Functional Performance of Ball Milling Circuits – A Plant Metallurgist’s Tool for Process Characterisation and Optimisation

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ABSTRACT

A voracious consumer of energy and grinding media, the modern ball milling circuit has a huge direct cost impact on a mineral processing operation. Through optimisation, grinding also has the potential to unlock great improvements in recovery and throughput, but how can the complex interactions between mills, classifiers, tonnage, ore-type and downstream recovery be measured, understood and managed in a systematic manner?

Functional performance analysis provides the tools and insights needed to measure, understand and improve the two key process efficiencies in ball milling circuits: classification system efficiency (CSE) and mill grinding efficiency.

CSE measures the composite performance of the classification system as a whole. In short, the purpose of the classification system is to ensure that grinding mill energy is used to grind coarse particles while minimising overgrinding. CSE is simple to measure in the plant and it provides immediate feedback to the plant metallurgist, mill superintendent and management about the performance of the classification system and the amount of wasted energy in the grinding plant.

Mill grinding efficiency measures the capacity of the grinding mill to convert feed-sized material into product-sized material on a tonnes per kilowatt hour basis. It is normalised based upon the ore resistance to breakage, so it provides feedback about the ‘health’ of the milling process under varying operating conditions and ore types. Mill grinding efficiency is measured at the same time as CSE through circuit sampling.

Functional performance analysis combines CSE and mill grinding efficiency to provide a measureable, manageable optimisation objective. It also provides a link to tonnage, ore type and recovery. As a result, systematic optimisation of a grinding circuit is a measureable and manageable process to meet business objectives.

INTRODUCTION

Comminution is the leading consumer of energy and is one of the highest expenses in a mineral concentrator (Coalition for Eco-Efficient Comminution (CEEC), 2013). Worldwide mining industry equipment efficiencies have been stagnant or dropping (Adsero and Lumley, 2013). More data is available to mining business decision makers than ever has been in the past, yet, as posited by Adsero and Lumley (2014), all of this data must be understood and acted upon to improve efficiencies. Thus, mining business decision makers need a clear conceptual framework and practical metrics to drive comminution improvement projects.

The functional performance equation (Equation 1) provides a practical basis for the understanding and improvement of the business performance of ball milling circuits. It does this by breaking the overall ball mill circuit efficiency into two subefficiencies that are measureable and linked to known improvement strategies.

FUNCTIONAL PERFORMANCE OF BALL MILLING

The functional performance equation was discovered by R E McIvor as a result of a career working as an application engineer for companies that manufactured and installed the three primary pieces of process equipment in a ball milling circuit: the mill, the hydrocyclones and the slurry pump (McIvor, 2006). The equation relates the amount of new product-sized material produced by the ball mill circuit to four key factors: mill power draw, classification system efficiency (CSE), ore grindability and mill grinding efficiency.

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12TH AUSIMM MILL OPERATORS’ CONFERENCE / TOWNSVILLE, QLD, 1–3 SEPTEMBER 2014 227
The functional performance equation is shown in Equation 1.

\[ Q = MP \times CSE \times G \times MG_{eff} \]  

(I)

where:
- \( Q \) = metric t/h of new fines (<P<sub>80</sub>) produced by the circuit
- \( MP \) = mill power draw (kW, measured at pinion)
- \( CSE \) = classification system efficiency (%)
- \( G \) = ore grindability (g/rev)
- \( MG_{eff} \) = mill grinding efficiency [(metric t/kWh)/(g/rev)]

Four of the five equation components are measured by means of a grinding circuit survey, while the fifth component is the calculated result. Each of the equation components and how they are measured in industrial operations is described in the following paragraphs. At the end of the paper, an optimisation strategy is described using each of the equation inputs.

**New fines production rate (Q)**

The particle size defining ‘fines’ is determined by the particular operation, but, in general, the circuit P<sub>80</sub> is a good value to use as a cut-off between ‘coarse’ and ‘fine’ particles. The circuit production rate (metric t/h) of new fines is measured during a circuit survey by means of the total tonnage into the ball mill circuit (eg weightometer), and the size distribution of a circuit survey by means of the total tonnage into the ball mill production rate (metric t/h) of new fines is measured during as a cut-off between ‘coarse’ and ‘fine’ particles. The circuit such as analog power draw metres, to increase the likelihood of accurate power draw measurement (McIvor, 2008). This check should be carried out prior to the survey day in case differences are discovered so that they can be resolved.

**Classification system efficiency (CSE)**

CSE is a composite measure of how well the classification system is performing the task of quickly removing fines from the circuit and keeping the mill full of coarse material. A high CSE minimises overgrinding and maximises the utilisation of mill power to produce finished product (Bartholomew and McIvor, 2013). The sources of overgrinding in a ball milling circuit are the misplacement of fines to the mill feed by the classifier and too long of a retention time in the mill. Sieve analysis of the mill feed determines how many fines were misplaced by the classifier (eg bypass fraction of hydrocyclone), and a sieve analysis of the mill discharge is related to retention time, as longer times result in more fines and overground material, in the mill discharge. CSE is defined as the average of per cent coarse in the mill feed and per cent coarse in the mill discharge. For example, if the mill feed contains ten per cent fines (90 per cent coarse) and the mill discharge contains 30 per cent fines (70 per cent coarse), the CSE for this circuit is 80 per cent – the arithmetic average of 70 per cent and 90 per cent.

CSE is a composite measure of the balance between classifier misplacement of fines and mill retention time, and it is simply an approximate measure of the percentage of coarse particles in the mill. It also represents the amount of mill power being applied to the particles of interest – the coarse.

It is easy to understand why misplaced fines are problematic and cause overgrinding; the material is already product-sized and needs no further grinding. Long mill retention times are also a source of overgrinding and wasted mill energy; they produce fines part way through the mill then overgrind them before giving them a chance to leave the circuit by way of the classifier. Short retention times, indicated by high circulating load ratios, are desirable to make sure mill power is being applied to coarse, not to overgrinding fines. This is demonstrated in early work by E W Davis (shown in Figure 1). Figure 1 demonstrates that a high circulating load ratio gives the best circuit production rate of new fines at a given energy input (Davis, 1925). In the development of CSE, McIvor (1988) studied this relationship along with a set of size distributions shown in Figure 2. Figure 2 shows that for two circuits grinding from the same P<sub>80</sub> to the same P<sub>80</sub> the circuit...
with the higher circulating load ratio had coarser mill feed and mill discharge, thus, more of the mill power is applied to coarse rather than overgrinding of material that has already reached target size. In addition, by the relationship shown in Figure 1, it is clear that the production rate of new product-sized material for the higher circulating load circuit would be higher as a result. CSE is the net measure of how well the classification system, as a whole, is performing the task of applying mill power to the proper particles. The CSE metric can be used independently as a quick, effective way of quantifying classification system performance, or in conjunction with the functional performance equation (Equation 1).

**Ore grindability (G)**

People in the business of mineral processing know that ore variability is one of the major factors that affects the profitability of their operations. In addition, no measure of ball mill circuit performance is complete without including an ore grindability component. The functional performance equation (Equation 1) includes ore grindability in the mill grinding efficiency metric. Mill grinding efficiency is essentially the mill grinding rate (t/kWh) normalised by a grindability value (g/rev). The ore grindability value is typically obtained by performing a batch grindability test on ball mill feed (cyclone underflow). The amount of milling conducted in the batch grindability test is set up to approximate the single-pass amount of grinding done by the plant grinding circuit. This technique is described in the Metcom training program (McIvor, 2008) and builds upon testing detailed by Yap, Sepulveda and Jauregui (1982). Using a batch test avoids the need for expensive and time-consuming locked-cycle testing (e.g., a Bond test) on circuit new feed as the equilibrium mixture of particles to grind are already present in the mill feed (typically cyclone underflow). It is important to use proper rigour in the laboratory test, and full details of procedure and quality assurance / quality control (QA/QC) can be found in The Complete Metcom Training Program on Improving the Performance of Plant Grinding Operations (McIvor, 2008).

**Ball mill grinding efficiency (MG<sub>ef</sub>)**

Mill grinding efficiency measures the capacity of the grinding mill to convert feed-sized material into product-sized material on a tonnes per kilowatt hour basis. As mentioned earlier, it is normalised based upon the ore resistance to breakage, so it provides feedback about the ‘health’ of the milling process under varying operating conditions and ore types. Mill grinding efficiency is most strongly affected by variables such as mill per cent solids and media sizing. It is measured during a circuit survey and is the calculated result of the functional performance equation (Equation 1).

The measurement and calculation of equation components Q, MP, CSE and G were described in earlier sections of this paper. An increase in mill grinding efficiency, by means of plant optimisation, directly results in higher productivity and energy efficiency.

**Optimisation using functional performance**

The functional performance equation (Equation 1) provides the insights that drive systematic optimization in the ball milling circuit. Generally, the best business case for comminution plant operation is to maximise the production rate of new product sized material (Q). To maximise Q, the four factors on the right side of the equation need to be maximised within economic constraints. First, the mill power draw should be fully utilised through proper ball charging and matching of the motor to the mill dimensions and speed. This ensures full utilisation of installed mill capacity. Alternatively, in cases where energy savings are of greater interest (e.g., a process constraint downstream), mill power draw can be adjusted downward to make the same production rate (Q) if gains can be made in the other equation factors.
Second, CSE needs to be maximised by improving the classification system performance. Factors such as water addition, circulating load ratio, utilisation of cyclone feed pump and motor capacity and sharpness of separation need to be measured in a survey, then improved by means of engineering analysis and plant experiments. An understanding of downstream requirements and constraints is needed to redesign the classification system to best utilise installed mill power on coarse material. The engineering techniques to maximise CSE are well understood and have been documented (McIvor, 2011). While not required for industrial circuit optimisation, CSE can be used in conjunction with ball mill circuit simulation to experiment with classification system design using CSE as the optimisation metric.

Following CSE optimisation, ore grindability should be considered. While not generally in the hands of the plant metallurgist, an understanding of incoming ore grindability will help the plant metallurgist in predicting throughput and changes to the circuit product. The conceptual framework provided by the functional performance equation (Equation 1) aids the plant metallurgist in day-to-day operation of the grinding circuit.

Finally, mill grinding efficiency ($M_{G-e}$) is typically most strongly influenced by slurry per cent solids in the mill and the sizing of the grinding media. These factors, and any others of interest, can be evaluated in the plant using the mill grinding efficiency metric. Again it is measured by solving the functional performance equation with known values from a plant survey, and it is adjusted by a standard laboratory measure of ore grindability. As a result, any extraneous effects of the classification system (eg ore) that occur on the day of the survey do not impact the validity of plant trials that strive to improve mill grinding efficiency. In addition, since the units of mill grinding efficiency are [T/kWh per g/rev], the cost/benefit impact of a measured improvement are easily translated into economic values. Industrial grinding circuit improvements using the mill grinding efficiency metric have been published where both mill solids and media sizing have been addressed (McIvor et al, 2000; McIvor, 1991).

Another example of CSE improvement using the functional performance approach comes from an experience at the Tulawaka operation. At this plant, cyclone overflow per cent solids was limited due to downstream constraints. This limits the amount of water that can be used to dilute cyclone feed. It has been shown that dilute cyclone feed tends to enable better classification performance (Heiskanen, 1993). The potential for addition of a thickener, prior to downstream processing, to lift the per cent solids constraint in the grinding circuit was investigated with CSE analysis (Bartholomew and McIvor, 2013). Table 2 shows the base case condition (50 per cent solids) and the potential improvement in circuit efficiency expected as a result of reducing cyclone overflow per cent solids through water addition. The expected results predicted by CSE analysis helped motivate implementation of the thickener at Tulawaka, with six to 11 per cent more fines being produced by the circuit causing gold recovery to increase by two per cent (Frostiak, personal communication, 2007).

In addition to classification improvements, the functional performance equation (Equation 1) can also be used to measure changes in mill grinding efficiency. The factors that tend to have the greatest effect on mill grinding efficiency include mill per cent solids and grinding media. At the Tilden mine, extensive experimentation was conducted to determine the optimum mill per cent solids. Test results were quantified and judged based upon the mill grinding efficiency component of the functional performance equation (Equation 1). Figure 1 (McIvor et al, 2000) shows the relationship measured between mill per cent solids and mill grinding efficiency at Tilden. Each data point on the curve represents a pebble mill circuit survey. Understanding this relationship has been important to the economic operation of the pebble mills at Tilden.

Many additional industrial examples of successful applications of the functional performance equation have also been published (Bartholomew and McIvor, 2013; McIvor, 2013).

**CONCLUSIONS**

The functional performance equation provides a practical basis for management of industrial ball milling circuits. It is a conceptual framework that breaks down the interactions
inherent in closed circuit grinding into manageable parts: mill power draw, classification system efficiency, ore grindability and mill grinding efficiency. The components of the equation are measureable in the plant environment by means of a circuit survey, and optimisation strategies are available, using known engineering techniques, for each of the factors. The relative simplicity of the functional performance equation helps business decision makers take action to improve the economic performance of their operations.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the management and staff of mining companies that have been generous enough to allow publication of results, including Tilden, Tulawaka and the many others that have supported previous publications. Additionally, we would like to thank McGill University for ongoing support.

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<th>Cyclone feed per cent solids (v/v)</th>
<th>Cyclone water Rec. to CUF (%)</th>
<th>Mill (kW)</th>
<th>Classification system efficiency at 106 µm (%)</th>
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TABLE 2

Grinding circuit steady state conditions at different COF per cent solids.