GETTING MORE OUT OF YOUR DRILL CORE

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ABSTRACT

The 1996 SAG/AG Conference summarized semi-autogenous (SAG), and fully autogenous (AG) grinding practices in many countries, and recommended the need to coordinate mine and mill operations by measuring SAG hardness. Hard ore, when not identified, causes unscheduled losses in tonnage and cash flow. Open pit mines are vulnerable because daily production can come from a single blast. The true magnitude of hardness variance is often unknown and this has caused many design mistakes.

A successful way to measure SAG hardness has been developed for use during exploration, on 2 kg core samples, to give accurate hardness data. This will result in higher metal production by matching mill design with the mining schedule. Test results now also show where pilot plant samples can most economically be taken to confirm SAG design.

The SAG Power Index Test as it is called, has worked because it measures the abrasion power component of the autogenous grinding process in a precisely scaled down SAG mill. Every new SAG/AG plant needs this data at an early stage in project development.

INTRODUCTION

The theme of this conference has demanded that we look at our respective fields to identify what new frontiers need to be developed and expanded, in order for the mining industry to progress into areas of greater productivity and profitability. A look back in the 20th century shows that there has been great progress in the field of semi-autogenous (SAG) grinding. But a further look ahead shows that until we get much more SAG hardness data from our drill core, as it comes out of the ground, we will probably not have met the challenge of optimizing SAG mill throughput in our mineral processing plants.

The importance of getting more out of drill core lies in the timely generation of data upon which a mine and a mill are designed. We readily accept that metal grades, impurity analyses, and other key parameters affecting the profitability of a mine, can and must be generated on each and every core sample that is pulled from the ground. But because of cost, we have in many instances, declined to generate urgently required SAG hardness data. This is not surprising in that up until two years ago, the smallest scale commercial SAG hardness test required about 200 kg of material for each test done.

Because of the successful development of the SAG Power Index Test on 2 kg samples of any commercial diamond drill core, it is now possible to identify a metal productivity factor for each core sample tested, based on measured values for metal grade and SAG mill power requirements (which controls throughput in a given mill). This information will allow better mine plans to be developed, and more cost effective grinding circuits to be designed.

It is worth noting as we begin this discussion, that the wide throughput variances which occur as many ore bodies are milled, have clearly shown how tonnage sensitive SAG mills are with respect to ore hardness changes. It will therefore be more important than ever for miners to take responsibility for metal productivity, not just grade, and for mineral processors to design a plant that is complete and practical enough to treat a reasonable blend of hard and soft ores, within the constraints of a well run mine. This will demand new ways of looking at a deposit, and will represent a SAG milling frontier to be won as we prepare to start a new century.

This paper will therefore look ahead to see how new techniques may significantly change the way in which we engineer our mine plans and design our semi-autogenous grinding circuits. As in any new frontier, there is much new ground to be explored and cultivated. The work described in this paper is a beginning which will require much more effort as we learn how to get more and better information from diamond drill core.

BACKGROUND

The 1996 SAG Conference in Vancouver (SAG 96), demonstrated that SAG milling has come of age as an economical way to grind ore in a modern mineral processing plant. Authors from all over the world presented papers on a variety of topics including testing, design, operations and maintenance. However there remain unresolved issues, much debate, and a wide variety of opinions on a number of key SAG milling questions, as noted below:

- At what point in the exploration program should SAG hardness data be generated?
- Is ore hardness a parameter that is as important to project economics as ore grade?
- Is it reasonable to infer SAG hardness from other generic tests, or is a specific lab SAG test required?
- How do you ensure that a pilot plant sample is representative of the design power for the mill?
- What is the proper way to define required power in a new SAG mill?
- What is the proper way to decide on the SAG/Ball Mill power split for a new ore?
- Under what conditions of hardness and power cost should a crusher be used ?
- Is SAG in-circuit crushing better than precrushing to a finer feed size?
- Just what is critical size and how should it be treated?
- To what degree of detail should hardness variance be defined?
- What is a reasonable budget to obtain SAG testing samples and do the testwork for a new project?

Some of these questions have answers proposed in this paper. Others will require several years of effort. The one thing that this list clearly highlights is that much more information and study is required to deal with all these issues.

DEVELOPMENT OF THE SAG POWER INDEX TEST

The SAG Power Index (SPI) Test was conceived in 1991 as an effort to answer some of the above questions. It was evident at that time that unless an inexpensive, reliable, small scale SAG test was developed, that some of the above questions might never be properly answered. None of the basic SAG test parameters have changed since the test was developed.

Since 1991, four test mills have been built, each one a little easier to operate than the one before. The protoype was a piece of 12” diameter pipe and ran on a set of rolls. The second was built in Iran on the Gol-E-Gohar processing site, to address a very serious hardness variance problem which was caused by the underground mining of an extremely soft 50 tonne sample for SAG testing which was thought by the owners to represent 100,000,000 tonnes of high grade iron ore. The third test mill was built for testing at Minnovex and is the industry standard model featuring a quick release lid, swivel mount for easy dumping and auto timer connected to the drive. The most recent one to be built will be delivered to a large copper producer in Chile for use on site. Due to the success of the SPI Test at Gol-E Gohar (a Davy Project), Kvaerner Davy has been supportive of this work and in Toronto the test is now being used on all in house projects involving SAG grinding.

The continued development and commercialization of this SAG test followed a deliberate path after Minnovex decided to become involved with this work in 1993. First, the technical procedure and theory were described in a paper entitled “A New Tool for SAG Hardness Testing” which was presented to the Annual meeting of the Canadian Mineral Processors in January 1994. This led to a MITEC (Mining Industry Technology Council of Canada) sponsored SAG test calibration project which was supported by six clients. Testwork was done in five Canadian SAG plants and included reproducibility work as well which was funded by CANMET. The final report of this work was issued in April 1995. This report gave a single straight line calibration equation for grinding a feed $F_{80} = 6$”, to a grind size of $P_{80} = 10$ mesh, for all the high aspect ratio mills in the study, and a second, size corrected equation for finer grind sizes. The natural grain size indicated in the testwork and achieved in four plants was much finer than 10 mesh, which allowed the second equation to be developed.

The reproducibility work also was positive and it was evident when the study was finished that the test would be of good value to operators and designers as well. The SPI Test has been used commercially since the study was completed. To communicate this information to the broadest possible audience, a paper describing the MITEC calibration work was presented at SAG 96 in Vancouver, in October 1996. That paper was titled “Application of the Minnovex SAG Power Index Test at Five Canadian SAG Plants”.

The calibration of the test against actual SAG operations has been the key to using this test on diamond drill core, to predict with confidence the power required to grind ores from various locations in a mine.

TECHNICAL SUMMARY OF TEST PARAMETERS

The SAG Power Index test mill is 12” in diameter x 4” long and was chosen to be the same diameter as a Bond mill and to maintain a 3 to 1 diameter to length ratio. The mill runs at 70% critical speed and uses 15% by volume of steel, the maximum for commercial use in a SAG mill and a practical requirement for testing to avoid long grinding times. Two kilogram samples of ore are used in each test and this size was chosen because it was a good fit for the 12 inch mill and because that is the size of sample normally used for flotation testing. It is now possible to do flotation tests on a sample which has been primary crushed to minus 1 inch, ground in a SAG mill to 10 mesh (oversize must be crushed), and finished in a ball mill to the required fineness for flotation recovery of the minerals so liberated.

The selection of the test feed size was chosen to be 80% passing ½ inch because it was felt that at this size, any commercial core could be crushed and used as feed. This was extremely important because once the data base was started it had to be able to include data from any source. If small core could not be tested, it would have excluded some mining properties from being able to use the test. The parameter of feed all passing 1 inch in a 1 foot diameter mill also seemed to be a good scale down of the traditional 6" feed in a 6' diameter pilot mill, which has been used by the industry for over 40 years. To achieve this feed size, each sample is crushed to 80 % passing half inch prior to riffling out the required 2 kg sample.

The most interesting parameter to be selected was how fine to grind the ore once it was in the mill. Fred Bond had based the majority of his work on ball mill feed which in his day was rod mill discharge. Since rod mill discharge usually is about 80% passing 10 mesh, it can rightly be concluded that the Bond work index equations relate to the comminution of this size of product. Mistakes in SAG power requirement and sizing were therefore thought by the author, to arise from a misunderstanding of the power required to grind from 6" feed down to 80% passing 10 mesh. If this could be measured, the difficulty of SAG power measurement may be resolved. It was therefore clear that the power required to grind an ore to 80% passing 10 mesh would be a key parameter in determining SAG power. Once that has been defined, the determination of total circuit grinding power would be easy and the power split between SAG and ball mill a matter of choice based on known facts. Therefore, 10 mesh was selected as the target size for the test.

The objective of the SAG Power Index Test was then to find how long in minutes it takes to grind a sample from 80% passing ½ inch to 80% passing 10 mesh. The only difference from test to test would be ore hardness, and the time to accomplish this size reduction should be a linear function of required mill power. Consideration was given to a test involving make-up sample as the test proceeded, similar to the Bond ball mill work index test. However, this idea was rejected because of the difficulty which would arise in obtaining ever smaller samples which would have to have identical size structures in order not to introduce a variable into the test procedure. The batch test staged grind was therefore selected, and all of the ore and steel charge is returned to the mill after each grinding period.

The theory behind the test is described above and it was the purpose of the MITEC study to demonstrate the validity of the major premise that grinding time can predict power in a linear relationship.

DISCUSSION OF TEST RESULTS

When the first several ore samples were ground to 80% minus 10 mesh (in 1991), it was surprising to discover that the Gaudin-Schuman plot of the test mill discharge screen analysis data, revealed that there was plus 4 mesh material (over 19%) and minus 28 mesh material (over 79%), but very little else.

It is also worth noting that the 10 mesh SAG Power Index Test product is fine enough to predict power required to grind any hard or “critical size” type material. It was clear from pilot plant grinding work done in the 1960’s by the author, that any ore can be ground in a SAG mill. The only things to be defined are, how much power and what size of mill to draw that power. A key point therefore about “critical size” material is that there is not enough power installed to grind it. For example, If an ore requiring 10 kWh/t to grind to a specific size, is processed in a mill with only 5 kWh/t installed, it will either cut the tonnage to approximately half, if milled alone, or show up as critical size in the mill, if blended with other softer material. Very few plants are built with 15 kWh/t installed, but of those who have this level of power available, none have significant critical size problems.

A second major observation from test results was made while working in Iran. SAG Power Index testing done on ore samples which had already been tested in an Aerofall pilot mill showed clearly that the laboratory 2 kg test would accurately indicate the natural grain size for any ore by taking the 80% passing size from the minus 10 mesh simulated “product”. This was a real bonus for the test because it meant that not only would the test predict the relative hardness of the ore, but also the natural grain size that the material will break to in a SAG mill. It is suggested that a SAG mill can readily produce any size coarser than the natural grain size, but if a finer grind is required, power consumption will increase.

It has been found during the entire six year period in which SAG power index tests have been done, that the vast majority of samples break to a natural grain size between 200 and 800 microns. It has also been observed that if an ore is very hard (i.e. $T > 60$ minutes), the natural grain size will less than 300 microns while softer ores do not show a direct correlation with grinding time.

The MITEC study then proved beyond reasonable doubt that the test grinding time was indeed a linear function of grinding time in the SAG Power Index Test for each plant studied. In addition, a single calibration equation was indicated for grinding to 80% passing 10 mesh (1.7 mm). The SAG Power Index (to 10 mesh), expressed in kWh/t, is determined as follows:

$$\text{SAG Power Index} = (0.11 \times T + 0.9)\ \text{kWh/t} \qquad \text{Where: } T = \text{Grinding time in minutes.}$$

SAG grinds finer than 10 mesh can be assessed by using a second, size corrected equation, or by adding a power component calculated using Bond formulas for grinding from 10 mesh to the desired size.

Since only 1 of the SAG mills in the MITEC study had a vari-speed SAG drive and all the mills were usually drawing full power, it was shown that changes in hardness caused changes in mill throughput. Indeed it was the throughput changes that allowed the correlation of kWh/t consumed with measured hardness. In order then to assure mill throughput under all conditions the mined hardness must be known.

Other observations came out if the MITEC work. Most of the plants visited used a calculated autogenous work index (AW_i) value, calculated using the Bond formula, from operating results for power, SAG feed and product sizes. MITEC results conclusively demonstrated that the calculated value of AW_i is a variable, depending on hardness, and the fineness of SAG product chosen. The Bond work index, W_i is useful because it is considered to be constant over a broad range of product sizes. AW_i however, only has significance in the calculation of grinding power to the product size for which it was determined. This comment applies to test and operating results alike and perhaps indicates why so many different procedures have sprung up over the years for choosing SAG power requirements.

Since the SAG Power Index Test has been used commercially, a number of properties have had SPI testing carried out on samples from the various ore bodies. In all cases tested to date, hardness variances to grind ores to 80% passing 10 mesh, measured in kWh/t, are plus or minus 50% from the mean or average value. This fact, we are sure gives ample cause to recommend that hardness variance be established for new ore bodies and that the choice of installed power should be increased to at least the top quartile of hardness variance, and that the developing mine plan be carefully reviewed for the impact of hardness variance on mill throughput.

The reason that this SAG Power Index Test has worked is that the test measures the abrasion power component in the SAG process, and that this is the largest power consumer, especially on hard ores. This is not to deprecate the value of the effect of impact forces in a SAG mill, because without the impact availability resulting from steel additions, no SAG mill could be assured of meeting its design throughput. The bottom line is that hard ores require power to grind and it is incumbent on the design engineers to provide an adequate amount of power and a mill size to draw it. Extra power at the design stage is cheap compared to adding crushers later. But the subject of when it is more economical to use a crusher will be the subject of a future investigation.

SELECTING A PILOT PLANT SAMPLE

There is no need to recount here a list of projects where great expense has been undertaken to obtain pilot plant samples which have been less than adequate in the definition of SAG power requirements. Mine owners must be aware that mill design is generally based on providing power to grind ore which is similar to that which was tested in the pilot mill. Very often however, the process engineer is not qualified to comment on the representativeness of the sample for mill design. It is a fact that in the absence of adequate hardness data, no one is qualified to answer the question of representativeness. The requirement for a pilot plant test sample is that it represent ore of design hardness, not necessarily the whole ore body .

This situation has existed since SAG milling first became a commercial process. Mining engineers have long insisted on their right to mine an ore body in the most straightforward and practical way. That is proper. But no one will suggest that an owner does not have the right to build a lower tonnage plant and mine a higher grade blend in order to minimize risk and maximize profits. The point here is that we now have a simple way to identify SAG hardness problems and to deal with them at the mine design stage. It is highly recommended that the owner require that his design engineers consider mill throughput at the mine design stage so that the proper integration of mine and mill production facilities can be achieved. To do less would be to leave the matter of final mill throughput to chance, or to the future addition of facilities which are always a disappointment to financiers and owners alike. Too often the cost of SAG hardness determination has been too costly from a sample availability perspective, and final tonnage for a new plant has been left to chance.

SAG hardness variance profiles, when developed from diamond drill core which is required for metal assaying, is not costly if the SAG Power Index Test is used. The best pilot plant sample chosen from these profiles, will be one of the proper hardness, and will be located near the surface unless metallurgical constraints dictate otherwise. Only one pilot plant sample should be tested under normal circumstances, and it is suggested that big savings in the cost of metallurgical sampling and SAG testwork can be achieved by taking a thorough approach to the subject of SAG design and throughput management.

MATCHING MILL DESIGN AND MINING SCHEDULE

The last item which will separate SAG milling today from SAG milling in the future, is the management in the mine of mill production throughput, by mining to a planned ore blend. The mine must control metal grade within certain limits and what is suggested here is that tonnage throughput requires management as well. Obviously there will be times when only the hardest ore is available, and throughput will suffer. But if this is known at the design stage, this kind of variance can be tolerated and balanced with appropriate grade control measures at the same time.

The benefits to a new property of knowing the hardness variance in the mine, will be great. In some cases it may well be judged correct to design the SAG mill for the top decile of hardness variance especially if the hardest zones contain more metal than the softer zones, and the variance is not too severe.

Other benefits will accrue to the mine where hardness control is practiced and integrated with metal production control. The classic case will be when a marginal grade zone, located in the corner of a pit, will be classed as waste if a whole new cut of wall must be taken to get at the ore which can only be processed at reduced throughput.

Two large mines in Canada are known to practice hardness control at this time. There may well be others. They are Highland Valley Copper and the Iron Ore Company of Canada. Both plants process in excess of 100,000 tonnes per day and throughput problems are not tolerated. At IOC, hard ores are set aside as waste because the viability of the plant depends on the constant recovery of iron from run of mine ore. They have developed an in-house lab hardness test over many years, which has worked because the ore is unusually soft. The SAG Power Index Test does the same job and is recommended because it simulates the SAG process and can be used as an industry standard on any ore.

LOOKING AHEAD

The work of Fred Bond has long been admired for his keen analysis and insight in developing a test which has served the industry well over the last 35 years and more. In the Western world, no one questions what data is required to design a ball mill. A Bond Work Index Test. Our goal here is therefore to provide the mining industry with a similar small scale reliable service for SAG mill design. It is our belief that this test now exists as the Minnovex SAG Power Index Test.

It is the managers and owners however who will decide what is useful and best for their respective companies and projects. And they will in large measure rely on the collective judgments of their geological, mining and mineral processing specialists in forming their opinions as to what is acceptable and what is not. At the same time it is very clear that in order to get urgently needed SAG hardness data from our drill core that geology, mining and milling personnel must all work together to get the right mine plan and the right SAG mill for a given property.

One major study yet to be done was mentioned above. That is the proper definition of when a crushing plant will pay for itself in terms of reduced power cost which will be offset by increased operating and perhaps capital as well. This study will have to consider hardness variance and the local cost of power, in order to be valid. It is suggested that the result may well be that it is cheaper to add an extra meter to mill diameter than to build a separate crushing plant with its attendant operating and maintenance challenges.

The SAG process has been attractive because it rolls all of the material handling problems of fine crushing plants into a single chamber which contains the six inch feed until it is approximately minus 1mm. This feature of the SAG mill needs to exploited to the fullest and future studies will set out to define the proper limits for SAG grinding.

Let us hope that the next century will see even more progress in the development of SAG milling as the method of choice for grinding ores in future mineral processing plants.