PRE-CRUSHING OF SAG FEED: FRIEND OR FOE

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Abstract

In the mineral processing sector, a common approach to expanding a SAG mill circuit is the addition of secondary or tertiary crushing to reduce the size of the mill feed. The addition of pre-crushing can increase the throughput of an existing SAG mill circuit by 10% to 30% or more, depending on the nature of the ore and the crushing equipment selected. In this paper, the principal author will discuss his experiences with the application of pre-crushing in SAG mill circuits over a 50+ year career, both at the design stage and as a retrofit expansion, and discuss some of the opportunities/challenges discovered along with potential high-energy mitigation strategies.

This is Starkey's first publication dealing with pre-crushing so no published references exist in support of certain factual statements made. Instead the reader is advised that these ideas and conclusions have been developed over a 25 year period during which the SPI and SAGDesign tests were created and shown to be useful in measuring the SAG hardness variability in ore deposits. Pre-crushing has not previously been a focal point prior to ore sorting because single stage SAG milling is the first recommended flowsheet option for simplicity. However, to implement ore sorting, pre-crushing is required. The rejection of waste and reducing the amount of coarse grinding that needs to be done both reduce grinding energy so this paper is important to co-ordinate these ideas.

Starkey has used pre-crushing in commercial projects for over 20 years so these ideas are sound and not new.

Keywords

SAG Mill, pre-crushing, ore sorting, energy reduction, SAGDesign testing

Introduction

Most SAG and AG mills are designed to treat primary crushed ore and a common size for primary crushing discharge is 80% passing 152 mm (6 inches). Recent advances in pre-crushing and ore sorting are leading to a shift in this design mentality. As ores become harder and more costly to grind the savings enjoyed from the simplicity of a single-stage grinding mill become the subject of trade-off studies. Furthermore the use of ore sorting which requires finely crushed feed provides additional advantages that further complicate those studies.

In the context of this paper pre-crushing refers to secondary, tertiary, and quaternary crushing to a size finer than an F_{80} of 152 mm. Secondary crushing can reduce the F_{80} feed size from 152 mm to a minimum of about 40 mm, tertiary crushing to about 10 mm, and quaternary crushing in high-pressure grinding rolls (HPGR) to about 2 mm (Basics in Mineral Processing, 2018). As HPGR technology evolves the possibility of even finer crushing at large tonnages is also becoming feasible. Recent advancements include tertiary HPGR treatment of 40 mm feed to produce an 80% passing 2 mm product.

There are many reasons to discuss pre-crushing in the preparation of grinding mill feed. Pre-crushing can be used to reduce the size of a new SAG mill or to implement ore sorting. It can be used to increase the capacity of an existing SAG mill or it can be used to remove the SAG mill from the circuit entirely if a crushed product of 80% passing 2 mm is created.

When used properly pre-crushing is an operator's friend because it can be used for the purposes noted above. However, if it is used to compensate for a poor SAG mill design it can be considered a foe because the addition of a pre-crushing plant represents significant additional capital. If these costs were not included in the original feasibility study the original economic analysis will be incorrect and the profitability of the plant will be reduced.

The capabilities of crushers to produce products fine enough for ball milling have been misunderstood in recent years. Because SAG mills have routinely been designed to produce a coarser product than a ball mill can treat with good efficiency it has become common practice for engineering companies to allow very coarse material to enter a ball mill. Indeed, if a SAG mill discharge screen or trommel has 12.7 mm square openings, the top size of material moving forward to the ball mill will be 12 mm and the P_{80} of the SAG mill discharge will be in the order of 4 to 6 mm, based on a normal relationship of screen opening to product size. According to Bond's ball mill equation (Bond, 1961), a coarse correction factor needs to be applied, and efficiency losses over 25% can occur in a ball mill. The savings on SAG mill power are offset by ball milling efficiency losses so the result of making a coarse SAG product is negative because the ball mill power is increased and the circuit will become SAG limited.

Bond's work was unique in that he related power calculations to specific energy (kWh/t), and his equations lead to the definition of the power required to grind each tonne of ore from a stated size to the defined liberation size. SAGDesign technology has been built on this same premise. The SAGDesign test and design equations give the energy to grind an ore from 80% passing 152 mm to 80% passing 1.7 mm. Since this transfer size is fine enough feed for a ball mill no ball milling inefficiencies will occur. A 5 mm closing screen will deliver this approximate size of SAG ground product to the ball mill.

The point in setting up the SAGDesign test was to give an accurate way to calculate total grinding energy. Part of this calculation relates to the empirically known reduction of SAG energy by pre-crushing. SAG energy is reduced by 5% for each 25.4 mm reduction in the F_{80} size as shown in Figure 2 below. This relationship was determined from benchmark studies involving pre-crushing of F_{80} 152.4 mm feed to ~101.6 mm, done during the development of SAG hardness measurement tests by John Starkey during the past 25 years. The extension of this graph to F_{80} 25.4 mm has not yet been adequately proven by benchmark testing but is supported by the experience of Starkey during the last 5 years while working on Russian projects involving pre-crushing to 10 mm. Accurate proof of the extension of the graph in Figure 2 when crushing to 25 mm and finer, is urgently required.

The present situation is even more challenging because as deposits are mined out, ore grades and reserves decline. Unstable metal prices can add to the burden of getting more throughput from existing SAG milling equipment. It is therefore a good idea when designing new mills to allow for pre-crushing (and pebble crushing) to be added when additional tonnage of low-grade ore from a mine is needed to maintain metal production.

In deciding what ore hardness tests to use to design SAG mill circuits involving pre-crushing it is important to note that SAGDesign SAG grinding tests measure ore hardness in kWh/t required to grind ore from F_{80} 152 mm to T_{80} 1.7 mm by grinding the ore sample in a scaled-down SAG mill. JK Drop Weight tests and SMC tests do not directly measure ore hardness but are a proxy for assessing ore hardness after breaking selected pieces from a sample in a JK Drop Weight testing device.

Challenges in Methods of Calculation and Design

The design of circuits with pre-crushing is surprisingly complex due to the impact of the modified mill feed on the rest of the grinding circuit. Conventional applications of Bond Ball Mill Work index (BM Wi) calculations are not reliable over the entire size range that may be considered as SAG or ball mill feed. As a result, additional care and consideration must be taken by design engineers to use appropriate design methodologies.

MEASURING ORE HARDNESS FOR PRE-CRUSHED MILL FEED

Fred Bond in creating the Bond Ball Mill Work Index (BM Wi) test (Bond, 1961), gave the mining industry a relatively precise way to measure ore hardness for a ball mill. Using the SAGDesign SAG test, SAG grinding energy required to grind to T_{80} 1.7 mm as noted above, can be accurately measured (< +/-5%) (Brissette, 2014 and Starkey, 2015[1 and 2]). Combining the SAG hardness with the BM Wi test on SAG ground ore from the SAGDesign test, allows for the calculation of total grinding energy, as illustrated in Figure 1.

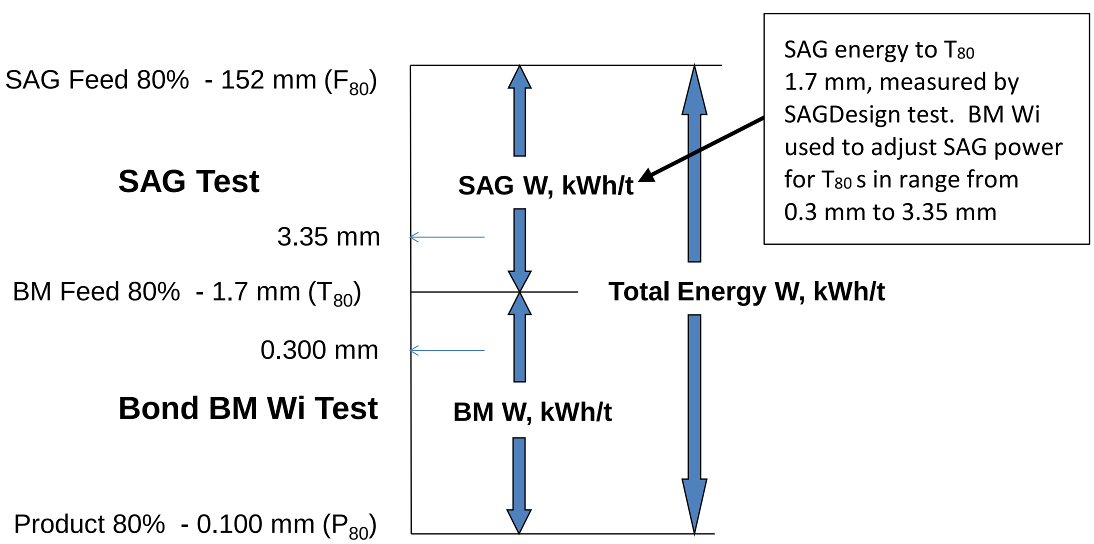

Figure 1 – Diagram of Grinding Energy Measurement

The influence of P_{80} on grinding energy is known from the work of Bond (Bond, 1961), but the influence of F_{80} at finer crushing sizes than 25 mm is still unclear. Figure 2 presents a methodology for calculating this effect based on a benchmark study case produced for an operating plant in Russia where two empirical curves are combined to cover the entire range of crushing sizes available as defined from 0% (crushed ball mill feed to F_{80} 1.7 mm) to 100% of SAG energy (crushed to F_{80} 152 mm). This benchmark project was evaluated where a 10 mm F_{80} was being used. In order to be conservative, Starkey estimated that pre-crushing to 10 mm reduced the SAG energy by 40%. As a corollary, the SAG mill still had to provide 60% of the measured SAG energy (from F_{80} 152 mm to T_{80} 1.7 mm). Pre-crushing to 10 mm gave an estimated annual production of 213,000 t/a. If an energy reduction of 50% was used the annual production estimate increased to 221,000 t/a. Reported annual production was 231,000 t/a so the numbers used were considered reasonable and conservative. The point showing 60% reduction of energy to crush to F_{80} 10 mm is shown as a point in the Figure 2 graph to show how this data fits for actual production. These functions shown need to be further refined with additional benchmark testing of operating plants treating similar sizes of pre-crushed feed.

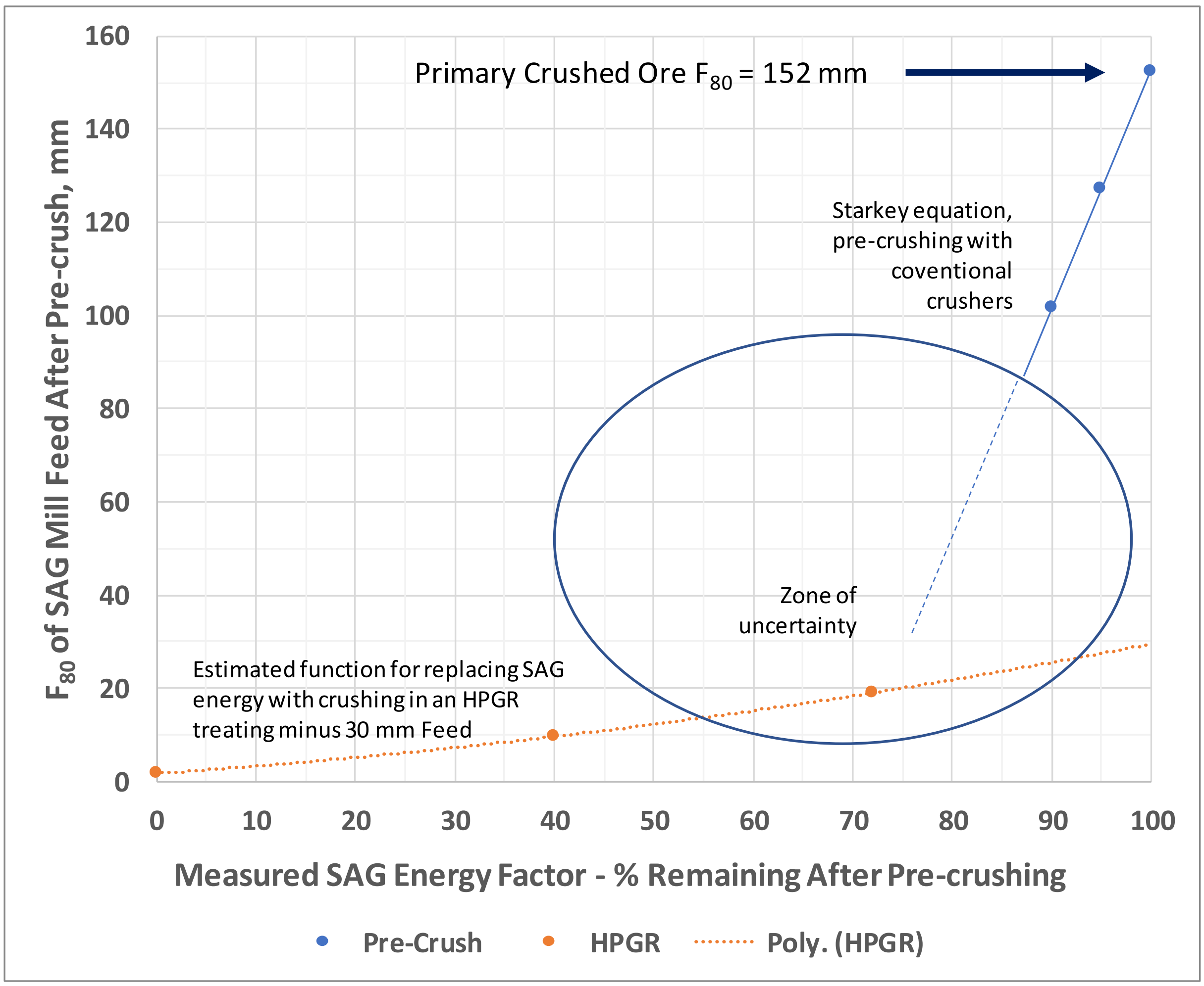

Figure 2 – Percent of Measured SAG Power to Grind from F_{80} 152 mm to T_{80} 1.7 mm vs Pre-crushed F_{80}

Used together, Figure 1 and Figure 2 show how to calculate the SAG energy and the total energy needed to grind the ore so that any possible configuration of pre-crushing, SAG plus ball mill, or single-stage SAG milling can be designed or evaluated with confidence.

Figure 2 shows how various levels of pre-crushing can be used, and the associated grinding mills chosen by deducting the pre-crushing reduction factor from the measured total SAG energy to grind F_{80} 152 mm ore to T_{80} 1.7 mm, as measured by a SAGDesign test.

For pre-crushing to 80% passing 25.4 mm, the energy reduction in a SAG mill is defined as about 25%. Further reduction toward T_{80} 2 mm in an HPGR is not well defined. Since this reduction in moving from F_{80} 25 mm to F_{80} 2 mm (~75% of the total measured SAG energy) is a very flat function, better plant benchmark definition is required to define and prove the curve shown in Figure 2.

The Russian plant data also indicates that using BM Wi data alone to evaluate this grinding process generated incorrect results because the coarse correction factor was over 1.5 and so the predicted plant tonnage was only 172,000 t/a. As the ball mills used for the first stage of grinding were grate discharge primary ball mills it was concluded and shown that the SAGDesign SAG energy adjusted using the BM Wi on SAG ground ore was the correct way to evaluate this production and to design new SAG mills for this purpose.

PRE-CRUSHING DESIGN AND ITS IMPACT ON MILLING

The preceding discussion of ore hardness measurement was necessary to show that to grind from any F_{80} between 152 mm and 2 mm to a 1.7 mm T_{80} (the 80% passing transfer size to a ball mill) the hardness of any ore is measurable in kWh/t.

Using this approach there is now a way to compare any flowsheet requiring pre-crushing to a reference design basis.

That is, a single-stage SAG mill where primary crushed ore is fed to a SAG mill and the product P_{80} is not finer than 71 µm. Previous mill design work by Starkey has considered 200 mesh (US standard, 75 µm) as the limit for a single-stage SAG mill grinding project but when the single-stage SAG mill at the Agh Darreh gold mine in Iran is considered it is evident that Bond's threshold of not finer than 71 µm for the application of the BM Wi fines correction factor is a relevant limit in this discussion of single-stage grinding product size. The Agh Darreh product was closer to 270 mesh (53 µm) in the plant, which confirms that 71 µm in a single-stage SAG mill is an achievable design target.

Single-stage SAG milling. This concept is the best technology in the mining industry and possibly the least understood. Why is it the best? Because projects like Lake Shore Gold in Timmins can be built. There the flowsheet is a primary crusher followed by SAG milling to a product P_{80} size of 75 µm feeding the leach circuit. Operating time and gold recovery are very high. Maintenance and operating labour costs are low and while energy used in grinding is higher than one would like to see, the net effect of no conveyors or dust collectors in the grinding area make this choice of flowsheet inviting. But evaluation is required before a plant is designed. Before other flowsheets are selected trade-off studies are needed to show that the best CAPEX and OPEX options are chosen. By including single-stage SAG milling in the options studied the most viable plant possible can be selected and built.

Why is single-stage SAG milling not well understood? There is no logical answer. Every single-stage SAG mill that the principal author has designed, reviewed, or visited has worked. The list is impressive including Lake Shore Gold in Timmins, Meadowbank in Canada, Kittila in Finland, Navachab in Namibia, and the new single-stage SAG mill for Mako in Senegal, which was discussed at the January 2019 Canadian Mineral Processors Conference in Ottawa. Full tonnage operation in 7 weeks, grinding to 80% passing 75 µm was reported. (Scinto, 2019)

There are other projects that could have been single-stage but were not. Was it fear of charge stability? Was it lack of knowledge and experience by the designer? Was it fear of failure from never having designed a single-stage SAG mill before? We don't know. But the potential advantages for low capital and operating costs and high production are so great that the design team has a duty to find out how to do single-stage SAG mill design work if they have not done one before. It does help when fundamental concepts are used instead of simulations because then the design can be done by anyone. And make no mistake it should be the goal of every mineral processing engineer to learn how to do this important job so that designs by others can be properly checked and vetted by the client's engineer when a new SAG mill is being purchased for a mining project. The use of private intellectual property to design SAG mills over the past 60 years has seriously held back the progress that otherwise should have been made, by restricting detailed knowledge to the few who have access to the confidential design information.

One of the most relevant points in favour of single-stage SAG milling is the ease of operation that is associated with high operating time. This translates to steady operation and high production because downtime events are less frequent. This benefit does not usually show in the trade-off study but is a worthwhile benefit that can happen using single-stage SAG milling.

There is another hidden benefit associated with the use of a single-stage SAG mill with no pebble crushing or pre-crushing. This benefit is the ability to increase production easily by coarsening the transfer size and adding a ball mill. Expansions to double capacity can be done in this way so long as the initial design did not specify a long SAG mill with the diameter less than the mill length. An aspect ratio (D/L) greater than 2 is recommended if easy future expansion is to be implemented. When this approach is taken and the SAG mill feed bin and conveyor are properly sized the expansion is completed with almost no changes to the front end SAG mill feed system. Smaller expansions can also be done by adding pebble crushing and/or pre-crushing to the comminution circuit.

To design SAG mills with confidence it is important to realize that some ores are considered by many designers to require pebble crushing because of the presence of "critical size" ore particles. (Starkey, 2016). The SAGDesign test mill proves that any ore can be ground in a SAG mill with no pebble crushing so long as the mill is of sufficient size and power. The problem with critical size is a myth. The only thing critical about critical size is that there is not enough power to grind it. Indeed, when rounded particles appear in a charge the operator has two choices. Add an in-circuit pebble crusher which may take a year or more to implement or cut the production rate until the problem is resolved. The lower rate consumes more power per tonne and so it becomes evident that had that higher level of power been installed in the first place there would not have been a problem. The SAGDesign test identifies the energy needed to grind the ore with no pebble crusher and so can be used as a firm measurement of SAG energy in a single-stage SAG milling circuit or in any SAG mill where the target feed and discharge product sizes are known.

There are those who will claim that without testing 50 mm and 100 mm pieces, this claim of certainty cannot be made because the SAGDesign test uses -25.4 mm feed. Experience and understanding reveal that this is not the case. The SAGDesign test does about 75% of the total work of a plant treating 152 mm feed and about 95% of the energy when the SAG feed is pre-crushed to an F_{80} of 51 mm. Plant benchmark comparisons confirm that the SAGDesign test does predict the required energy in a commercial plant and that the predicted tonnage is achieved when benchmark results are compared with SAGDesign tests on the SAG mill feed. (Brissette, 2014)

REASONS TO PRE-CRUSH

As stated in the introduction to this paper, there are several good reasons why a designer may decide to pre-crush an ore prior to fine grinding to the required treatment size as determined by studying the mineralogy of the ore and performing ore sorting tests to establish relevant facts. Reducing the size of the SAG mill is one of the first potential benefits of pre-crushing. With it goes a reduction of required SAG mill energy in the range of 10% to 30% (see Figure 2), depending on the pre-crush size chosen.

Another reason to pre-crush is to implement ore sorting, which is generally considered to be optimum in the F_{80} size range of 75 mm to 15 mm where the ejection of particles can be accomplished with solenoid-activated air jets impacting and moving individual particles of ore away from the main flow.

Ore sorting should not be considered without a proper trade-off study because there will be discarded metal in the waste steam from the ore sorter and the comparisons between design cases must show weight and metal loss in the ore sorter and evaluation of the capital and operating costs and revenue for both options.

Finally, pre-crushing is a valid method to expand an existing plant when increases in throughput up to 30% are desired though this adds capital and operating costs. If the target throughput gain is larger than this, significant consideration should be given to adding additional milling capacity instead of adding a pre-crushing circuit.

REASONS TO AVOID PRE-CRUSHING

Pre-crushing, while being a friend for the above-noted applications should be avoided if possible for several reasons. These are the creation of dust at each crushing stage, the addition of capital cost to buy, install, and design the supports and building enclosures for the pre-crushing equipment, and the additional maintenance cost and lost production time when additional process equipment is added to the flowsheet. The high operating times achieved in a single-stage SAG operation make this approach attractive and the first one to be looked at for use at a new project because additional revenue can be achieved when less interruptions occur.

One common omission from trade-off studies is the labour needed to clean up conveyor galleries in new crushing plants. When a crushing plant starts up without this needed labour the galleries can quickly become safety hazards and impact negatively on the whole operation.

Other Considerations

CRUSHER TYPE

Pre-crushing of SAG mill feed is usually done with conventional crushing equipment starting with a secondary standard cone crusher to reduce the largest lumps from the primary crusher to about one quarter of the feed size; that is, from F_{80} 152 mm to about 40 mm. Tertiary shorthead cone crushers are next used to further crush the feed from 40 mm to about 10 mm, the finest product possible when treating high tonnages of ore in a conventional, 7 ft diameter shorthead crusher. Smaller crushers can crush finer but for high capacity crushing plants, products finer than 12 mm to 15 mm are not considered to be common or practical by the authors.

It has been established above that crushing to F_{80} 25 mm will reduce measured SAG energy by about 25% as seen in Figure 2. As crushing gets finer the relationship is not clear and it is likely that the shape of the function and the fineness achievable will vary according to the type of crusher used. If the crushing is done in conventional equipment the straight-line function might well be close to reality. If however, an HPGR is used to achieve finer sizing it is possible that the quadratic equation function depicted in Figure 2 may be more accurate. In any case once crushing finer than F_{80} 20 mm is implemented the amount of grinding energy conserved per millimetre of feed size reduction is a very flat line or a curve, as the Figure 2 implementation function suggests. Only one reference was used to create the HPGR curve in Figure 2 so more research and plant data will be needed to fully understand this subject and to handle fine pre-crushing design issues with full confidence.

FINE CRUSHING USING HPGR

Very fine crushing to F_{80} 2 mm can be done in an HPGR to produce normal ball mill feed. The comparative energy required to do this reduction in an HPGR is lower than in a SAG mill because particles are broken by compression, not by abrasion or impact which requires more energy to turn the SAG mill, lift the charge and so create fines. Since breakage energy can be saved using an HPGR fine pre-crushing becomes part of this discussion.

As indicated above in the order of 75% of measured SAG mill energy to grind primary crushed ore is consumed in grinding the -25 mm ore to T_{80} 2 mm in a SAG mill. If this product size is achieved in an HPGR, a SAG mill is not required. Referring to Figure 2 all the measured SAG energy (grinding to 2 mm) has been eliminated.

The mill required to grind -10 mm feed from an HPGR (or any other crusher) can be either a SAG mill or a grate discharge primary ball mill. To grind ore with an F_{80} of 10 mm, a grate discharge mill is required in order to do required and relevant calculations. Bond ball mill calculations of required energy at this feed size are not valid for feeds greater than F_{80} 6 mm. If coarser feed than 6 mm is sent to an overflow ball mill, the coarse correction becomes so large that it does not reflect reality in the operation because Bond's ball milling equations and published correction factors were based on empirical data from grinding finer feed material. (Bond, 1961). In Bond's day coarse feed over 6 mm would usually be sent to a rod mill.

SAGDesign technology and calculations are the same for both primary grate discharge ball mills and SAG mills which also use grates. The uniqueness of SAGDesign technology is that it uses a precise measurement of SAG energy to grind F_{80} 152 mm feed to a T_{80} of 1.7 mm. The actual T_{80} is then manually limited to 3.35 mm to calculate the SAG power adjustment using the BM Wi. This avoids using the coarse ball mill correction factor entirely in ball milling and gives the most accurate prediction for SAG mill sizing and for predicting t/h from mill size. A grate discharge primary ball mill should be long when grinding F_{80} 10 mm feed because the longer mill can save capital compared to a larger diameter SAG mill but both configurations will work well from a technical perspective.

Replacing SAG mills with HPGR equipment has been discussed and implemented in recent years. The above discussion shows how this is done and since three stages of dry crushing (two before the HPGR) are needed to efficiently replace a SAG mill, it is misleading to suggest that an HPGR has replaced the SAG mill. This is especially relevant since a SAG mill uses wet grinding to repress dust in grinding and only the primary crusher, usually located in a remote building, creates dust but it is far away from the SAG milling plant.

ORE SORTING

A major advantage of a pre-crushing circuit is that it provides operators with an opportunity to treat ores with varying top size limits and particle size range splits for sorted SAG mill feed. Recent advances in ore sorting (Hilscher, 2018) have made it possible to treat the ore on a particle-by-particle basis to reject those below a specified grade. With proper design consideration this can reduce the total feed mass to the downstream milling and recovery circuits significantly reducing capital, energy consumed, and overall operating costs.

The primary constraints of contemporary particle-by-particle ore sorting are related to the suitability of the ore to various sensing technologies, throughput per unit, and additional operating costs due to instrument air consumption. This requires that sufficient engineering be completed at an early stage to determine if the ore and project are suitable for sorting. Such studies must include evaluation of all of the main mineralization types in the ore body so that metal losses caused by variability in the mineralization are discovered during design.

Alternatively, size-by-size sorting can also be considered by simple screening. This allows the operator to reject or accept specific size fractions that enrich the head grade and reject either coarse or fine waste. Ore sorting should not be selected until metal losses have been thoroughly analyzed and shown to improve the project's ROI.

Summary & Conclusions

This paper outlines a direct way to accurately design SAG milling circuits in the context of pre-crushing with and without ore sorting and provides a method to integrate pre-crushing and ore sorting into SAG mill designs to provide direct energy reduction and waste removal to further reduce the energy in SAG milling.

In this context pre-crushing is a friend because it can be used in many ways to benefit the economics of the plant being designed. Production targets can be met with confidence and the re-establishment of SAG milling as a desirable leading comminution technology can be enhanced.

The use of BM Wi calculations to design ball mills for F_{80} 10 mm crushed feed have been found to be incorrect. Historically, rod mills were used to grind this size of feed, because it was too coarse for a ball mill. Today, however, rod mills cannot be used for new high-tonnage projects due to the practical limitations of rod length in 20 ft long rod mills. Following from this, the diameter of a rod mill is restricted to 15 ft, and makes the scaling up of rod mills above these dimensions is impossible. It is therefore concluded that primary grate discharge ball mills are needed to meet the demand for processing high tonnages of F_{80} 10 mm crushed ore.

This paper also confirms that one correct way to design a primary grate discharge ball mill is to use SAGDesign technology for measurement of ore hardness and for performing reliable calculations to determine the size and power of the primary and secondary ball mills required.

SAG milling a pre-crushed product size F_{80} of 51 mm or coarser needs a conventional SAG mill as the primary grinding mill. If the F_{80} is to be finer than 51 mm, a longer grate discharge primary ball mill can be selected to produce the finished grind as long as the final grind P_{80} is 71 µm or greater. An advantage for using grate discharge primary ball mills is that the loading can be 35% instead of the usual limit for a SAG mill of 26% load. At this time it is not known what the relationship between maximum load and ore feed top size is.

For crushed feed with F_{80} over 4 mm and less than 20 mm a single-stage grate discharge primary ball mill should be used and the sizing calculations should be done using SAGDesign technology not just BM Wi equations because BM Wi calculations are not valid for $F_{80} > 5$ mm due to the application the coarse correction factor.

Using HPGR pre-crushing for primary mill feed, develop a realistic benchmark function for primary mill feed F_{80} and SAG energy requirements. At present the benchmarking of primary mill feed in the range of 4 mm to 20 mm is not well enough defined to be fully confident of the results when assessing required SAG energy.

Pre-crushing is required for new projects where ore sorting is to be used. The target SAG mill F_{80} normally lies between 10 mm and 100 mm and is dependent on the ore liberation size and the type of ore sorter used.

Secondary and tertiary pre-crushing before SAG milling should be reserved for expansions only unless required to keep a single line grinding mill design. The reason it is preferable to start a new plant without pre-crushing is that operating costs will be lower and future expansion will be easier to implement. Pre-crushing of SAG mill feed adds complexity and cost and is unlikely to be part of the most efficient new plant design.

When crushing ore to feed a ball mill an F_{80} of 3.35 mm or finer should be selected for the pre-crushed product. Coarser feed sizes will result in the need to use a coarse correction factor when sizing the ball mill. BM Wi data and overflow ball mills should not be used when the ore F_{80} is coarser than 5 mm.

When designing a SAG mill with a product P_{80} over 71 µm, consider first a single-stage SAG mill with no pre-crushing or pebble crushing. Comparing CAPEX and OPEX results for other options will show the proper choice.

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