A SIMPLE METHOD OF ASSESSING BALL MILL HEALTH USING BOND TESTS AND FUNCTIONAL PERFORMANCE

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ABSTRACT

Health checkups are just as important for grinding circuits as for grinding circuit operators. This paper describes a process for performing a non-intrusive survey of the operating plant (no mill shut-downs required), collecting a sample of plant feed for testing at a commercial laboratory, and then interpreting the survey to decide if further investigation is needed. If the health check comes back "clean", then the mill is declared healthy and no further work is needed. If the health check comes back "sick", then the Functional Performance equations identify which part of the grinding circuit is operating poorly and future corrective action can be tailored to that unit operation. A case study of a grinding circuit survey conducted at the Detour Gold Corporation mine in Ontario demonstrates the process.

Functional Performance has been used for many years to disentangle different types of ball mill circuit efficiencies. The novel component of this work is to use a set of standard Bond ball mill grindability tests at different closing mesh sizes to generate a "Levin B" metric which is then substituted into the Functional Performance ball mill grinding efficiency equation to determine the industrial mill's efficiency as a percentage of the laboratory mill's efficiency. This removes the ore hardness as an unknown variable, providing a simple percentage score rather than the arcane metric returned in the conventional Functional Performance grinding efficiency metric.

KEYWORDS

Grinding, comminution, benchmarking, functional performance

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INTRODUCTION

Mill metallurgists need to know when a circuit is running poorly in order to avoid wasting time optimizing a circuit that is running well. When a circuit is running inefficiently, the metallurgists must then identify which part of the circuit needs attention in order to focus on the root cause of the problem.

The Functional Performance framework by Metcom Technologies provides a great tool for performing these sorts of analyses (McIvor, 2005; McIvor et al, 2017; Metcom Technologies, 2013). A standard laboratory Bond ball mill grindability test that provides a ball mill work index and other parameters can be combined with Functional Performance permitting the performance of an industrial ball mill to be assessed independent of ore hardness.

The purpose of this Paper is to present an extension to the Metcom framework that compares the industrial mill to the standard laboratory mill using the same units of measurement for both, specifically the kWh of grinding energy needed to produce one kilogram of finished product.

METHODOLOGY

The methodology of Functional Performance has been described frequently in conferences, and only a brief summary will be provided to re-introduce the key concepts. Functional Performance is a method to assess the health of a closed-circuit ball mill circuit by separating the overall circuit efficiency into separate efficiency measurements for the classification and grinding components of the circuit. This permits plant metallurgists to determine which unit operations (hydrocyclone or grinding mill) require optimization.

A ball mill circuit survey is required to generate a mass balance and where the percent solids and particle size determinations are made for each of the following streams:

- hydrocyclone overflow (circuit product);
- hydrocyclone underflow (or ball mill feed);
- ball mill product; and
- (optional) hydrocyclone feed and/or feed to the ball mill circuit (Eg. SAG mill product).

The survey is normally done for between thirty minutes to an hour with periodic stream cuts resulting in representative samples. It is not necessary to stop the mill during this survey, the plant will run continuously throughout the survey, meaning that no production is lost as a result of the survey.

A sample of raw ore is also required, for example, from the stockpile feed conveyor belt. The raw ore sample will be tested in a standard Bond ball mill grindability test (aka. the Bond ball mill work index test) with a closing screen size chosen so the test product P_{80} closely matches the survey product P_{80}. Depending on the plant configuration, it may be possible to also collect this raw ore sample without shutting down any grinding mills.

Conventional Functional Performance equations

McIvor defines two size classes of interest: “fines” that are the desired size (or smaller) and “coarse” that require grinding down to the product size.

The first measurement of interest is the classification circuit efficiency which is the average of the coarse fraction in the ball mill feed and ball mill product. This metric describes what fraction of the solids in the ball mill actually needs grinding. Classification circuit efficiency is computed by simply taking the average of the percentages of coarse material in the ball mill feed and product.

The second measurement of interest is the ball mill’s grinding efficiency. This is calculated by first determining the quantity of fines being generated in the ball mill (the difference between the %fines in the mill discharge minus the %fines in the mill feed, multiplied by the ball mill solids flow rate).

t/h of new fines = (%fines in mill product – %fines in mill feed) × mill feed dry t/h solids

The efficiency depends on the amount of grinding power consumed to make the new fines. The mill grinding rate is defined as the kg/h of fines created per effective kilowatt of mill power.

mill grinding rate kg/kWh = (t/h of new fines) × (1000 kg/t) ÷ (motor kW at mill shell) ÷ CSE

Extended Functional Performance equations

The way that McIvor treats the mill grinding efficiency comparison to a standard Bond ball mill grindability test is useful for performing plant on/off trials (Eg. comparing grinding media), but is not useful as a benchmarking tool because the units of measurement are unwieldy: (t/h fines)/(g/rev). See Torrealba-Vargas et al, 2019 for the classical Functional Performance evaluation of this Detour Gold survey. A simpler benchmarking method is to determine the energy required to create fines in both the industrial mill and the laboratory mill using the same measurement units of (kg of fines)/kWh.

To accomplish this requires the kg of fines production per kWh consumed in the Bond grindability test. This isn’t reported in a standard ball mill work index test, but the method of Levin, 1989, can be used to calculate a “Levin B value” which is the kW·h per revolution of a Bond laboratory ball mill. Dividing ball mill grindability (g of product/rev) by the Levin B (kWh/rev) gives the desired units of measurement (g/kWh). The Levin B is calculated from a Bond ball mill grindability test as follows:

$$B=\frac{4.9\times10^{-3}\times G^{0.18}}{P_{100}^{0.23}\left(100-U\right)}$$

where: G is the g/rev,
P_{100} is the test closing screen aperture size, and
U is the percentage of under size in the feed to the test.

CASE STUDY, DETOUR GOLD

A grinding circuit survey was done on February 16, 2017 on the ball mill № 1 circuit at the Detour Gold Mine in north-eastern Ontario. The Detour Gold grinding circuit has two lines each consisting of a single SAG mill in closed circuit with a pebble crusher and a single ball mill in closed circuit with hydrocyclones, as described in Torrealba-Vargas et al, 2015.

Mill survey measurements

- Fresh feed rate 1651 dry t/h (SAG product);
- Hydrocyclone feed rate 4577 dry t/h (654 t/h diverted to gravity circuit);
- Ball mill feed rate 2270 dry t/h;
- Ball mill power draw 14 354 kW (corrected to pinion output/mill shell);
- Hydrocyclone overflow P_{80} 90.5 µm;
- Hydrocyclone underflow (ball mill feed) 15.8% passing 90.5 µm;
- Ball mill product 40.3% passing 90.5 µm; and
- SAG mill screen undersize 41.0% passing 90.5 µm.

Laboratory test result, survey ore sample

A Bond ball mill grindability test was performed at the Dawson laboratory on a sample of SAG mill feed collected at the time of the survey.

Table 1 – Ball mill grindability test

Test closing mesh, µm	Feed F_{80}, µm	Product P_{80}, µm	grams/rev	Work index, metric	Feed %pass undersize	Levin B kWh/rev
75	1908	58.7	1.258	14.0	14.6	2.22×10^{-5}

Worked calculations

- The classification system efficiency is 71.95% = (100 – average of 15.8% and 40.3%).
- The ball mill circuit specific energy consumption is 8.69 kWh/t = (14 354 ÷ 1651).
- Fines generation rate in the ball mill 556 t/h = (2270 × [0.403 – 0.158]).
- Plant mill grinding rate 54 kg/kWh = (556 × 1000 ÷ 14354 ÷ 0.7195).
- Laboratory mill grinding rate 57 kg/kWh = (1.258 ÷ [2.22×10^{-5}] ÷ 1000).

- Ball mill grinding efficiency 95.0% = (54 ÷ 64).

Benchmark result

A ball mill grinding efficiency above 80% is considered “good”; the measured efficiency of 95% is “very good”. This suggests that the ball mill is functioning well, and would not see any substantial benefit from further optimization.

DISCUSSION

The ball mill test was done at too fine a closing mesh size to replicate the P_{80} observed in the plant. The “very good” efficiency conclusion is questionable because of the significant difference in the survey product size and the laboratory test product size. Performing a series of ball mill work index tests at different closing mesh sizes on the survey sample would have been beneficial because they would remove any doubt in the conclusion due to particle size.

Sensitivity of Levin B to product size

It is reasonable to consider whether or not choosing a different closing screen on the ball mill test would provide a different result. Earlier grindability tests conducted at SGS Lakefield during the project design phase evaluated the ball mill work index at a range of different product sizes. The main ore type (KMF composite) returned the following:

Table 2 – Detour Gold KMF composite ball mill grindability results

Test closing mesh, µm	Feed F_{80}, µm	Product P_{80}, µm	grams/rev	Work index, metric	Feed %pass undersize	Levin B kWh/rev
150	2101	112	1.65	14.1	14.5	1.98×10^{-5}
106	2101	82	1.40	14.4	12.3	2.03×10^{-5}
74	2101	44	0.94	16.1	8.7	1.97×10^{-5}

The Levin B results were very consistent for the other Detour Gold ore types except for the soft “talc” ore type “TC” (see Figure 1). The Levin B value does not change much in the size range of 45 µm to 110 µm, so there is no need to provide a size correction on the survey grindability Levin B value. This is good and supports the conclusion that the ball mill is operating efficiently.

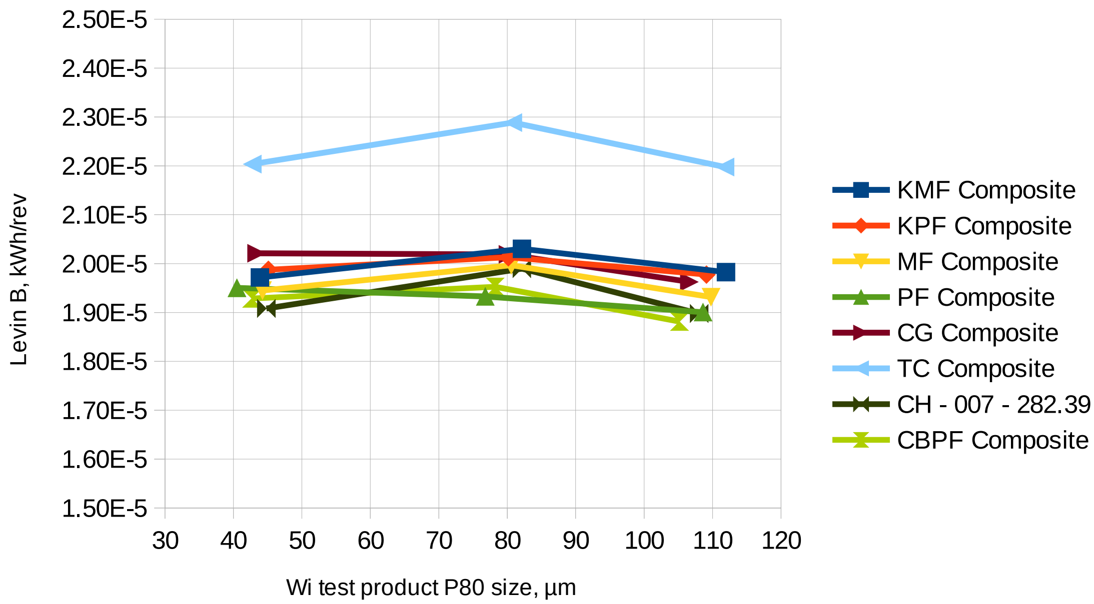

Figure 1 – Detour Gold Levin B variation by test product size

Sensitivity of grams per revolution to product size

The grams per revolution of the grindability test change significantly at different test P_{80} sizes, as seen in Table 2. It is possible to determine a synthetic grams per revolution "corrected" for product size, but this requires a lengthy and convoluted set of computations that is not recommended for plant metallurgists to undertake. Re-running the Bond grindability tests at different closing sizes is the recommended procedure.

If it is not possible to re-run the Bond tests, then computations involving the method of Josefin & Doll (2018) using the variation in work index by product size and back-calculating Bond's ball mill grindability equation (Bond, 1962) can provide a synthetic grams per revolution.

$$G^{0.82} = \frac{4.45}{P_{100}^{0.23} \times Wi\left(\frac{1}{\sqrt{P_{80}}} - \frac{1}{\sqrt{F_{80}}}\right)}$$

The KMF composite sample was fitted to the ore's specific energy consumption by size (Hukki, 1962), with a resulting Hukki exponent of –0.76 (for comparison, the Bond equation exponent is –0.5). The measured ball mill work index of 14.0 (metric) at 59 µm P_{80} is predicted to be 13.2 metric units at 90.5 µm according to the Josefin equation. To get a precisely 90.5 µm test P_{80} would require a closing screen aperture size of 127.5 µm, which is not a standard screen size (we are dealing with synthetic data, why not synthetic laboratory equipment, too?). The synthetic test result is predicted to be as per Table 3.

Table 3 – Synthetic grindability test result corrected to 90 µm P_{80} product

Test closing mesh, µm	Feed F_{80}, µm	Product P_{80}, µm	grams/rev	Work index, metric	Feed %pass undersize
127.5	1908	90	1.609	13.2	12.0

Entering the synthetic grams per revolution and Levin B value into the Functional Performance framework gives a very different outcome: the ball mill grinding efficiency is 72% rather than 95%. This demonstrates a high degree of sensitivity to the ball mill grindability test closing mesh size, and suggests that the conclusion that the ball mill was operating efficiently might be optimistic.

Grinding efficiency sensitivity to finer product size target

The efficiency of the ball mill circuit making 60 µm product is easier to access, as this is roughly the product size observed in the Bond ball mill grindability test. The ball mill feed and product percentage passing 60 µm is 11% and 34%, respectively. The computed classification system efficiency is 77.5%, indicating good efficiency as this size.

- The plant mill grinding rate is 47 kg/h of fines per kW = 560 t/h × 1000 kg/t ÷ 14573 kW ÷ 0.775
- The laboratory grinding rate is 57 kg/kWh = 1.26 g/rev ÷ 1000 g/kg ÷ (2.22×10^{-5})
- The industrial mill grinding efficiency at 60 µm is 83%, suggesting good efficiency.

Next step, how to improve the circuit efficiency

If the classification system efficiency is less than 70%, then work to improve the hydrocyclone operation. For example, increase the %solids in the underflow to squeeze more of the fines-bearing water into the overflow.

If the grinding efficiency is less than 80%, then more work is needed to identify what is causing the poor efficiency. One possibility is the ball size is a mismatch for the particle sizes of the mill charge. This can be observed by fitting a population balance model such as MolyCop Tools to the ball mill and observing the Selection Function (or the Breakage Rate vector in JKSimMet) versus the mill feed sizes. The example in Figure 2 shows a copper mine with a poor grinding efficiency of 70%. Investigation showed that the ball mill selection function is focused on too fine a size class, meaning that grinding energy is not being efficiently transferred to the coarse particles that need to be ground. To grind these coarser particles, a larger ball size is recommended.

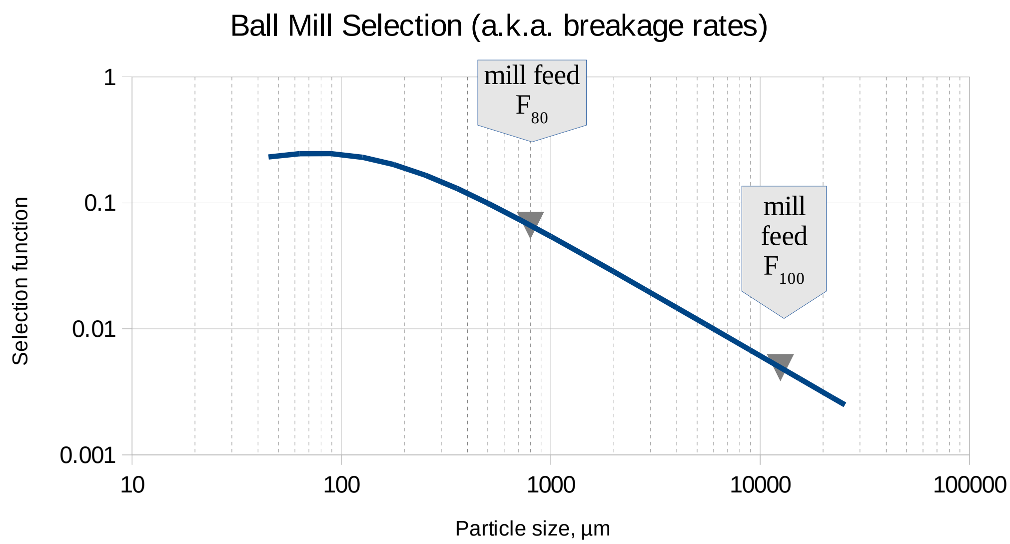

Figure 2 – Example of the effect of too small a ball size on ball mill selection function

CONCLUSIONS

- An unobtrusive grinding circuit survey around a ball mill circuit combined with a sample of raw ore can provide a useful basis of assessment of the efficiency of the ball mill circuit. The survey can usually be done without shutting down any mills and should have negligible impact on plant production.

- Functional Performance provides a way to determine the mill grinding rate of an industrial mill as the kilograms of fines generated per kWh of energy consumed.

- The Levin B value provides a way to determine the mill grinding rate of a laboratory mill as the kilograms of fines generated by kWh of energy consumed.

- The fraction of industrial mill grinding rate over the laboratory mill grinding rate is a useful metric of mill efficiency that can be expressed as a simple percentage. Results above 80% are generally indicative of an efficient grinding circuit.

- The laboratory mill grinding rate is very sensitive to the ball mill grindability test closing mesh size, and the test should be conducted on at least two closing mesh sizes so as to straddle the industrial circuit product P_{80} size.

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