SAG MILL TESTING - AN OVERVIEW OF THE TEST PROCEDURES AVAILABLE TO CHARACTERIZE ORE GRINDABILITY

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ABSTRACT

Several grindability tests were developed over the years to design grinding circuits or optimize existing operations. Each test has its own strengths and weaknesses and it is imperative to select the proper test procedure(s) to meet project deliverables and minimize the risk of a project. Pilot plant testing of large bulk samples historically constituted the traditional approach for AG or SAG design, but was gradually replaced by small-scale tests. Nowadays, conducting grindability tests requiring only a few kilos of material on several samples, is a more typical approach to grinding mill design. This paper summarises the requirements and deliverables of various bench-scale test procedures, their strengths and weaknesses, and cases where AG/SAG pilot testing should still be performed.

KEYWORDS

Comminution, grindability, grinding, SAG mill, AG mill, milling, HPGR, work index, pilot plant

INTRODUCTION

The resistance of ore samples to breakage (or hardness) is measured through grindability testing. Several grindability tests have been developed over the years for different applications and each test has its own strengths and weaknesses. Grindability testing is a compromise between test cost and its deliverable(s). Because a large fraction of the cost component is driven by the sampling requirement, tests that can be performed on small drill cores offer a significant cost advantage over those that require large diameter drill cores and substantial weight. On the other hand, the test deliverables are generally superior for tests requiring more weight. Overviews of grindability testing methodology and the compromise between test sample requirement and deliverables were discussed in previous SAG conferences by Mosher and Bigg (2001 & 2002) and McKen and Williams (2006), introducing the now updated list presented in Table 1.

SUMMARY

The highest degree of deliverables is achieved in a pilot plant, which is undoubtedly the most reliable test procedure to determine the resistance of ore samples to AG/SAG grinding. The pilot plant can test coarse feeds (150mm), as well as essentially any test conditions, so it presents the lowest degree of scale-up within all the methodologies available, but pilot testing is also the most expensive test, as it requires the greatest sampling effort, in the form of bulk samples or large diameter cores (>150mm). Therefore, it is not cost-effective to test a large number of samples at pilot-scale, and small-scale tests were developed for this purpose. However, the ability to test natural size distribution including coarse rocks, which are generally responsible for impeding AG/SAG throughput, but also for the supply of grinding media for low steel charge applications, is unique to pilot plant. The hardness of coarse rocks cannot be inferred from fine rocks, because the gradient of hardness by size varies from one sample to another. The problem is that the tests that are performed at a coarse size statistically require larger samples, and thus a greater (more expensive) sampling effort.

Table 1 shows that the sample requirement of the tests generally increases with top size, with the media competency (150mm rocks) being at the top of the requirement scale. The work index series (ball mill, rod mill, and MacPherson autogenous) and pilot plant tests require relatively more weight (for a given top size) because they are run until a steady-state is achieved, which involves replacing the mill charge several times throughout the test. The Bond tests are typically run for a minimum of seven cycles, while the MacPherson and pilot plant tests are operated for about 6-10 hours. The achievement of steady-state is desirable in a grinding test, because harder components may build up over time. For AG/SAG mills, this may result in a critical size build-up and associated throughput losses. The importance of steady-state testing increases with the ore heterogeneity. On the other hand, the batch tests (e.g. Mod Bond, SPI®, SMC Test®) generally require less sample, which make them more suitable candidates for variability testing. Sample requirements in Table 1 are approximate and they may vary with ore hardness/friability and rock density.

GRINDABILITY TEST	MILL DIA.	TOP SIZE		CLOSING SIZE	SAMPLE REQUESTED[1]	SAMPLE CONSUMED[2]	TYPE	STEADY-STATE	DATABASE
	(M)	(MM)	(CORE)3	(MM)	(KG)	(KG)		(Y/N)	(Y/N)
Bond Low-energy Impact	N/A	76.2	PQ/HQ	N/A	25	10	Single Particle	N	Y
Media Competency	1.83	165	-	N/A	750	300	Batch	N	Y
MacPherson Autogenous	0.46	32	NQ	1.18	175	100	Continuous	Y	Y
JK Drop-weight	N/A	63	PQ/HQ	N/A	75	25	Single Particle	N	Y
SMC Test®	N/A	31.5	Any	N/A	20[4]	5[4]	Single Particle	N	Y
JK Rotary Breakage Test®	0.45[5]	53	HQ	N/A	75	15	Single Particle	N	Y
SAGDesign	0.49	38.1	NQ	1.7	10	8	Batch	N	Y
SPI®	0.305	38.1	NQ	1.7	10	2	Batch	N	Y
AG Pilot Plant	1.75	200	-	Various	>50,000	>50,000	Continuous	Y	Y
Lab-scale HPGR	0.25[6]	12.7	BQ	3.35	400[7]	360	Locked-cycle	Y	Y
SPT	N/A	19.1	BQ	3.35	10	7	Locked-cycle	Y	Y
HPGR Pilot Plant	0.9[6]	50	-	Various	>2,000	>2,000	Continuous	Y	Y
Bond Rod Mill	0.305	12.7	Any	1.18	15	10	Locked-cycle	Y	Y
Bond Ball Mill	0.305	3.35	Any	0.149	10	5	Locked-cycle	Y	Y
Mod Bond	0.305	3.35	Any	N/A	2	1.2	Batch	N	Y

Table 1 – Summary of Grindability Test Procedures

[1]Weight requested for the test, for typical ores (S.G. = 2.8g/cm3). Denser samples require more weight, proportional to the S.G.

[2]Approximate weight consumed in the test for typical ores (S.G. = 2.8g/cm3).

[3]Minimum whole core size required for a complete test. Partial results can sometimes be obtained with smaller cores.

[4]The recommended top size for an SMC test is 31.5mm, but the test can be performed on smaller rocks or drill core, requiring smaller weights.

[5]Rotor Diameter.

[6]Roll Diameter of the HPGR.

[7]Includes 250kg for a series of 7 batch tests to determine the optimal operating conditions and 150kg for a locked-cycle test.

Grindability tests are generally designed to mimic the grinding mechanisms observed in industrial units. The best examples of this can be observed in the Bond series, where ball mills, rod mills, and crushers are tested using similar laboratory-scale apparatuses. Similarly, the MacPherson and media competency tests were designed to mimic autogenous grinding mechanisms. HPGR, similarly, are generally tested with roller or piston press, to represent compression breakage. By opposition, the JKMRC approach to autogenous mill characterisation was to separate impact and abrasion mechanisms into two different tests (drop-weight and abrasion tests).

Equally important is the need to represent, approximately, the correct size reduction in a comminution device. Because grinding theories are imperfect and ore hardness can vary with size, grindability tests are designed to best represent the size reduction of the industrial equipment analysed. For that reason, it is preferable to design a primary ball mill from a rod mill work index rather than a ball mill index, because the industrial mill will operate over a coarser size reduction range as measured in the rod mill test, which may exhibit different grindability characteristics than would be observed at the ball mill index range.

Table 2 compares the typical range of size reduction observed in grindability tests to those of the most common industrial devices. The list is not exhaustive, but it covers most of the comminution tests and commercial devices used in hard rock mining. Note that the size ranges presented in Table 2 are indicative only and may vary depending on the application, the operating conditions and ore characteristics.

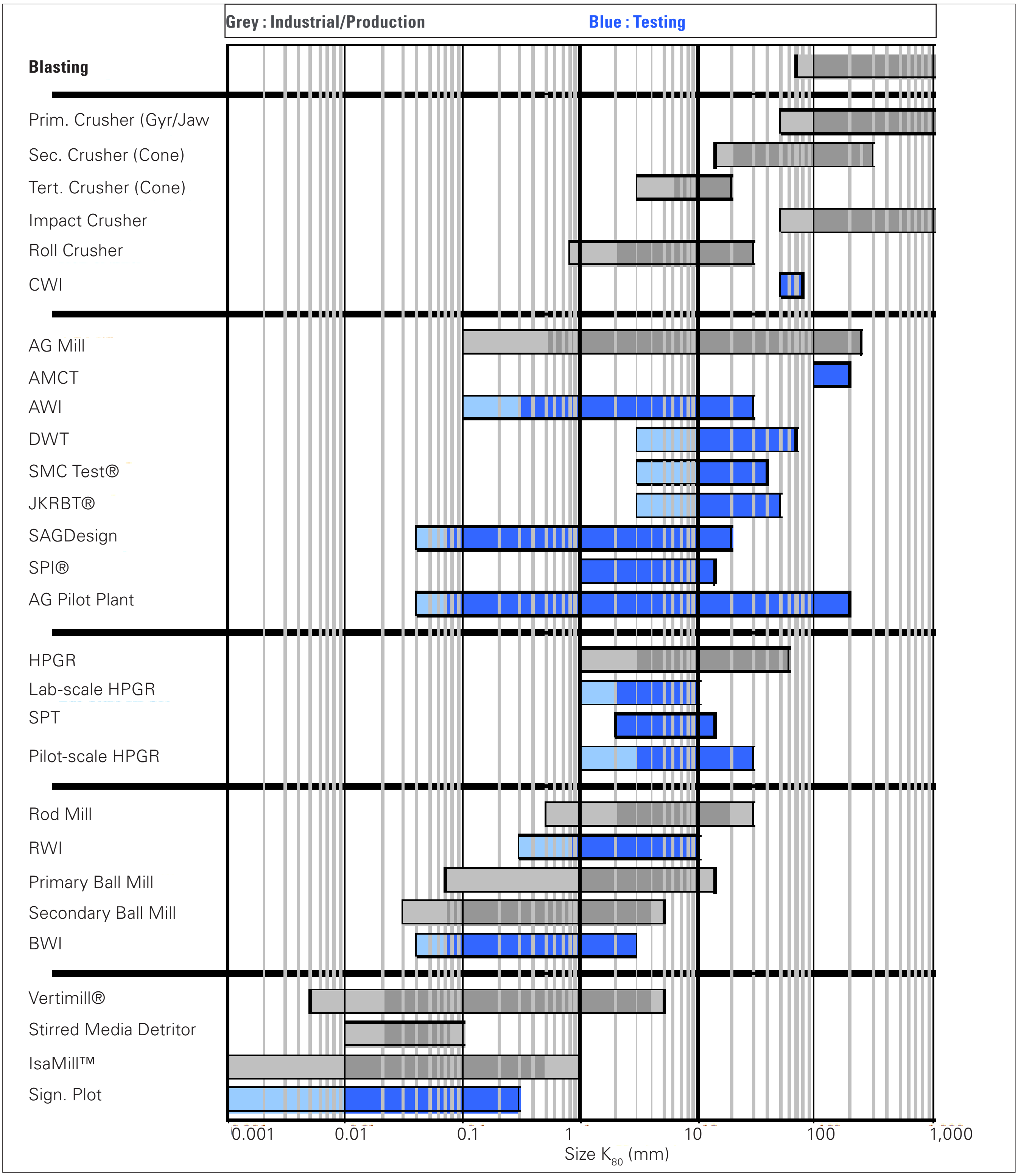

Table 2 – Approximate Range of Size Reduction in Comminution Tests, Devices and Processes

Interestingly, crushing, which covers a fairly wide range of size reduction and devices, is poorly represented in terms of commercial testing. Although, pilot plant trials can be carried out in unusual situations, crushers are more often designed from a crusher index only, which covers a very small reduction range, or using suppliers' charts, sometimes without any testing.

At the other extreme, autogenous testing is arguably over-represented in the testing world, with at least six distinct small-scale testing methodologies (MacPherson, work index series, advanced media competency, DWT/SMC, SPI, and SAG Design) supported by an even wider number of interpretation schools and hybrids. This is probably because autogenous mills are more complex devices and the elaboration of adequate models for their comprehension have been driven by numerous expert consultants around the world, which has resulted in various characterisation methodologies. Most autogenous mills nowadays are designed using one or a combination of these small-scale methodologies (Barratt & Doll, 2008), with pilot plant confirmation sometimes required.

Although HPGR is a more recent innovation in hard rock mining, it has gradually been accepted by the industry. There are now small-scale methodologies available to develop preliminary circuit designs, but suppliers will generally require pilot-scale confirmation that they generally carry themselves.

The design of rod and ball mills is still carried out with the Bond ball mill and rod mill grindability tests. As discussed earlier in this paper, it is important in this case to match the reduction size of the test to that desired from the industrial mill. As such, primary ball mills should be designed with the rod mill work index, and single-stage ball mills should be with both the rod mill and ball mill indices. This is because it is common to observe a difference (sometimes significant) between the rod mill and ball mill index values for a given ore type (McKen, Verret, & Williams, 2006). On average, the rod and ball mill indices are essentially equal, but the ratio between the two can be quite variable. High RWI/BWI ratios indicate competent ores with low ball mill hardness, while low ratios represent friable or coarse-grained ores.

Fine and ultra-fine grinding, also more recent innovations, have developed in various forms and technologies, and testing is generally carried out by the suppliers of those technologies, the most significant exception being the signature plot for IsaMill™ design which is licensed to independent labs by Xstrata (Burford & Niva, 2008).

GRINDABILITY TESTS

The following is an updated review of the principal grindability tests that are currently commercially available for ore characterization and their application to circuit design. It is presented as a reference guide and the reader is encouraged to consult the references that are more specific to each individual test. All of these tests are supported by fairly large databases (McKen, Verret, & Williams, 2006).

BOND LOW-ENERGY IMPACT TEST

The Bond low-energy impact test apparatus consists of two pendulum hammers mounted on two bicycle wheels, so as to strike equal blows simultaneously on opposite sides of each rock specimen. The height of the pendulum is raised until the energy is sufficient to break the specimen (Bond, 1947), and then the crusher work index (CWI) or impact work index is calculated. The test is generally performed on 20 rocks in the -76.2/+50.8mm size fraction. One of the strengths of the test is its ability to measure the natural dispersion in the sample. Another advantage of the test is the coarse size at which the rocks are tested, which makes it unique in the Bond series. The test requires >76.2mm rocks or full PQ core, although relevant numbers may be obtained from full HQ core. Two slightly different apparatus designs have been used in North America and Australia.

The test is mostly used for crusher design, but it can also be used along with the other Bond tests (BWI and CWI) for SAG mill design (Barratt et al., 1996).

ADVANCED MEDIA COMPETENCY TEST

There have been some variations of media competency tests developed over the years. The principal objective of these tests is the assessment of media survival in autogenous milling, and the most successful of these tests has been the Advanced Media Competency Test (AMCT), developed by Orway Mineral Consultants and Amdel (Siddall & White, 1989; Lunt, Thompson & Ritchie, 1996) which features a 'tumble test' in a 6' x 1' mill using ten large rocks in five size fractions in the range 104 to 165mm. The mill is rotated for 500 revolutions and the charge is dumped and the size distribution analyzed. The surviving rocks are submitted to the fracture energy test procedure, which consists in a series of Bond low-energy impact tests in five size fractions. The fracture energy test provides the relationship between the first fracture energy requirement and rock size. The relationship is used for data interpretation, along with the other Bond indices (rod and ball), and database support. With a top particle size of 165mm, the media competency test is the most suitable to address media competency issues.

MACPHERSON AUTOGENOUS GRINDABILITY TEST

The MacPherson autogenous grindability test was developed by Arthur MacPherson (MacPherson & Turner, 1978; McKen & Chiasson, 2006), as a continuous test performed in a 46cm (18") semi-autogenous mill, with an 8% ball charge. A draft fan supplies the airflow required to remove the ground material from the mill, and a collection system recovers the ground material from the air stream. This includes a vertical classifier, a cyclone and a dust collector (baghouse). The cyclone underflow is classified on a 14 mesh screen with the oversize returning to the mill. The mill is fed from a feed hopper by a Syntron feeder actuated automatically by a Milltronics control system. This control system continuously regulates the feed rate by maintaining a pre-set sound level with a microphone located below the mill shell, controlling the mill level to 25% charge by volume. The circulating load is controlled to 5% by adjusting the airflow through the mill. The test requires material with a top size greater than 32mm (1-1/4"), and sufficient weight to operate until all of the steady-state conditions are met, and for a minimum of six hours. This can normally be achieved with less than 100kg, but typically, a 175kg sample is requested to allow for soft and/or dense ores. The test is run continuously, similar to a small pilot plant, for a minimum of six hours and until steady state is achieved. At test completion, all of the products are submitted for particle size analysis, and the mill charge is dumped and observed. The charge is submitted to a particle size analysis as well as size-by-size S.G. determinations. This allows the evaluation of any preferential coarse build-up or particle density concentration in the mill charge. The mill power draw, throughput and product size distribution are used to compute a specific energy input and the MacPherson Autogenous Work Index (AWI). Although the importance of achieving steady-state in a grinding test is widely accepted (Bond tests), the MacPherson test remains the only small-scale AG/SAG mill test that offers this option. Steady-state is especially important in AG/SAG mills where a harder component can build up over time and affect the production negatively.

JK DROP-WEIGHT TEST (DWT)

The JK drop-weight test, as shown by Napier-Munn et al. (1996), developed at the Julius Kruttschnitt Mineral Research Center, is divided into three components. First, the test measures the resistance to impact breakage of coarse particles in the range of 63 to 13.2mm (five fractions). Then, it evaluates the resistance to abrasion breakage of particles of 53 by 37.5mm dimension. Finally, the rock density of 30 particles is measured to assess the ore average density and dispersion. The test generates the appearance function (e.g. breakage pattern) of the ore under a range of impact and abrasion breakage conditions, which is subsequently reduced to three parameters: A, b (impact) and ta (abrasion).

The test procedure requires 75kg of material, which is prepared by the testing facility, to generate 30-90 particles in five size fractions, in the range of 13.2 to 63mm. About 25kg of material is actually consumed in the test, and all of the products and unused material can be re-used for metallurgical testing. In the impact test, the five size fractions are submitted to three series of impact testing at different energy levels, for a total of 15 test series. Each test series is composed of 10-30 rock specimens, which are submitted to an impact of a known energy level, given by the height and weight of the drop weight head. The fragments from all of the test series are collected and submitted to particle size analyses, which are reduced into a family of normalized ‘t’ values, representing size reduction. The t values are defined as the percent weight of fragments that passes 1/t of its original size. For the abrasion test, a 3kg sample of 53 x 37.5mm rocks is used. The sample is rotated in a 30cm x 30cm tumbling mill for 10 minutes, after which the product is submitted for a particle size analysis. By convention, the abrasion parameter (ta) is equal to 1/10 of the t10 achieved in the abrasion test. The density determination is performed on 30 rock specimens, using a water displacement technique. The density distribution of the ore is important for AG/SAG milling evaluation, as it will ultimately affect the bulk density of the mill charge and associated power draw, especially if the AG/SAG mill is designed for a low steel charge. One other interesting feature of the drop-weight test procedure is that it provides a measurement of the variation in rock hardness by size, from 13.2mm to 63mm. Typically, the t10 values will increase with rock size, which means that the hardness of the ore actually decreases, which is often the effect of the increased frequency of cracks in the coarser rocks. For very competent ore, the gradient of hardness by size will tend to zero, while non-competent fractured ore will show a high gradient of t10 with increasing size. Decreasing trends of t10 by size are fairly rare.

The drop-weight test parameters are commonly used in the JKSimMet modeling and simulation package to predict the ore response to comminution processes; to analyse, optimise, and design circuits. The software allows the simulation and calibration of various comminution and separation devices, most notably crushers, AG and ball mills, cyclones and screens.

SMC TEST®

The SMC Test® was developed by Steve Morrell (2004). It is an abbreviated drop-weight test, which can be performed at low cost on small rocks or drill cores (cores can be cut into ¼ cylinders using a diamond saw). The test is performed similarly to the standard drop-weight test procedure, except that a single size fraction is tested. The test can be performed at various rock sizes, the minimum acceptable top size being 16mm. The recommended particle size is -31.5/+26.5mm, which requires preparing about 30kg of samples, with only 5kg actually tested, and all the products and unused material can be re-used for metallurgical testing. Testing of smaller rocks or drill core requires significantly smaller weight. A bulk sample, or essentially any size of drill core, is adequate for the test. The test generates the Drop-weight Index (DWI) expressed in kWh/m3, as well as the A and the b parameters, but it does not generate the crusher parameters, which must be obtained through a full drop-weight test. The test also provides an estimated value of the ta, as well as the Mia, Mic and Mih parameters, more recently developed by Morrell (2009). Normally, the main ore zones/types in the deposit are submitted to the full drop-weight test procedure and the SMC Test® is used to measure the variability within the main ore zones/types. When the gradient of hardness is measured through the full procedure, the results from the SMC Test® can be calibrated to better reflect the hardness of the ore on the size range of interest for AG/SAG mills. Note that no calibration is required when performing the test on the coarsest size fraction (-31.5/+26.5mm).

The Mia, Mic and Mih parameters along with the Mib, which is obtained as part of the Bond ball mill grindability test, can be used to evaluate AG mill/ball mill and HPGR/ball mill circuit. The A and b values can also be used directly in JKSimMet for plant design, expansion and optimisation.

JK ROTARY BREAKAGE TEST® (JKRBT®)

The JK Rotary Breakage Test® is a new test developed by the Julius Kruttschnitt Mineral Research Center (Kojovic, Shi, Larbi-Bram & Manlapig, 2008) which was recently commercialised. This test, as with the DWT, measures the t10 of rocks after being fragmented by impact. The main difference is the way the impact is produced. The rocks are fed one by one on the middle of a rotating disc (rotor) through a vibrating feeder. The rotor has a diameter of 450mm and has four guide channels, placed at 90 degrees. The rotor speed is adjusted to achieve the specific energy level required. The rocks are accelerated along a guide channel and projected on the surrounding anvils (stator). The products are collected at the end of the test and submitted for a particle size analysis. The JKRBT® can treat particles from 1 to 45mm and at specific energy levels from 0.001 to 3.8 kWh/t, for every particle size. In the standard JKRBT® procedure, four size fractions are tested from 13.2 to 45mm and each size is impacted at three specific energy levels. Thirty rocks are tested for each size/energy combination and the energy levels tested are the same as the DWT. As part of the test, the resistance to abrasion breakage (ta) is measured, using the same tumbling mill and procedure as for the DWT. About 100kg of material is required to conduct the JKRBT® (which includes the ta measurement) and the rocks must be provided in the -53/+12.5mm size range, or as full core with a diameter of at least 50mm.

SAGDESIGN TEST

The SAGDesign test was developed by the SAGDesign Consulting Group (Starkey, Hindstrom & Nadasdy, 2006) and consists of a batch grinding test conducted in a 0.488m diameter SAG mill. About 10kg of drill core is required for testing. The feed is prepared to 80% passing 19mm and ground to 80% passing 1.7mm. The SAGDesign product is then crushed to 100% passing 3.35mm and used for a Bond ball mill grindability test. The direct output of the SAGDesign test is the number of revolutions required to achieve 80% passing 1.7mm. The SAGDesign and Bond ball mill test results are used by Starkey & Associates to design commercial mills.

SAG POWER INDEX (SPI®) TEST

The SAG Power Index (SPI®) test (Starkey & Dobby, 1996), expressed in minutes, is defined as the time (T) necessary to reduce an ore sample from a F_{80} of 12.7mm to a P_{80} of 1.7mm. The batch test is carried out in a laboratory mill of 304.8mm diameter x 101.6mm length, loaded with 15% steel balls of 31.8mm diameter. The SPI® test itself requires 2kg of ore with a top size of 19mm (¾"), but a total of 10kg of 38.1mm (1-½") is generally preferred, which allows for the determination of a crusher index (the crusher index is used to estimate the size distribution of the primary crusher). The sample is prepared to have an F_{80} of 12.7mm, and the test is run to determine the time required to reach a P_{80} of 1.7mm. Higher grinding time indicates higher resistance to grinding, thus a harder ore. The SPI® has the advantage of requiring a low weight, and is therefore well suited for geometallurgical mapping of ore deposits. The SPI® test has been widely used in recent years and deposits that are submitted to the study can therefore be compared to a database, in terms of hardness and variability profile.

The SPI® is transformed into kWh/t and is used for production forecast and circuit design using the CEET2® software, which was developed with the technical and financial support of 13 major mining companies (Dobby, Bennett & Kosick, 2001) in the iGS software.

LAB-SCALE HIGH PRESSURE GRINDING ROLL (HPGR) TEST

As for autogenous mills, the traditional methodology for the testing and scale-up of HPGR's has consisted of processing a large sample in a pilot unit (normally performed by the supplier). This has the disadvantage of requiring a large quantity of material. Lab-scale units, requiring a minimum of about 25kg per test are available and are now used by SGS as an alternative to a pilot plant for preliminary designs. A typical test consists of a series of batch tests at various pressure and feed moisture contents followed by a locked-cycle test performed over a 6 mesh screen. The HPGR product is submitted to a standard Bond ball mill grindability test, and the result can be translated into kWh/t using proprietary relationships, the work index alone computed from K_{80}'s being inadequate in the case of HPGR's, as for the AG/SAG mill circuits (McKen, Raabe & Mosher, 2001).

Preliminary HPGR circuit designs can be developed using the results of the HPGR and ball mill tests, using a methodology that combines HPGR (Klymowsky, Patzelt, Knecht & Burchardt, 2002) and SGS' scale-up interpretation. Final designs normally require pilot confirmation by the supplier.

STATIC PRESSURE TEST (SPT)

The Static Pressure Test is a small-scale static test which measures the specific energy for compression breakage and is used to evaluate the specific energy required by a HPGR (Bulled & Husain, 2008). The test equipment comprises a hydraulic press which applies a controlled pressure (up to 55MPa) onto a sample confined in a steel cylinder of 100mm in diameter by 200mm in height. The feed is normally prepared to 100% passing 19mm and 80% passing 12.7mm as for the SPI® test. The test can also be conducted on minus 12.7mm samples, to allow direct comparison with a 0.25m small scale HPGR. The full test, which is a locked-cycle test, requires up to 7kg of material, but an abbreviated procedure exists, which requires 3kg of material and can therefore be tested on a large number of samples to describe variability across the ore body. The abbreviated test should be calibrated against full locked-cycle tests conducted on a portion of the samples for each variability study. In the full locked-cycle test procedure, up to 5 or 6 cycles are completed, with the minus 3.35mm created in each cycle removed and replaced with fresh feed prior to the next cycle. The average specific energy from the three last cycles (E, in kWh/t), along with the measured F_{80} and P_{80} are used to calculate the High Pressure grindability Index (HPI). In the abbreviated version of the SPT test, only two cycles are completed to provide a good estimate of the HPI.

BOND ROD MILL GRINDABILITY TEST

The Bond rod mill grindability test is performed according to the original Bond procedure (Bond, 1960). The feed sample is stage-crushed to 12.7mm (½") and the test is run under a 100% circulating load. The test can also be closed with various sieve sizes, but for AG/SAG mill analyses the standard 1.18mm (14 mesh) sieve is typically used. The test is performed as a locked-cycle with a circulating load of 100%, until it reaches a steady-state. The number of new grams per revolution created during each cycle is measured, and the Bond rod mill work index (RWI) is calculated using the Bond equation.

The RWI is used to calculate the power requirement at intermediate size, i.e. from 12.7mm to about 1mm. The test has been mainly used for the design of rod mills or primary ball mills, but it can also be used along with the other Bond tests (BWI and CWI) for SAG mill design (Barratt, Matthews & deMull, 1996).

BOND BALL MILL GRINDABILITY TEST

The Bond ball mill grindability test is performed similarly to the rod mill test. It requires 10kg of minus 3.35mm (6 mesh) material that is preferably prepared at the testing facility, by stage-crushing the sample to 100% passing 3.35mm, but normally less than 5kg are used in the test. The test is closed with a fine screen (typically in the range 65 mesh to 270 mesh), and the size of the screen is normally selected to achieve a required final product P_{80}. The test is conducted in locked-cycle with a circulating load of 250%. The Bond ball mill work index (BWI) is computed with an equation very similar to that of the rod mill test (Bond, 1960).

The world has historically relied widely on the ball mill work index for the design and analysis of ball mill circuits, even for those that treat AG/SAG mill or HPGR circuit products, which have a non-standard particle size distribution.

MODIFIED BOND BALL MILL TEST (MOD BOND)

A modified Bond ball mill procedure (Mod Bond) was developed by MinnovEX Technologies (now SGS) which requires 1.2kg of sample crushed at minus 3.35mm. The 1.2kg charge is milled with the standard Bond ball mill for a set time. A particle size analysis is performed on the feed and ground product, and a modified work index is calculated using a proprietary model. The Mod Bond results must be calibrated against sufficient standard Bond ball mill work indices, typically 10% of the total.

The Mod Bond test is used for large variability programs because it provides significant savings in terms of costs (less material required and testing time) and turnaround time, without jeopardising the quality of the results. Because it is not closed with a given sieve, the test can be used to simulate any closing screen, which is very useful when large datasets with variable target grinds are considered, and/or when the exact final grinds have not been established.

BOND ABRASION TEST

The test determines the Abrasion Index (AI) which can be used to estimate steel media and liner wear in crushers, rod mills, and ball mills. The abrasion test was adapted by Allis-Chalmers (Bond, 1963) using a method and apparatus used by the Pennsylvania Crusher Division of Bath Iron Works. The equipment consists of a rotating drum with an impact paddle mounted on a centre shaft rotating in the same direction of the drum. A 400g charge of ore is tumbled in the drum for 15 minutes and dumped. A new 400g charge is placed in the drum and tumbled for another 15 minutes. This procedure is repeated for a total of four times. The paddle, which is made of standard alloy steel hardened to 500 Brinell, is weighed before the first cycle and after the fourth one. The abrasion index is determined from the weight loss of the paddle under standard operating conditions. The test requires 1.6kg of material in the size range of -19.0/+12.7mm. The Bond abrasion test is not a grindability test as such, in the sense that it does not measure the resistance of an ore to grinding but rather its abrasivity, but it is relevant to include it in this compilation because of its wide use to estimate metal wear in the design of comminution circuits.

The wear rate of steel media as well as liner wear in crushers, rod mills, and ball mills can be predicted from Bond's correlations (1963) or similar models revisited to better reflect today's reality.

PILOT PLANT TESTING

Comminution circuit designs can generally be developed using a combination of grindability tests as described in this paper and a scale-up model that converts the results from the tests into plant performance indicators such as throughput rate, product P_{80}, recycle rates, etc. These models are abundant and have different levels of complexities but they generally fall under two mains categories, i.e. breakage-based and power-based. Modern designs normally rely on bench-scale testing, conducted on numerous variability samples to develop hardness profiles that can be compared to large databases. These models are generally calibrated against plant data obtained from circuit audits and, over time, they have gained increasing levels of confidence, such that many of the circuits designed nowadays exclude pilot plant testing. Pilot plant testing must still be used to produce material for downstream metallurgical testing and is also highly recommended when unusual ores/circuits are considered. Models have limitations and are only as good as their inputs are. Examples of situations requiring pilot plant confirmation are discussed below.

Any Combination of Unusual Ores, Circuit Configuration and/or Operating Conditions

Piloting may be required when an ore depicts unusual grindability characteristics, which will typically result in apparent hardness discrepancies in the interpretation of grindability test results (soft to hard). It should also be considered when highly heterogeneous ores are considered, or when ores of significantly different grindability characteristics are to be blended.

Piloting should also be performed when an ore falls outside the normal range of hardness (e.g. extremely hard), or if it depicts any other behaviour that would challenge conventional scale-up methodologies, such as an unusually coarse grain size, contains flakes or fibres that would build-up in the recycle, or has unusual rheology (high clays). The presence of a significant soluble component in the ore can also warrant a pilot plant.

Unusual or less frequent circuit configurations may also require pilot confirmation. For example, single-stage autogenous or HPGR milling to a fine size may create an excessive circulating load, which would be difficult to predict at bench-scale. The introduction of high yield metallurgical separation within the comminution circuit (frequent for iron ores) can also make bench-scale interpretation difficult.

The design around any operating conditions (mill speed, ball size, ball charge, mill load, etc.) that would fall outside the typical range may also warrant a pilot plant. Comminution models contain empirical parameters that were calibrated against typical circuits, and operation outside that typical range may not be predictable with these models.

Fully-autogenous Grinding (FAG) and Pebble Milling

Fully-autogenous milling, including pebble milling, offers the possibility to eliminate the use of steel media and significantly reduces the operating costs, but these systems are very ore-dependant. When fully-autogenous grinding is contemplated, pilot testing must be performed in order to confirm the amenability of the ore to FAG milling. These systems are very sensitive to the feed size distribution which is very difficult to predict from small-scale tests. It is also not possible to predict from most of the bench-scale test procedures if a proper balance between the coarse grinding media and the finer rock charge can be achieved. It must be proven at pilot-scale that the coarse grinding media can survive in sufficient quantity to efficiently grind the finer rocks without producing a critical size build up. Similarly, the balance between pebbles extracted from an AG mill and its use as ball mill grinding media must be confirmed in a pilot plant.

Pre-crushing or Selective Crushing

Pre-crushing (and/or selective crushing of a fraction of the feed) is often considered to de-bottleneck an existing SAG mill operation to increase production. The maximum achievable throughput rate after the introduction of a pre-crush plant is hard to accurately determine using models that were mostly developed and calibrated against typical grinding operations. Piloting remains the best option to estimate the reduction in specific energy requirement to the SAG mill and to evaluate the effect of the pre-crushing on the circulating load and on the transfer size. The standard feed size should be tested first to benchmark the pilot plant to the full scale performance and then the feed can be pre-crushed to various sizes. The effect of crushing only a portion of the feed (selective pre-crush) can also be compared to straight pre-crushing.

Conflicting Results

Naturally, 'problematic' designs are likely to create 'conflicting' results when submitted to different scale-up methodologies. Small differences are always expected since both the tests and the models have fundamental differences and incorporate experimental errors, but larger differences of economical significance may warrant a pilot plant. If bulk samples can be made available, and if a final 'verdict' is required, a pilot plant should be carried out as it involves the lowest level of scale-up and uncertainty, and it will allow the final decision to be made at lower risk.

Pilot Plant Deliverables

The pilot plant will confirm the specific power requirement, but also the specific gravity of the charge and any preferential build up of light or heavy minerals in the charge, which is critical for autogenous milling. It will also provide the complete mass balance and particle size analysis around the circuit. Other parameters, such as the circulating load, transfer size and ball mill power requirement would also be established in the pilot plant. The results of the pilot plant can also be used to calibrate an existing model, resulting in a more robust final circuit design. Finally, the products generated as part of this exercise can be used to test continuous closed-circuit metallurgical operation (e.g. float pilot plant).

CONCLUSION

Simple tests requiring low sample weights can be used for AG/SAG variability testing and geometallurgical mapping of an ore deposit, but they have to compromise on the deliverables. More sophisticated tests can provide a more accurate and complete picture of ore grindability, but they require more material, so they can only be performed on a minimum of samples.

It is highly desirable to submit all the major ore types or alterations from a deposit to a detailed characterisation which covers the entire size range of comminution. The Bond low-energy impact test can be used to measure the hardness at coarse size (up to 76.2mm), while the variation of ore hardness by size can be measured in the range 13.2 to 63mm using the JK drop-weight test. The DWT results may be used to extrapolate potential problems at coarser size or to calibrate the tests that can only be performed at finer size, such as the SMC. The MacPherson autogenous grindability test, which is a steady-state test and cost-effective pilot plant alternative, should also be performed, because it will show if a hard component of the ore, with same or different specific gravity than the feed, builds up over time, and if it causes throughput problems. The Bond rod mill and ball mill, as well as the Bond abrasion tests should also be performed on the main ore types to measure the hardness at finer sizes and to evaluate the ore abrasivity. Variability in the deposit should be addressed through a proper program. SPI and/or SMC tests can both be used to test hardness variability at AG mill size, while the Bond ball mill grindability (or Mod Bond) test remains the most appropriate way to measure hardness at ball mill size. The number of samples to be tested will largely depend on the project size and economics, as well as the level of acceptable risk. High throughput/low grade projects will require the highest amount of testing. The combination of methodologies will increase the confidence in the design.

HPGR should also be considered as a power-efficient alternative to conventional or autogenous circuits early in a project. The lab-scale HPGR test or the Static Pressure Test (SPT) can be used to evaluate the specific energy required by a HPGR from about 12.7mm down to the closing screen size, but pilot plant confirmation must be conducted for final design.

It is highly recommended and common practice to combine different test procedures and design methodologies in order to maximize the information and reduce the risk, or to highlight any unusual behaviour. All the tests described in this paper have both strengths and weaknesses, and none of the tests produce all the desirable deliverables.

Ultimately, the most reliable way to establish the grindability of an ore is to process it in a pilot mill, which minimizes the magnitude of the scale-up. Pilot testing sits at the far end of the sampling effort, but it will also offer the most detailed set of deliverables. It is always desirable to perform a pilot plant, before proceeding with the sizing of a commercial AG/SAG mill or HPGR, especially if a tight design is required to meet the project economics. Piloting must be performed for 1) unusual ore or circuit configurations, 2) FAG or pebble milling, 3) pre-crushing or selective crushing and 4) when well-established methodologies provide conflicting results in terms of mill size and specific energy requirement. A pilot plant will eliminate surprises and minimize the risk.

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