The basics of grinding circuit optimisation

A Giblett[1] and B Putland[2]

1. FAusIMM, Senior Technical Advisor – Mineral Processing, Newmont Mining Services, Subiaco WA, 6008. Email: aidan.giblett@newmont.com
2. Principal Metallurgist Orway Mineral Consultants, Perth WA.

ABSTRACT

This paper provides a simple guiding framework for grinding circuit optimisation, focussing on common themes in past optimisation success stories, the conditions for success and techniques that can be employed to identify and define opportunities. Many significant grinding circuit improvements have been reported for operating plants, based on recurring themes such as the optimisation of mill feed size, mill liner design, process control, critical size, grinding media and classification. The paper condenses these experiences into a set of simple questions for the operator to ask, and provides guidance towards identifying and achieving the optimisation goals.

INTRODUCTION

There is a substantial quantity of books in circulation on the subject of comminution. This material generally addresses the description of common machines, basic operating concepts, design principles and the relative merits of specific equipment and comminution flowsheets very well. When it comes to the optimisation of comminution flowsheets, the literature tends to be more operation specific and widely dispersed in the form of conference proceedings. As such it is a difficult task to find consolidated guidance on the important topic of grinding circuit optimisation, which is notable given that there are a number of recurring themes evident in the published optimisation case studies. It is rare for substantial grinding circuit improvement to be reported that results from the application of some novel emerging technology, although such examples do exist. The best chances for significant productivity improvements will be found by following the well-trodden paths laid by previous successful programs.

The compilation of an all-encompassing grinding circuit guideline is a substantial task, the daunting nature of which goes some way to explaining the absence of anything resembling such a guideline in the literature. It is practically impossible to write something that could address all possible site conditions for all possible combinations of ore properties, grinding equipment and flowsheet configurations. However the authors believe that there is considerable benefit in compiling an introductory guideline that consolidates a number of basic principles of grinding circuit optimisation, based on the recurring themes evident in documented case studies.

Many optimisation efforts are constrained by the initial scope, such as focussed mine to mill optimisation studies, or grinding circuit survey and simulation exercises, which can in turn limit the outcomes. It is suggested that an optimisation program should instead start by working through a generic list of items that represent potentially high value opportunities. It is the objective of this paper to present and discuss such a list, such that it may be used as the starting point for site optimisation studies. Invariably there will be cases where other opportunities can be identified, but the authors have attempted to keep the list to a manageable number of items, reflecting the objective to get the basics in order. Only once the basics are suitably addressed, should the operation look for more novel and innovative opportunities to further improve performance and efficiencies.

OPTIMISATION SUCCESS STORIES

Understanding how other grinding circuit operators have realized substantial improvements in performance is a key step towards identifying low hanging opportunities at your operation. Particular attention is warranted when multiple operators report benefits from similar initiatives. Much can be learned about how to approach optimisation in these area's by understanding the successes and failures based on these documented experiences. Some examples follow, where the outcomes of grinding circuit optimisation were reported to realise increased mill throughput rates approaching or exceeding 10 per cent. In a number of instances benefits were also associated with increased recovery or improved product grades associated with reduced variability in or better control of grind size.

Focus	Performance Benefit	References
Mine to Mill	12-18% increased throughput	Porgera, KCGM, Batu Hijau and Red Dog
Secondary Crushing	10-60% increased throughput	Porgera, Granny Smith, Kidston, Mt Rawdon, Geita, St Ives, Ray, Phoenix, , Copper Mountain
Process Control	1-8% increased throughput	Strathcona, Raglan, Palabora, Nkomati, Lone Tree, Carlin, Goldstrike, Ahafo, Collahuasi, KCGM
Mill Liners	2-20% increased throughput	Collahuasi, El Teniente, Candelaria, Los Pelambres, Alumbrera, Batu Hijau, Cortez, Alcoa, Cadia, Northparkes
SAG Mill Transfer Size	5-15% increased throughput	Northparkes, Telfer, Los Pelambres, Kidston, Batu Hijau
Ball Mill Feed Size	10- 20% increased throughput	Boddington, Tropicana
Grinding Media	~10 µm grind size reduction	Boddington, New Afton, Freeport
Benchmarking	~15% throughput Increase	North Mara, Cowal, Cortez, Hemlo

Table 1 – Summary of optimisation projects.

Mine to mill optimisation

McKee (2013) consolidates a number of case studies where the mine to mill optimisation concept has been applied to substantially impact grinding circuit capacity. There are a great many examples in the industry of where optimising the blast design to achieve increased fragmentation has substantially increased the capacity of grinding circuits that might otherwise be constrained at the SAG mill. Documented examples include KCGM (Karageorgos *et al*, 2001), Batu Hijau (McCaffery *et al*, 2006), Red Dog (Paley and Kojovic, 2001) and Porgera (Lam *et al*, 2006).

There are numerous other examples of where blast optimisation in the mine has been used to effectively resolve a grinding circuit constraint at the SAG mill. In most instances there is generally either unutilised ball mill power, or an ability to tolerate a coarser grinding circuit product. Blast optimisation is applied to manipulate the SAG mill feed size distribution in order to approach optimum utilisation of the grinding power installed in the SAG and ball mill circuit. The fact that this can often be achieved with no capital expenditure makes it a popular approach.

Other benefits can be realised from these programs, such as improved availability and productivity of mining equipment, optimised mining costs and increased crusher productivity. A number of operations have been able to extend the mine to mill concept with a degree of selectively. This requires the identification of ore domains based on primary comminution properties, such strength and structure, and optimising a blast design specific to each of these types. Batu Hijau (McCaffery *et al*, 2006, Wirfayata and McCaffery, 2011) provides a particularly useful example from operational experiences.

Secondary crusher installations

Several operations have opted to retrofit a secondary crushing stage ahead of the SAG mill to achieve similar, sometimes greater, increases in mill throughput than those possible by mine to mill optimisation. Generally the same baseline conditions apply as in the mine to mill projects: a SAG mill constrained circuit; unutilised ball mill power; and/or a capacity to tolerate a coarser grinding circuit product. The purpose of the secondary crusher, which can be operated in open or closed circuit, generally receiving a scalped feed, is to reduce all or part of the SAG mill feed to nominally 80 per cent passing 25-50 mm. This reduces the amount of autogenous media and coarse critical size material feeding the SAG mill, increases the required steel to rock ratio in the mill, and consequently increases the overall breakage rates, transfer size and often the wear rates of liners and grinding media.

Siddall and Putland (2007) consolidated a number of successful case studies, including St Ives (Atasoy *et al*, 2001), Mt Rawdon (Putland *et al*, 2004), Granny Smith and Porgera (Thong *et al*, 2006), Geita (Mwehonge, 2006), Ray (McGhee *et al*, 2001) and Kidston (MacNevin and Stephenson, 1997). There have been several others since, including Phoenix (Lee *et al,* 2013) and Copper Mountain (Westendorf *et al*, 2015). North Parkes (Sulianto *et al*, 2016) is an excellent example of comminution circuit optimisation following a secondary crusher retrofit, maximising installed power utilisation to maximise throughput and producing a finer product size.

Mill feed size optimisation

Mine to mill optimisation tends to dominate discussions around feed size optimisation, followed reasonably closely by secondary crushing, given the magnitude of the benefits that are often associated with those efforts. In some instances SAG mill feed size optimisation may involve something considerably less dramatic, such as reducing the primary crusher gap, or modifying the liner profile, where smaller gains are required. For single stage ball mills the benefits of reducing the mill feed size have been well demonstrated by circuits using HPGR crushers in tertiary and quaternary grinding duties, such as Tropicana (Ballantyne *et a*l, 2017), Boddington (Petrucci *et al*, 2018) and Grasberg (Villanueva *et al,* 2011). These projects leverage the unique capability of HPGR crushers to produce fines, and allow very fine feed sizes to the single stage ball milling circuits when operated in combination with fine wet screening. Regardless of the specifics they clearly demonstrate the impact of feed size on single stage ball mill performance.

Transfer size optimisation

Other methods to achieve more moderate increases in grinding circuit capacity have been applied to modify the transfer size distribution between the SAG and ball mill stages by modifying screen aperture, installing or optimising a pebble crushing circuit or modifying the flowsheet to direct crushed pebbles to the ball mill (SABC/B configuration). Examples include KCGM (Giblett and Hart, 2016) for trommel size optimisation, Los Bronces (Vesely and Fernandez (1986), Suttill (1988) and Kidston (Bartrum *et al*, 1988) for pebble crusher installation; Telfer (Crawford *et al*, 2009) for pebble crusher optimisation; and Batu Hijau (Burger *et al*, 2006) and Los Bronces (Powell *et al*, 2006) for SABC/B flowsheet modifications. Generally, the objective is to coarsen the transfer size to the ball mill and therefore increase SAG mill capacity in these optimisation efforts, although Northparkes (Sulianto *et al*, 2016) provide an effective example of how to reduce transfer size in instances where SAG mill capacity exceeds ball mill capacity.

Mill liner optimisation

The optimisation of pulp lifter design in SAG mills has in certain cases realised substantial throughput increases, such as the Cortez (Steigler *et al*, 2007) and Alcoa (Nicoli *et al*, 2001) operations. Such dramatic improvements tend to be associated with volumetrically overloaded SAG mills, commonly single stage SAG mills or open circuit SAG mills operating at very high throughput rates. In these scenarios that have realised dramatic benefits, the presence of a slurry pool in the SAG mill was a clear indicator of the inefficiency of the incumbent discharge system design. However other circuits have reported improvements in energy efficiency or liner wear, where the baseline mill operating conditions were more typical, and or less obviously inefficient than mill demonstrating slurry pooling. Northparkes (Dunn *et al*, 2006), Cadia (Hart *et al*, 2001, Hart *et al*, 2006), Cowal (Buckingham *et al*, 2011), Ahafo (Giblett and Hart, 2016) and Masbate (Ciutina and Soriano, 2014) are such examples. These operations particularly demonstrate the benefits of looking for an opportunity to optimise mill performance by pulp lifter redesign when the volumetric capacity of the SAG mill is not so obviously challenged.

Shell liner design, particularly in SAG mills, is frequently subject to continuous focus and modification over the life of a milling operation, but particularly so in the early years of operation. Generally speaking the benefits from modifications to SAG mill liner profiles will yield subtle benefits in terms of grinding efficiency, unless there is something dramatically wrong with the liner design in the first place. There was a large number of liner optimisation case studies in the late 90's for large SAG mills, in many cases reporting dramatic performance benefits as reflected in Table 1. Examples include Collahuasi (Villouta, 2001), El Teniente (Bustos, 1996), Candelaria (Miranda *et al*, 1996), Los Pelambres (Villanueva *et al*, 2001), Alumbrera (Sherman, 2001). In most instances the more dramatic benefits were associated with one of two major flaws in the initial design: lifter spacing or lifter face angles. Tight lifter spacing led to packing between lifters and a reduction in effective mill diameter and therefore mill capacity. Aggressive (steep) lifter face angles led to overthrowing of the charge toe and excessive liner breakage due to ball on liner strikes. If these two items are adequately addressed in the initial design, there is then limited opportunity to make further step changes in grinding efficiency by further modifying the liner profile. At that point the benefits generally relate to improving wear performance, and the suitability of the liner profile should constantly be revised based on observed wear performance. Where there are major changes to the SAG mill feed size distribution, such as by increased blast intensity or the addition of crushing stages, the suitability of the liner design should be reviewed immediately as the liner wear profile will undoubtedly change.

Other examples of liner optimisation include converting between rubber and steel in ball mills, such as at Batu Hijau, (MacLean *et al*, 2014) and the optimisation of grate design in SAG mills is a common component of SAG mill liner optimisation studies previously referenced in this discussion.

Process control

There are many cases of reported benefits in grinding circuit optimisation due to the implementation or enhancement of process control systems. Table 2 attempts to provide a useful summary considering a variety of comminution circuit flowsheets. Successful process control initiatives generally improve the stability and maximise utilisation of the grinding circuit capacity. This can be done initially by evolving the control logic to incorporate appropriate control loops (mill weight, sound, power, feed size, cyclone pressure or feed density) or by implementing higher level 'expert' control systems with the ability to effectively manage interdependent loops at the same time.

The basic objectives of process control are effectively illustrated by Figure 1 from Bartsch *et al* (2008) demonstrating the improvement expected when moving to a situation of improved control. In this example for SAG mill power draw (kW) and bearing pressure (kPA) the use of process control has moved the operation to a higher average operating condition with less variability. This demonstrates that the operation is performing at a higher level more consistently, with reduced production losses resulting from process instability or inefficiency. Running in a well-controlled state should be expected to deliver higher overall throughput rates more often than not, or alternatively improved control of the product size distribution.

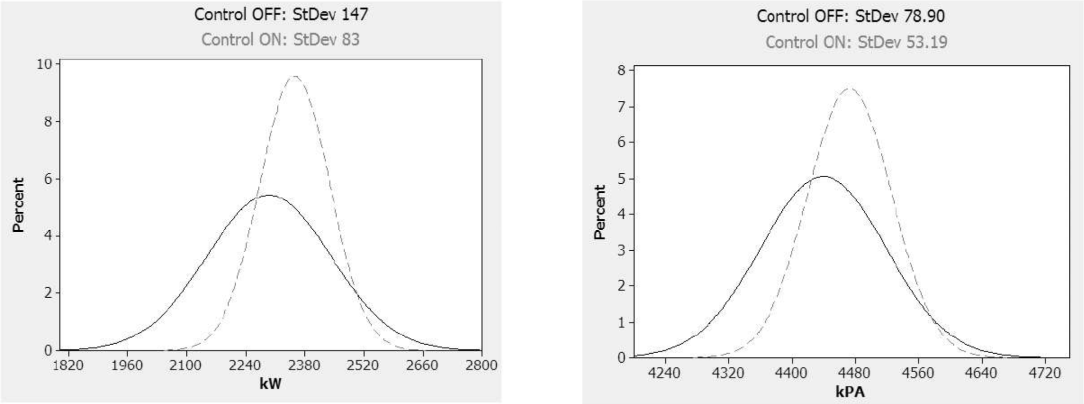

Figure 1 – Mill Power and Bearing Pressure Distribution Charts (Bartsch *et al*, 2008).

There are a number of influences that can cause a process to demonstrate high variability and as a result suboptimal performance, which should be identified and corrected wherever possible. These can include feed variability (hardness, particle size and cyclic delivery), absent or inoperable automation, poor control loop tuning, defective instruments or equipment, and process cycles (concentrator dump cycles, wash cycles etc). On the other extreme, as noted by Powell *et al* (2015), an overly reactive control philosophy can actually introduce instability, and in many cases keeping the control philosophy as simple and uncomplicated as possible is an effective approach.

Operation	**Author**	**Flowsheet**	**Throughput Benefit**
Strathcona	Nunez *et al,* 2009	Rod mill / ball mill	7-8%
Raglan	Bartsch *et al,* 2008	SABC	3-6%
Palabora	Du Plessis, 2001	Rod/ball/ball	2-3%
Nkomati	Almond *et al,* 2011	AG/PM	4.3%
Lone Tree	Veigel and McKay, 2002	SAB	6.6%
Carlin	Collins & Danninger, 2005.	Dry double rotator	7.4%
Goldstrike	Custer *et al,* 2001	SABC	1.8-2.9%
Ahafo*	Broussaud *et al,* 2011	SABC	1.1%*
Collahuasi	Yutronic *et al,* 2011	SABC	2.3%
KCGM	Karageourgeous *et al,* 2001	SABC	5%

Table 2 – Grinding circuit process control optimisation references. *Ahafo advanced process control project (Broussaud *et al,* 2011) was also credited with a 2.8 per cent increase in gold recovery.

Grinding media

Grinding media size optimisation in tumbling mills is often a popular initiative, as estimates can readily be generated using the equations of Bond (1961) or Azzaroni (1980), for better or worse. While these equations generally work well for primary ball mills, rod-ball circuits and series ball mill circuits, they do not accommodate SAG mills or ball mills following SAG mills nearly as well. In the particular case of SAG mills there is no demonstrated desktop methodology for optimising ball size, and in most cases the media selection is based on benchmarking or previous operator experience. The fact that the top ball size used in conventional SAG milling can range from 100 to 150 mm demonstrates that the selection of optimum ball sizes for SAG mills generally lacks scientific grounding. Where grinding circuit survey data is available, population balanced based simulation methods can however provide some useful guidance on optimum media selection.

There are a number of examples in literature where people have used a combination of laboratory testwork and simulation modelling to identify opportunities to improve ball mill performance through more appropriately sized grinding media. These include Boddington (Petrucci *et al*, 2018), Freeport Grasberg (Villanueva *et al*, 2011) and New Afton (La Marsh, 2015), and provide effective demonstration that more than simple regression equations are required in several instances.

Benchmarking

Benchmarking is perhaps a curious selection for an optimisation initiative as it directly doesn't change anything about circuit performance, however it provides essential context to support or challenge current performance expectations. Studying the performance of similar grinding circuits on comparable ore has long been a fundamental of process development studies, and it has no less value when evaluating the efficiency of an operating grinding circuit. Benchmarking may consider any number of parameters, including specific energy consumption, grinding media consumption, liner wear life, mill utilisation or grind size. Often times comparing a mine site's performance against a larger database of operations provides a level of clarity around efficiency that was otherwise missing.

A common example is the use of specific energy to define performance expectations. A range of models exist which have been validated against the performance of a number of operations, and define performance expectations in specific energy terms as a function of ore properties and circuit conditions. Applying these models allows a direct comparison of circuit efficiency, by considering actual energy consumption against predicted energy consumption. The approach is the basis of the Global Mining Standards and Guidelines Group's Industrial Comminution Efficiency Guidelines, described by Giblett and Daniel (2016). The effectiveness of this approach was well demonstrated by Barrick Gold Corporation in their application towards efficiency improvements at a number of operations, as described by Buckingham *et al* (2011) and Connolly and Buckingham (2012). By understanding where the current plant performance sits against a reasonable benchmark, the operation can more effectively identify optimisation targets and importantly secure management support to resource the required improvement efforts.

Other optimisation themes

Other common themes in grinding circuit optimisation will include grind size optimisation and classification system performance. These are important components of an efficient grinding operation and will be considered in the following section.

GUIDELINES FOR GRINDING CIRCUIT OPTIMISATION

Based primarily around these large value optimisation opportunities that have been discussed in the previous section, a series of investigations are proposed as the starting point for any grinding circuit optimisation assessment. The investigations are proposed as a series of simple questions, supported by additional guidance on how to generate the correct answer as appropriate.

Question 1: can I draw more power?

At its simplest level, the question speaks to the maximisation of power draw mill by mill. A general assumption is that a SAG mill should be expected to average a motor input power draw of 90 per cent of the installed motor capacity. A value of 95 per cent is assumed for ball mills, as ball mills receive a much more consistent feed size distribution and are less susceptible to overloading. These benchmarks assume the motor has been appropriately sized for the mill dimensions and structural design (maximum ball loads particularly), and the targets may vary slightly due to the size of the motor and the capacity of the supporting electrical system.

Achieving a high utilisation of installed power does not in itself guarantee efficient use of that power, and it is important to consider the potential impacts of ore viscosity (pulp density) and mill speed on grinding efficiency. However, achieving high power draws at practical mill operating speeds (72-78 per cent NCs for ball mills, 60-80 per cent NCs for SAG mills with typical shell liner profiles), at practical levels of slurry viscosity, will generally deliver good operating performance.

For multiple stage grinding circuits, there is the added complexity of balancing the workload between grinding stages, so that power draw can be maximised for each mill and for the circuit in total. This will often require focus on the primary mill feed size distribution, the particle size distribution of transfer streams between grinding stages, and the operating conditions of each stage.

For example, the initial objective should be to determine if there is unutilised power in a primary or secondary grinding stage. This can be assessed by comparing the motor power draw (average, maximum) against the installed motor capacity, and the indicative per cent motor power utilisation figures defined previously. This analysis should be supplemented by utilising a validated power model (i.e. Morrell's power model available at www.smctesting.com) to determine what power the motor can actually draw under sensible operating conditions. These operating conditions must be consistent with the structural and mechanical design of the mills, considering motor torque, maximum mill loads and so on.

The project can then progress to an evaluation of how to increase the capacity of the secondary mill by improving classification efficiency, increasing grinding media loads, optimising grind size, grinding media size etc. Alternatively there may be a need to increase the transfer size to the secondary mill to increase its workload and better utilise the asset in that manner. Varying the distribution of the work between the primary and secondary mill will generally involve manipulation of the transfer size, through manipulation of the primary mill feed size, operating conditions (grinding media size or filling levels, mill speed) and/or classification system (screen aperture, cyclone cut size).

Question 2: is the primary mill feed size optimal?

Primary mill feed size has previously been discussed as a significant contributor to primary mill capacity and transfer size. As demonstrated by standard calculation methods for grinding power, mill feed size is a significant influence on mill capacity, although this is not only due to the 80 per cent passing size of the distribution. The vast majority of mine to mill optimisation studies (McKee, 2013) have realised benefits by optimising not only F80, but the fines content of the SAG mill feed in particular as a key influence on mill capacity. In most cases, commonly with SAG ball circuits, the optimisation of primary mill feed size is a prerequisite of maximising mill power draw on a two stage circuit. As a result both items can be addressed at the same time, and are complimentary.

Effective optimisation of mill feed size in a mine to mill sense requires optimisation of fragmentation by material type, through ore specific blast design. This requires some degree of categorisation of ore hardness and structural properties, and is therefore founded on geometallurgical principles. Understanding the ore properties and optimising fragmentation to maximise mill capacity has realised benefits in a great many operations.

In the case of a single stage ball mill, there are many examples of where mill capacity has been increased by reducing the ball mill feed size. This requires the ability to either redistribute work in the crushing circuit, or simply increase the utilisation of the tertiary crushing stage. Some good examples exist in the hard rock HPGR circuits including Boddington (Tavani *et al*, 2015), Cerro Verde (Koski *et al*, 2011), Tropicana (Kock *et al*, 2015) where ball mill specific energy values generally exceeded design expectations, while HPGR efficiency was better than design. This allowed a reduction in fine screen slot size, significant reductions in ball mill feed size (in the 2-3 mm F80 range) and significant increases in ball mill circuit throughput. In those cases significant efforts to optimise the crushing circuit paid substantial dividends in overall metal production rates.

Question 3: is the grind size (liberation) optimal?

Grinding circuits are generally operated to deliver a final grind size, or defined range of grind sizes, as a proxy measure of mineral liberation. The grind size is selected to represent optimum economic mineral liberation, such that metal/mineral production rates are optimised. Circuits that operate to more flexible grind size targets will have typically demonstrated that mineral/metal recoveries are less sensitive to grind size, and often will be processing lower grade material.

The suitability of the selected grind size is best demonstrated by plant recovery values, and liberation is deemed adequate if plant recovery aligns with expectations. In more complex or sophisticated processes the use of modal mineralogy is essential to understand the nature and extent of any liberation issues. In most cases target recoveries are influence by laboratory recovery testwork, and in many cases that is the only study of grind sensitivity that is performed. Limited field testing of alternative grind sizes may be performed.

It should be fairly self-evident that laboratory performance can vary significantly from plant performance, both in terms of mineral liberation at specific grind sizes and recovery process performance. It also holds that historical plant recovery performance and expectations do not necessarily represent the optimum value for the current operating condition due to changes in ore type, plant configuration or plant conditions. Without ongoing rigorous diagnosis of metal losses through mineralogical, analytical and metallurgical analysis, it can be difficult to determine the extent of any grind optimisation opportunities.

In many cases even with a significant diagnostic effort it can be unclear if there is a better operating condition. The Bazin technique, discussed in detail by Runge *et al* (2014) is an elegant method that can be used to quantify opportunities for grind size optimisation using size assay data on key process streams. By routinely performing this analysis, on weekly or even monthly stream composites, it can be determined if there are opportunities to increase metal production rates by grinding coarser or finer. This approach represents a practical, low cost approach that can be used on an ongoing basis to demonstrate operational efficiency.

Question 4: is the classification process efficient?

Classification for the purpose of this discussion can be considered to extend to screening, although this discussion will be specifically focussed on cyclones as the most common means of classification in grinding circuits. Inefficient cyclone performance can have significant impacts on metal recovery and circuit throughput, and is commonly the area of greatest concern in this context. Inefficient screening can cause plugging and wear issues in pebble crushing circuits due to excessive fines and water reporting to screen oversize. Alternatively poor screen maintenance can cause increased wear and potential blockages in pumps, pipes and cyclones, and may lead to overloading in ball mills. In the common applications of screening pebbles or scats from tumbling mill discharge streams such issues can be both readily identified and easily corrected.

A well utilised grinding circuit will in many cases demonstrate a bottleneck at the cyclone feed pump, where the pump is utilised to maximum capacity. This is generally reflected by the pump operating to some speed, temperature or power constraint, and demonstrates that the maximum slurry flowrate to cyclones has been reached. There are many other reasons why mill capacity may be restricted in a ball mill circuit, including limited capacity of the water distribution system, or in some cases high slurry flowrates through the grinding circuit. The latter is generally caused by very high throughput rates (in which case no-one is complaining) or high recirculating loads. As high circulating loads can be caused by inefficient classification, the plant operator should be vigilant in monitoring circuit performance as this will generally represent a capacity (throughput) loss that can be readily corrected.

Recirculating loads are an interesting but imprecise marker for grinding circuit operation. Comparing recirculating loads between one operation and another is not necessarily a practical comparison, as the operating conditions can vary significantly between mills. Influences are many and will include mill feed size (particularly at the coarse end, above 2-3 mm) and the strength of these coarser particles as indicated by Axb values, grinding media size, cyclone configuration (diameter and component sizes), cyclone operation (pressure, feed density, target grind size) and mill operating conditions (ball size, slurry density, slurry velocity, mill speed, mill diameter). Given that few operations will have most of these properties in common, there is a practical limit to how directly comparable their respective recirculating loads are. However recirculating load is a useful metric in terms of historical operation of the plant in question, and past performance will be a useful guide to what represents an acceptable recirculating load for a given operation.

The optimal circulating load in many cases tends be as a high a circulating load as possible without reaching physical constraints that impact throughput or efficiency. In the case of a closed circuit SAG mill, too high a circulating load will generate a slurry pool, reducing power draw and impact breakage, reducing throughput. Similarly in an overflow ball mill too high a circulating load will increase the height of the slurry pool reducing power and will increase the superficial velocity of the slurry through the mill. This may reduce grinding efficiency and if too high will result in ball ejection from the mill. Too low a circulating load and over generation of fines can occur wasting grinding energy and reducing efficiency. As flow is the constraint in these cases, the size and diameter of the mill is important as well as the feed rate. For this reason, duties requiring high specific energy input (very hard ore and or fine grind sizes) can be optimised at higher circulating loads while low specific energy input (soft ore and or a coarse grind) can only be optimised at low circulating loads.

The circulating load in a stable circuit is directly related to the selected cyclone overflow density. If a higher overflow density is required, less cyclones should be operated. If a lower overflow density is required more cyclones should be operated. Every cyclone used in turn contributes to the circulating load. Spigot size and cyclone pressure also influence the circulating load, the smaller the spigot size typically the lower the operating pressure and in turn the circulating load. Large spigots are associated with higher pressure and higher circulating load. The larger the vortex finders the lower the number of cyclones you need to operate for a set overflow density and vice versa. As a whole you optimise your circulating load by adjusting your cyclone components as best you can within any constraints you have on overflow density and volumetric flow through the mill.

In terms of classification efficiency the lower the water split to underflow the better the efficiency. To meet this goal you should 1) run as higher cyclone pressure as you can for the spigot size without roping the cyclones, 2) You should configure your cyclones so that the spigot to vortex ratio is as high as possible within any cyclone overflow density set point constraint. This should provide reasonable efficiency. Lastly if the circuit water addition is operated to overflow density to meet a downstream requirement (not recommended unless essential) do not operate more cyclones than required. This leads to an artificial circulation of fines to maintain flow reducing cyclone and grinding efficiency.

To achieve good efficiency operating the cyclone to constant pressure with the circuit operating parameters adjusted to achieve the target cyclone feed density is recommended. Operating constant pressure allows optimisation of the cyclone underflow density.

Question 5: is my process stable, and the assets effectively utilised?

The performance of the grinding circuit should be constantly reviewed to determine if the process is well controlled and appropriately constrained. The validity of control set points should be continually evaluated to ensure that the circuit is being driven up against practical constraints and not perceived limitations. Sources of instability should be identified, understood and managed effectively by the control system. Key control loops can include mill feed rate, mill feed size, reclaim feeder speed ratio's, stockpile or bin levels, water additions, mill weight, mill power, crusher power draw, mill sound, cyclone pressure, slurry densities and particle size. The process control logic should consider cyclic water and slurry flows associated with ancillary equipment cycles, such as batch gravity concentrators. Ideally the control logic should be as simple as possible to avoid introducing instability, and higher level control systems should be considered as the control philosophy becomes more complex. Bass *et al* (2014) give a useful description of control system development based on experiences at PanAust mine sites.

Question 6: do I have the correct grinding media?

The appropriate selection of grinding media in many cases is not a key influence on grinding circuit performance, however if any one of a number of key considerations are not addressed the impact on plant performance can be material. The key considerations relate specifically to quality, metallurgy and media size.

If the quality of a given grinding media is not fit for purpose this can have a number of detrimental impacts associated with cost and performance. This can be a result of inferior raw material specifications and quality upstream of the grinding media production, inferior heat treatment practices or inadequate process control. The immediate impact will be cost related, as high media wear rates will be compensated for by high addition rates, and unit processing costs will increase. Longer term impacts can include a reduction in grinding efficiency as the mill load builds an accumulation of junk steel within the grinding circuit, and high wear rates through pumps, pipes, screens and cyclones. All are issues that can be avoided with appropriate due diligence prior to selecting a grinding media supplier.

The metallurgical properties of ball mill grinding media have been demonstrated to have a significant impact on metal recovery by flotation at many operations such Perilya, Ernest Henry and Ridgeway as reported by Greet (2012) and Greet et al, (2014). It can also have a material impact on operating costs depending on how suited the metallurgical properties are to the abrasive properties of the ore and corrosive nature of the grinding environment. Some operations have achieved reductions in operating costs by optimising the grinding media properties in light of these considerations, a process that can readily facilitated by the use of marked ball wear testing and full grinding media charge displacement trials. For SAG mills the range of media suitable is more constrained due to the high impact resistance required of the media. As the media grade increases – specifically the higher the carbon content, the performance of the manufacturer becomes more critical. This particularly relates to good raw material control, production control and maturity of production practices. Any deficiency in those criteria at large media sizes can lead to excessive media breakage, and the risk of safety and production related losses.

Question 7: do I have the correct liners?

Initial evaluations should focus on major defects. Does the mill suffer from excessive liner breakage, or is the mill operation excessively constrained in order to avoid liner breakage? A good example would be running at consistently low speeds or low ball loads to protect the mill. If so then the study should consider what options are available to alleviate these issues, with lifter profile the main opportunity. Other extreme conditions like packing, pooling, racing, grate pegging or excessive pulp lifter or discharge cone wear give strong indications of opportunities to improve liner designs.

Question 8: can mill run time be improved?

Mill utilisation is often the domain of the maintenance department and dictated by the mechanical availability of key equipment, sometimes equipment or process downstream of the grinding circuit, or even upstream ore availability in mine constrained operations. Regardless opportunities should be sought to eliminate run-slow situations or operational downtime wherever possible, with the overall objective to ensure that mill utilisation is at least equivalent to comparable operations. For large capacity circuit operating off coarse ore stockpiles utilisation levels of 92-94 per cent are common. For smaller circuits with over 24 hours in crushed ore storage in fine ore bins utilisation levels of 94-95 per cent are more usual. A number of operations in recent times are trialling double cord and/or light weight shell liner materials to significantly reduce mill reline times, and similar efforts around reline optimisation and component wear life are often beneficial.

Question 9: does the mill performance benchmark well against comparable operations?

The use of power modelling and simulation modelling techniques to perform an initial assessment of circuit performance can be a very powerful demonstration to management of the need to optimise. Power based modelling methods described by Morrell (2004), Barratt and Allan (1986), Starkey *et al* (1994, 2006) and Ballantyne *et al* (2015) provide simple methods to define performance expectations and compare against actual performance. The Global Mining Standards and Guidelines Group's Industrial Comminution Efficiency Guidelines, described by Giblett and Daniel (2016), detail the processes that can be used to perform this analysis. Following this process will give the operator a clear indication of whether there is any low hanging fruit, or at the least ideally give some ammunition to garner higher level support for required optimisation initiatives that may not otherwise be obvious to management.

CONCLUSIONS

This paper has considered a broad range of optimisation initiatives documented by practitioners and distilled this analysis into a series of questions that should be answered when determining the performance condition of any grinding circuit. It is hoped that these questions, and the supporting references, will help guide plant operators to critique their existing performance and support successful continuous improvement endeavours.

It is worthy of note that ongoing focus is required to ensure the benefits of any optimisation program continue to be realised for the life of the mine. There are notable examples where large benefits were initially realised from large initiatives, in high impact areas such as process control or mine to mill optimisation, only for performance to revert back to the original baseline over time due to a loss of focus. This is often associated with staff turnover, but can be caused by a number of influences. Every optimisation program should consider the project requirements to clearly communicate the performance benefits, embed system changes and implement ongoing monitoring of key performance indicators. Site leadership should in turn continually challenge technical staff to ensure effective utilisation of past performance benefits and to continue to look for further improvement opportunities as time goes on.

The questions proposed in this paper as the basis for any grinding circuit optimisation study are in summary:

1. Can I draw more power?
2. Is the primary mill feed size optimal?
3. Is the grind size (liberation) optimal?
4. Is the classification process efficient?
5. Is my process stable, and the assets effectively utilised?
6. Do I have the correct grinding media?
7. Do I have the correct liners?
8. Can mill run time be improved?
9. Does the mill performance benchmark well against comparable operations?

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