SME Annual Meeting
Feb. 25-Feb. 28, 2007, Denver, CO

Preprint 07-079

PROCESS DESIGN AND IMPLEMENTATION TECHNIQUES FOR SECONDARY CRUSHING TO INCREASE MILLING CAPACITY

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Abstract

By understanding the ore breakage characteristics and utilising comminution circuit modelling, the benefits of SAG mill feed size manipulation can be readily assessed.

This paper looks at the benefits and problems of total secondary crushing of mill feed and advocates partial secondary crushing as a means of improving grinding efficiency for certain hard ores.

Case studies are reviewed for new and existing SAG mill circuits.

Introduction

Comminution is second only to smelting in the mineral industry's ranking of energy intensive operations. It typically accounts for between 50 – 80% of all energy use at mine sites. A significant 4% of the world's electricity is used for the size reduction of ores, rocks and cement (Hill, 2002). In future, lower head grades and increasingly complex ore mineralogy will increase the energy required to produce each ton of mineral extracted.

Applying energy efficiency measures to existing operations and introducing energy efficient plant and processes is one of the most important ways of reducing cost. Such measures are also consistent with operating a site at optimum efficiency and maximum output. Hence, there is an urgent need for innovation to decrease energy requirements in this area.

One of the difficulties is that there is no universally recognised measure of efficiency in SAG mills and related comminution circuits. OMC utilises a method based on a consideration of the total power involved in the comminution process for a standard feed (80%<150 mm) and product size (80%<75 µm). The specific energy (in kWh/t) necessary for the circuit is compared to the Bond Ball Mill Work Index based specific energy that is theoretically needed to effect comminution from feed to product. The ratio of the two is referred to as $f_{(SAG)}$.

Typically, many modern hard rock SABC comminution circuit designs have $f_{(SAG)}$ values of 1.3 – 1.4. For a coarse grind of 100 to 200 µm, this equates to around 50% inefficient power utilisation, falling to ~30% to 40% at 75 µm!.

Table 1 summarises the predicted power analysis of three high capacity milling operations recently studied by this consultancy. All circuits are designed to treat primary crushed feed in SABC configuration to a product size of 80% passing 75 µm.

Table 1. Examples of Inefficient SABC Circuits.

Example	**1**	**2**	**3**
Circuit Capacity (Mtpa)	**20**	**17**	**10**
SPECIFIC ENERGY (kWh/t)			
SAG Mill	11.5	8.9	10.5
Pebble Crusher	0.4	0.2	0.2
Ball Mill	11.3	6.8	11.2
Total Circuit Energy to P_{80}	**23.2**	**15.9**	**21.9**
$f_{(SAG)}$ CALCULATION			
Bond Spec. Energy to 75um	16.9	11.6	16.3
$f_{(SAG)}$	**1.37**	**1.37**	**1.34**

The power required in the grinding mills is a staggering 31 MW more than is theoretically needed! This paper looks at ways of identifying inefficiency and bringing the specific energy demand closer to that predicted by the Bond equation, i.e $f_{(SAG)}$ values approaching 1.0.

Ore Type Characterisation

This consultancy has an extensive database of testing and plant operations, gathered over 20 years of comminution specialization. For many years, OMC has used a measure of competency based on the energy required to achieve first fracture in an impact test. Figure shows energy to first fracture vs. size class profiles for typical ore types in OMC's database:

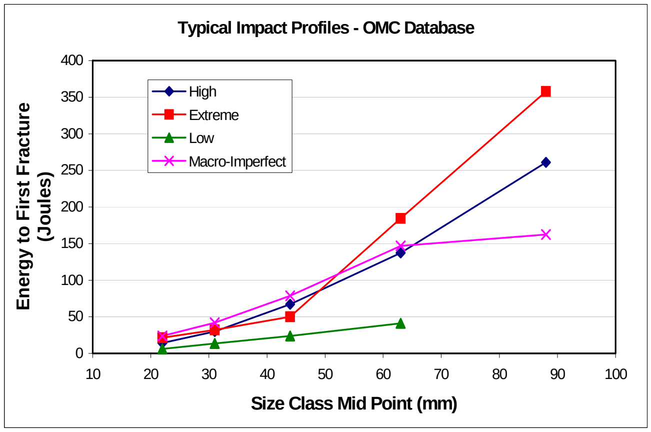

Figure 1. Typical Impact Responses – OMC Database.

Correlations were carried out between F_{80} and $f_{(SAG)}$ for a number of comminution circuits in the database where survey data on multiple feed sizes existed. In cases where the ore exhibited a high to extreme competency impact profile, sharp increases in $f_{(SAG)}$ were observed as the feed size increased, as detailed in Figure 2.

Such behavior is not observed or is minimal in ores of lower impact strength. Thus ore characterisation offers a means of diagnosis of potential problem materials.

Testwork is undertaken on feed samples or PQ drillcore. A standard Media Competency Test (Kjos, 1985) is performed on selected lumps of ore/core. Test survivor lumps are subjected to twin pendulum impact testing, using a rig similar to that described by Bond (1951). Ranging in size from 12 to 100 mm, 100 particles, are tested, with the energy required to obtain first fracture recorded. The input energy is progressively increased until rock breakage occurs. Where repeated impacting is necessary to obtain fracture, only the final energy level is noted, not the cumulative energy. The impact energy is determined as the sum of the potential energies of the active components of the apparatus. Increasing the release height of the pendulums increases the impact energy imparted to the specimen under test. Figure 3 presents results for typical candidate material.

If particle size is converted to equivalent spherical volume or mass, the breakage energy required to achieve fracture increases linearly, Figure 4. The higher the competency of the ore, the higher the gradient. When this high competency behavior is observed, it is diagnostic of the rate-limiting condition.

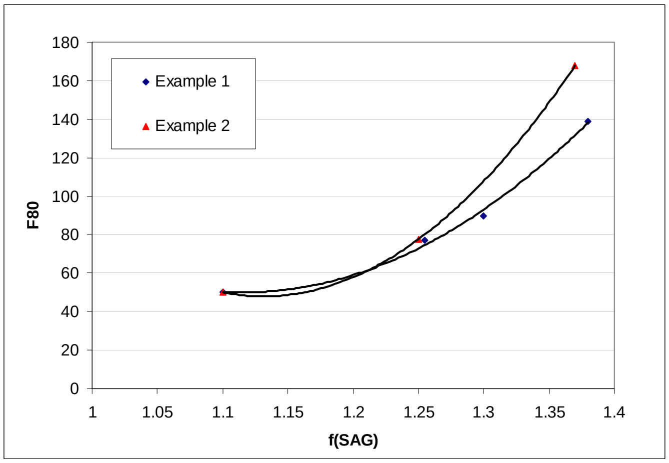

Figure 2. Change in $f_{(SAG)}$ with Increasing Feed Size.

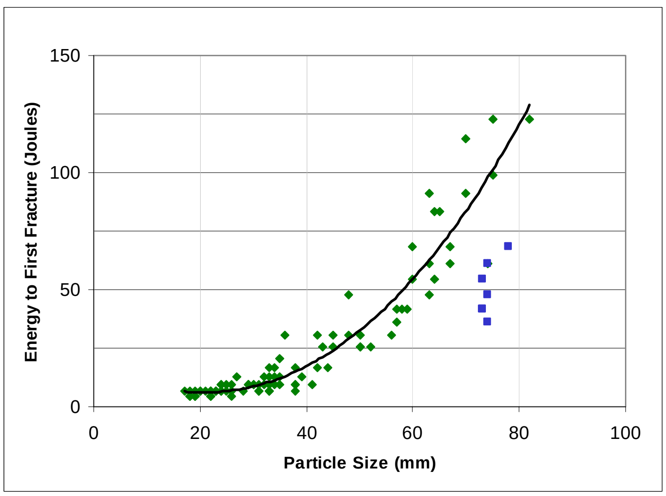

Figure 3. Variation in Energy to First Fracture with Particle Diameter.

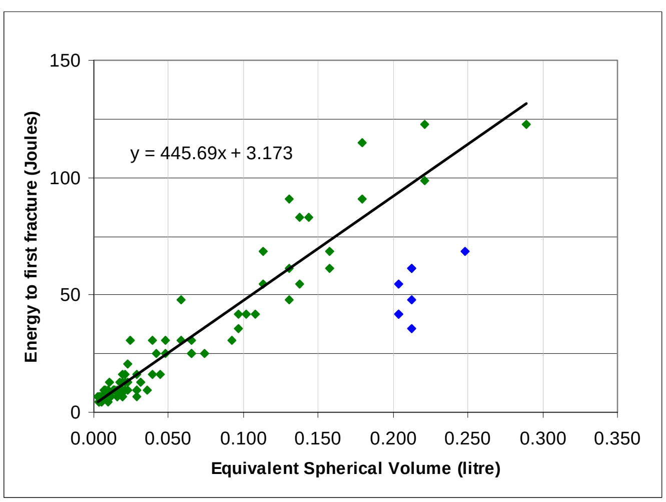

Figure 4. Variation in Energy to First Fracture with Particle Volume (High Competency Ore).

In contrast, ores that exhibit a low competency behavior show a shallow gradient or trend asymptotically to constant impact strength, Figure 5. This is the likely result of extreme macro-imperfection (coarsely spaced discontinuities such as veins). The difference between the two is not significant as in either case the rock breaks down easily to sub-grate size.

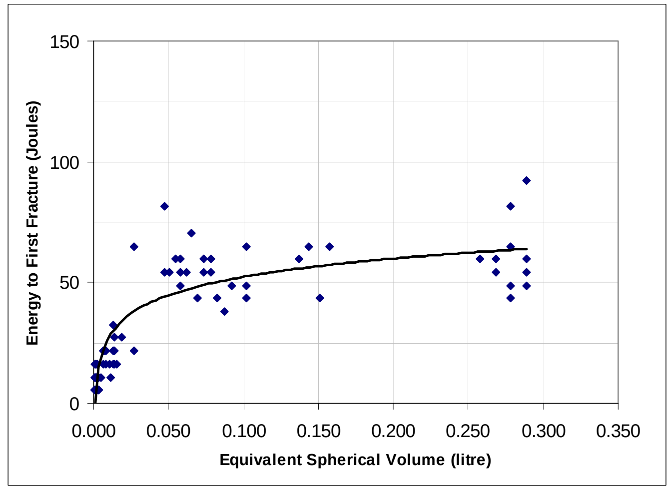

Figure 5. Typical Energy to First Fracture Profile with Low Competency Ore.

Ore which is typically referred to as showing Macro Imperfect behavior exhibits a random response varying between high competency and low depending on the extent of macro-imperfection, Figure 6.

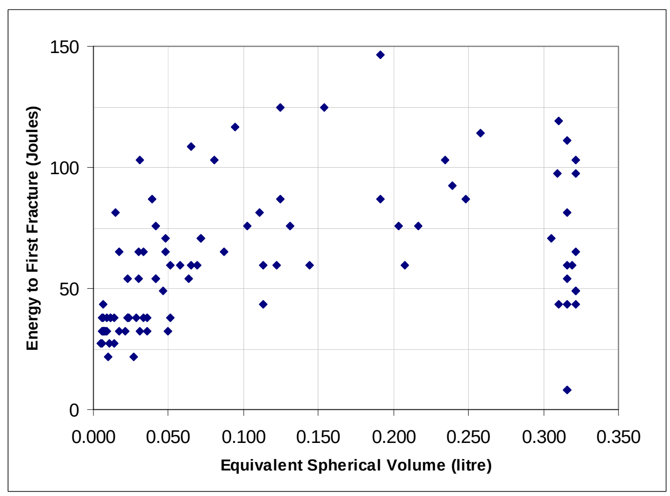

Figure 6. Typical Energy to First Fracture Profile with a Macro Imperfect Ore.

The standard suit of comminution design tests often do not diagnose macro-imperfection since the variability in the result typically occurs at +50 mm, above the predominant test particle size (eg MacPherson, SPI, JK Dropweight). The Advanced Media Competency Test (AMCT) described here requires a large sample compared to other testing methods. However because of the invaluable data it provides OMC recommends it be undertaken in unison with small sample comminution tests such as the SMC or SPI test. The test not only provides a second method of predicting the energy required in grinding but also recognises extreme and macro-imperfect rock behaviour not identified by other methods. Once the condition is identified, RQD data (fracture density, etc.) is essential in predicting SAG mill capacity.

Analyzing the data in Figure 3, energetic impacts of >50 Joules are required to break particles in excess of ~55 mm, rising to 100 joules at 75 mm. DEM Modelling of SAG mills (Morrison & Cleary, 2003) suggests that the frequency of 100 Joule impacts is less than 1 per second in an 11m diameter mill. As such, rocks requiring energy to first fracture above 100 joules will only be reduced in size slowly, and thus become severely rate-limiting. Size reduction of such rocks is thought to occur predominately through low energy abrasion and chipping events (Morrell et al, 2001).

Critically, the size of the problem material is coarser than the normal grate or pebble port opening, indicating that the use of a recycle crusher does not solve the problem. The answer to improved efficiency in the SAG mill for these ores is to move from primary crushed feed to partial or full secondary crushing. In so doing, the impact energy required is readily available in a SAG mill increasing and steadying production.

The Use of Secondary Crushed Feed

In Australia, there are several examples of the retrofitting of secondary crushing circuits to reduce feed size and hence increase SAG mill capacity, most notably those of Kidston Gold Mine (MacNevin, 1997) and St Ives Gold Mine (Atasoy, 2001). Recently, other examples have appeared, such as Geita (Tanzania), Porgera (PNG), North Mara, Mt Rawdon and Wallaby (Aust).

Effects of Secondary Crushed Feed

Secondary crushing dramatically reduces the SAG specific energy to around 4 – 6 kWh/t for typical competency ores. Consequences are:

- The product is quite coarse, shifting the main grinding requirement from the SAG mill to the ball mill;
- F_{SAG} improves to around 1.05, dramatically increasing power efficiency. This allows higher throughput in existing circuits;
- The crushed rock is small and unsuitable as media. Grinding now takes place using steel balls as media. This will result in higher overall ball consumption and possible liner damage if not effectively managed;
- There is no benefit in having more than ~5% rock load over the ball charge. The energy consumed is not used efficiently and load stability becomes a control issue.

Total Crush or Blend?

Treating 100% secondary crushed feed is difficult in anything other than a purpose built and controlled circuit. Therefore the use of partial secondary crushed feed best satisfies the operating requirements of stability and balance. It:

- decreases inefficiencies;
- allows the use of rock as media and
- fully utilises the available installed power by balancing the energy demand between grinding stages.

Hence the amount of crushed ore in the blend should be tailored to match the required efficiency and power split (new circuit) or the mill power installed (retrofit).

Engineering Design Considerations

A number of factors such as configuration and location must be considered in the design of a secondary or partial secondary crush circuit.

Feed Splitting, Screening and Feed Bins

Feed splitting to the secondary crushing circuit is readily achieved by use of an overflowing bin. The bin provides the feed to the secondary crusher, whilst the primary crushed material overflowing the bin by-passes the secondary crusher. Varying the rate of discharge from the bin using a reclaim feeder varies the amount of primary crushed material overflowing to the grinding circuit. This provides a large degree of flexibility and thus allows optimisation of the grinding circuit. The split material can be fed to the secondary crusher directly or a further surge bin and feeder can be installed. Use of the single feeder is lower capital but may result in higher operating costs as it does not guarantee choke feeding of the secondary crusher.

The alternative strategy of screening all the primary crushed material into two or more size fractions is not favored for partial secondary crushing, since the objective is to split the coarse fraction, providing just enough lump media to the mill, whilst crushing the remainder of the tough coarse material. Another problem with this arrangement is that there is no control of the split ratio of crushed to uncrushed ore as this is affected by the variability in the product of the primary crusher.

Crushing and Screening Configurations

A number of screening options are available to achieve a secondary crush, once the feed has been split. These include:

- Open Circuit, no screening (100% feed to secondary crusher).
- Open circuit, scalping screen – The installation of a scalping screen ahead of the secondary crusher to remove fines.
- Open circuit, Intermediate crushing – The primary crushed feed is sized on a double deck screen with the top deck oversize bypassing the crusher, the bottom deck undersize bypassing the crusher and the bottom deck oversize feeding the crusher.
- Closed circuit product screen – The secondary crusher is placed in closed circuit with a product screen.

Table 2 (see Appendix) defines selection criteria for partial secondary crushing circuit configurations based on ore competency, secondary crusher reduction ratios and down stream processing.

Location

The final major consideration is the location of the secondary crushing circuit. It can either be after the primary crusher and before the stockpile or it can be between the stockpile and the grinding circuit. Each circuit has advantages and disadvantages.

Operation as part of the primary crushing circuit is typical. This configuration requires higher capital, as the rate of secondary crushing must match that of the primary crusher, but the availability of the crushing circuit does not affect the grinding circuit. Stockpile segregation is still an operating variable with this circuit, however it is less severe than that of a primary crushed feed circuit. Changes in the amount of secondary crushed feed will have a lag time between the crusher and mills depending on the size of the stockpile.

Installation of the partial secondary crushing circuit off the mill feed conveyor will reduce the capital cost of the installation, as the circuit capacity is only required to match the milling rate. Operation off the mill feed conveyor also allows immediate changes to the mill feed composition. Under these conditions the portion of the feed secondary crushed could be controlled to maintain a consistent feed through the use of an optical monitoring system. This would result in very steady feed to the mill and thus steady production rates. The negative of this configuration is that the lower availability of the crusher will affect mill throughput, as the grinding circuit would be forced to treat primary crushed feed when the crusher is offline. The effect on production would be expected to be similar to that experience when a recycle crushing circuit is taken off line.

Examples

Table 3 (see Appendix) shows a compilation of secondary crush circuits and provides references to the original papers.

Most operations reported substantial benefit from retrofitting in the face of increasing ore hardness. Challenges include:

Crusher problems

The addition of further crusher capacity in the circuit brings attendant difficulties including increased maintenance, availability issues and the operation of belts and screens.

Higher wear rates were reported at Granny Smith in all aspects of the crushing circuit due to abrasive ore from Wallaby.

Load Control

It was found at Ray that with the reduced size of SAG mill feed less pebble port area was required to maintain a given SAG mill load.

Decreasing grate open area allowed operation at a higher mill load, resulting in increased fine grinding, and also reduced the load on the pebble crusher. This strategy appears to be in response to reported difficulties with splitting the feed between primary and secondary crushing.

Liner Damage

Lifter bolt breakages were suffered at Porgera due to coarse and variable feed size changes, resulting in SAG mill overloading (low sound) and underloading (high sound). Again, this appears to be related to load control in the SAG mill. Corresponding liner cracks were found in the feed end-shell filler liners, shell plates and lifters.

The Future

The partial secondary crush concept suggests that it may be possible to apply this thinking to HPGR circuits. Here coarse media could be scalped from the crusher feed and used as media in a fully autogenous circuit comprising HPGR crushed feed to a Pebble mill.

In addition to reduction in the operating cost associated with energy and media cost savings, significant benefits in flotation and leaching behavior are expected from such an arrangement.

Conclusions

Using a measure of grinding circuit efficiency designated as $f_{(SAG)}$ significant inefficiencies in power utilisation have been identified. These are common for hard-rock ores when processed in SABC circuits.

A means of identifying such ores is discussed, based on measuring the energy required to achieve first fracture at coarse size. OMC's database shows only certain ores termed “High Competency” exhibit the diagnostic behaviour. Others show different characteristics such as low competency or macro-imperfect behaviour.

The diagnostic AMC Test requires a larger sample than other testing methods. such as the SMC or SPI test. However it provides invaluable data allowing the prediction of energy efficiency in SAG milling whilst recognising extreme and macro-imperfect rock behaviour not identified by other methods. For this reason it is recommended that the AMC test be undertaken as a part of an overall test program that includes small sample comminution tests.

The use of secondary crushing is an effective way to improve comminution circuit efficiency for high competency ores and reduce capacity variability. There is a strong case for retaining some coarse material in the feed to the circuit to provide media and minimise liner damage. Partial secondary crushing circuit arrangements vary between scalping and selective crushing of an intermediate fraction.

Most operations where secondary crushing was retro-fitted show significant improvement, often in excess of 40% increase in capacity.

The concept of controlling the circuit feed by partial secondary crushing, taken further, can lead to higher efficiency and lower operating cost circuits. The extension of this is an HPGR/Pebble mill circuit where complete control of the mill feed is obtained to achieve high efficiency comminution without the use of grinding media.

Acknowledgements

Permission from OMC and its parent company Lycopodium Limited, to publish this paper is gratefully acknowledged.

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Appendix

Table 1. Configuration selection criteria

Configuration	Advantage	Consequence
Open circuit, no screening	Low Capital	Requires a fine CSS on the primary crusher and operates at a coarse closed side set on the secondary crusher which results in more intermediate material
Open circuit, scalping screen	Medium Capital	Secondary crusher CSS may be restricted by the primary crusher product size
Open circuit, Intermediate crushing	Medium capital. Allows finer secondary crusher closed side sets	Not suitable for extremely top end competent ores. The amount of secondary crushed material is influenced by the primary crusher product.
Closed circuit product screen	No intermediate size generation	High Capital. Avoids critical size issues.

Table 3. Examples of Secondary Crushing Circuits

Project	Porgera	Wallaby	Kidston	Mt Rawdon	Geita	St Ives	Ray
Location	PNG	WA, Aust.	Qld. Aust.	Qld. Aust.	Tanzania	WA, Aust	USA
Size (Mtpa)	5.5	3.0	7.0	3.2	+6	3.2	4.0
New/Retro	Retro	Expansion	Retro	Retro	Retro	Retro	Retro
Partial/Total	Partial	Total	Total	Partial	Partial	Either	Partial
Location	Before Stockpile	Before Stockpile	Before Stockpile	Before Stockpile	Before Stockpile	Before Stockpile	Before Stockpile
Open/Closed	Open	Closed	Open	Open	Open	Closed	Open
Feed splitting	Screen at 25 mm	Screen at 40 mm	No	Screen at 30 mm	Scalp 120 x 30 mm	Screen at 35 mm	Scalp 120 x 30 mm
F80 (mm)	90 - 110	25 - 30	24	~50		25 - 30	37
No. of SAG	2	1	1	1	1	1	1
Power	4.5	3.9	4.0	2 x 1.85	2 x 4.5	2.5	2 x 5.2
SAG Size (m) Dia x EGL	8.53 x 3.19	8.53 x 3.04	8.53 x 3.32	8.53 x 3.92	9.14 x 5.5	7.32 x 3.0	10.36 x 5.18
% Increase	0 - 16	37	51	54	20	60	49
Reference	Thong et al, 2006	Thong et al, 2006	MacNevin, 1997	Putland et al, 2004	Mwehonge, 2006	Atasoy et al, 2001	McGhee et al, 2001