Ball mill media optimization
through functional performance modeling

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The objective of the study conducted by the authors is to determine what media size(s) addition will maximize any given plant ball mill's grinding efficiency (Fig. 1). The functional performance parameters "mill grinding rate through the size of interest," and "cumulative mill grinding rates" from both plant and small-scale tests are applied to this task. A plant media sizing methodology, and industrial case studies, are provided.

Figure 1

A typical plant ball mill.

Background

A previous article ("Ball mill classification system optimization through functional performance modeling," Nov. 17, McIvor et al., 2017, *Mining Engineering*) described circuit classification system efficiency (CSE), equal to the percentage of coarse (plus circuit P80 target size) material in the ball mill. It can be measured and then increased through pump and cyclone adjustments. By so transferring the application of ball mill power from fine (minus P80 product size) to coarse material, circuit efficiency is increased and overgrinding is decreased.

The other factor that determines overall circuit efficiency is how well the power that is applied to the coarse material grinds it. This is affected by design and operating variables like the media sizing and mill percent solids. From circuit functional performance (McIvor et al., 1990):

Circuit production rate of new fine material (t/h) = Power applied to coarse material (kW) x Mill grinding rate of coarse material (t/kWh) (1)

The power applied to coarse material is the total mill power multiplied by the CSE. Therefore:

Circuit production rate of new fine material (t/h) = Total mill power (kW) x CSE (%) x Mill grinding rate of coarse material (t/kWh) (2)

Production rate, mill power and CSE can be measured during a plant circuit survey. The mill grinding rate of coarse material is then calculated. At the circuit target P80 size, this is the mill grinding rate (of coarse material) through the size of interest. The objective is to maximize this rate. The mill grinding efficiency can also be calculated by taking the ratio of the mill grinding rate over the material's grindability as measured in the lab. Mill percent solids optimization has thusly been achieved (McIvor et al., 2000). For media sizing, maximizing the mill grinding rate on a given ore is equivalent to maximizing the mill grinding efficiency. Ores of different grindability will be part of the discussion.

As shown below, "mill energy specific cumulative grinding rates" can be calculated for all screen sizes from mill specific energy input (kWh/t) and mill feed and product size distributions (Hinde, 1999; McIvor and Finch, 2007; McIvor et al., 2017). These include the mill grinding rate through the size of interest, calculated independently as above. Media sizing

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directly affects these rates.

Results of literature review

A previous literature review on ball mill media sizing (McIvor, 1997) was updated (Staples et al., 1997; Banasi et al., 1999; Orford et al, 2006; LaMarsh, 2015). The main findings are as follows.

- Plant results from changing media size were sometimes significant (Taggart, 1945; Orford et al., 2006; LaMarsh, 2015), but also often produced no measurable effect. Lakeshore reported that “the curve of mill performance was relatively flat over the range of 0.8 to 1.1 times the optimum ball diameter” (Taggart, 1945).
- Test mills used for media sizing investigations need to be reasonably large (at least 0.4 m in diameter was suggested), depending on size of balls and ore being tested.
- Ball surface wear rate is approximately constant, but with variations due to hardness, and other factors. Consumption is closely related to total ball charge surface area.
- A useful guideline for make-up ball size for a new circuit was provided by Bond (1958).

$$B = (F80/K)^{0.5} \times [(WI \times SG)/(Cs \times D^{0.5})]^{1/3} \qquad (3)$$

In the historical British units:

B	Recommended make-up ball size, inches.
F80	Circuit feed 80 percent passing size, microns.
K	A constant, 350 for wet overflow mills, etc.
WI	Bond test Work Index, kWh/short ton.
SG	Ore specific gravity.
Cs	Mill speed in percent of critical.
ID	Mill inside (liners, working) diameter, feet.

It pre-dated (semi-)autogenous grinding, and needs to be adjusted for those applications. Other guides (e.g. Azzaroni, 1981) provide different results. These serve only as an initial guide. Determining the optimum for any operating mill requires more work.

Figure 2

Media size testing apparatus.

- Prior to the functional performance equation (McIvor et al., 1990), the absence of a performance parameter to isolate ball mill grinding efficiency handicapped efforts to study the effect of any ball mill design or operating variable. Along with plant testing difficulties, only fairly large changes in circuit performance could be linked to a media size change.
- Population balance modelling was deemed unsuitable for this purpose. As noted by Meloy et al., (1990), any number of different breakage rate curves can be derived from the same mill feed and product sizing. Mill residence time of coarse versus fine particles is unaccounted for (McIvor, 2018). Conflicting conclusions regarding the effects of media sizing have been reported by these modelers. However, some of the experimental data they generated was useful.

Grinding test apparatus and procedure

The test mill (Fig. 2) is 0.6 m (2 ft) inside diameter by 0.2 m (0.67 ft) inside length. It is operated at 65 percent of critical speed. Each ball charge is close to 95 kg (209 lb), occupying 34 percent of the mill volume. Balls are used that represent a fully graded charge based on constant wear rate in a continuously operating mill. Slurry volume occupies the 40 percent voids volume in the 34 percent ball charge. The drive shaft is torque-metered and records once per second. Drive losses (a roller bearing between the mill and the torque meter) have been measured to be negligible.

Media charges were prepared by weighing and counting out the number of balls needed in each size class, determined by their individual weights and the specific gravity of steel. Twenty-seven equilibrium media charges are currently available for testing. Examples are given in Table 1.

The test mill feed is screen

Table 1

Examples (ten) of equilibrium ball charges for the torque mill (top sizes).

89 mm (3.5 in)	64 mm (2.5 in)	38 mm (1.5 in)	50/50 wt% 76/25 mm	50/50 wt% 51/25 mm
76 mm (3.0 in)	51 mm (2.0 in)	25 mm (1.0 in)	50/50 wt% 76/51 mm	30/70 wt% 64/32 mm

analyzed, in duplicate. The mill is loaded with the grinding media, solids and water. The grinding time is estimated for a desired energy input, E, in kWh/t. The mill speed is manually set and confirmed with a revolution counter. After grinding, the slurry is separated from the charge, dried, the solids rotary split and screen analyzed in duplicate. The torque readings and mill speed are used to calculate the energy input. The specific energy input (E, in kWh/t) is the energy input divided by the mill solids load. The energy specific cumulative grinding rate (k) at each particle size is then calculated from the test feed and product size distributions using the first order disappearance rate equation (Equation 4).

Weight of + size remaining (any mesh size) =

Weight of + size in test feed x $e^{(-k \times E)}$ (4)

Test work has shown that 'k' values are essentially constant with reasonable variations in energy input.

Example calculation of test mill grinding rates

Whether from a plant survey or torque-mill test, the calculation method of the mill energy specific cumulative grinding rates is shown by the following example. Using plant data, the value of E is the specific energy input to the solid material as it passes through the plant mill (the mill power draw divided by the mill solids throughput rate), and assumes plug flow and equal residence time of all particle sizes (see later note). The value of E for the torque mill test is the mill energy input divided by the solids load.

The energy specific cumulative grinding rate at each screen size is calculated from a torque-mill test as in the example that follows.

Torque mill solids load during test: 11.25 kg (24.8 lb) of ball mill feed sample from plant survey.

Sample is reconstituted with water to be the same percent solids as the plant ball mill discharge.

Mill speed: 35.2 rpm (65 percent of critical speed)
Length of time of test: 363 seconds
Average torque reading: 1,056 in-lbs
Mill HP = (1,056 in-lbs / 12 in./ft) x (35.2 rpm x 5252 HP/(ft-lbs /rpm) = 0.590 HP (or 0.440 kW)
E = 0.440 kW x (363 s / 3600 s/h) / (11.25 kg / 1,000 kg/mt) = 3.942 kWh/mt

At 150 µm, the mill feed was 69.74 percent cumulative retained, and the mill discharge 53.70 percent (with two decimal places carried for clarity). Using Equation 4:
$53.70 = 69.74 \times e^{(-k \times 3.942 \text{ kWh/mt})}$

Solving, k = 0.0663 mt/kWh

The complete size distributions and (cumulative energy specific) grinding rates from the above test are in Table 2.

Table 2

Example test mill feed and product size distributions and cumulative grinding rates.

Screen opening (µm)	Mill feed (Cum. % Ret.)	Mill discharge (Cum. % Ret.)	Cum. Gr. rate (mt/kWh)
16,000	0.07	0.00	-
12,500	0.68	0.12	0.440
9,500	1.70	0.46	0.332
6,730	3.12	0.96	0.299
4,760	4.51	1.24	0.328
3,360	6.01	1.38	0.373
2,380	7.73	1.56	0.406
1,680	9.72	1.76	0.433
1,190	12.35	2.11	0.448
840	16.62	3.13	0.424
595	22.65	5.76	0.347
420	31.72	12.38	0.239
300	44.76	25.2	0.146
212	58.53	40.58	0.0929
150	69.74	53.70	0.0663
106	78.61	64.81	0.0490
75	83.80	71.86	0.0390
54	87.28	77.11	0.0314
37	90.23	81.85	0.0247

Comparison of test mill and plant mill grinding rates

The mill grinding rate through the size of interest (150 µm, the circuit target P80) calculated from the plant survey data using the functional performance equation was 0.0568 t/kWh. The 'energy specific cumulative grinding rates' for the survey calculated from ball mill feed and discharge size distributions, including the rate through 150 µm of 0.0569 t/h, are plotted in Fig. 3 along with the comparative torque mill grinding rates from the above test done on a sample of the ball mill feed.

In this case the calculated grinding rates are higher in the plant at the coarsest sizes than the test mill. Note that plant rate calculations provide "apparent" values, i.e. assume equal residence time for all particle sizes. Preferential retention of coarser particles, a known phenomenon (McIvor, 2018), exaggerates their grinding rates. The grinding rate through 150 µm, the circuit target P80 and therefore the size of interest, is higher for the test mill (0.0663 t/kWh) than was measured in the plant mill (0.0569 t/kWh).

Case studies

Plant parallel ball milling with different ball sizes. Figure 4 displays plant grinding rates of parallel ball mills receiving the same feed, but using different ball sizes.

The target P80 for these circuits falls under the crossing region of the two grinding rate curves. This shows that use of two different media sizes can yield the same ball mill grinding efficiency through a specific size. If the grind target was finer, the smaller media would be more efficient, and vice versa, showing that the most efficient media depends on the circuit product size. With lower consumption rate and lower unit cost, the larger media is the better choice of the two for these mills.

Batch torque-mill results showing grinding efficiency improvements with certainty. When the batch test grinding rates on mill feed with an alternative ball charge are all higher than those with the current ball charge, increased grinding efficiency in the plant is a virtual certainty. These data can take two forms. The first is shown in Fig. 5, where going to smaller ball sizes than the 38 mm (1.5 in) make-up size in use results in increased grinding rates at all particle sizes. In this case the smallest media are capable of breaking the coarsest particles, and the increased rate appears to be a matter of the frequency of breakage.

The second case, Fig. 6, is when grinding rates reach a maximum before reaching the coarsest particle sizes, but an alternative charge, in this case a mix of top ball sizes (versus use of a single

Figure 3

Calculated plant (apparent) and test mill grinding rates on the same feed material.

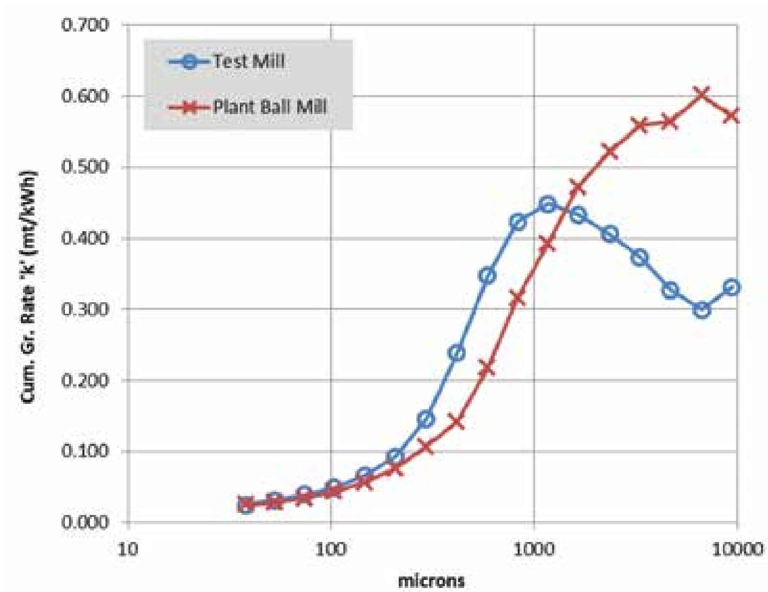


Figure 4

Plant cumulative grinding rates of parallel ball mills with different media sizes.

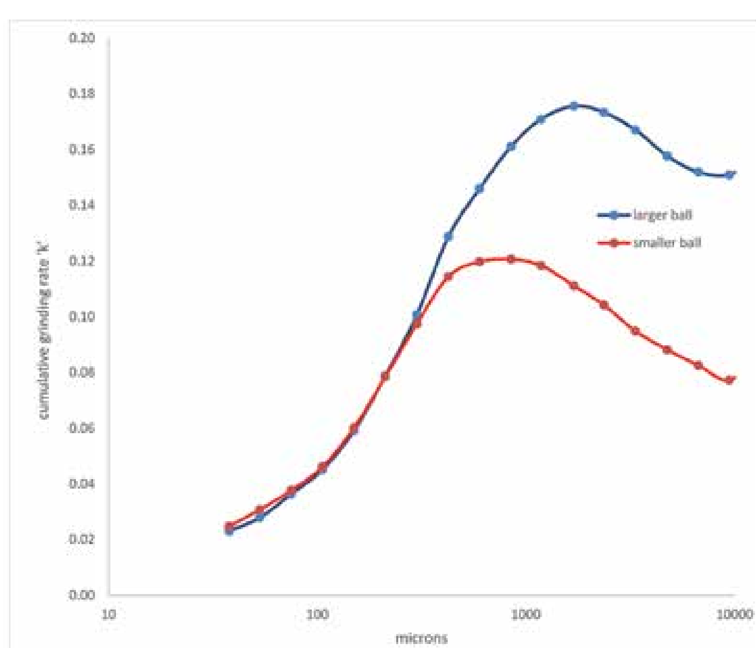
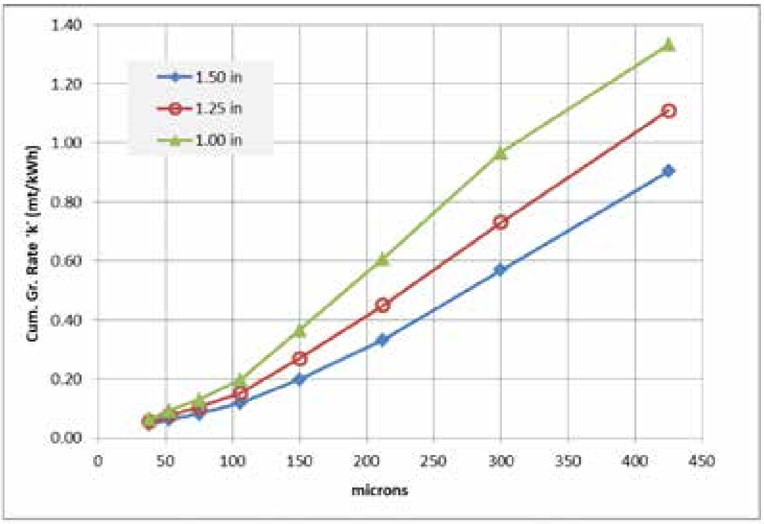


Figure 5

Grinding rates increasing to coarsest particle size.



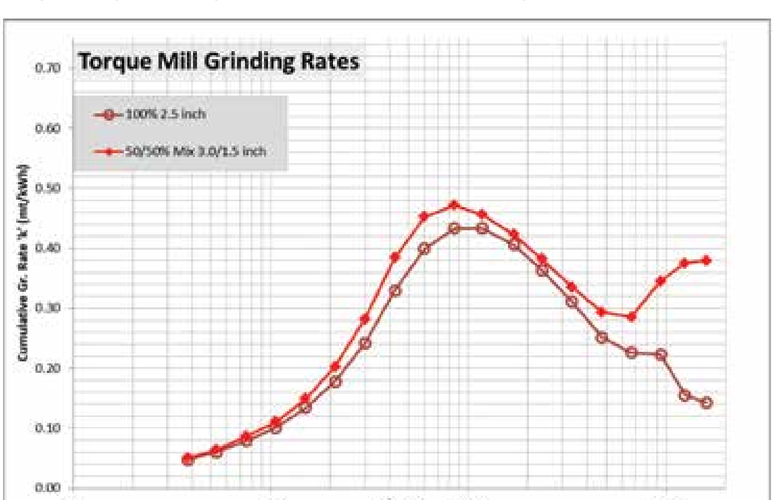
make-up size) yields increased grinding rates over the entire size range of particles.

Batch torque-mill results showing the need for locked-cycle testing. Among several charges tested, batch testing on mill feed (cyclone underflow) with a 50-50 percent by weight make-up mix of 76 mm and 38 mm (3 in. and 1.5 in.) balls showed an 11-percent increase in the grinding rate through the size of interest (300 µm) over the single size of 63.5 mm (2.5 in.) make-up balls used in the plant (Fig. 7).

The lower coarse particle grinding rates with the mix will discount the advantage at 300 µm an unknown amount. Therefore, locked cycle testing was carried out on samples of the circuit feed with the two charges. The tests used a 300 µm screen and were run to equilibrium with a circulating load of 300 percent. The energy usage (kWh/mt) for both media charges was identical. Therefore, this plant maintained its single ball size usage.

Figure 6

All grinding rates higher with multiple versus single media size addition.



Batch grind-through tests with different pebble sizes: At the Tilden Mine, pebbles for secondary milling of iron ore come from the primary autogenous mills, which are equipped with 100 mm by 100 mm (4 in. by 4 in.) pebble ports. Figure 8 shows pebbles removed from a pebble mill have a remarkable likeness to grinding balls.

The grind target P80 of 25 µm made locked-cycle testing of the (- 2mm) circuit feed impractical. As an alternative, batch tests were run grinding circuit feed through to the final grind size with three top sizes of pebbles. Torque-mill testing showed that a - 50 mm pebble charge used 20 percent less energy than the - 100 mm pebbles in use at the plant. This was tested in the plant by installing a 50-mm scalping grizzly over the pebble feed line to one of the pebble mills. Fortunately, the time for a pebble charge to reach equilibrium is very short compared to a ball charge (days, versus months). The result was a notably finer cyclone overflow grind measured by the particle size analyzer. A followup plant survey showed a 12-percent increase in pebble mill grinding efficiency, providing an equal reduction in pebble milling circuit energy consumption (Ritthaler, 2014).

Observations and conclusions

This work is ongoing. However, a number of key observations and conclusions can be made at this time.

- Size by size cumulative energy specific grinding rates can be used to characterize mill grinding performance and changes in performance, as a function of media sizing. They can be used for both plant and test mill data. The cumulative grinding rate through the size of interest is the identical parameter as the ball mill grinding rate calculated from the functional performance equation. Its maximization is the technical optimization criterion for ball sizing studies.
- Plant ball mill preferential retention of coarser particles, ignored by most population balance modeling, confounds interpretation of plant grinding rates.

However, when the calculated apparent cumulative grinding rates increase from the smallest to the largest particle sizes, the potential for increasing efficiency with a media size change is greatest.

- A suitably sized, torque-metered test mill can be used to experiment with the currently used plant ball charge and alternative ball charges. Three types of tests are being conducted: batch tests on plant ball mill feed; locked-cycle tests on plant circuit feed; and batch "grind through" tests on plant circuit feed to circuit product size.
- Comparative batch tests on ball mill feed with the current and an alternative ball charge may show increased grinding rate through the size of interest, but lower rates at coarser particle sizes. Locked cycle tests are then needed to determine whether a net increase in grinding efficiency will result.
- "Grind through" tests on a circuit feed to circuit product sizing (P80) that have displayed increased efficiency with a media size change in the test mill have shown similar results in closed-circuit grinding in the plant.
- The optimum media sizing depends on the fineness of the circuit product sizing (P80), as well as the circuit feed size.
- Multiple size charging can sometimes outperform charging any single size.
- Different plant media sizing can result in the same grinding rate (efficiency) on the same ore at a specific particle size, even though they perform differently at other particle sizes. This explains why changing media sizing may produce no effect on circuit performance.
- Numerous torque mill tests, in addition to the growing plant data base compiled to date, show that media charging near the size that provides highest ball mill grinding efficiency provides a degree of robustness with changing ore grindability. It is rare that the media is incapable of breaking the largest particles as they become tougher. Rather, they do so at a lower rate. (References are available from the authors.) ■

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Figure 7

Batch test results on ball mill feed with currently used single make-up and a mix of two ball make-up sizes.

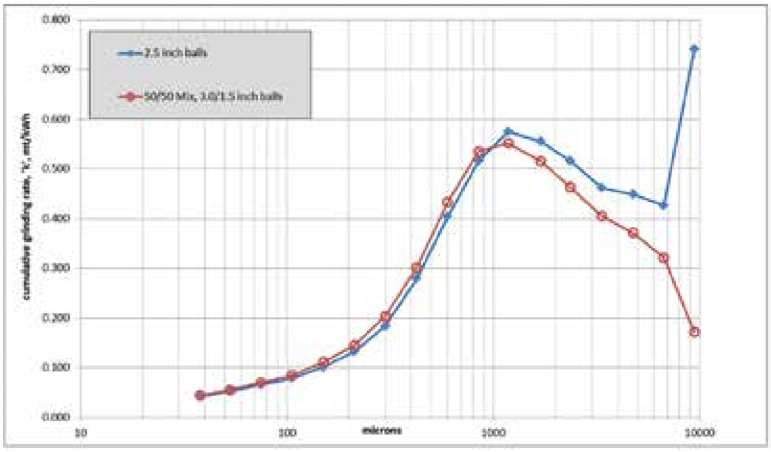

Figure 8

Pebbles collected from inside a pebble mill at the Tilden Mine.

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