opening, in microns.

P_{80} and F_{80} are the test product and feed 80% passing sizes, respectively, in microns.

See attached example test report and calculations.

List of Symbols

IPP Mass of Ideal Potential Product from a test cycle

P1 Closing screen opening size used during the test, µm

Gpr Grindability, in net grams (new minus closing screen size) per mill revolution

F_{80} 80% passing size of the test circuit feed, µm

P_{80} 80% passing size of the test circuit product, µm

WIRM Bond rod mill test Work Index, kWh/t

References

"Crushing and Grinding Calculations", Bond, F.C., Allis-Chalmers Publication No. 07R9235D, reprinted from British Chemical Engineering, Part l, June 1961 and Part ll, Aug. 1961, with additions and revisions, Apr. 1962.

"Bond Closed Circuit Grindability Tests", B.H. Bergstrom, Mineral Processing Handbook, SME, 1985, pp. 30-65 to 30-68.

"Bond Rod Mill Work Index Test Laboratory Procedure", Allis-Chalmers Form 7669-M-4, provided to McGill University (R.E. McIvor), January 13, 1986.

"Grinding Circuit Study at Les Mines Selbaie: Report on Field Trip to Allis-Chalmers, Milwaukee, Wisconsin", R.E. McIvor, McGill University, January 17, 1986.

Example Test Report

See following.

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ALLIS-CHALMERS
BOND ROD MILL CLOSED CIRCUIT GRINDABILITY TEST
AT 1180 MICRO-METERS (14 TYLER MESH)

MATERIAL [redacted]
SUBMITTED BY [redacted]

TEST NO. [redacted] DATE [redacted] 1983

PERIOD	REVOLUTIONS OF MILL	GRAMS OF PRODUCT	GRAMS IN FEED	NET GRAMS PRODUCED	NET GRAMS PER REV.
1	200.0	1315.1	238.0	1077.1	5.386
2	197.0	1411.3	131.3	1280.0	6.497
3	162.0	1308.2	140.9	1167.3	7.205
4	147.0	1394.2	130.5	1263.7	8.596
5	122.0	1226.9	139.1	1087.8	8.916
6	120.0	1180.2	122.4	1057.8	8.815

LAB MILL FEED IS 1.91 KG/LITER, PACKED (=119.0 LB/FT**3)
EQUIVALENT TO 2384 GRAMS (1250 CC.) IN MILL
IDEAL POTENTIAL PRODUCT = 1191.2 GRAMS SPECIFIC GRAVITY = 3.06
AVERAGE OF LAST 2 PERIODS, 98.1 PER CENT CIRCULATING LOAD
GRINDABILITY AT 1180 MICRO-METERS = 8.865 NET GRAMS PER REV.

SIZE OF EQUIV. T.MESH	SIEVE ASTM MU-M	LAB.MILL FEED PERCENTAGE ON	PASSING	CIRCULATING LOAD PERCENTAGE ON	PASSING	LAST PER.PRODUCT PERCENTAGE ON	PASSING
1/2	13200	0.	100.00	0.	100.00	0.	100.00
3/8	9500	28.90	71.10	.88	99.12	0.	100.00
3	6700	29.30	41.80	4.89	94.23	0.	100.00
4	4750	14.89	26.90	5.84	88.39	0.	100.00
6	3350	6.19	20.71	8.99	79.39	0.	100.00
8	2360	5.21	15.50	15.49	63.90	0.	100.00
10	1700	4.05	11.45	26.98	36.92	0.	100.00
14	1180	1.47	9.98	35.22	1.70	.52	99.48
20	850	2.37	7.61	1.67	.03	23.61	75.87
28	600	1.47	6.14	0.	*00.00	15.52	60.35
35	425	1.16	4.98	0.	*00.00	11.90	48.45
48	300	.86	4.12	0.	*00.00	8.41	40.04
65	212	.61	3.51	0.	*00.00	6.02	34.02
100	150	.56	2.96	0.	*00.00	4.72	29.30
150	106	.47	2.49	0.	*00.00	3.82	25.49
200	75	.47	2.02	0.	*00.00	3.95	21.54
270	53	0.	*00.00	0.	*00.00	0.	*00.00
325	45	0.	*00.00	0.	*00.00	0.	*00.00
400	38	0.	*00.00	0.	*00.00	0.	*00.00
500	26	0.	*00.00	0.	*00.00	0.	*00.00
PAN	0	2.02	0.	.03	0.	21.54	0.

SCREEN ANALYSES DO NOT REPRESENT PLANT OPERATION RESULTS

80 PCT.PASSING FEED SIZE EQUALS 10644.7 MICRO-METERS
80 PCT.PASSING PRODUCT SIZE EQUALS 906.3 MICRO-METERS
BOND WORK INDEX FROM ABOVE TEST EQUALS 13.2
WORK INDEX METRIC = 14.6

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ANNEX C1: THE BOND BALL MILL WI TEST EQUIPMENT AND PROCEDURE

Rev. 4, March 26, 2015

Introduction and Background

This description of the Bond Ball Mill WI Test was developed from the listed references, a report from a visit to the Allis-Chalmers manufacturing facilities in Milwaukee, Wisconsin, and lab facilities in Oak Creek, Wisconsin, by the writer in 1986, and discussions with the current inheritors of the original equipment and procedure, the staff at the testing laboratories of Metso in York, PA. There are numerous other references which describe or mention this test, but it is believed those listed capture both its essence and sufficient details. This "guide" is aimed at accurately reflecting the test procedure as described in the references, while also intending that it meets the functional intentions of the developers. It is recognized that deviations from the equipment and procedure may be perfectly acceptable as long as the functional requirement of the test is met, that is, it is able to reproduce the Work Index value for the material being tested. Ultimately, calibration against accepted "standard" test equipment and procedures using reference samples will verify the acceptability of any particular variation(s) from this guide.

It is also recognized that different laboratories will apply extensively greater detail in the sub-procedures for this test (e.g. s, packing density determination, screening load and times, use (or not) of calibrated screens, determination of feed and product 80% passing sizes, etc.). This will greatly increase the reproducibility and comparability of test results from the same, versus different, laboratories. Once again, calibration against a "reference" laboratory will aid in making more accurate comparisons of test Work Index values between laboratories.

Discussion of test result variability (due to the nature of the ore, nature of samples tested, and test equipment and procedures) will come later.

The developers used a mix of British and metric units, and either or both are used here where convenient.

Apparatus

The Bond ball mill is made of metal, 12 inches (30.5 cm) inside diameter, and 12 inches (30.5 cm) inside length, with rounded corners. It is smooth except for the door hole used for charging.

The grinding charge consists of 285 iron or steel balls weighing a total of 20,125 grams. There are forty-three balls of 1.45 inch (36.8 mm) diameter, sixty-seven of 1.17 inch (29.7 mm) diameter, ten of 1 inch (25.4 mm) diameter, seventy-one of 0.75 inch (19.1 mm) diameter, and ninety-four of 0.61 inch (15.5 mm) diameter. This ball charge surface area is 842 square inches (5,432 square cm).

The mill runs at 70 rpm, and has a revolution counter.

The normal root of 2 series sieve analysis equipment is used for test feed, test product, and circulating load (screen oversize) material size analyses. Dry screening on one or more sieves is done between grinding cycles when the size of opening ("closing screen size") chosen to close-circuit the test is 75 µm (200 mesh) or coarser. Wet screening between grind cycles is used when the closing screen is 53 µm (270 mesh) or finer.

Sample

Ensure the material is dry. The ball mill test feed is all stage crushed through a 3.36 mm (6 Tyler mesh) screen. Avoid over crushing by screening, then crushing the oversize, successively, until it all passes the 3.36 mm screen.

It is best to start with approximately 8 kg of material with SG 2.7, proportionally more with higher material SG. This will allow for up to 10 grinding cycles. The material used for the feed size analysis can be re-used for the grind test.

Procedure

Summary:

The test feed is crushed to minus 3.36 mm, and 700 packed cubic centimeters are weighed, screen analyzed, and ground dry in closed circuit with 250 percent circulating load.

Tests can be made at 28 mesh, 600 µm (closing screen) or finer. The test control size to be chosen for the test is described in the Guideline for Determining Grinding Circuit Work Index Ratio Efficiency.

At the end of each grinding period the mill is discharged, and the discharge is screened at the designated closing screen size. The undersize is weighed, and an equal amount of fresh feed is added to the oversize to make up the total weight of 700 cc originally charged to the mill. This is returned to the mill and ground for the number of revolutions calculated to give a circulating load of 250%. The grinding cycles are continued until the grams of undersize produced per revolution reaches equilibrium, and/or reverses its direction of increase or decrease. Then the final circulating load and the undersize from the last three cycles are screen analyzed.

Steps:

1. Ensure the sample is dry. Crush and screen the sample through 3.36 mm (6 Tyler mesh).
2. Conduct a screen analysis of the test feed, at minimum through the test closing screen size.
3. Determine the packed bulk density of the test material using a suitably sized container.
4. Calculate the weight of 700 cc of the material when packed. This is the material charge weight to be present in the ball mill.
5. Calculate the IPP (Ideal potential Product) for 250% circulating load, which is the material charge weight divided by 3.5.
6. Rotary split the sample into suitably small batches, slightly smaller than the IPP. Further rotary split one or two of these batches into smaller sub-batches.
7. Make up the initial 700 cc mill material charge from its calculated weight using the batches and sub-batches. Place the material and ball charge in the mill and run for, say, 150 revolutions. (This number can vary, chosen according to the closing screen size and experience of the lab.). If the fresh feed contains more than 30% minus the closing screen size, assign zero as the first cycle number of revolutions, screen out the undersize, and add fresh feed to make up the charge to the desired weight to be ground first.
8. Dump the material charge, screen it with the closing screen(s), and weigh screen oversize and undersize product.
9. Determine the weight of Net Product = Undersize Product – Undersize in Mill Feed
10. Determine the Net Grams (of product) per Revolution = Net Product / No. of Revs. (Gpr)
11. Add new feed to oversize (circulating load) to bring it up to the desired material load in the mill.
12. Calculate the number of mill revolutions to use for the next cycle. No. Revs. = (IPP – Weight of Undersize in newly add fresh feed) / Previous Net Grams per Rev.
13. Repeat steps 8 – 12 a minimum of five grind cycles, or until the Net Grams per Revolution reaches equilibrium, and/or reverses its direction of increase or decrease.
14. Determine the circulating load ratio for the last 3 cycles, equal to the material charge less the average product weight, then divided by the average product weight.
15. Conduct screen analyses of the combined undersize (product) of the last three cycles and the oversize (circulating load) from the last cycle.

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Calculations

The average grams per revolution of the last three grind cycles is the ball mill grindability (Gpr).

The Bond Ball Mill Work Index (kWh/st) is then calculated:

WIBM = 44.5 / [(P1) ^0.23 x (Gpr)^0.82 x (10/$\sqrt{P_{80}}$ – 10/$\sqrt{F_{80}}$)]
Multiply by 1.1025 for kWh/mt.

P1 is the closing screen opening, in microns.

P_{80} and F_{80} are the test product and feed 80% passing sizes, respectively, in microns.

See attached sample test report and calculations.

List of Symbols

IPP Mass of Ideal Potential Product from a test cycle

P1 Closing screen opening size used during the test, µm

Gpr Grindability, in net grams (new minus closing screen size) per mill revolution

F_{80} 80% passing size of the test circuit feed, µm

P_{80} 80% passing size of the test circuit product, µm

WIBM Bond ball mill test Work Index, kWh/t

References

"Crushing and Grinding Calculations", Bond, F.C., Allis-Chalmers Publication No. 07R9235D, reprinted from British Chemical Engineering, Part I, June 1961 and Part II, Aug. 1961, with additions and revisions, Apr. 1962.

"Bond Closed Circuit Grindability Tests", B.H. Bergstrom, Mineral Processing Handbook, SME, 1985, pp. 30-65 to 30-68.

"Bond Ball Mill Work Index Test Laboratory Procedure", Allis-Chalmers Form 7669-3, revised May 17, 1983, provided to McGill University (R.E. McIvor), January 13, 1986.

"Grinding Circuit Study at Les Mines Selbaie: Report on Field Trip to Allis-Chalmers, Milwaukee, Wiscomsin", R.E. McIvor, McGill University, January 17, 1986.

Example Test Report

See following.

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ALLIS-CHALMERS
BOND BALL MILL CLOSED CIRCUIT GRINDABILITY TEST
AT 106 MICRO-METERS (150 TYLER MESH)

MATERIAL [redacted]
SUBMITTED BY [redacted]

TEST NO. [redacted] DATE [redacted] 1983

PERIOD	REVOLUTIONS OF MILL	GRAMS OF PRODUCT	GRAMS IN FEED	NET GRAMS PRODUCED	NET GRAMS PER REV.
1	225.0	444.7	96.6	348.1	1.547
2	229.0	408.2	31.8	376.4	1.644
3	217.0	409.1	29.2	379.9	1.751
4	204.0	397.9	29.3	368.6	1.807
5	198.0	393.0	28.4	364.6	1.841
6	194.0	382.5	28.1	354.4	1.827

LAB MILL FEED IS 1.93 KG/LITER, PACKED (=120.4 LB/FT**3)
EQUIVALENT TO 1351 GRAMS (700 CC.) IN MILL
IDEAL POTENTIAL PRODUCT = 385.8 GRAMS SPECIFIC GRAVITY = 3.06
AVERAGE OF LAST 3 PERIODS, 245.4 PER CENT CIRCULATING LOAD
GRINDABILITY AT 106 MICRO-METERS = 1.825 NET GRAMS PER REV.

SIZE OF EQUIV. T.MESH	SIEVE ASTM MU-M	LAB.MILL FEED PERCENTAGE ON	PASSING	CIRCULATING LOAD PERCENTAGE ON	PASSING	LAST PER.PRODUCT PERCENTAGE ON	PASSING
1/2	13200	0.	100.00	0.	100.00	0.	100.00
3/8	9500	0.	100.00	0.	100.00	0.	100.00
3	6700	0.	100.00	0.	100.00	0.	100.00
4	4750	0.	100.00	0.	100.00	0.	100.00
6	3350	0.	100.00	0.	100.00	0.	100.00
8	2360	32.51	67.49	9.91	90.09	0.	100.00
10	1700	21.09	46.40	15.79	74.30	0.	100.00
14	1180	6.41	39.99	7.81	66.50	0.	100.00
20	850	13.88	26.11	6.44	60.06	0.	100.00
28	600	6.46	19.65	5.32	54.74	0.	100.00
35	425	3.95	15.70	6.39	48.35	0.	100.00
48	300	2.99	12.71	8.02	40.33	0.	100.00
65	212	2.40	10.30	12.27	28.06	0.	100.00
100	150	1.76	8.54	11.75	16.30	0.	100.00
150	106	1.39	7.15	15.66	.64	3.04	96.96
200	75	1.55	5.61	.64	0.	20.17	76.80
270	53	1.23	4.38	0.	*00.00	14.64	62.15
325	45	.59	3.79	0.	*00.00	3.59	58.56
400	38	.32	3.47	0.	*00.00	9.81	48.76
500	26	0.	*00.00	0.	*00.00	9.81	38.95
PAN	0	3.47	0.	0.	*00.00	38.95	0.

SCREEN ANALYSES DO NOT REPRESENT PLANT OPERATION RESULTS

80 PCT.PASSING FEED SIZE EQUALS 2746.1 MICRO-METERS
80 PCT.PASSING PRODUCT SIZE EQUALS 79.7 MICRO-METERS
BOND WORK INDEX FROM ABOVE TEST EQUALS 10.0
WORK INDEX METRIC = 11.0

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