Test Methods for Characterising Ore Comminution Behavior in Geometallurgy

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Cover illustrations: Interactions of the test method with geometallurgical and process systems.
Comminution test methods used within mineral processing have mainly been developed for selecting the most appropriate comminution technology for a given ore, designing a grinding circuit as well as sizing the equipment needed. Existing test methods usually require comparatively large sample amounts and are time-consuming to conduct. This makes comprehensive testing of ore comminution behavior – as required in the geometallurgical context – quite expensive. Currently the main interest in the conduct of comminution test lies in the determination of particle size reduction and related energy consumption by grindability test methods, which provide the necessary information about mill throughput. In this procedure mineral liberation is regarded as a fixed parameter due to missing this information in ore characterization as well as a lack of suitable comminution models. However, ignoring the connection between particle size and mineral liberation prevents the scheduling and controlling of the production process from being optimal.

For these reasons new comminution tests need to be developed or alternatively the existing test methods need to be suited to geometallurgical testing where the aim is to map the variation of processing properties of an entire ore body. The objective of this research work is on the one hand to develop small-scale comminution test methods that allow linking comminution behavior and liberation characteristics to mineralogical parameters, and on the other hand establish a modeling framework including mineral liberation information.

Within the first stage of the study the comminution of drill cores from Malmberget’s magnetite ore, classified by modal mineralogy and texture information, have been investigated. It was found that there is a direct correlation between the mechanical strength of the rock, as received from unconfined compressive or point load tests, and the crusher reduction ratio as a measure for crushability. However, a negative correlation was found between crushability and grindability for the same samples. The grindability showed inverse correlation with both magnetite grade and the magnetite’s mineral grain size. The preliminary conclusion is that modal mineralogy and microtexture (grain size) can be used to quantitatively describe the ore comminution behavior although the applied fracture mechanism of the mill cannot be excluded.

With crushed ore samples from Malmberget also grindability tests and mineral liberation analyses were conducted using laboratory tumbling mills of different size. Starting from the dimensions of the Bond ball mill a modified test method was developed where small size samples of approximately 220 g were pre-crushed and ground in a down-scaled one-stage grindability test. Down-scaling was done by keeping similar impact effects between the mills. Mill speed and grinding time were
used for adjusting the number of fracture events in order to receive similar particle size distributions and specific grinding energy when decreasing mill size by the factor 1.63. A detailed description of the novel geometallurgical comminution test (GCT) is given.

With respect to ore crushability and autogenous and semiautogenous grinding (AG/SAG) also drop weight tests were conducted. For a more accurate and precise measurement of the energy transferred to the sample a novel instrumented drop weight was used. Initial tests with fractions of drill cores and pre-crushed ore particles showed that the simple energy calculation based on potential energy needs to be corrected. For the future work these tests will be extended to other ore types in order to investigate the effects of mineralogy and to include mineral liberation in comminution models suitable for geometallurgy.

**Keywords:** ore comminution behavior, ore comminution test, mineral texture, modal mineralogy, geometallurgy.
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List of Papers

The thesis is based on the following papers:

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II. Mwanga, Abdul, Lamberg, Pertti and Rosenkranz, Jan. Comminution test method using small drill core samples. (Submitted)

Following papers are not included in the thesis:

Conference contributions


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Paper I

Paper II
Part I
1. Introduction

Comminution is usually the first stage in mineral processing plants. Normally the comminution circuit includes several stages starting with crushing and followed by grinding (Figure 1). Primary crushing is often done close to the mining area, e.g. underground or in the pit. Depending on the ore and process types there can be several crushing steps and different kind of crushers have been developed for different purposes. The size reduction ration is commonly between 5 and 10 in crushing stages, i.e. if the starting size is 1 meter in two-three stages the material can be crushed down to 1 mm particle size.

Crushing is followed by grinding and it is quite common to use nowadays two grinding stages in a semi-autogenous – ball mill circuit (SABC). The size reduction ratio in grinding gets lower the finer the material gets and from 1 mm to 100 microns often two grinding stages are required.

Comminution circuits include also particle size separation in classifiers. For coarse particle sizes screens are used, e.g. the SAG product is sent to a screen and oversize is returned to pebble crushers. For finer particle sizes hydrocyclones, screw classifiers and air classifiers are used, the first mentioned being the most common.

Figure 1. Simplified flow sheet of a typical comminution circuit.

The primary reason for comminution in ore processing is to liberate minerals for successful separation in downstream processing. In some cases grinding is needed purely for size reduction or for cleaning of mineral surfaces. An example is continued grinding of final grade Fe concentrate to receive suitable particle size distributions for iron ore pelletizing. In flotation it is common to regrind rougher concentrate to have fresh mineral surfaces for new reagents to be used in cleaning flotation.
Comminution circuits are often the bottle neck in a mineral processing plant, i.e. they define the plant material throughput. Normally the target for the comminution circuits is to produce targeted size distribution and at the same time maximize the throughput. If a material is very hard it normally means that the throughput must be restricted to reach a targeted particle size. In addition there are some process variables that can be adjusted: e.g. rotational speed in mills, amount of grinding media in the mill (as steel balls) and the cut size in classification steps. If the high throughput is maintained to the expense of particle size reduction the consequence will be poorer mineral liberation and subsequently lower recovery due to increased losses by locked particles.

Therefore it is very important to design the comminution circuit in the right way, select proper types of unit operations and size the equipment correctly for reaching targeted throughput and particle size distribution. The design and control requires extensive testing and for that reason representative ore samples are needed. Four different purposes of tests in mineral processing can be identified: 1) testing for flow sheet development, 2) testing for sizing the operational units, 3) testing for validating metallurgical performance and 4) variability testing:

Flow sheet development aims to define the proper technology and circuit to be used. In comminution this includes tests to compare different processing alternatives like autogenous grinding, semi-autogenous grinding, ball mill grinding, rod mill grinding, high pressure grinding rolls, as well as for investigating suitable pre-treatment methods, e.g. microwave treatment (Amankwah, Khan, Pickles, and Yen, 2005) or high voltage electric pulses (Shi, Zuo, and Manlapig, 2013). At this stage testing is done often in relatively small scale, typically with samples of 10-100 kg.

Unit sizing requires specific tests for each technology. This is commonly done after flow sheet selection and sample sizes are slightly larger, i.e. 100-500 kg. Validating the metallurgical performance requires even larger scale testing using pilot plants. Sample sizes reach 10-500 tons and feed rates of 1-10 t/h are used. Pilot tests take from several days to several weeks and consider the entire process flow sheet, i.e. besides comminution also concentration stages and even dewatering.

As the previously listed tests are done with quite large samples the number of different samples to be included in a testing program is comparatively small. To find out about the ore related variations in comminution and other mineral processing properties it is customary to run a larger number of variability tests, also described as geometallurgical testing.

Geometallurgy combines geological and metallurgical information to create spatially-based predictive model for mineral processing plants to be used in production management (Lamberg, 2011). Ore testing is the essential part of so-called geometallurgical programs, being the industrial application of geometallurgy for a particular ore body (Bulled and McInnes, 2005; David, 2014; Dobby, Bennet, Bulled, and Kosick, 2004). Ore samples are collected and characterized with respect to their chemical composition, mineralogy, comminution properties and other properties related other process (Table 1). For comminution testing the available test methods use large ore
samples, i.e. special geometallurgical tests for comminution are not available. This hinders the detailed mapping of ore variability using small samples as for instance drill core samples. Some of the test methods used in geometallurgy are simple drop weight tests (Napier-Munn et al, 1996; Narayanan, 1985), rotary breakage tests (e.g. Shi et al, 2009) and abbreviated tests as the SMC test (Morrell, 2004).

<table>
<thead>
<tr>
<th>Type of test</th>
<th>Number of samples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chemical assays</td>
<td>10 000+</td>
</tr>
<tr>
<td>Mineralogy</td>
<td>1 000+</td>
</tr>
<tr>
<td>Grinding</td>
<td>100-300</td>
</tr>
<tr>
<td>Metallurgical tests (e.g. flotation)</td>
<td>100-300</td>
</tr>
</tbody>
</table>

Mineral processing properties within an ore body can vary a lot and bring several challenges during production. For the Collahuasi concentrator Alrui et al. (2009) and Suazo et al. (2010) showed how the plant throughput and copper recovery varies strongly between different geometallurgical domains, i.e. areas of the ore body where metallurgical properties are similar.

With current practices the throughput is mostly determined by solely fixing the particle size of the mill product which is questionable when there is a big variation on micro-texture or liberation size within a deposit. However, comminution characterization studies that take into account mineral information are very rare (Kim, Cho and Ahn, 2012; Kim and Cho, 2010; Groger et al., 1999).

Lund (2013) showed for the Malmberget iron ore in Northern Sweden that there is a big variation in the grain size of magnetite and therefore operation with fixed feed particle size distribution may not be the most efficient solution. Therefore one of the challenges in developing efficient comminution test methods is the consideration of the liberation properties of the ore and how liberation information can be used in geometallurgical models (Lamberg et al., 2013).

This licentiate thesis aims at establishing such a comprehensive method and, by using a case study from the Malmberget iron ore, Northern Sweden, at demonstrating how and why modal mineralogy, mineral textures and liberation should be considered already in the comminution test work.

1.1. Objectives of the work

The main objective of this work is to develop a set of enhanced comminution test methods that are time and cost efficient when characterizing the comminution properties
of an ore sample for geometallurgical purposes. This objective is divided into following sub-sets:

1. Literature survey of existing test methods to find out the best candidates for further developing special geometallurgical tests.
2. Developing comminution test for geometallurgical purposes.
3. Develop a test methodology to link mineral liberation with particle size reduction and energy in geometallurgical concept.

1.2. Working hypotheses

The hypotheses to be answered in this study are:

1. Comminution characteristics can be tested for geometallurgical purposes with small (<0.5 kg) drill core samples.
2. Mineralogy defines the comminution properties and the number of tests required for geometallurgical characterization of an ore body can be significantly decreased by knowing the mineralogy.
3. Two mineralogical parameters: modal mineralogy and mineral textures fully define the comminution properties.
4. Rather than by particle size the efficiency of ore comminution should be measured by energy vs. mineral liberation.

2. Comminution tests used in geometallurgy

Before concentrating metal ores have to be crushed and ground in order to liberate the metal bearing minerals. A sufficient size reduction is not only the prerequisite for any downstream physical separation. Comminution is also the processing step within mineral processing having the highest energy demand and in practice being much often the limiting factor for plant capacity. Reliable testing of the ore’s comminution behavior, i.e. information about the particle size distribution after fracture, the achieved mineral liberation as well as the comminution energy needed, is therefore an important step in the proper design and control of ore beneficiation plants.

In the past the process design has usually been based on particular reference samples that were analyzed and tested at different scale but did not describe all the mineralogical variations occurring in an ore body. The limited picture received from that has quite often been the cause for insufficient mineral liberation or on the contrary for too fine grinding leading to low recovery and selectivity in physical separation, and thus resulting in poor plant performance and limited production capacity.

For the last years geometallurgy as a new interdisciplinary approach has evolved that combines geological and metallurgical information to create a spatially-based predictive model for mineral processing to be used in production management (Lamberg, 2011). Within the geometallurgical approach the entire ore body is explored in order to identify the spatial domains that show different response to mineral processing. Using the
geometallurgical domains in the design and control of ore beneficiation plants allows for higher flexibility towards changes in the plant feed when mining different parts of the ore.

Setting up a geometallurgical program for an ore deposit requires extensive test work that on the one hand pays back by improved plant operation, but on the other hand is time consuming and correspondingly costly. Also the best possible utilization of the available sample material is a crucial point as geological and rock mechanical analyses are also requiring samples and thereby limiting the available amount. Accordingly the need of efficient geometallurgical testing gives a stimulus for developing new fast comminution test methods or for the revision of existing test procedures, respectively. Also improved process models need to be established that subsequently make use of the additional information provided by the geometallurgical approach.

2.1. Criteria for evaluation

The term comminution behavior comprises the complex interaction of material properties and process parameters. In practice different comminution test methods are used that can be categorized by several attributes, compare Figure 2: As the comminution properties are affected by particle size different tests ranging from crushing to grinding and very fine grinding are employed accordingly. Also the type of mechanical stress applied in a certain crusher or mill type, i.e. compressive or impact stress, as well as the stress intensity and rate have to be considered in the selection of a suitable test method.

![Figure 2: Dimensions in test categorization](image-url)
Finally the applicability of a comminution test will depend on the available sample amount, ranging from drill core sections or hand-picked single particles used in lab tests to several tens or hundreds of kilograms for a technological test work on bench or pilot scale. At larger scales also the effort in terms of time and costs is per test is increasing. This third dimension will limit the test work to certain methods for the different scales during the individual project stages.

For geometallurgical purposes the outcome of the experimental work has to serve as an input to process modeling, i.e. comminution test results need to be linked to the parameters used in the comminution process models. Within process modeling different levels of modeling depth are used. Simple approaches use defined size distribution functions based on single parameters as energy for grinding or machine-specific size reduction ratios. More sophisticated, rigorous models apply population balancing methods. Here the entire breakage distribution function needs to be constructed based on experimental test work or sampling and back-calculation from continuous comminution tests even at larger scale. In this context it has to be noted that a closed methodology that not only comprises size reduction and energy for size reduction but also incorporates mineral liberation within experimental work and process modeling is still missing.

As discussed above a geometallurgical program imposes particular requirements on the efficiency and manageability of processing test methods. A comminution test method for geometallurgical purposes should therefore fulfill several technical and economic criteria:

- **Simplicity** – Tests should be relatively simple and easy to execute. Use should be made of instruments that are available in common analytical and mineral processing laboratories.

- **Repeatability** – Test should be repeatable and not depending on the individual person conducting the test.

- **Sample preparation** - Sample preparation should be possible with low efforts and possible to do with basic skills or after short training.

- **Time exposure and costs** – Tests should be fast and inexpensive, i.e. for execution times of one hour it should be possible to conduct 1000 tests within half a year.

- **Sample amount** – The amount of sample per test should be < 0.5 kg. Preferentially rejects from assaying should be enough.

- **Link to modeling** – Tests should provide parameters that can directly be used in process modeling and simulation.

- **Mineral liberation** – Tests should be easy to extend in order to include mineral liberation information.
Another criterion is given by the precision and the statistic quality of the test results. With respect to accuracy a proper quantification is not an easy task as the entire chain of sampling and sample preparation together with the test and analysis method needs be considered. Statistic quality is a parameter that from the perspective of geometallurgy is judged in a different way. Repetition of single tests is neglected to the credit of generating a comprehensive data set for the entire geometallurgical program.

In the following commonly used comminution test methods having potential to be used in geometallurgical context are reviewed against the criteria listed above. The tests are classified in three groups: 1) rock mechanical tests, 2) particle breakage tests, and 3) bench-scale grindability tests.

2.2. Rock mechanical testing

Rock mechanical tests for rock strength are conducted by means of universal test machines or simplified instruments. Loading takes place at comparatively low velocities. The instrumentation of the test machine allows recording of the load applied to the sample and the displacement over time. Several standard test methods are used that differ in the loading conditions applied Russell and Muir (2009).

Samples consist of drill core sections, parts of drill core sections and single particles of cut regular but also irregular shape. Measured strength parameters depend not only on modal mineralogy but also on textural effects and anisotropy (Shea and Kronenberg, 2009).

2.2.1. Compression tests

In compression tests the drill core sample is pressed between the two parallel planes of the test machine, which are then loaded up to failure of the specimen. Data for the applied load and the resulting displacement is recorded over time, providing the maximum load for calculating the compressive strength. Sample preparation comprises careful cutting of the specimen’s top and bottom planes in order to prevent bending effects during the test.
In case the specimen is not further supported the test is referred to as unconfined compressive strength (UCS) test, compare Figure 3. For triaxial compression tests the drill core specimens are cut to the required length and then enveloped on the lateral surface by a membrane that seals the specimen from the surrounding pressure medium, usually oil, that provides the radial support. When increasing the axial compressive load also the oil pressure is increased in parallel up to failure of the specimen.

A similar experimental setup is used in the point load test (PLT), see Figure 4. Instead of using parallel planes here the compressive load is applied between the tips of two cones, putting a point load on the specimen. Test instruments are more compact and can even be used in field work.
From the point load test the point load strength index $I_{S_{50}}$ is obtained that needs to be corrected to the standard equivalent core diameter $D_e$ of 50 mm if other specimen are used (equation 1).

$$I_{S_{50}} = \frac{P}{D_e^2} \text{ (in psi)} \quad (1)$$

with the failure load $P$ in lbf and $D_e$ in in. The point load strength index can be transferred into uniaxial compressive strength using a linear conversion factor that needs to be determined for a particular ore (Rusnak and Mark, 2000).

2.2.2. Indirect tensile strength test

Using cylindrical of a specimen as slices from drill cores and loading these radially by compression forces between two sockets (plates, cushioned plates, curved clamps) gives an indirect tensile stress and an according deformation in orthogonal direction. This experimental setup is also known as the Brazilian test, compare Figure 5.

The sample is stressed under the linear compressive load that induces the tensile stress. Assuming that the material is homogeneous, isotropic, and linearly elastic before failure (Wong, 2013) the failure is expected at maximum tensile stress. The corresponding tensile strength is then calculated by

$$\sigma_t = \frac{2 \cdot P}{\pi \cdot D \cdot t} \quad (2)$$

where $P$ is the failure load, $D$ the specimen diameter, and $t$ the thickness of the test specimen.

![Figure 5. Brazilian test](image_url)
2.2.3. Evaluation of rock mechanical tests

Using results from rock mechanical tests for describing comminution behavior is an attractive approach as no additional test work and sample material is needed. Also the necessary sample amounts are small.

All the tests discussed above apply slow compressive stress in a well-defined way, meaning that the repeatability of the method is given, though the interpretation has to take into account the textural effects and inhomogeneity in samples from natural mineral resources. The conduct of the test is rather simple and can partly be done in the field. More effort has to be put on proper samples preparation, e.g. when sawing drill cores. The fragments received are usually too coarse for using them in quantitative mineralogical analyses.

It has been shown that mechanical parameters of rock samples can be used to describe and model comminution processes at least in the case of crushing (Bearman et al., 1997, Koch et al., 2013, Olaleye, 2010). For this purpose mechanical strength expressed by the maximum load at the point of failure needs to be transformed into quantities that can be used within the design of crushing stages. Usually empirical ore-specific correlations are provided for calculating crushing index or crusher reduction ratio from UCS or PLT strength values.

The evaluation of the different rock mechanical tests with respect to the criteria defined in section 2.1 is summarized in Table 3.

Table 2. Rock mechanical tests

<table>
<thead>
<tr>
<th>adverse (–), acceptable (o), advantageous (+)</th>
<th>UCS</th>
<th>PLT</th>
<th>Brazilian</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simplicity</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Repeatability</td>
<td>O</td>
<td>O</td>
<td>O</td>
</tr>
<tr>
<td>Sample preparation</td>
<td>–</td>
<td>O</td>
<td>–</td>
</tr>
<tr>
<td>Time exposure and costs</td>
<td>O</td>
<td>O</td>
<td>–</td>
</tr>
<tr>
<td>Sample amount</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Link to modeling</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Mineral liberation</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>

2.3. Particle breakage tests

Fracture tests here means a test where specimen is broken with certain energy and the particle size distribution of the progeny particles is measured for defining the energy required for size reduction. The relevant tests for geometallurgical context are:
2.3.1. Simple drop weight test

In the drop weight test a weight is lifted to a certain height and then released to fall on the ore sample, which is arranged on a rigid anvil underneath, compare Figure 6. The fragments from the sample are afterwards collected and analyzed by their particle size to receive a breakage distribution. The test sample can comprise single particles, a part or an entire drill core section or several particles as received from pre-crushing. Several apparatus have been presented (Napier-Munn et al., 1996, Bearman et al., 1997, Genc et al., 2004). For conducting particle bed fracture tests with fine particles the anvil is replaced by a die (Eksi et al., 2011).

Different impact levels and amounts of specific comminution energy can be obtained by varying the drop weight, the falling height or the sample mass. The energy provided to the ore sample can be described by the potential energy of the drop weight at the initial height:

\[ E = m_{dw} \cdot g \cdot h \]  

where \( m_{dw} \) is the mass of the drop weight and \( h \) the distance between the drop weight and the top of the specimen.

![Figure 6. Drop weight tester](image)

For evaluating the breakage distribution a method has been developed that links the breakage distribution and comminution energy to the modeling of particle size reduction (Narayanan and Whiten, 1988). The percentage passing \( \frac{1}{n} \) of the starting particle size can be related to the comminution energy by:

\[ t_n = A \cdot (1 - e^{-bE_{com}}) \]  

(4)
where $E_{sp}$ is the specific energy in kWh/t and $A$ and $b$ are ore-specific parameters. Typically the $t_{10}$-value is used as a fineness index to characterize a certain ore sample. In process modeling and simulation average sets of $A$ and $b$ are used assuming that particles of different size will break in a similar way.

For determining the several $t_n$ curves five different initial particle sizes in the range of 13.2 to 63 mm and 3 energy levels need to be investigated giving a total of 15 tests. This drop weight test as defined by the Julius Kruttschnitt Mineral Research Centre therefore normally requires 75 to 100 kg of sample material.

In order to reduce the sample amount and the number of particle size fractions an abbreviated drop weight test, called SAG Mill Comminution (SMC) test, has been suggested. Using only a single size fraction, i.e. particles or parts cut from drill cores in the size range 19/22 mm, the necessary sample amount can be reduced to 5 kg. The test provides the parameters $A$ and $b$ as well as a Drop Weight Index (DWi in kWh/t) but not the $t$-values.

2.3.2. Instrumented drop weight test

The simple drop weight test has been by adding instrumentation. A well-established instrumented drop weight test is the Ultra-fast load cell device (UFLC) developed at the University of Utah (King and Bourgeois, 1993, Tavares and King, 1998, Tavares, 1999), see Figure 7.

![Figure 7. Ultra-fast load cell](image)

The sample, consisting of individual particles or a bed of particles, is placed on a vertical steel bar and then hit by the falling weight. As with the split Hopkinson pressure bar (see 3.3.4) the bar is instrumented by a pair of strain gauges for detect the impact wave that allows for inference on the load applied to the sample. Based on load-time profiles and the calculated deformation the transferred energy can be calculated.
A portable impact load cell, using the same principles as in the Ultra-fast load cell, has been developed by Bourgeois and Banini (2001) for in-situ quantification of ore breakage properties. The so-called SILC – Short Impact Load Cell is reduced in height and weighs only 30 kg.

Based on the principle design of the simple drop weight test another instrumented drop weight tester has been designed (Abel et al, 2009), initially used for the investigation of particle compaction processes (Figure 8). Here the drop weight itself is instrumented by a load cell and an inductive displacement transducer that yield time-dependent measurement profiles for the entire sequence of primary impact and subsequent rebounds. The comminution energy transferred to the sample is received from integration of the load-displacement relation.

2.3.3. Twin pendulum tests

In twin pendulum tests a single particle is fractured between two pendulum-mounted hammers that are released from a certain height. Figure 9 shows the experimental setup for the Bond twin pendulum test (Bond, 1946). A single particle is mounted on a socket and then simultaneously hit by the hammers. The procedure is repeated until the particle breaks, thereby incrementally increasing the deflection angle of the hammers.

Bond defined a crushing work index by:

\[
CW_i = \frac{53.5 \cdot C_D}{\rho_p} 
\]  

where \( \rho_p \) is the particle density in g/cm\(^3\) and \( C_D \) the impact energy per particle thickness \( d_p \) in J/mm for the last pendulum deflection angle of \( \Theta \).
Also the twin pendulum test has been extended by adding instrumentation that allows the recording of the pendulum motion (Weedon and Wilson, 2000, Sahoo et al, 2004). Lifting only one pendulum and mounting the particle on the other allows for determining the energy transferred to the sample by evaluating the rebound movements of the two pendulums after collision.

\[ C_B = \frac{117 \cdot (1 - \theta)}{d_p} \]  

Figure 9. Bond twin pendulum tester

2.3.4. Split Hopkinson pressure bar test

The split Hopkinson pressure bar, originally developed for testing stress propagation in materials from the detonation of explosives, has been used for fracturing a sample particle between two horizontally mounted steel bars called the incident bar and the transmitted bar, compare Figure 10. The mechanical stress is induced by a loading system, i.e. a gas gun, and the travel of the deformation waves is recorded with strain gauges. The signals provide information about load-displacement profiles and allows for energy balancing.

Even though the experiments with the Hopkinson pressure bar are laborious there has been a phase of intensive development of the test method, leading to for instance the Modified Hopkinson Pressure Bar for higher resolution (Briggs and Bearman, 1996) or the CSIRO Hopkinson pressure bar for larger specimen (Fandrich et al, 1998) having a vertical assembly like the Ultrafast load cell.
2.3.5. Rotary single impact tester

In single impact tests the stress applied to a sample results from the collision with one single tool. This can be achieved either by accelerating the sample against a plate using gravitational forces or the acceleration forces from a gun, or by advancing the sample with a fast moving tool, commonly realized in a rotor-stator impact system.

Such a rotary impact tester design was first presented by Schönert and Marktscheffel (1986) and has meanwhile been commercially adapted also for ore testing (Kojovic et al, 2008, Shi et al, 2009). Figure 11 shows a schematic of the rotor–stator impacting system. Particles are fed to the evacuated impact chamber by centrifugal action via several channels in the rotor. The surrounding stator has a saw tooth profile that allows for a perpendicular impact of the particles. Compared to other particle breakage tests significantly more particles can be tested.

The probability for breakage can be described as a function of the impact energy using a Weibull distribution (Vogel and Peukert, 2003):

\[
S = 1 - \exp\left(\frac{E_{\text{kin}} - E_{\text{kin,min}}}{k \cdot x}\right)
\]  

(7)
where \( f_{\text{mt}} \) is a material constant, \( x \) the initial particle size, \( k \) the number of impacts, and \( E_{\text{kin}} \) and \( E_{\text{kin, min}} \) the kinetic energy impact and the energy threshold without fracture, respectively.

The specific kinetic energy is described by

\[
E_{\text{kin}} = \frac{1}{2} v^2
\]  

(8)

Comminution test are used to determine the parameters within the probability for breakage and the breakage distribution.

2.3.6. Evaluation of particle breakage tests

Particle breakage test use impact stress for striking the sample (Table 3). Except for the rotary breakage test mounting of the sample and the conduct of the tests are in most cases quite tedious. Repeatability is more affected by the sample characteristics than by the test method.

The necessary sample amounts are small if using cut drill core sections. Testing fractionated material from crushing and screening requires significantly more material. This is particularly the case if not only the initial particle size is varied but also different energy levels are tested, e.g. when using the concept of \( t_n \)-values for process modeling.

Depending on the initial sample size the fragments received after breakage are usually too coarse for using them in quantitative mineralogical analyses, i.e. only for the case of ultra-fast load cell or when using small bars with the split Hopkinson pressure bar test sufficiently small particles are generated that are meaningful to investigate.

Table 3. Particle breakage tests

<table>
<thead>
<tr>
<th>adverse (−), acceptable (0), advantageous (+)</th>
<th>Drop weight</th>
<th>UFLC</th>
<th>Twin Pendulum</th>
<th>Split Hopkinson bar</th>
<th>Rotary breakage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simplicity</td>
<td>O</td>
<td>−</td>
<td>−</td>
<td>−</td>
<td>−</td>
</tr>
<tr>
<td>Repeatability</td>
<td>O</td>
<td>O</td>
<td>−</td>
<td>O</td>
<td>+</td>
</tr>
<tr>
<td>Sample preparation</td>
<td>−</td>
<td>−</td>
<td>O</td>
<td>−</td>
<td>O</td>
</tr>
<tr>
<td>Time exposure and costs</td>
<td>−</td>
<td>−</td>
<td>O</td>
<td>−</td>
<td>O</td>
</tr>
<tr>
<td>Sample amount</td>
<td>−</td>
<td>−</td>
<td>O</td>
<td>−</td>
<td>O</td>
</tr>
<tr>
<td>Link to modeling</td>
<td>+</td>
<td>O</td>
<td>+</td>
<td>O</td>
<td>+</td>
</tr>
<tr>
<td>Mineral liberation</td>
<td>O</td>
<td>O</td>
<td>O</td>
<td>O</td>
<td>O</td>
</tr>
</tbody>
</table>

1) Based on the JK drop weight test
2.4. Bench-scale grindability tests

2.4.1. Bond test

The Bond test is used to analyze the grindability for a material. The test applies a standardized ball mill of 305 mm (12 in.) in diameter and also in length with a grinding media charge of certain size distribution and operated at a defined speed. The sample amount is defined by the bulk volume of 0.7 liters, consisting of particles smaller 3.35 mm. The test is conducted as a dry batch test with sieving of the mill product. Fines are replaced by feed material and grinding times are varied in order to reach a simulated circulating load of 250%. Usually samples of 10 kg smaller 3.35 mm are required.

From the grinding test the Bond ball mill work index $W_i$ is determined (Bond, 1961):

$$W_i = \frac{1.1 \cdot 44.5}{x^{0.23}_8, G^{0.82} \left( \frac{10}{\sqrt{x_{80,P}}} - \frac{10}{\sqrt{x_{80,F}}} \right)}$$  \hspace{1cm} (9)

Where $x_8$ is the screen aperture, $G$ the grindability (in g of product per mill revolution), and $x_{80,P}$ and $x_{80,F}$ are the 80% passing particle sizes in μm for the mill feed and product, respectively.

The test results are used to calculate the change in particle size during grinding based on the grinding work input $W$ using the Bond formula, also referred to as Bond’s law, as a process model (Bond, 1952):

$$W = W_i \left( \frac{10}{\sqrt{x_{80,P}}} - \frac{10}{\sqrt{x_{80,F}}} \right) \text{ in kWh/t}$$  \hspace{1cm} (10)

2.4.2. Variations of the Bond test

Besides for determining ball mill grindability the Bond test has been adapted to other mill types. Bond also defined a test for rod mill grinding using a 305mmx610mm standard mill requiring up to 20 kg. Test conditions are differing, e.g. the circulating load changed to 100%, and also the Bond equation for calculating the rod mill work index is slightly different. For describing comminution in AG/SAG mills and HPGR using the Bond test method requires model extensions by empirical relations.

In the past several attempts have been made in order to simplify the Bond procedure. One approach has been to replace the circulating load test by a pure batch test in order to minimize the timely effort and also the sample amount needed, by developing new test mills, e.g. Nitti (1970) and Nematollahi (1994) or by modifying the test procedure Tuzun (2001), Magdalinovica (1989) and Tavares et al (2012).

2.4.3. Evaluation of grindability tests

In grindability tests a combination of impact stress and attrition is applied to a bulk of material. The original Bond test is quite tedious as several grinding experiments are necessary to reach the stationary state of the simulated closed circuit. Also the sample
amount can be quite high if only drill cores are available. Sample preparation is limited to pre-crushing and screening.

The test is reliable and has a good repeatability if procedure and test mill comply with the standard. One of the major advantages is surely the huge data base that has developed over the last decades. With respect to modeling the coupling between the work index and the particle size reduction can directly be used together with a size distribution function. Attention has to be paid to the applicability of the function type in the individual case (Table 4). The size range of the mill product is prepared to conduct mineral liberation analyses.

Table 4. Grindability tests

<table>
<thead>
<tr>
<th>adverse (−), acceptable (o), advantageous (+)</th>
<th>Original Bond ball mill</th>
<th>Original Bond rod mill</th>
<th>Single pass e.g., Mergan mill</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simplicity</td>
<td>O</td>
<td>O</td>
<td>+</td>
</tr>
<tr>
<td>Repeatability</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Sample preparation</td>
<td>O</td>
<td>O</td>
<td>O</td>
</tr>
<tr>
<td>Time exposure and costs</td>
<td>−</td>
<td>−</td>
<td>O</td>
</tr>
<tr>
<td>Sample amount</td>
<td>−</td>
<td>−</td>
<td>−</td>
</tr>
<tr>
<td>Link to modeling</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Mineral liberation</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
</tbody>
</table>

2.5. Pilot and bench-pilot scale tests

Comminution test work using bench-pilot scale or pilot scale equipment is done for different types of crushers and mills. Typically this comprises:

- Cone crushers
- High pressure grinding rolls (HPGR)
- Ball mills
- Stirred media mills, e.g. IsaMill or vertical stirred mills

Stress type and stress rate are based upon the respective machine type.

Tests require several tens to hundreds of kilograms and are done in batch or continuous mode. Sample preparation usually comprises pre-crushing and screening for adjusting the initial size distribution, as well as sample splitting. Mosher et al. (2001) uses and developed the methodology for SAG mill design and mill optimization.
Sampling from the test mill or circuit provides the data base for determining breakage probabilities or grinding rates as well as breakage distributions from back-calculation using population balance methods. Using the data from liberation and association analyses allows for describing the particles based on their mineral composition (Lamberg and Vianna, 2007).

Pilot and bench-pilot scale tests are used to verify the metallurgical performance of a designed circuit. In the geometallurgical context these result can be used in calibrating the small scale test results towards full scale operation.

2.6. Indirect methods for determining comminution behavior

Another way of obtaining information about rock mechanical strength is to evaluate the core drilling process by according instrumentation, also referred to as measurement while drilling (MWD). Variations of the conditions at the drill bit, as for instance torque, normal or bending forces, result from changes in the rock hardness. However, recorded down hole measurements have to be corrected by considering the dynamic process of wearing down the drill bit. Alternatively also drill cuttings can be evaluated.

Also petrophysical data from multi-sensor drill core logging has been used for calibration against measures of ore breakage parameters and grindability that were received from conventional destructive comminution tests (Vatandoost, 2010). Using density, magnetic susceptibility and seismic wave parameters from Australian copper-gold deposits the Bond mill work index and the crushability parameters received from drop weight testing could be predicted with acceptable accuracy.

In conjunction with recent advances in quantitative mineralogical analyses the development in geometallurgical characterization today is towards identifying correlations between ore comminution behavior and mineralogical properties. The idea behind is to reduce the number of comminution tests necessary for characterizing a deposit and to arrive at a more generic description of mechanical properties based on the occurring minerals (Mwanga et al, 2013).

2.7. Summary and conclusions

Table 5 summarizes the findings from the evaluation of the individual test methods. None of the tests is fulfilling all criteria but by emphasizing the requirements on sample amount and effort for conducting the tests as well as modeling issues several methods can be identified to be promising for the further development of geometallurgical comminution test.

Results from rock mechanical tests should only be used where already available. But as the results cannot be used directly correlations need to be found for the description of ore crushing properties. Generally speaking, rock mechanical tests should not be part of a geometallurgical program as they do not provide information about grinding behavior down to the particle liberation level.
Particle breakage tests have a potential to be used within geometallurgy in case they are not depending on too large sample amount and high effort. This is for instance the case for the SMC test based on the standard drop weight testing where only single size samples are required. Also the rotary breakage test is promising despite the need for the technically and monetarily intensive test machines.

Table 5. Summary for evaluation results of the reviewed test method commonly used and have potential for the development of suitable geometallurgical test methods.

<table>
<thead>
<tr>
<th>Fracture test method</th>
<th>– (Adverse)</th>
<th>O (Acceptable)</th>
<th>+ (Advantageous)</th>
<th>Relevance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unconfined compressive strength test</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Point load test [2]</td>
<td>2</td>
<td>3</td>
<td>2</td>
<td>(V)</td>
</tr>
<tr>
<td>Brazilian test [3]</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Drop weight test [4]</td>
<td>3</td>
<td>3</td>
<td>1</td>
<td>(V)</td>
</tr>
<tr>
<td>Ultra-fast load cell test [5]</td>
<td>4</td>
<td>4</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Twin Pendulum test (Bond CWI) [6]</td>
<td>2</td>
<td>4</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Split Hopkinson bar test [7]</td>
<td>4</td>
<td>3</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Rotary breakage test [8]</td>
<td>1</td>
<td>4</td>
<td>2</td>
<td>(V)</td>
</tr>
<tr>
<td>Bond ball mill test (Bond BWI) [9]</td>
<td>2</td>
<td>2</td>
<td>3</td>
<td>(V)</td>
</tr>
<tr>
<td>Bond rod mill test (Bond RWI) [10]</td>
<td>2</td>
<td>2</td>
<td>3</td>
<td>(V)</td>
</tr>
</tbody>
</table>


Grindability tests are well established and provide a huge amount of reference data. The Bond equation links comminution energy and resulting particle size reduction thus already providing a comminution process model. With regard to geometallurgical testing
a clear disadvantage lies in the timely effort for conducting the Bond test and the comparatively large sample amount. Here the route for further development should be put towards modified Bond tests with the objective of significantly minimizing the sample amount needed.

![Diagram of comminution tests](image)

**Figure 12: Available comminution tests**

Considering different dimensions, like particle sizes, mechanical stress and comminution techniques described in this chapter it can be stated that it is practically impossible to a single universal method for determining ore comminution behavior in the geometallurgical context. Figure 12 shows the test methods existing today with their placement in the matrix as introduced in Figure 2 but without using the dimension of stress type.

The further development in geometallurgical comminution test methods will have to focus on replacing the remaining interrogation marks either by developing entirely new comminution test methods or by enhancing the existing methods.

**3. Linkage between comminution test work and process modeling**

For conducting a geometallurgical program suitable comminution test methods have to provide not only material properties but also the relevant parameters that can be used within process modeling and simulation. In the following some principles of comminution process modeling are discussed in order to point out how this linkage between test work and modeling looks like.

Different types of process models are available do describe the comminution behavior of a material in a certain unit operation. This refers to the purpose of the model (size reduction, power draw, capacity, liberation) and the detailedness or modeling depth. With respect to modeling depth the description of the particulate state is a criterion to distinguish shortcut and rigorous models.
3.1.1. Size reduction models

One approach is to describe the change in one representative particle size during processing. An example of this approach is the utilization of the size reduction ratio. If defined by the maximum particle size the \( \frac{RR}{x_{\text{max},F}} \) can be used to calculate the product size distribution using for instance a Gaudin-Schuman distribution function.

\[
Q(x) = \left( \frac{x}{x_{\text{max},F}} \right)^n \tag{11}
\]

\[
Q(x) = \left( \frac{x}{x_{\text{max},F} \cdot RR} \right)^n \tag{12}
\]

where \( n \) is a material and machine dependent parameter.

Also energy-size relations as for example the Bond equation can be used in the same manner when information about the starting particle size \( x_{80,F} \), the energy \( E \) and the ore’s work index \( W_i \) are provided:

\[
Q(x) = a \cdot \left( \frac{x}{x_{80,F}} \right)^\beta \tag{13}
\]

\[
Q(x) = a \cdot \left[ \frac{x}{\phi(x_{80,F}, E, W_i)} \right]^\beta \tag{14}
\]

where \( a \) and \( \beta \) are material and machine dependent parameters.

A more detailed description is possible by using so-called population balance methods where the entire particle size distribution is considered. Here the distribution of material of one size to smaller sizes during crushing or grinding is described by the breakage distribution. Different mathematical formulations are available that need to be fitted to experimental data, e.g. the cumulative distribution function of Broadbent and Callcott (1956)

\[
B(d_i) = 1.58 \cdot \left[ 1 - e^{-\frac{y}{y_i}} \right] \tag{15}
\]

where \( B(d_i) \) is the cumulative mass of materials finer than \( d(i) \), and \( d(j) > d(i) \). Another distribution type that is frequently used has been defined by Austin (1972). The function has three parameters \( \gamma, \beta \) and \( \phi \) for describing ore specific breakage behavior.

\[
B(x, y) = \phi \cdot \left( \frac{x}{y} \right) + (1 - \phi) \cdot \left( 1 - \frac{x}{y} \right)^\beta \tag{16}
\]
Besides describing in which size fractions the fragments from breakage end up also the fraction of material that undergoes size reduction has to be quantified. This selection function \( S \), or specific rate of breakage when describing comminution as a kinetic process, is a function of machine properties and material properties, especially depending on particle size.

\[
S(x) = S_b \cdot \left( \frac{x}{x_n} \right)^b
\]  

(17)

According to the unit operation different balance types are used to formulate the population balance model for different process conditions, i.e. for single pass breakage, for ideally mixed mills or for plug flow. In the case of the ideally mixed mill one receives for the mass fraction in the i-th size fraction in the mill product

\[
p_i = f_i - \tau_{\text{mean}} \cdot S \cdot p_i + \tau_{\text{mean}} \sum_{j=1}^{i-1} S_j \cdot b_{ij} \cdot p_j
\]  

(18)

where \( f \) is the mass fraction in the feed, \( S \) the specific rate of breakage and \( b \) the breakage distribution coefficient. The mean residence time \( \tau_{\text{mean}} \) is defined by

\[
\tau_{\text{mean}} = \frac{M}{M}
\]  

(19)

Depending on the feed rate into the comminution equipment, appearance rate of a size class \( i \) from previous class is experimentally established and used in the model to predict the comminution properties of an ore. The triangular matrix structure of the model provides the fraction rates at which the components of the mill discharge. The model has diagonal matrix which describes the breakage rate of each component in the mill. For complex system or equipment empirical model are used to enhance the function-ability of the model to the entire equipment (King, 2001).

Another modeling approach is to determine the breakage distribution function based on \( t_{10} \) of the particle distribution size from a single particle breakage tests at different breakage energy levels, compare chapter 2. The \( t_{10} \) function is expressed as:

\[
t_{10} = A \times \left[ 1 - \exp(-bE) \right]
\]  

(20)

The values of \( A \) and \( b \) in conjunction with population balance model are used to simulate the performance of mineral processing. During the test, variations in breakage rates and energy consumption are measured and used for better process control, circuit design, circuit modeling and simulation, throughput forecast and sizing comminution equipment (Weedon and Wilson, 2000). Narayanan (1985) suggested that the higher the value of \( A \times b \) the softer is material subject to comminution and vice versa. These parameters give an insight on hardness of the ore deposit without considering the liberation properties of mineral particles. On other hand variations in \( A \times b \) is reported to be useful for geometallurgical modeling and mapping of a deposit.
Some attempts have been made for combining mineralogy with comminution properties (Bonnici et al., 2008; Hunt et al., 2013; Vatandoost, 2009). It has been proposed that detailed and accurate information on modal mineralogy and mineral textures fully describes the comminution and concentration properties of an ore sample (Lund, 2013; Shea and Kronenberg, 1993; Lamberg et al., 2013; Lund et al., 2013).

3.1.2. Considering mineral liberation

The liberation models are developed based on particle grade and size. The grinding model by Andrews and Mika (1975) is an example of models developed in comminution. The model describes the relationship between product size and liberation which is suitable for plant simulation but requires a quite huge number of parameters that makes application complicated (Wei and Gay, 1999). There have been efforts to improving the modeling of mineral liberation by Wei and Gay (1999), using experimental data from Schneider (1995) to validate the dispersion model which assume perfect mixing of the mill discharge in a continues comminution process.

According to Wei and Gay (1999), liberation models based on ore texture are useful for mill design but not on grinding circuit performances and simulations because after grinding the particle has lost its original texture. When liberation models are developed it is important to have good assumptions on fracturing phenomena. Fandrich et al. (1997), observed slightly existence of breakage behavior dependence of particle grade of iron oxide ores. The liberation measurement of particles from particle bed breakage test may be an indicative of preferential breakage (Fandrich et al., 1997).

Gay (2004) developed a liberation model for comminution process. The Gay liberation model still requires more work to be practically used to quantify liberation properties of an ore based on texture information although it has good foundation to quantitatively explain liberation properties based on mineral texture.

King (2001) suggested differential breakage as a relevant assumption when considering progeny size distribution resulting from changing particle composition during comminution. Ore comminution behavior (mill product size) changes by changing particle composition during comminution. By changing mill product liberation behavior of an ore within an ore deposit is affected.

Many studies for the liberation models are based on random fracture of particles. Fandrich et al. (1997) observed that the breakage behavior of a particle slightly depends on the grade distribution of minerals. Fandrich et al (1997) concluded that preferential breakage of the binary iron ore oxides is an indication of the particle bed breakage mechanism. According to Vizcarra et al (2010) liberation of minerals is independent of breakage mechanism for sulphide minerals with different texture characteristics. The conclusion by Vizcarra et al (2010) particle-bed do not enhance liberation properties of metalliferous ores is contrary to other researchers Benzer (2012), Dhawan (2012) and Wang (2012), Phaninra et al. (2011) who concluded that bed breakage mechanism enhances the liberation of minerals.
4. Development of geometallurgical comminution test methods

A test method that combines modal mineralogy and mineral texture has potential in geometallurgy (Lamberg, 2011). Quantitative mineralogical approach has not been fully used in geometallurgy. In a geometallurgical program the ore properties collected in resource characterization must match with the parameters needed in the modeling of mineral processing circuit. Figure 13 is a demonstration of how a test method should position by itself in geometallurgy. Mechanism applied to fracture the materials (ore); modal mineralogy and mineral texture are the connection between mineral liberation and energy required for comminution. It is therefore essential to quantitatively test how modal mineralogy and mineral texture link with the comminution behavior.

4.1. Samples and applied methods

4.1.1. Samples

Samples for this study were collected from Malmberget iron ore located in Northern Sweden. In the Malmberget iron field more than 20 separate ore bodies are known and production is coming from several different underground operations (Lund, 2013). Ore is processed in Malmberget concentrator in two lines: one for magnetite dominating ore and another for hematite dominated ore. Lund (2013) developed a preliminary geometallurgical classification of the ore body based on modal mineralogy and mineral textures (see also Lamberg and Lund, 2012; Lamberg et al., 2013; Lund et al. 2013). This model, however, did not take into account comminution properties.

To further develop the geometallurgical model of Malmberget samples for this study were collected to represent different ore types from the deposit. Two sample sets were
collected. The first one consists of composite magnetite and hematite ore samples which were collected from the Malmberget process plant on 11th and 12th of April in 2012. As the plant feed includes country rock the ore samples are represented by the cobb plant concentrates FAR and HAR. For more information of the Malmberget process and flow sheet see Allden Oberg et al. (2008), Tano et al. (1999) and Oberg and Palsson (2004). The second sample set includes small drill core pieces from different textural types of Malmberget ore classified by Lund (Koch, 2013; Lund, 2013). They represent typical samples for geometallurgical program whereas the first ones are in their size and nature closer to the ones used commonly in comminution tests.

To incorporate modal mineralogy, mineral textures and mineral liberation for the geometallurgical testing polished epoxy samples were prepared and assess the quality of sample before automated SEM mineralogy (see figure 14, 15 and 16).

Mineralogical analyses on modal composition and liberation distribution were made using scanning electron microscope (SEM) based automated mineralogy. Zeiss Merlin SEM and IncaMineral system (Liipo et al. 2012) for automated mineralogy were used. In modal and liberation analyses minerals were identified and classified using back-scattered electron image and EDS analysis. Magnetite grain size estimates were done by optical microscopy (Lund, 2013). Chemical compositions of samples were done by X-ray fluorescence (XRF) at LKAB laboratories. Table 6 shows the corresponding modal composition.

Table 6. Mineralogical, mineral texture and comminution properties of characterized samples

<table>
<thead>
<tr>
<th>Sample</th>
<th>1F</th>
<th>2F</th>
<th>3F</th>
<th>4F</th>
<th>5F</th>
<th>6F</th>
<th>7C</th>
<th>8F</th>
<th>8C</th>
<th>FAR</th>
<th>HAR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main Fe mineral</td>
<td>Mgt*</td>
<td>Mgt*</td>
<td>Mgt*</td>
<td>Mgt*</td>
<td>Mgt*</td>
<td>Mgt*</td>
<td>Mgt*</td>
<td>Mgt*</td>
<td>Mgt*</td>
<td>Mgt*</td>
<td>Mgt*</td>
</tr>
<tr>
<td>Texture type</td>
<td>1.0</td>
<td>2.0</td>
<td>3.0</td>
<td>4.0</td>
<td>5.0</td>
<td>6.0</td>
<td>7.0</td>
<td>8.0</td>
<td>8.0</td>
<td>Blend</td>
<td>Blend</td>
</tr>
<tr>
<td>Grain size</td>
<td>Fine</td>
<td>Fine</td>
<td>Fine</td>
<td>Fine</td>
<td>Fine</td>
<td>Fine</td>
<td>Coarse</td>
<td>Fine</td>
<td>Coarse</td>
<td>Blend</td>
<td>Blend</td>
</tr>
<tr>
<td>Fe wt%</td>
<td>5.5</td>
<td>10.0</td>
<td>22.0</td>
<td>28.0</td>
<td>57.0</td>
<td>55.0</td>
<td>55.0</td>
<td>80.0</td>
<td>80.0</td>
<td>62.9</td>
<td>51.1</td>
</tr>
<tr>
<td>Magnetite grain size (μm)</td>
<td>44.0</td>
<td>75.0</td>
<td>95.0</td>
<td>61.0</td>
<td>64.0</td>
<td>74.0</td>
<td>106.0</td>
<td>32.0</td>
<td>180.0</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Modal composition</td>
<td></td>
<td></td>
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<td></td>
<td></td>
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<td></td>
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</tr>
<tr>
<td>Magnetite</td>
<td>14.8</td>
<td>54.6</td>
<td>59.1</td>
<td>84.4</td>
<td>90.5</td>
<td>87.6</td>
<td>2.7</td>
<td></td>
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<td>Hematite</td>
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<td>70.8</td>
<td></td>
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<td></td>
<td></td>
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<td></td>
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<tr>
<td>Albite</td>
<td>53.7</td>
<td>28.0</td>
<td>29.9</td>
<td>1.8</td>
<td>1.1</td>
<td>2.0</td>
<td>4.6</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Acanthite</td>
<td>15.8</td>
<td>7.5</td>
<td>5.8</td>
<td>3.2</td>
<td>4.8</td>
<td>2.6</td>
<td>0.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Apophyllite</td>
<td>0.0</td>
<td>0.2</td>
<td>0.1</td>
<td>0.7</td>
<td>0.9</td>
<td>1.2</td>
<td>4.4</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Orthoclase</td>
<td>2.3</td>
<td>6.2</td>
<td>0.4</td>
<td>1.6</td>
<td>2.6</td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Biotite</td>
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<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>2.5</td>
<td>5.2</td>
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<tr>
<td>Others</td>
<td>2.0</td>
<td>5.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Rock mechanical properties</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>UCS (N/mm2)</td>
<td>84.1</td>
<td>27.3</td>
<td>63.0</td>
<td>16.4</td>
<td>47.1</td>
<td>58.1</td>
<td>20.0</td>
<td>36.3</td>
<td>20.1</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>P(LT(N/mm2))</td>
<td>27.8</td>
<td>11.5</td>
<td>15.5</td>
<td>5.8</td>
<td>17.2</td>
<td>15.2</td>
<td>7.3</td>
<td>8.5</td>
<td>8.9</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Crushing properties</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reduction ratio</td>
<td>5.6</td>
<td>8.4</td>
<td>6.4</td>
<td>9.7</td>
<td>6.4</td>
<td>8.9</td>
<td>7.8</td>
<td>8.8</td>
<td>9.2</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Grindability properties</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>F80 of the test (μm)</td>
<td>2821.9</td>
<td>2115.4</td>
<td>2455.9</td>
<td>1892.9</td>
<td>2609.0</td>
<td>2821.9</td>
<td>2221.4</td>
<td>2236.5</td>
<td>2064.9</td>
<td>298.0</td>
<td>1032.6</td>
</tr>
<tr>
<td>N80 of the test (μm)</td>
<td>109.4</td>
<td>125.3</td>
<td>112.7</td>
<td>132.3</td>
<td>126.7</td>
<td>126.7</td>
<td>N/A</td>
<td>129.9</td>
<td>140.3</td>
<td>257.9</td>
<td>977.1</td>
</tr>
<tr>
<td>Estimated Bond work index(kWh/t)</td>
<td>9.0</td>
<td>9.3</td>
<td>10.1</td>
<td>9.5</td>
<td>10.0</td>
<td>10.4</td>
<td>N/A</td>
<td>10.3</td>
<td>11.0</td>
<td>10.9</td>
<td>13.5</td>
</tr>
</tbody>
</table>

Mgt* = magnetite, Hmt* = Hematite
Test methods for characterizing ore comminution behavior in geometallurgy

Figure 14: Coarse grained magnetite, FAR sample, size fraction 3.35-10 mm.

Figure 15: Minerals are well liberated in size fraction 75-106 μm, FAR sample.
4.1.2. Rock mechanical tests

Rock mechanical tests were conducted using two different experimental set-ups. The point load test (PLT) was carried out according to D5731-08 standard (ASTM 2011). Quarters of drill core were clamped between the tops of cone-shaped tools giving a point load on the outer perimeter of the specimen (see figure 17). For the unconfined compressive test (UCS) the specimen was pressed between two parallel planes of a universal testing machine. Fracture patterns observed were variable and usually not symmetric.
4.1.3. Crushing tests

Crushing tests were done with laboratory jaw crusher (model Retech Type BB Mach. Nr. 31648). Fixed closed size setting of 3.35 mm was used. For the crushing test sample was passed through the crusher only once. For the sample preparation for the grinding test sample was continuously sized with 3.35 mm sieve and the oversize was crushed again until all the material passed the sieve.

4.1.4. Grinding tests

The grinding tests were evaluated according to the Bond approach by using the recorded electrical energy consumption meter (corrected by the mechanical efficiency of the device) together with the change in the 80% passing particle size in order to determine grindability which describes specific work index of a given ore.

The experiments were conducted using two different ball mills (see figure 18): standard Bond ball mill (22 L) and Capco Jar ball mill (1.4 L; Figure 18). Mass of steel ball (kg) was calculated based on degree of mill filling, ore density (4800 kg/M3) and mill volume. The steel ball size distributions used in the experiments ranges from four to 50 per cent for smallest and biggest steel ball diameter sizes (mm), respectively (Table 7).

Table 7. Size distribution of steel grinding media used in Bond ball mill grindability test and in down-scaled test with a small mill.

<table>
<thead>
<tr>
<th>Size of the steel ball (mm)</th>
<th>Distribution weight (%)</th>
<th>Number of balls in a small mill</th>
</tr>
</thead>
<tbody>
<tr>
<td>36.0</td>
<td>15</td>
<td>1</td>
</tr>
<tr>
<td>28.5</td>
<td>51</td>
<td>7</td>
</tr>
<tr>
<td>21.8</td>
<td>29</td>
<td>9</td>
</tr>
<tr>
<td>15.0</td>
<td>4</td>
<td>5</td>
</tr>
</tbody>
</table>
4.2. Crushability tests

A simple single pass crushing test was done for the Malmberget samples using 5 mm closed side settings in a laboratory jaw crusher. Rock mechanical tests were done for comparison. A strong correlation between the strength parameters determined by the point load test (PLT) and the unconfined compressive strength (UCS) test was found in tested samples (figure 19). Values of the point load test are smaller than the corresponding strength determined by the uniaxial compressive strength test as shown before by several authors (Akram and Bakar, 2007; Flores et al. 2005; Rusnak and Mark, 2000; Singh and Kainthola, 2011). As expected the samples showing high mechanical strength are hard to crush, i.e. crusher reduction ratio and uniaxial confined strength show an inverse proportionality (figure 20).
Figure 19. Correlation between point load test (PLT) and uniaxial compressive strength (UCS) of Malmberget samples.

Figure 20: Correlation between mechanical strength (uniaxial compressive strength, UCS) and crusher reduction ratio.
4.3. Downscaling the Bond grindability test

4.3.1. The original Bond grindability test

The starting point selected for the new grindability test was the standard Bond ball mill grindability test (figure 21). The test is a locked cycle test that simulates a closed continuous comminution circuit with a classifier (figure 21). The test starts with 0.7 liters of bulk sample (corresponding to 3.4 kg FAR sample) and it is repeated until steady state is reached. It usually takes at least six grinding-screening cycles. The test aims for 250 % circulating load at a defined cut screen size of 100 μm or close to that. After each grinding step the mill product is sized and material passing 100 microns screen is removed and replaced by an equal amount of fresh feed material to maintain the 3.4 kg sample in the tumbling mill. The grinding time is adjusted after each round to reach 250 % circulation load and a steady-state condition.

Figure 21. Schematic flow sheet of the Bond ball mill grindability test.

The average mass per number of revolution of the undersize materials of the last three cycles of the grinding test is used to determine the so-called grindability and the Bond work index according to the Bond formula. In total the test uses about 10 kg of sample and it takes more than one working day to be completed. Figure 22 shows the number of cycles used to determine the work index of the magnetite ore sample (FAR).
Advantages of the test are that it is relatively simple to do, it can be done by any technician with minor training; it uses simple equipment; it is repeatable and there is large amount of accumulated data on Bond Work Index values for different kind of ores. However, to be applicable to geometallurgical testing the test should be faster and it should use smaller sample (< 2 kg). Therefore a solution was search by doing the test in single pass with electrical energy measurement, similar to the Mergan mill test (Niitti, 1970) but with a significantly smaller mill and according sample size.

4.3.2. Approach to downscaling the Bond grindability test

Downscaling of the Bond grindability test is not a straightforward question due to the presence of the various complex micro-processes inside a tumbling mill. These generate different fracture forces, mill conditions that are affected by size of the mill (Cleary, 1998) and dynamics of the mill during the particle size reduction.

Despite the complex phenomena in the mill, impact is the main distinguishable fracture force occurring at the toe during the tumbling of the mill in cataracting mode (Wills et al. 2006). By accelerating the grinding media from the highest lifting point down to the toe of the charge the theoretical maximum impact velocity can be calculated that gives the impact energy used for particle fracture. With respect to the impact energy the key variables are therefore the geometry parameters of a mill and the dynamics of the mill charge.
In this work principles of similitude were used in order to downscale the Bond test method. The following equations summarize the steps in determining the downscaling factors that characterize the relationships between the mills.

a) Geometric similarities of standard bond ball mill (L) and modeled small ball mill (S)

Reducing the mill size gives a certain geometric scaling factor:

\[
\lambda_D = \frac{D_L}{D_S} = \frac{305}{115} = 2.65
\]  

(21)

Where;

\(\lambda_D\) is the characteristics dimensionless factor (scale factor) between two mills

\(D_L\) is a diameter of a Bond ball mill

\(D_S\) is a diameter of a small ball mill

b) Kinematic similarities between the two mills.

For receiving the same fracture effects the impact from ball motion has to follow the similarity principles. Here the impact velocity of a grinding ball at a certain throw angle \(\beta\) is used. The characteristic dimensionless factor for the impact velocity

\[
\lambda_{v_{imp}}(\beta) = 1
\]  

(22)

In the formulation of this dimensionless factor the Froude number \(Fr = \frac{v}{\sqrt{gL}}\), i.e. the ratio between inertia to gravitational forces, has been considered as a suitable quantity for describing the grinding ball movement inside a tumbling mill, with the mill diameter being the characteristic length is in this case.

Applying the principles of the Buckingham Pi theorem gives

\[
(\Pi) = \Phi \left( \frac{l_1}{l_u}, \frac{v}{\sqrt{gL}} \right)
\]  

(23)

where

\(l_1\) : Characteristics length of the Bond ball mill and in this study it is \(D_L\)

\(l_u\) : Characteristics length of the small ball mill and in this study it is \(D_S\)

\(v\) : Velocity of the grinding ball at throw

\(g\) : Gravity constant

The dimensionless factor for the impact velocity is defined by
Where,

\( V_{imp L} (\beta) \) : Impact velocity of large mill (Bond ball mill) at any throw angle \( \beta \)

\( V_{imp S} (\beta) \) : Impact velocity of modeled mill (small ball mill) at any throw angle \( \beta \)

Keeping the kinematic similarity between the two mills is expressed by

\[
\frac{V_{imp L}}{V_{imp S}} \cdot \frac{D_S}{D_L} = 1 \tag{25}
\]

\[
\frac{V_{imp L}}{V_{imp S}} \cdot \frac{D_L}{D_S} = \sqrt{\frac{L}{D}} \tag{26}
\]

\[
V_{imp S} (\beta) = \frac{V_{imp L} (\beta)}{\sqrt{\frac{L}{D}}} \tag{27}
\]

The calculation of scale factor \( \sqrt{\frac{L}{D}} \) is based on the ratio between the diameters of the two mills. For the geometries of the considered ball mills one obtains

\[
V_{imp S} = \frac{V_{imp L}}{1.63} \tag{28}
\]

This expression can be used for scaling the impact velocity of ball charge hits the impact zone for different mill sizes to provide similar effects to the particles. First the Bond ball mill impact velocity has to be calculated and then downscaled by dividing it with the scale factor.

The impact velocity can be estimated from simulating the trajectory motion of the ball charge. Using advanced modeling techniques several numerical models have been developed for investigating mill liners and optimizing mill designs and operations (Cleary, 1998, Powell and Nurick, 1996). Valery and Morrell (1995) developed a more sophisticated model using numerical simulation for prediction of power draw after Mishra and Rajamani (1992) estimate and simulated the motion and dynamic equilibrium of individual ball charge in a tumbling mill. Later Venugopal and Rajamani (2001) used discrete element method to simulate the motion of ball charge in 3D.

In this work a basic equation for calculating the grinding ball velocity has been used. The technique is quite easy to use for scaling the impact velocity starting from the throw at the charge shoulder angle. The velocity at the point of throwing is given by
$$V_{\text{imp}} = \sqrt{\left(v_t \cos \beta \right)^2 + \left(v_t \sin \beta \right)^2 - \frac{g \cdot v_t}{\left(\cos \beta \right)^2}} \quad (29)$$

where

$\beta$ : Throw angle of the ball charge inside the ball mill,

$v_t$ : Tangential velocity of a ball charge.

Throw angle and tangential velocity are determined by the lifting of the ball charge during tumbling and therefore depend on the shoulder angle and the rotational speed. The final impact velocity of the ball is then depending on the time available for acceleration, i.e. the distance from the upper lifting point to the surface of the charge.

Full description of the behavior of ball charge by physical means is possible only in limits. Instead empirical functions are used to describe the position and location of the ball charge inside the tumbling mill, based on the work of Perez-Alonso and Delgadillo (2012) that validated simulated velocity profiles from a DEM simulation of a laboratory ball mill charge.

$$\gamma = 0.048199 \times (\phi)^{0.585266} \times \left(\frac{n}{n_C}\right)^{1.145184} \quad (30)$$

$$\theta = \left[ \frac{389.7247}{(\phi)^{0.143446}} \times \left(\frac{n}{n_C} - 0.143446 \times 2 \times 0.042218 \right)^{1.2} \right] \quad (31)$$

$$\beta = 90 - \gamma \quad (32)$$

$\gamma$ Shoulder angle of the ball charge inside a ball mill,

$\theta$ Toe angle of the ball charge inside a ball mill,

$\phi$ Percentage level of ball charge fillings,

$\% \frac{n}{n_C} \quad$ Percentage of mill critical speed.

By adjusting the shoulder angle and fraction of mill charge fillings, the ball charge accurately hits the target at the toe. Here the maximum of the impact velocity is calculated and used to determine the impact energy and to adjust the amount of sample in a ball mill. Morrell (1996, refer to Gupta and Yan, 2006) related shoulder and toe angle to the fraction of critical speed and empirically showed the effects of percentage ball charge and fraction of critical speed on grinding action. Less balls sliding and cascading are expected at 80-90 percentage fraction of the critical speed. The position of the charge inside the mill depends on the mill rotational speed.
Figure 23 and figure 24 are examples that illustrate the trajectory path of ball charge calculated for the large and small diameter mill. With equation 29 the magnitude of impact velocity is determined based on vertical displacement of the ball flight just before it hits a toe. The hitting velocity determines the kinetic energy of a single ball. This energy is transferred to the mineral particles. For example in the Bond mill when operated at percentage fraction of mill fillings 19.3 % and fraction of the mill critical speed 91 % (shoulder angle 47.8°) the balls hits the target (toe at an angle 243°) with an impact velocity of 0.91 m/s. This agrees with findings of Morrell (1996, refer to Gupta and Yan, 2006).

Figure 23. A plot showing the path of a single ball inside the large mill (Bond mill) directed to hit the sample at mill filling level 45 % of mill charge and 56 % fraction of the critical speed.

Figure 24. A plot showing the path of a single ball inside the small mill directed to hit the sample at mill filling level 45 % of mill charge and 56 % fraction of the critical speed.
In this study the corresponding impact velocity for the small ball mill is 0.57 m/s at the percentage fraction of mill fillings 19.3% and fraction of the mill critical speed 91%. At that point the ball charge experiences cataracting motion in a similar way as in the Bond mill thereby providing the same impact effects if the number of fracture event is 1.63 higher.

One option would be operating the small ball mill at the same mill rotational speed 70 rpm as Bond mill. In order for small ball mill to hit the target at 70 rpm, it should have 45% ball charge mill loadings and 56% fraction of the critical speed (compare 24). However at this condition small ball mill shows more cascading effects compare to Bond mill . Therefore this condition is not providing similar type of stress as Bond grindability test conditions.

To keep the same ball mass and provide the same impacts, small mill require a higher number of fracture events to compensate the magnitude of the impacts compared to the large mill. In practice the compensation is achieved by longer grinding time of materials by small ball mill. Figure 25 compares various product size distributions as a result of the impacts at different conditions for two laboratory tumbling mills. The number of events of small ball mill is reduced from 25 minutes to 17 minutes residence grinding time to provide similar grinding results as with the Bond ball mill. At that point it can be clearly seen that particle size distribution by small ball mill is converging to full Bond grindability mill discharge and after applying the downscale factor 1.63 the small ball mill estimate the same work index as Bond full grindability test method.

### 4.4. Small scale grinding test

In down-scaling the Bond ball mill grindability test, the principle was to keep the impact effects similar in the Bond and in a smaller mill. Therefore ball sizes and their size distribution was kept constant. The total ball charge was defined by keeping the ball charge filling fixed (19%). The target was to minimize the sample size and therefore to find the smallest possible mill fulfilling the conditions on similar impact effect. The diameter vs. length of the mill was not fixed because the aim was to find a suitable commercially available laboratory mill and length of mill does not affect the impact of ball charge inside a mill (Table 8). To maintain similar type of stress and ball hitting location inside a tumbling mill, ball trajectories and ball impact velocities were calculated based on throw angle and tangential velocity of rotating mill. Calculations showed that a CAPCO laboratory 1.4 l stainless steel ball mill model 2 variable speed (Ref. 337SS, www.capco.co.uk) with 115 mm mill internal diameter gives similar conditions as the Bond mill with similar fraction of critical speed. The sample size was defined by keeping the proportion between ball and sample weight similar for both mills. The mill speed was maintained at 91% of the critical speed.
Table 8: Parameters for down-scaling the Bond ball mill test.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Condition for downscaling</th>
<th>Standard Bond ball mill</th>
<th>Small ball mill</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mill dimensions</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 Diameter (mm)</td>
<td>To be changed</td>
<td>305</td>
<td>115</td>
</tr>
<tr>
<td>2 Length (mm)</td>
<td>To be changed</td>
<td>305</td>
<td>132</td>
</tr>
<tr>
<td>Ball charge</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3 Percentage mill volume fillings by ball charge (%)</td>
<td>Fixed</td>
<td>19</td>
<td>19</td>
</tr>
<tr>
<td>4 Average ball size (mm)</td>
<td>Fixed</td>
<td>27</td>
<td>27</td>
</tr>
<tr>
<td>5 Ball charge (kg)</td>
<td>Scaled by filling (3)</td>
<td>21.9</td>
<td>1.33</td>
</tr>
<tr>
<td>Sample</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6 Sample to balls ratio (w/w)</td>
<td>Fixed</td>
<td>0.16</td>
<td>0.16</td>
</tr>
<tr>
<td>7 Sample size (kg)</td>
<td>Scaled by ratio (6)</td>
<td>3.4</td>
<td>0.220</td>
</tr>
<tr>
<td>8 Sample particle size distribution (mm)</td>
<td>Fixed</td>
<td>&lt;3.5</td>
<td>&lt;3.5</td>
</tr>
<tr>
<td>Operational conditions</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9 Speed, vs. critical (%)</td>
<td>Fixed</td>
<td>91</td>
<td>91</td>
</tr>
<tr>
<td>10 Grinding time (minutes)</td>
<td>To be changed</td>
<td>10.5</td>
<td>17.0</td>
</tr>
<tr>
<td>11 No of revolutions/minute</td>
<td>To be changed</td>
<td>70</td>
<td>114</td>
</tr>
<tr>
<td>12 Test type</td>
<td>To be changed</td>
<td>Locked cycle</td>
<td>Single pass</td>
</tr>
<tr>
<td>13 Mill product sizing</td>
<td>Fixed</td>
<td>Standard sieve series</td>
<td>Standard sieve series</td>
</tr>
</tbody>
</table>

The Bond mill gives bigger impact because of its large diameter compared to the small ball mill. By prolonging the grinding time in the small ball mill the material experiences higher number of impacts. Sample FAR was used to find the grinding time in the smaller mill giving identical particle sized distribution in the mill discharge compared to the Bond test. It was found that 17 minutes grinding time in single pass gives similar particle size distribution for the mill discharge (80% passing size, P80 = 259 μm) as the Bond test procedure in the steady state (see figure 25). This was therefore selected as a standard condition for further testing in the small ball mill.

By shifting the Bond grinding conditions to the small ball mill the kinetics are changed because of the differences in geometry. Another thing to consider is the change from a closed circuit test to single pass test. Therefore a scale factor is needed to equalize the results with the Bond test. From geometrical relationship the scale factor (square root of the ratio of the diameter of large to small ball mill) between the Bond and the small mill is 1.63. The reason for using square root is because of the proportion of impact velocity between Bond mill and small ball mill is defined as

\[
\frac{\text{Impact velocity by Bond mill}}{\text{Impact velocity by Small ball mill}} = \sqrt{\frac{\text{Diameter of Bond mill}}{\text{Diameter of small ball mill}}}
\]

With the FAR iron ore sample the measured specific energy with 17 minutes grinding time is 10.56 kWh/t. The Measured Bond Work Index with full Bond test gave 10.6
kWh/t. By applying back calculation with the Bond energy equation 33 the calculated work index with the small mill is 10.87 ± 0.42 kWh/t (28). This confirms that scale-down factor of 1.63 from the geometry can be applied and is used in this study for the estimation of the Bond Work Index.

\[
BWI = \frac{E}{k \times EF1 \times EF2 \times EF3 \times EF4 \times 10 \times \left( \frac{1}{\sqrt{P80}} - \frac{1}{\sqrt{F80}} \right)}
\]

......................... (33)

Where

- BWI = Bond Work Index (estimated),
- E = Measured specific energy in the small mill,
- P80 = The product 80% passing size (microns),
- F80 = The mill feed 80% passing size (microns) and
- k = Scale factor defined by square root of the ratio of the diameter of Bond to small ball mill equal (1.63)
- EF1 = Correction factor for dry grinding (1.3; Rowland and Kjos, 1978; Mular et al. 2002).
- EF2 = Correction factor efficient diameter (1.842) (Rowland and Kjos, 1978; Mular et al. 2002).
- EF3 = Ball mill efficient factor (0.835) (Rowland and Kjos, 1978; Mular et al. 2002).
- EF4 = Efficient factor for fineness (0.95) (Rowland and Kjos, 1978; Mular et al. 2002).
4.5. Linking comminution properties with mineralogy

A weak negative correlation was found between crushability and grindability with tested samples (figure 26). When sample was easy to crush it appeared to be difficult to grind. The explanation for the observation requires more information on mineralogy of the samples.

Drill core samples with seven different textural classes from Malmberget were used to test the developed method and to study how mineral liberation can be connected with the comminution properties. Lund (2013) developed a textural classification for Malmberget iron ore with two dimensions: magnetite grain size (fine/coarse) and relationship of melanocratic and leuocratic parts. Melanocratic material is rich in magnetite and it brecciates the leuocratic albite-orthoclase-rich magnetite-poor matrix. The textural types are by increasing magnetite grade as follows: (1) disseminated, (2) banded, (3) waving veins, (4) patchy, (5) granules, (6) clustered, (7) small veins, (8) speckled and (8) massive ore. Here the division between fine and coarse grained texture is put 100 microns. Besides above listed minerals sample includes commonly actinolite, apatite and albite. In the sample set the magnetite grade shows negative correlation with albite and actinolite grades. Apatite grade shows positive correlation with magnetite grade. Most of the samples are classified as fine grained (See figure 27 ).
Considering mineralogical properties the higher the content of magnetite the higher is reduction ratio (soft to crush) and but in grinding the opposite is true: the higher is the magnetite content the higher is the P80 of the grinding product (Figure 27). Applying multivariate statistics for the small data set it can be found that the mill product size (P80) is controlled besides magnetite grade by the magnetite grain size according to following empirical equation (see equation 34).

\[ P80(\text{microns}) = 0.139 \times \text{Mgt}(\text{wt\%}) + 0.054 \times \text{Mgt\_grain\_size\_(microns)} + 118 \] (34)

Positive correlation means that the higher is the grain size of magnetite the higher is the P80 and therefore the harder is the material to grind. As the P80 is between 110 and 140 microns in coarse grained materials, where the magnetite grain size is >100 microns, the grinding action is to break individual magnetite grains and therefore the material appears to be very hard to grind. The purpose of grinding is to liberate and with the coarse grained sample the particle size in the mill product is already well below the average magnetite grain size and most probably also of the liberation size, i.e. the size where the mineral occurs liberated enough for the downstream processes. For the geometallurgical context the grindability of the material is not the proper measurement since for different material the degree of liberation of the mineral may be very different. Therefore the

Figure 26: Crushability vs. grindability of Mahnberget samples Weak positive correlation indicates that samples easy to crush (having high size reduction ratio) seems to be difficult to grind (high work index).
grindability is here extended to mineral liberation and term liberability is introduced: It is defined as relative ease with which an ore mineral can be liberated by grinding.

In Malmberget the degree of liberation (i.e. mass proportion of mineral in particles containing more than 95% of mineral in question) shows negative relationship with particle size, as expected (Figure 27). The relationship is close to linear and passes through the point 0 microns particle size and 100% liberation. It is not very practical to introduce a liberability term in geometallurgy if it means that for each sample after grinding several size fractions must be analyzed for liberation using automated mineralogy. Therefore an alternative approach was developed. Firstly, a key size fraction was selected for liberation measurement. This should be close to expected liberation size and in Malmberget a size fraction of 53-75 microns was selected. The liberation characteristic of the size fraction was measured with automated mineralogy. Based on the measurement on size fraction 53-75 microns the degree of liberation of magnetite was estimated in the other size fractions by applying a linear equation which passes through the measured point and the point (0,100). The degree of liberation in the bulk sample was calculated from the size fractions as weighed average. In the Fabian Fsp sample

Figure 27. Mill product size P80 after grinding in small –scale ball mill at the same impact energy of Malmberget samples. Positive correlation can be observed between the magnetite grade and 80% passing and multivariate statistics indicates that magnetite grain size (used as a plot mark, microns) is the second most important factor. The coarse grained high grade sample (8C=180 microns) appears to be much harder to grind than corresponding fine grained type (8F = 32 microns). Error shows standard deviation of the P80 with 3 repeats.
The grinding test gave certain particle size distribution which was measured by sieving. The degree of liberation for the bulk sample was estimated as described above. To estimate how the liberation changes with grinding energy a simple approach was used. Firstly the P80 of each ore type with different grinding energies was estimated by using the Bond grindability equation. Estimated Bond Work Index (equation 35) and fixed F80 were used. The result for different textural types of Malmberget is shown in figure 26.

\[ E = 10 \times BWI \left( \frac{1}{\sqrt{P80}} - \frac{1}{\sqrt{F80}} \right) \] (35)

The received P80 was converted to full particle size distribution by using the Rosin-Rammler equation and taking the parameter describing the spread of the distribution from the 17 minutes grinding product. A new D63.2 parameter to give identical P80 as received from the Bond equation was searched. Finally to get an estimate on the degree of liberation of magnetite it was assumed that the degree of liberation within the narrow size fractions remains constant and the overall value is a product of each size fraction by their mass proportions. A worked out example is given in Table 9. The liberability graph, i.e. the liberation degree vs. specific grinding energy is shown in Figure 30.

![Figure 28. Particle size versus degree of liberation of the main minerals in Malmberget, sample Fabian Fsp ore type (Lund, 2013).](image-url)
Figure 29. Specific power prediction for target size for magnetite liberation from five different mineral texture classes of Malmberget iron ore deposit.

Figure 30. Specific power prediction for degree of liberation of magnetite ore of Malmberget iron ore from five different mineral texture classes.
Significant difference is observed between the liberability and the grindability (see Figure 29 and Figure 30). Grindability indicates that two high grade samples, 8F and 8C require quite different grinding energy but when the mineral liberation is set as a target the ores appear to be very similar. Because the main purpose of grinding is to achieve required liberation the liberability information will clearly tie technical and economical ways of how to utilize the resource in an optimal manner. This will change the plant operators to change their operating strategies.

Table 9. Worked out example how the grinding energy to degree of liberation relationship was established. Meas = measured, calc = calculated; for (a)-(h) see text.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Measured with grinding test (t=17 min)</th>
<th>Forecasted for given energy (example 9 kWh/t)</th>
</tr>
</thead>
<tbody>
<tr>
<td>E kWh/t</td>
<td>10.59 (meas)</td>
<td>9.00 (a)</td>
</tr>
<tr>
<td>BWI kWh/t</td>
<td>11.04 (c, calculated)</td>
<td>11.04 (c)</td>
</tr>
<tr>
<td>F80 microns</td>
<td>2064.9 (d, meas)</td>
<td>2064.9 (d)</td>
</tr>
<tr>
<td>P80 microns</td>
<td>71.95 (meas)</td>
<td>93.36 (b)</td>
</tr>
<tr>
<td>Rosin-Rammler D63.2 microns</td>
<td>53.56 (meas)</td>
<td>68.36 (f)</td>
</tr>
<tr>
<td>Rosin-Rammler alpha</td>
<td>1.68 (e, meas)</td>
<td>1.68 (e)</td>
</tr>
<tr>
<td>Size fraction</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bulk</td>
<td>96.2 (calc)</td>
<td>95.2 (h)</td>
</tr>
<tr>
<td>0-38 microns</td>
<td>43.0 98.0 (calc)</td>
<td>31.1 98.0</td>
</tr>
<tr>
<td>38-53 microns</td>
<td>19.6 96.7 (calc)</td>
<td>16.8 96.7</td>
</tr>
<tr>
<td>53-75 microns</td>
<td>20.2 95.3 (meas)</td>
<td>21.0 95.3</td>
</tr>
<tr>
<td>75-106 microns</td>
<td>12.9 93.4 (calc)</td>
<td>18.7 93.4</td>
</tr>
<tr>
<td>106-150 microns</td>
<td>3.9 90.6 (calc)</td>
<td>10.0 90.6</td>
</tr>
<tr>
<td>150-212 microns</td>
<td>0.4 86.7 (calc)</td>
<td>2.2 86.7</td>
</tr>
</tbody>
</table>

4.6. GCT – The Geometallurgical Comminution Test

Based on the work done a small-scale test method for mapping variation of ore comminution properties in geometallurgy was established and the flow chart is shown in Figure 31. The test is designed for drill core samples and each sample is ideally a 30 cm long piece of a drill core half (Step 1, Figure 31). In magnetite ore this equals to about 500 g sample. In the sample preparation stage (2) the drill core is cut to about 2x2 cm pieces. (3) The pieces are then crushed by laboratory jaw crusher at closed side setting 3.35 mm. (4) if crushability is to be determined then after one pass crushing, the crusher product is sized. (5) Otherwise the crusher product is split with 3.35 mm sieve and oversize is crushed again. This is continued until all passes 3.35 mm sieve. This should give a product with 80% passing close to 1 mm. (6) Crushed sample is split to 2-3 parts. (7) One is used for sieving to obtain F80. (8) One part is used for the grinding test. The grinding test is performed as described in chapters 4.1 and figure 25. When using the
Capco jar mill 337SS the sample size is 220 g and the ball charge is 1.3 kg with diameters as given in Table 5. Grinding time is 17 minutes. With these conditions electrical energy meter is not required because the reading will be identical in all the tests. The target P80 should align with the Bond tests and therefore some other grinding time might be used. But the idea of the test is to use fixed time for a given ore body and geometallurgical program. (9) After grinding, the material is sized and the result of the grinding test is the particle size distribution of the product described as 80% passing and the Rosin–Rammler parameters. One size fraction close to the final targeted overall P80 of the grinding-classification circuit is used to determine the degree of mineral liberation and mineral associations. The size distribution is determined using a sieve series from 3.35 mm down to 38 μm following the $\sqrt{2}$ series.

Figure 31. Flow chart of the geometallurgical comminution test (GCT).

The designed comminution test can be suited with normal sample preparation scheme used for the chemical assays. The crusher product can be split and one part can be used for determining the bulk chemical composition of the sample, e.g. with XRF/AAS. For the modal mineralogy element to mineral conversion method can be applied (Lund et al. 2013, Whiten, 2007) one may need to use additional techniques like XRD (A2) and SEM based automated mineralogy (A3).

In the grinding test (8) the sample size is defined by mass rather than volume as in the Bond test. Therefore the volume of the sample can be varying significantly in e.g.
massive sulphide and iron ores. However, this is considered as one part of material properties in this methodology.

The outcome of the test results when combined with chemical assays are then:

A. Chemical composition of the sample

B. Crushability index as a reduction ratio (F80/P80)

C. Grindability index as P80 or calculated BWI

D. Degree of liberation for the key minerals and their association indices

To be cost effective geometallurgical program one might come to a solution where chemical assays are done for all samples, crushability and grindability for 50% of samples and liberation analysis for 10% of samples.

5. Outlook on a novel instrumented drop weight test

As described earlier drop weight testers use the impact from a falling weight for fracturing the sample on an anvil. Fracture tests range from single particle breakage and breakage of drill cores via multiple particle breakage of single layers or particle beds. Conventional drop weight tests consider the potential energy of the falling weight as being the energy transferred to the specimen. Efforts have been made in order to improve accuracy and detailedness of the tests resulting in quite elaborate designs like the ultrafast load cell (Weichert, 1986).

Within the work on geometallurgical testing a robust experimental set-up of this type of test has been tried out using a drop weight with an instrumented head that originally was developed to conduct stamping tests (Abel et al, 2009). The falling weight is equipped with a load cell for measuring the current force acting on the sample and an inductive displacement transducer for recording the corresponding vertical position of the weight (see Figure 32).
Based on the time-dependent measurement of the two quantities a force-displacement graph can be constructed. Figure 34 shows an example from an indicative test conducted with 3 fragments from the same section of a drill core. Several peaks in force are visible when the weight strikes the particles with a subsequent drop in force while the particles fail. Towards the end of the entire curve a rebound of the weight is visible before it remains on the sample.

From this graph not only the single breakage events can be read out. The data pairs also allow to determine the net energy transferred to the specimen during the test. The average percentage of net energy transferred to the particle sample has shown to be around 75% of the theoretically determined energy based on the height difference, with variations depending on the material and orientation of the specimen.
Figure 33. Force and displacement measurements during fracturing

Within first tests using the instrumented drop weight tester fragments of the same samples as used in the rock mechanical tests were selected. The particles were hand-picked wedges of drill core of approximately 2 to 3 cm height.

Figure 4 is showing the particle size distributions received from several drop weight tests using the same falling height of 30 cm except for coarse grain sample where sample orientation seems does not control its breakage properties. For coarser grain sizes the amount of fines after impact fracture is increasing and the particle size distribution is becoming broader, compared to the fine grained specimens that produce a bimodal distribution with comparatively coarse and into some fine material from crumbling.

For a more accurate and precise energy measurement this instrumented drop weight test is seen as an alternative compliment for the determination of crushability index and when combined with developed small ball mill grindability test, it will improve the developed test method for full geometallurgical characterization. The observations from the initial experiments summarized in figure 34 have indicated that there is a need of defining a standard method for dealing with textural effects and sample orientation when conducting the breakage tests.
6. Discussion

The developed test method aims to characterize the essential comminution properties of small samples in a single test. This is an ambitious goal since most of the geomechanic programs use different tests for different particle sizes. It is common to do separate characterization tests for crushing, SAG grinding and ball mill grinding (e.g. Bulled and Lozano, 2009; Bergholtz and Schreder, 2004; Flores et al. 2005; Keeney et al. 2011; Montoya et al. 2011; Harbort et al. 2013). Even though the Bond Work Index generally speaking has a positive correlation with SAG grindability indexes like A*b (e.g. Bulled and Lozano, 2009) the difference is so significant that it is rare to use Bond test only as an estimate for the full grindability in geomechanic programs (Oyarzúin and Arévalo, 2011; Philander and Rozendaal, 2011b). Vatandoost (2009, 2010) developed petrophysical methods to be used for proxies for comminution characterization. This approach is very practical for geomechanic mapping but it misses important information about mineral liberation.

In geomechanic programs comminution characterization aims to provide reliable models to be used to forecast plant throughput. As the comminution circuits consists of several different type of comminution units like crushers, SAG mills and ball mills also the models must be capable of treating these units separately but also in a circuit. Parameters like scat handling (e.g. does the circuit includes a pebble crusher), transfer size between SAG and ball mill and handling of slimes may be more important for the
throughput estimate than the actual grindability. This addresses that methodology
developed here can’t provide all this important information needed for reliable
forecasting. Rather the developed test is designed to be used in early stages for
identification of the variability in the comminution properties leading to successful
geometallurgical domaining. After this the sampling and testing can be done in larger
scale to economically and efficiently serve circuit design, sizing of the unit operations and
to model and simulate the throughput. This ensures the quality of the process; circuit
configurations based on material properties variations which is a key foundation of any
geometallurgical programs.

Linking of liberation and comminution characteristics in geometallurgy is not very
common. Philander and Rozendaal (2011a, 2011b) compared grindability and liberation
of zircon at Namakwa Sands mine resulting in a successful expansion program. Instead
many different kind of liberation models have been developed before geometallurgy was
known (e.g. Gay, 1999; King and Schneider, 1998; King, 1979; Wei and Gay, 1999,
Gay 2004). Most of the liberation models require a good quality textural picture to start
with. This is a limitation when thinking of geometallurgical programs. Scanning drill
holes with pixel sizes of some microns would be required and with currently available
techniques this is impossible or at least very slow (Leichliter et al. 2012; Hunt et al.
2008). If this picture is available then limitations occur in the assumption of non-
preferential breakage, the limitation to binary systems (i.e. two minerals: valuable and
others) or the requirement of Kernel function (King, 1967).

Mineral liberation may not be sufficient information because associating minerals and
type of particles is important for downstream processes to produce saleable product.
Lamberg and Lund (2012) and Lund (2013) developed a methodology how to
incorporate full liberation information into a geometallurgical model but the concept was
missing grindability. The developed methodology has potential to fill this gap.

Methodology proposed here requires validation for each deposit that bulk liberation can
be estimated only using one size fraction and that the assumption that liberation within a
narrow size fractions is constant regardless of particle size distribution of the bulk material
(Vizcarra et al. 2010). How to combine liberation and size reduction in comminution
models is also an open question to be solved. Current crusher and grinding models
provide forecast on particle size distribution, grinding energy and throughput
dependency but they are not capable to forecast neither how the grade varies by size nor
the liberation distribution of the products. Before the developed test method can be
linked with process simulations reliable mineral by size and mineral liberation models on
comminution need to be developed.

The question how much energy is needed to achieve required liberation when feed
composition (texture) is changing is crucial and important for building a suitable
geometallurgical model. An interesting observation from this study is that, there is a
significant difference between grindability and liberability at the same grinding energy
when the mineral texture is different. It implies that domaining an ore body by only
grindability (hardness) may be misleading in ore classification at the early stage of a
geometallurgical programs and has consequences for the project development and investment. Therefore it is important to collect information on mineral liberation, grinding energy and particle size relationships before defining geometallurgical domains.

Comminution mechanisms and texture characteristics are seen as drivers for the prediction of the liberation properties of minerals. The possibility of using different breakage mechanisms on different mineral textures will increase knowledge on use of liberation models in geometallurgical modeling and comminution process monitoring. More cases will be considered in ongoing research work for generalized application of the method particularly on liberation studies. Application of special microscopic forces to follow breakage phenomena (ore comminution behavior) vs. texture and mineralogical properties of the same texture class is considered. This will help to understand the effect of applied forces on breakage and its implication to liberation properties. This idea has been suggested by Wills and Atkinson (1993).

7. Conclusions and further work

Comminution test methods commonly used in geometallurgy require large samples and are time demanding and expensive. Small scale testing is needed to be applied early in the ore characterization for collecting information on the variability of crushability and grindability properties in order to do a proper geometallurgical domaining. A review of existing rock fracture testing showed that none of the available methods fulfill the criteria set for proper geometallurgical tests. The most promising ones were found to be small scale Bond ball mill test, instrumented drop weight test and rotary breakage tester.

The Bond test method was selected as a basis due to its simplicity and repeatability. It is an industrial standard method for determining the grindability and practices are established for how to use Bond Work Index in modeling and simulation of comminution circuits. The test was scaled down to use about 200 g of sample and the procedure was changed to a single pass. The test work was complemented with crushability tests and mineral liberation measurement on one selected size fraction for establishing quantitative information on the relationship of grindability and mineral liberation.

The trend of magnetite grade by size in various mineral textures (low to high grade magnetite) indicates that the magnetite grade decreases by particle size (Figure 35). The variation in the magnetite grade by size must be taken into consideration when evaluating the degree of liberation in the full sample basing on one size fraction. Thus, a model on mineral grades by particle size needs to be developed.

The variation in the mineral grade by size is direct evidence on non-random breakage, since there should not be any difference in the composition between size fractions if the breakage is fully random. The main focus in liberation characteristics has been the degree of liberation. However, one should not forget different associations (Figure 36), and that there might be variation in the association by size. More work is needed.
Figure 35. Degree of magnetite liberation for five size fractions for six different mineral textures of Malmberget iron ore.

Figure 36. Mode of occurrence of magnetite in five narrowed size fractions.

Based on the work presented the answers to the working hypothesis are:
1. Comminution characteristics can be tested for geometallurgical purposes with small (<0.5 kg) drill core samples. However, the data should be used merely for domaining and to designing sampling for larger scale samples than directly forecasting the metallurgical performance (e.g. throughput).

2. Mineralogy defines the comminution properties to some extent and the number of tests required for geometallurgical characterization of an ore can be significantly decreased by knowing the mineralogy.

3. The two mineralogical parameters: modal mineralogy and mineral textures DO NOT fully define the comminution parameters. There are some hidden properties besides these two since with studied samples the crushability can’t be explained satisfactorily.

4. The comminution efficiency should be measured by energy vs. mineral liberation rather than particle size vs. energy. Liberation information is the more appropriate information for downstream concentration processes.

The developed method is still a prototype and before applying it routinely in geometallurgical programs the following studies are suggested:

- Study on how accurate the estimated Bond Work Index is compared to full scale Bond grindability test
- Study on whether the crushability test can be used for estimating SAG characterization parameters like A*b
- Study on whether the degree of liberation can be estimated for the bulk samples based on one size fraction also with other ore types
- Study on the observation and assumption that liberation in narrow size fractions is independent on overall particle size distribution
- Study on how grindability and liberation information can be combined in process simulations using the concept proposed by Lamberg and Lund (2012) and Lund (2013).
8. References


Paper I

Testing of Ore Comminution Behavior in the Geometallurgical Context – A review.
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Testing of Ore Comminution Behavior in the Geometallurgical Context- A review

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Abstract

Comminution tests are an important step in the proper design of ore beneficiation plants. In the past test work has been conducted for particular representative reference samples. Within geometallurgy the entire ore body is explored in order to also identify the variation within the resource and to establish spatial geometallurgical domains that show the different response to mineral processing. Setting up a geometallurgical program for an ore deposit requires extensive test work. Methods for testing the comminution behavior have therefore to be more efficient in terms of time and cost but also with respect to sample requirements. Also the integration of the test method in the geometallurgical modeling framework is important. This paper provides an overview of standard comminution test methods used for the investigation of ore comminution behavior and evaluates their applicability and potential in the geometallurgical context.

Keywords: Geometallurgy, comminution behavior, metallurgical testing.

1. Background

Before concentrating metal ores have to be crushed and ground in order to liberate the metal bearing minerals. A sufficient size reduction is not only the prerequisite for any downstream physical separation. Comminution is also the processing step within mineral processing having the highest energy demand and in practice being much often the limiting factor for plant capacity. Reliable testing of the ore’s comminution behavior, i.e. information about the particle size distribution after fracture, the achieved mineral liberation as well as the comminution energy needed, is therefore an important step in the proper design and control of ore beneficiation plants.

In the past the process design has usually been based on particular representative reference samples that were analyzed and tested at different scale but did not describe all the mineralogical variations occurring in an ore body. The limited picture received from that is a potential cause for insufficient mineral liberation or on the contrary for too fine grinding leading to low recovery and selectivity in physical separation [1], and thus resulting in poor plant performance and limited production capacity.
For the last years geometallurgy as a new interdisciplinary approach has been evolved. Geometallurgy combines geological and metallurgical information to create a spatially-based predictive model for mineral processing to be used in production management [2]. Within the geometallurgical approach the entire ore body is explored in order to identify the variation within the ore body and to establish spatial geometallurgical domains that show different response to mineral processing. Using the geometallurgical domains in the design and control of ore beneficiation plants allows for higher flexibility towards changes in the plant feed when mining different parts of the ore [3].

Setting up a geometallurgical program for an ore deposit requires extensive test work that on the one hand pays back by improved plant operation, but on the other hand is time consuming and correspondingly costly. Also the best possible utilization of the available sample material is a crucial point as chemical and rock mechanical analyses are also requiring samples and thereby limiting the available amount. Accordingly the need of efficient geometallurgical testing gives a stimulus for developing new fast comminution test methods or for the revision of existing test procedures, respectively. Also improved process models need to be established that subsequently make use of the additional information provided by the geometallurgical approach.

This paper provides an overview of standard test methods used for the investigation of ore comminution behavior and evaluates their applicability and potential in the geometallurgical context. Besides the test work itself also the provision of suitable parameters for process modeling is considered.

2. Criteria for evaluation

The term comminution behavior comprises the complex interaction of material properties and process parameters. In practice different comminution test methods are used for different practices (Figure 2). As the comminution properties change with particle size different tests ranging from crushing to grinding and very fine grinding are employed accordingly. Also the type of mechanical stress applied in a certain crusher or mill type, i.e. compressive or impact stress, as well as the stress intensity and rate have to be considered in the selection of a suitable test method.

Finally the applicability of a comminution test will depend on the project stage and the available sample amount, ranging from drill core sections or hand-picked single particles used in the early stages of the resource evaluation and in laboratory scale to pilot scale tests where the metallurgical performance is verified and several tens or hundreds of kilograms are used. At larger scales also the effort in terms of time and costs per test is increasing. This third dimension will limit the test work to certain methods for the different scales during the individual project stages.
For geometallurgical purposes the outcome of the experimental work has to serve as an input to process modeling, i.e. comminution test results need to be linked to the parameters used in the comminution process models. Within process modeling different levels of modeling depth are used. Simple approaches use defined size distribution functions based on single parameters as energy for grinding or machine-specific size reduction ratios. More sophisticated, rigorous models apply population balancing methods. Here the entire breakage distribution function needs to be constructed based on experimental test work or sampling and back-calculation from continuous comminution tests even at larger scale [4]. In this context it has to be noted that a closed methodology that not only comprises size reduction and energy for size reduction but also incorporates mineral liberation within experimental work and process modeling is still missing.

As discussed above a geometallurgical program imposes particular requirements on the efficiency and manageability of test methods. A comminution test for geometallurgical purposes should therefore fulfill several technical and economic criteria:

- **Simplicity** – The test should be relatively simple and easy to execute. It should use instruments that are available in common analytical and mineral processing laboratories.

- **Repeatability** – The test should be repeatable and not depending on the individual person conducting the test.

- **Sample preparation** – Sample preparation should be possible with low efforts and possible to do with basic skills or after short training.
- **Time exposure and costs** – The test should be fast and inexpensive, i.e. for execution times of one hour it should be possible to conduct 1000 tests within half a year.

- **Sample amount** – The amount of sample per test should be < 0.5 kg. Preferentially rejects from chemical assays should be enough.

- **Link to modeling** – Tests should provide parameters that can directly be used in process modeling and simulation.

- **Mineral liberation** – Tests should be easy to extend in order to include mineral liberation information.

Another criterion is given by the precision and the statistic quality of the test results. With respect to accuracy a proper quantification is not an easy task as the entire chain of sampling and sample preparation together with the test and analysis method needs to be considered. Statistic quality is a parameter that from the perspective of ge metallurgy has not only to be judged with respect to the repetition of single tests but in relation to generating a comprehensive data set for the entire geometallurgical program, i.e. there is a compromise between the quality of single measurement and the quantity of measured points.

### 3. Review of existing test methods

In the following commonly used comminution test methods having potential to be used in geometallurgical context are reviewed against the criteria listed above. The tests are classified in three groups: 1) rock mechanical tests, 2) particle breakage tests, and 3) bench-scale grindability tests.

#### 3.1 Rock mechanical testing

Rock mechanical tests for rock strength are conducted by means of universal test machines or simplified instruments. Loading takes place at comparatively low velocities. The instrumentation of the test machine allows recording of the load applied to the sample and the displacement over time. Several standard test methods are used that differ in the loading conditions applied [5].

Samples consist of drill core sections, parts of drill core sections and single particles (crab samples) that are cut to regular shape but also irregular shaped particles. Measured strength parameters depend not only on modal mineralogy but also on textural effects and anisotropy [6].

##### 3.1.1 Compression tests

In compression tests the drill core sample is pressed between the two parallel planes of the test machine, which are then loaded up to failure of the specimen. Data for the applied load and the resulting displacement is recorded over time, providing the maximum load for calculating the compressive strength. Sample preparation comprises
careful cutting of the specimen’s top and bottom planes in order to prevent bending effects during the test.

![Figure 2: Uniaxial unconfined compression test](image)

In case the specimen is not further supported the test is referred to as unconfined compressive strength (UCS) test (Figure 3). For triaxial compression tests the drill core specimens are cut to the required length and then enveloped on the lateral surface by a membrane that seals the specimen from the surrounding pressure medium, usually oil, that provides the radial support. When increasing the axial compressive load also the oil pressure is increased in parallel up to failure of the specimen.

A similar experimental setup is used in the point load test (PLT), see Figure 4. Instead of using parallel planes here the compressive load is applied between the tips of two cones, putting a point load on the specimen. Test instruments are quite compact and can even be used in field work.

From the point load test the point load strength index $I_{50}$ is obtained that needs to be corrected to the standard equivalent core diameter $D_e$ of 50 mm if other specimen are used.

$$I_{50} = \frac{P}{D_e^2} \text{ (in psi)}$$

with the failure load $P$ in lbf (pound force) and $D_e$ in inches. The point load strength index can be transferred into uniaxial compressive strength using a linear conversion factor that needs to be determined for a particular ore [7].
3.1.2 Indirect tensile strength test

Using cylindrical of a specimen as slices from drill cores and loading these radially by compression forces between two sockets (plates, cushioned plates, curved clamps) gives an indirect tensile stress and an according deformation in orthogonal direction. This experimental setup is also known as the Brazilian test (Figure 5).

The sample is stressed under the linear compressive load that induces the tensile stress. Assuming that the material is homogeneous, isotropic, and linearly elastic before failure [8] the failure is expected at maximum tensile stress. The corresponding tensile strength is then calculated by
\[
\sigma_t = \frac{2 \cdot P}{\pi \cdot D \cdot t}
\]  

(2)

where \( P \) is the failure load, \( D \) the specimen diameter, and \( t \) the thickness of the test specimen.

### 3.1.3 Evaluation of rock mechanical tests

Using results from rock mechanical tests for describing comminution behavior is an attractive approach as no additional test work and sample material is needed. Also the necessary sample amounts are small.

All the tests discussed above apply slow compressive stress in a well-defined way, meaning that the repeatability of the method is given, though the interpretation has to take into account the textural effects and inhomogeneity in samples from natural mineral resources. The conduct of the test is rather simple and can partly be done in the field. More effort has to be put on proper samples preparation, e.g. when sawing drill cores. The fragments received are usually too coarse for using them as such in quantitative mineralogical analyses.

It has been shown that mechanical parameters of rock samples can be used to describe and model comminution processes at least in the case of crushing [9], [10], [11]. For this purpose mechanical strength expressed by the maximum load at the point of failure needs to be transformed into quantities that can be used within the design of crushing stages. Usually empirical ore-specific correlations are provided for calculating crushing index or crusher reduction ratio from UCS or PLT strength values.

The evaluation of the different rock mechanical tests with respect to the criteria defined in section 2.1 is summarized in table 1.

Table 1. Rock mechanical tests

<table>
<thead>
<tr>
<th>adverse (−), acceptable (o), advantageous (+)</th>
<th>UCS</th>
<th>PLT</th>
<th>Brazilian</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simplicity</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Repeatability</td>
<td>O</td>
<td>O</td>
<td>O</td>
</tr>
<tr>
<td>Sample preparation</td>
<td>−</td>
<td>O</td>
<td>−</td>
</tr>
<tr>
<td>Time exposure and costs</td>
<td>O</td>
<td>O</td>
<td>O</td>
</tr>
<tr>
<td>Sample amount</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Link to modeling</td>
<td>−</td>
<td>−</td>
<td>−</td>
</tr>
<tr>
<td>Mineral liberation</td>
<td>−</td>
<td>−</td>
<td>−</td>
</tr>
</tbody>
</table>
3.2 Particle breakage tests

3.2.1 Drop weight test

3.2.1.1 Simple drop weight test

In the drop weight test a weight is lifted to a certain height and then released to fall on an ore sample, which is arranged on a rigid anvil underneath (Figure 6). The fragments from the sample are afterwards collected and analyzed by their particle size to receive a breakage distribution. The test sample can comprise single particles, a part or an entire drill core section or several particles as received from pre-crushing. Several apparatus have been presented [12], [9], [13]. For conducting particle bed fracture tests with fine particles the anvil is replaced by a die [14].

![Drop weight tester](image)

Figure 5: Drop weight tester

Different impact levels and amounts of specific comminution energy can be obtained by varying the drop weight, the falling height or the sample mass. The energy provided to the ore sample can be described by the potential energy of the drop weight at the initial height:

\[ E = m_{dw} \cdot g \cdot h \]  

(3)

where \( m_{dw} \) is the mass of the drop weight and \( h \) the distance between the drop weight and the top of the specimen.

For evaluating the breakage distribution a method has been developed that links the breakage distribution and comminution energy to the modeling of particle size reduction.
The percentage passing $1/n$ of the starting particle size can be related to the comminution energy by:

$$t_n = A \left( 1 - e^{-b E_{spc}} \right)$$

(4)

where $E_{spc}$ is the specific energy in kWh/t and $A$ and $b$ are ore-specific parameters determined by model fitting the experimental data obtained from tests with different energies. Typically the $t_{p-10}$-value is used as a fineness index to characterize a certain ore sample. In process modeling and simulation an average set of $A$ and $b$ is used assuming that particles of different size will break in a similar way.

For determining the several $t_n$ curves five different initial particle sizes in the range of 13.2 to 63 mm and 3 energy levels need to be investigated giving a total of 15 tests. This drop weight test as defined by the Julius Kruttschnitt Mineral Research Centre therefore normally requires 75 to 100 kg of sample material.

In order to reduce the sample amount and the number of particle size fractions an abbreviated drop weight test, called SAG Mill Comminution (SMC) test, has been suggested [16]. Using only a single size fraction, i.e. particles or parts cut from drill cores in the size range 19/22 mm, the necessary sample amount can be reduced to 5 kg. The test provides the parameters $A$ and $b$ as well as a Drop Weight Index (DWi in kWh/t) but not the $t$-values.

3.2.1.2 Instrumented drop weight test

The simple drop weight test has been improved by adding instrumentation. A well-established instrumented drop weight test is the Ultra-fast load cell device (UFLC) developed at the University of Utah [17], [18], [19] (Figure 7).
A sample, consisting of individual particles or a bed of particles, is placed on a vertical steel bar and then hit by the falling weight. As with the split Hopkinson pressure bar (see 2.3.4) the bar is instrumented by a pair of strain gauges for detecting the impact wave that allows for inference on the load applied to the sample. Based on load-time profiles and the calculated deformation the transferred energy can be calculated.

A portable impact load cell, using the same principles as in the Ultra-fast load cell, has been developed by Bourgeois et al. [20] for in-situ quantification of ore breakage properties. The so-called SILC – Short Impact Load Cell is reduced in height and weighs only 30 kg.

![Micro-stamping device](image)

**Figure 7: Micro-stamping device**

Based on the principle design of the simple drop weight test another instrumented drop weight tester has been designed [21] and initially used for the investigation of particle compaction processes. Here the drop weight itself is instrumented by a load cell and an inductive displacement transducer that yield time-dependent measurement profiles for the entire sequence of primary impact and subsequent rebounds. The comminution energy transferred to the sample is received from integration of the load-displacement relation.

### 3.2.2 Twin pendulum tests

In twin pendulum tests a single particle is fractured between two pendulum-mounted hammers that are released from a certain height. Figure 9 shows the experimental setup for the Bond twin pendulum test [22]. A single particle is mounted on a socket and then simultaneously hit by the hammers. The procedure is repeated until the particle breaks, thereby incrementally increasing the deflection angle of the hammers.
Bond defined a crushing work index by:

\[ CW_i = \frac{53.5 \cdot C_B}{\rho_p} \]  

(5)

where \( \rho_p \) is the particle density in g/cm\(^3\) and \( C_B \) the impact energy per particle thickness \( d_p \) in J/mm for the last pendulum deflection angle of \( \Theta \)

\[ C_B = \frac{117 \cdot (1 - \Theta)}{d_p} \]  

(6)

Also the twin pendulum test has been extended by adding instrumentation that allows the recording of the pendulum motion [23], [24]. Lifting only one pendulum and mounting the particle on the other allows for determining the energy transferred to the sample by evaluating the rebound movements of the two pendulums after collision.

3.2.3 Split Hopkinson pressure bar test

The split Hopkinson pressure bar, originally developed for testing stress propagation in materials from the detonation of explosives, has been used for fracturing a sample particle between two horizontally mounted steel bars called the incident bar and the transmitted bar, compare Figure 10. The mechanical stress is induced by a loading system, i.e. a gas gun, and the travel of the deformation waves is recorded with strain gauges. The signals provide information about load-displacement profiles and allows for energy balancing.

Even though the experiments with the Hopkinson pressure bar are laborious there has been a phase of intensive development of the test method, leading to the Modified Hopkinson Pressure Bar for higher resolution [25] or the CSIRO Hopkinson pressure bar for larger specimen [26] having a vertical assembly like the Ultrafast load cell.
3.2.4 Rotary single impact tester

In single impact tests the stress applied to a sample results from the collision with one single tool. This can be achieved either by accelerating the sample against a plate using gravitational forces or the acceleration forces from a gun, or by advancing the sample with a fast moving tool, commonly realized in a rotor–stator impact system.

Such a rotary impact tester design was first presented by Schönert et al. [27] and has meanwhile been commercially adapted also for ore testing [29], [30]. Figure 11 shows a schematic of the rotor–stator impacting system. Particles are fed to the evacuated impact chamber by centrifugal action via several channels in the rotor. The surrounding stator has a saw tooth profile that allows for a perpendicular impact of the particles. Compared to other particle breakage tests significantly more particles can be tested in a given time.

The probability for breakage can be described as a function of the impact energy using a Weibull distribution [28]:

Figure 9: Split Hopkinson pressure bar

Figure 10: Rotary impact tester
where \( f_{mat} \) is a material constant, \( x \) the initial particle size, \( k \) the number of impacts, and \( E_{kin} \) and \( E_{kin,min} \) the kinetic energy impact and the energy threshold without fracture, respectively.

The specific kinetic energy is described by

\[
E_{kin} = \frac{1}{2} v^2
\]

Comminution test are used to determine the parameters within the probability for breakage and the breakage distribution.

3.2.5 Evaluation of particle breakage tests

Particle breakage tests use impact stress for striking the sample. Except for the rotary breakage test the mounting of the sample and the conduct of the tests are in most cases quite tedious. Repeatability is more affected by the sample characteristics than by the test method.

<table>
<thead>
<tr>
<th>adverse acceptable advantageous (-) (o) (+)</th>
<th>Drop weight</th>
<th>UFLC</th>
<th>Twin Pendulum</th>
<th>Split Hopkinson bar</th>
<th>Rotary breakage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simplicity</td>
<td>O</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Repeatability</td>
<td>O</td>
<td>O</td>
<td>–</td>
<td>O</td>
<td>+</td>
</tr>
<tr>
<td>Sample preparation</td>
<td>–(^{1)})</td>
<td>–</td>
<td>O</td>
<td>–</td>
<td>O</td>
</tr>
<tr>
<td>Time exposure and costs</td>
<td>–(^{1)})</td>
<td>–</td>
<td>O</td>
<td>–</td>
<td>O</td>
</tr>
<tr>
<td>Sample amount</td>
<td>–(^{1)})</td>
<td>–</td>
<td>O</td>
<td>–</td>
<td>O</td>
</tr>
<tr>
<td>Link to modeling</td>
<td>+</td>
<td>O</td>
<td>+</td>
<td>O</td>
<td>+</td>
</tr>
<tr>
<td>Mineral liberation</td>
<td>O</td>
<td>O</td>
<td>O</td>
<td>O</td>
<td>O</td>
</tr>
</tbody>
</table>

\(^{1)}\) based on the JK drop weight test

The necessary sample amounts are small if using cut drill core samples. Testing fractionated material from crushing and screening requires significantly more material. This is particularly the case if not only the initial particle size is varied but also different energy levels are tested, e.g. when using the concept of \( t_c \)-values for process modeling.
Depending on the initial sample size the fragments received after breakage are usually too coarse for using them as such in quantitative mineralogical analyses, i.e. only for the case of ultra-fast load cell or when using small bars with the split Hopkinson pressure bar test sufficiently small particles are generated that are meaningful to investigate for mineral liberation.

3.3 Bench-scale grindability tests

3.3.1 Bond test

The Bond test is used to analyze the grindability for a material. The test applies a standardized ball mill of 305 mm (12 in.) both in diameter and length with a grinding media charge of certain size distribution and operated at a defined speed. The sample amount is defined by the bulk volume of 0.7 liters, consisting of particles smaller than 3.35 mm. The test is conducted as a dry locked cycle test with sieving of the mill product after each stage. Fines are replaced by an equal amount of fresh feed material and grinding times are varied in order to reach a simulated circulating load of 250%. Usually samples of 10 kg smaller 3.35 mm are required.

From the grinding test the Bond ball mill work index \( W_i \) is determined \([31]\):

\[
W_i = \frac{1.1 \cdot 44.5}{x_S^{0.23} \cdot G^{0.82} \left( \frac{10}{\sqrt{x_{80,F}}} - \frac{10}{\sqrt{x_{80,P}}} \right)}
\]

(9)

Where \( x_S \) is the screen aperture, \( G \) the grindability (in grams of product per mill revolution), and \( x_{80,F} \) and \( x_{80,P} \) are the 80% passing particle sizes in \( \mu m \) for the mill feed and product, respectively.

The test results are used to calculate the change in particle size during grinding based on the grinding work input \( W \) using the Bond formula, also referred to as Bond’s law, as a process model \([32]\):

\[
W = W_i \left( \frac{10}{\sqrt{x_{80,F}}} - \frac{10}{\sqrt{x_{80,P}}} \right)
\]

in kWh/t

(10)

3.3.2 Variations of the Bond test

Besides for determining ball mill grindability the Bond test has been adapted to other mill types. Bond also defined a test for rod mill grinding using a 305mmx610mm standard mill requiring up to 20 kg sample. Test conditions are differing, e.g. the circulating load is changed to 100%, and also the Bond equation for calculating the rod mill work index is slightly different. For describing comminution in AG/SAG mills and HPGGR using the Bond test method requires model extensions by empirical relations.
In the past several attempts have been made in order to simplify the Bond procedure. One approach has been to change the test from locked cycle to a pure single pass batch test in order to minimize the timely effort and also the sample amount needed, by developing new test mills, e.g. Mergan mill [33] or NSBM [34], or by modifying the test procedure [35], [36].

### 3.3.3 Evaluation of grindability tests

In grindability tests a combination of impact stress and attrition is applied to a bulk of material. The original Bond test is quite tedious as several grinding experiments are necessary to reach the stationary state of the simulated closed circuit. Also the sample amount appears quite high if only drill cores are available. Sample preparation is limited to pre-crushing and screening.

The test is reliable and has a good repeatability if procedure and test mill comply with the standard. One of the major advantages is surely the huge data base that has been developed during the last decades. With respect to modeling the coupling between the work index and the particle size reduction can directly be used together with a size distribution function. Attention has to be paid to the applicability of the function type for the individual case. The size range of the mill product can be used as such to conduct mineral liberation analyses.

<table>
<thead>
<tr>
<th>adverse (–), acceptable (o), advantageous (+)</th>
<th>Original Bond ball mill</th>
<th>Original Bond rod mill</th>
<th>Single pass e.g. Mergan mill</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simplicity</td>
<td>O</td>
<td>O</td>
<td>+</td>
</tr>
<tr>
<td>Repeatability</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Sample preparation</td>
<td>O</td>
<td>O</td>
<td>O</td>
</tr>
<tr>
<td>Time exposure and costs</td>
<td>–</td>
<td>–</td>
<td>O</td>
</tr>
<tr>
<td>Sample amount</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Link to modeling</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Mineral liberation</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
</tbody>
</table>

### 3.4 Pilot and bench-pilot scale tests

Comminution test work on bench-pilot or pilot scale is done by using different types of crushers and mills. Typically this comprises:

- Cone crushers
• High pressure grinding rolls (HPGR)
• Ball mills
• Stirred media mills, e.g. IsaMill or vertical stirred mills

Stress type and stress rate are based upon the respective machine type.

Tests require several tens to hundreds of kilograms sample material and are done in batch or continuous mode. Sample preparation usually comprises pre-crushing and screening for adjusting the initial size distribution, as well as sample splitting.

Sampling from the test mill or circuit provides the data base for determining breakage probabilities or grinding rates as well as breakage distributions from back-calculation using population balance methods. Using the data from liberation analyses allows for describing the particles based on their mineral composition [37].

Pilot and bench-pilot scale tests are used to verify the metallurgical performance of a designed circuit. In the geometallurgical context these result can be used in calibrating the small scale test results towards full scale operation.

3.5 Indirect methods for determining comminution behavior

Another way of obtaining information about rock mechanical strength is to evaluate the core drilling process by according instrumentation, also referred to as measurement while drilling (MWD). Alternatively also drill cuttings can be evaluated. Variations of the conditions at the drill bit, as for instance torque, normal or bending forces, result from changes in the rock hardness.

Despite of the huge data sets that are continuously collected in a large number of operations the MWD data is seldom used for assessing the comminution properties of ore bodies. One of the obstacles is the lack of reliable on-line information on the condition of the drill bit, which is needed for correcting the recorded down hole measurements by the dynamic process of drill bit wear off.

Also petrophysical data from multi-sensor drill core logging has been used for calibration against measures of ore breakage parameters and grindability that were received from conventional destructive comminution tests [38]. Using density, magnetic susceptibility and seismic wave parameters from Australian copper-gold deposits the Bond mill work index and the crushability parameters received from drop weight testing could be predicted with acceptable accuracy.

In conjunction with recent advances in quantitative mineralogical analyses the development in geometallurgical characterization today is towards identifying correlations between ore comminution behavior and mineralogical properties. The idea behind is to reduce the number of comminution tests necessary for characterizing a deposit and to arrive at a more generic description of mechanical properties based on the occurring minerals [39].
4 Conclusions

Table summarizes the findings from the evaluation of the individual test methods. None of the tests is fulfilling all criteria but by emphasizing the requirements on sample amount and effort for conducting the tests as well as modeling issues several methods can be identified to be promising for the further development of geometallurgical comminution test.

Results from rock mechanical tests should only be used where already available. But as the results cannot be used directly correlations need to be found for the description of ore crushing properties. Generally speaking, rock mechanical tests should not be part of a geometallurgical program as they do not provide information about grinding behavior down to the particle liberation level.

Table 4: Summary table, relevance for geometallurgy

<table>
<thead>
<tr>
<th>Fracture test method</th>
<th>–</th>
<th>O</th>
<th>+</th>
<th>Relevance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unconfined compressive strength test</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Point load test</td>
<td>2</td>
<td>3</td>
<td>2</td>
<td>(v)</td>
</tr>
<tr>
<td>Brazilian test</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Drop weight test (^1)</td>
<td>3</td>
<td>3</td>
<td>1</td>
<td>(v)</td>
</tr>
<tr>
<td>Ultra-fast load cell test</td>
<td>4</td>
<td>4</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Twin Pendulum test (Bond CWI)</td>
<td>2</td>
<td>4</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Split Hopkinson bar test</td>
<td>4</td>
<td>3</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Rotary breakage test</td>
<td>1</td>
<td>4</td>
<td>2</td>
<td>v</td>
</tr>
<tr>
<td>Bond ball mill test (Bond BWI)</td>
<td>2</td>
<td>2</td>
<td>3</td>
<td>(v)</td>
</tr>
<tr>
<td>Bond rod mill test (Bond RWI)</td>
<td>2</td>
<td>2</td>
<td>3</td>
<td>(v)</td>
</tr>
<tr>
<td>Single pass test, e.g. Mergan mill</td>
<td>1</td>
<td>2</td>
<td>4</td>
<td>v</td>
</tr>
</tbody>
</table>

\(^1\) based on the JK drop weight test

Particle breakage tests have a potential to be used within geometallurgy in case they are not depending on too large sample amount and high effort. This is for instance the case for the SMC test based on the standard drop weight testing where only single size samples are required. Also the rotary breakage test is promising despite the need for the technically and monetarily intensive test machines.
Grindability tests are well established and provide a huge amount of reference data. The Bond equation links comminution energy and resulting particle size reduction thus already providing a comminution process model. With regard to geometallurgical testing a clear disadvantage lies in the timely effort for conducting the Bond test and the comparatively large sample amount. Here the route for further development should be put towards modified Bond tests with the objective of significantly minimizing the sample amount needed.

Considering different dimensions, like particle sizes, mechanical stress and comminution techniques described in chapter 2.1 it can be stated that it is practically impossible to have a single universal method for determining ore comminution behavior in the geometallurgical context. Figure 11 shows the test methods existing today with their placement in the matrix as introduced in Figure 2 but without using the dimension of stress type.

The further development in geometallurgical comminution test methods will have to focus on replacing the remaining interrogation marks either by developing entirely new comminution test methods or by enhancing the existing methods.

Figure 11: Available comminution tests

5 Acknowledgements

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6 List of References


Comminution test method using small drill core samples

Mwanga, Abdul, Lamberg, Pertti and Rosenkranz, Jan

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Comminution test method using small drill core samples
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ABSTRACT
Comminution tests aim to measure the comminution properties of ore samples to be used in designing and sizing the grinding circuit and to study the variation within an ore body. In the geometallurgy context this information is very essential for creating a proper resource model for production planning and management and process control of the resource's exploitation before and during production.

Standard grindability tests require at least 10 kg of ore sample, which is quite a lot at early project stages. This paper deals with the development of a method for mapping the variability of comminution properties with very small sample amounts. The method uses a lab-scale jaw crusher, standard laboratory sieves and a small laboratory tumbling mill equipped with a gross energy measurement device. The method was evaluated against rock mechanical tests and standard Bond grindability test. Within this approach textural information from drill cores is used as a sample classification criterion.

Experimental results show that a sample of approximate 220 g already provides relevant information about the grindability behavior of iron ores at 19 % mill fillings and 91% fraction of the critical mill speed. The gross energy measured is then used to calculate an equivalent grinding energy. This equivalent energy is further used for predicting the variations in throughput for a given deposit and process.

Liberation properties of the ore connected to grindability elaborates energy required for grinding and significances of it when deciding to go to higher grinding energy considering the improvement of liberation of desired mineral. However, high energy improved significantly the degree of liberation of magnetite and is expected to improve the concentrate grade after downstream treatment. The higher the magnetite content the better is liberability of magnetite mineral and lower energy required to liberate the desired mineral. Liberability of magnetite is also affected by texture classes contain low magnetite content. A method that combines this information has been developed as a practical framework of geometallurgical modeling and simulation in order to manage technical and economic exploitation of resource at early, project stages and during mining operations.

1. Introduction
Ore testing is an important part of the geometallurgical experimental framework and modeling. Tests are used in characterization of ore behavior at different process stages, such as comminution. Several test methods are available for testing comminution behavior but they use large (>10 kg) sample. In the early stage of resource evaluation
only drill core samples are available while for metallurgical testing only half or quarter of
the drill core is available. Therefore commonly samples collected for the testing are
composite samples representing a broad mineralogical variation within them. This
hinders the detailed mapping of ore variability using drill core samples. Some of the
methods used in geometallurgy are the JK Tech drop weight test (Napier-Munn et al,
1996; Narayanan, 1986), JK Rotary Breakage Test (JKRBT; Shi et al, 2009) and SMC
test (Morrell, 2004). For detailed characterization of metallurgical properties along the
mineralogical variability small-scale test methods are needed.

Mineral processing properties within an ore body can vary a lot and bring several
challenges for production. For the Collahuasi copper mine Alruiz et al (2009) and Suazo
et al. (2010) showed how the plant throughput and copper recovery varies strongly
between the geometallurgical domains. In geometallurgical programs like the Collahuasi
it is common that the comminution circuit throughput is determined by fixing the
particle size of a comminution product. This is questionable when there is a big
variation on micro-texture or liberation size within a deposit, e.g. like shown by Lund
(2013) in Malmberget iron ore. However, comminution characterization studies that
would take into account mineral information are very rare (Kim, Cho, and Ahn, 2012;
Kim and Cho, 2010; Schreier and Groger, 1999).

This study aims at establishing a comminution test method for geometallurgy and
evaluating it with a case study from Malmberget iron ore, Northern Sweden. Another
aim of the study is to demonstrate how and why modal mineralogy, mineral textures and
liberation should be considered already in comminution tests.

2. Comminution tests most suitable for geometallurgy

A short review on existing comminution tests is here done to estimate their directly
usability and easiness to modify for geometallurgical purposes. A suitable geometallurgical
comminution test should fulfill the following requirements:

1. The test should be relatively simple and use instruments available in common
analytical and mineral processing laboratories.

2. The test should be repeatable and not dependent on person.

3. The test should be easy to execute so that technicians with basic skills in
sample preparation should be able to do it with short training.

4. The test should be fast (max 1 hour) and inexpensive.

5. The amount of sample per test should be less than 0.5 kg; preferentially the
test could use assay rejects.

6. The test, or rather a combination of tests, should give measured values on
both crushability and grindability.
7. It should be possible to use the parameters derived from the test directly in the modeling and simulation of a comminution circuit.

8. It should be easy to extend the test to include mineral liberation information.

Comminution tests are here classified into three groups (compare Table 1): 1) Geological and rock mechanical tests, 2) Single particle breakage tests and 3) Grindability and bed breakage tests. Another dimension in classification is their particle size. As shown by Hukki (1962) comminution energy vs. size reduction equation changes by particle size. In coarse range the energy required for size reduction is smaller than in finer grain size. Three different particle size areas following different laws can be identified: A) coarse range (crushing, >1 cm, Kick, 1885), B) middle range (grinding, 0.1-1 cm, Bond, 1952) and C) fine range (fine grinding, < 100 microns, von Rittinger, 1867).

Rock mechanical test are used to measure the mechanical strength of the rock in coarse particle size (A). They are commonly used in geotechnical studies. The most potential ones for geometallurgical tests are point load and unconfined compressive tests. They are used for testing small scale drill core samples. It has been shown that the mechanical strength of rock measured from point load are correlated with comminution parameters (Akram and Bakar, 2007; Flores, Limitada, and Minería, 2005). These kinds of tests are simple and can quickly generate information about the hardness of an ore and therefore are relevant for geometallurgical mapping. However, they require reasonable large sample amounts and the measured parameters cannot be directly used in comminution or throughput models (Flores et al., 2005).

Single particle breakage tests such as JK Drop Weight tests, SAG Mill Commination test (SMC) by Morrell (2004), pendulum and ultrafast load describe the fractureability/crushability (grindability) of the materials in coarse-middle particle sizes (A-B) using empirical parameters which are further used in specifically developed process models (Napier-Munn et al. 1996). As these tests are used especially in designing and optimizing autogenous or semi-autogenous grinding circuits they use large samples, typically >10 kg, which makes it difficult to be practically used in geometallurgical programs (Bailey et.al. 2009). JK Rotary Breakage Test is developed to rapidly assess the hardness of the materials (Shi et al 2009 (Hunt et al., 2008). Despite the JKRBT capability to measure hardness of the materials and general suitability for geometallurgical programs (Table 1) it is still relatively rarely used for that purpose.
Table 1. Common fracture test methods having potential for geotechnical tests. Requirements (see text): 1) Simple, 2) Repeatable, 3) Easy to execute, 4) Fast and inexpensive, 5) Uses small samples, 6) Gives both crushability and grindability, 7) Parameters can be used in modeling and simulation, 8) Can be extended to mineral liberation.

<table>
<thead>
<tr>
<th>Fracture test method</th>
<th>– (Adverse)</th>
<th>O (Acceptable)</th>
<th>+( Advantageous)</th>
<th>Relevance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unconfined compressive strength test [1]</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Point load test [2]</td>
<td>2</td>
<td>3</td>
<td>2</td>
<td>(v)</td>
</tr>
<tr>
<td>Brazilian test [3]</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Drop weight test (^\d) [4]</td>
<td>3</td>
<td>3</td>
<td>1</td>
<td>(v)</td>
</tr>
<tr>
<td>Ultra-fast load cell test [5]</td>
<td>4</td>
<td>4</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Twin Pendulum test (Bond CWI) [6]</td>
<td>2</td>
<td>4</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Split Hopkinson bar test [7]</td>
<td>4</td>
<td>3</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Rotary breakage test [8]</td>
<td>1</td>
<td>4</td>
<td>2</td>
<td>(v)</td>
</tr>
<tr>
<td>Bond ball mill test (Bond BWI) [9]</td>
<td>2</td>
<td>2</td>
<td>3</td>
<td>(v)</td>
</tr>
<tr>
<td>Bond rod mill test (Bond RWI) [10]</td>
<td>2</td>
<td>2</td>
<td>3</td>
<td>(v)</td>
</tr>
</tbody>
</table>


Grindability tests are done for multiple particles to characterize the material properties in milling in a middle particle size range (B). The most widely used is the Bond grindability test (Man, 2002). The test has been further improved for wet grinding and different types of circuits (Armstrong, 1985; Wills and Bruce, 1966; Smith and Lee, 1968; Wills 196 and Napier-Munn, 2006). However, the test is not very suitable for geology, because it requires large sample (>10 kg), and the test takes several hours to complete.
A literature survey and simple ranking showed that no single fracture test method fulfills all eight criteria (Table 1). Three tests were identified having best potential for further development towards a comminution test for geometallurgy using small drill core samples: Bond ball mill test, instrumented drop weight test and Rotary Breakage Test (RBT). Here, the Bond test was selected as a base as it has been used for almost a century, it is accepted industrial standard, large databases for the test results (Bond Work Index, BWI), the test is easy to do, it does not require special equipment and it seems to be easy to extend to the liberation level.

3. Samples and applied methods

Samples for this study were collected from Malmberget iron ore located in Northern Sweden. In the Malmberget iron field more than 20 separate ore bodies are known and production is coming from several different underground operations (Lund, 2013). Ore is processed in Malmberget concentrator in two lines: one for magnetite dominating ore (FAR) and another for hematite dominated ore (HAR). Lund (2013) developed a preliminary geometallurgical classification of the ore body based on modal mineralogy and mineral textures (see also Lamberg and Lund, 2012; Lamberg et al., 2013; Lund et al. 2013). This model, however, did not take into account comminution properties.

Two sample sets were collected. The first one consists of drums of composite magnetite and hematite ore samples which were collected from the Malmberget process plant on 11th and 12th of April in 2012. These samples represent sample types and sample sizes used normally in comminution characterization. As the plant feed includes country rock (wall rock dilution) the ore samples are represented by the cobbing plant concentrates FAR and HAR. For more information of the Malmberget process and flowsheet see Alldén Öberg et al. (2008), Tano et al. (1999) and Öberg and Pålsson (2004). The second sample set includes a small drill core pieces from different textural types of Malmberget ore classified by Lund (Koch, 2013; Lund, 2013). They represent typical samples for geometallurgical program. The textural classification used for Malmberget follows the one developed by Lund (2013). The classification has two dimensions: magnetite grain size (fine/coarse) and relationship and mass proportions of melanocratic and leucocratic parts. Melanocratic material is rich in magnetite and it brecciates the leucocratic albite-orthoclase-rich magnetite-poor matrix. The textural types are by increasing magnetite grade (Table 2) as follows: (1) disseminated, (2) banded, (3) waving veins, (4) patchy, (5) granules, (6) clustered, (7) small veins, (8) speckled and (8) massive ore. Here the division between fine and coarse grained texture is put to 100 microns (the average grain size of magnetite). Besides the above listed minerals the sample includes commonly actinolite and apatite. In the second sample set the magnetite grade shows negative correlation with albite and actinolite grades. Apatite grade shows positive correlation with magnetite grade. Most of the samples are classified as fine grained.
Table 2. Mineralogical, mineral texture and comminution properties of characterized samples

<table>
<thead>
<tr>
<th>Sample</th>
<th>1F</th>
<th>2F</th>
<th>3F</th>
<th>4F</th>
<th>5F</th>
<th>6F</th>
<th>7C</th>
<th>8F</th>
<th>8C</th>
<th>FAR</th>
<th>HAR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main Fe mineral</td>
<td>Mgt*</td>
<td>Mgt*</td>
<td>Mgt*</td>
<td>Mgt*</td>
<td>Mgt*</td>
<td>Mgt*</td>
<td>Mgt*</td>
<td>Mgt*</td>
<td>Mgt*</td>
<td>Hmt*</td>
<td></td>
</tr>
<tr>
<td>Texture type</td>
<td>1.0</td>
<td>2.0</td>
<td>3.0</td>
<td>4.0</td>
<td>5.0</td>
<td>6.0</td>
<td>7.0</td>
<td>8.0</td>
<td>8.0</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Grain size</td>
<td>F</td>
<td>F</td>
<td>F</td>
<td>F</td>
<td>F</td>
<td>C</td>
<td>F</td>
<td>C</td>
<td>C</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Fe wt%</td>
<td>5.5</td>
<td>10.0</td>
<td>22.0</td>
<td>28.0</td>
<td>57.0</td>
<td>55.0</td>
<td>55.0</td>
<td>80.0</td>
<td>80.0</td>
<td>62.9</td>
<td>51.1</td>
</tr>
<tr>
<td>Mgt grain size (μm)</td>
<td>44.0</td>
<td>75.0</td>
<td>95.0</td>
<td>61.0</td>
<td>64.0</td>
<td>74.0</td>
<td>106.0</td>
<td>32.0</td>
<td>180.0</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

**Modal composition**

<table>
<thead>
<tr>
<th></th>
<th>14.8</th>
<th>54.6</th>
<th>59.1</th>
<th>84.4</th>
<th>90.5</th>
<th>87.6</th>
<th>2.7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnetite</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hematite</td>
<td>0.5</td>
<td>70.8</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Albite</td>
<td>53.7</td>
<td>28.0</td>
<td>29.9</td>
<td>1.8</td>
<td>1.1</td>
<td>2.0</td>
<td>4.6</td>
</tr>
<tr>
<td>Actinolite</td>
<td>15.8</td>
<td>7.5</td>
<td>5.8</td>
<td>3.2</td>
<td>4.8</td>
<td>2.6</td>
<td>0.0</td>
</tr>
<tr>
<td>Apatite</td>
<td>0.0</td>
<td>0.2</td>
<td>0.1</td>
<td>0.7</td>
<td>0.9</td>
<td>1.2</td>
<td>4.4</td>
</tr>
<tr>
<td>Orthoclase</td>
<td>2.3</td>
<td>6.2</td>
<td>1.5</td>
<td>0.4</td>
<td>0.1</td>
<td>1.6</td>
<td>2.6</td>
</tr>
<tr>
<td>Biotite</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>2.5</td>
<td>5.2</td>
</tr>
<tr>
<td>Others</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2.0</td>
<td>5.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Rock mechanical properties**

| UCS (N/mm²) | 84.1 | 27.3 | 63.0 | 16.4 | 47.1 | 58.1 | 20.0 | 36.3 | 20.1 | -   | -   |
| PLT (N/mm²) | 27.8 | 11.5 | 15.5 | 5.8  | 17.2 | 15.2 | 7.3  | 8.5  | 8.9  | -   | -   |

**Crushing properties**

| Reduction ratio | 5.6 | 8.4 | 6.4 | 6.4 | 8.9 | 7.8 | 8.8 | 9.2 | -   | -   |

91
Grindability properties

<table>
<thead>
<tr>
<th>F80 of the test (µm)</th>
<th>2822</th>
<th>2115</th>
<th>2456</th>
<th>1893</th>
<th>2609</th>
<th>1983</th>
<th>2221</th>
<th>2237</th>
<th>2065</th>
<th>2980</th>
<th>1033</th>
</tr>
</thead>
<tbody>
<tr>
<td>P80 of the test (µm)</td>
<td>109</td>
<td>125</td>
<td>113</td>
<td>132</td>
<td>127</td>
<td>127</td>
<td>N/A</td>
<td>140</td>
<td>258</td>
<td>977</td>
<td></td>
</tr>
<tr>
<td>Estimated Bond work index (kWh/t)</td>
<td>9.0</td>
<td>9.3</td>
<td>10.1</td>
<td>9.5</td>
<td>10.0</td>
<td>10.4</td>
<td>N/A</td>
<td>10.3</td>
<td>11.0</td>
<td>10.9</td>
<td>13.5</td>
</tr>
</tbody>
</table>

Mgt = magnetite, Hmt = hematite

The experimental work is divided into three parts. The first part describes the work done to downscale the Bond ball mill grindability test to be applicable for small drill core samples. The second part incorporates modal mineralogy, mineral textures and mineral liberation for the geometallurgical testing. The third part brings the geometallurgical test into practical level, i.e. the full procedure is developed and described. In addition mechanical test results are compared with the developed test.

Rock mechanical tests were conducted using two different experimental set-ups. The point load test (PLT) was carried out according to D5731-08 standard (ASTM 2011). Quarters of drill core were clamped between the tops of cone-shaped tools giving a point load on the outer perimeter of the specimen. For the unconfined compressive test (UCS) the specimen was pressed between two parallel planes of a universal testing machine. Fracture patterns observed were variable and usually not symmetric.

Crushing tests were done with laboratory jaw crusher (model Retsch Type BB Masch. Nr. 31648). Fixed closed size setting of 3.35 mm was used. For the crushing test sample was passed through the crusher only once. For the sample preparation for the grinding test sample was continuously sized with 3.35 mm sieve and the oversize was crushed again until all the material passed the sieve.

The grinding tests were evaluated according to the Bond approach by using the recorded electrical energy consumption meter (corrected by the mechanical efficiency of the device) together with the change in the 80% passing particle size in order to determine grindability which describes specific work index of a given ore.

The grinding experiments were conducted using two different ball mills (see Figure 1): standard Bond ball mill (22 L) and Capco Jar ball mill (1.4 L; Figure 1). Mass of steel ball (kg) was calculated based on degree of mill filling, ore density (4800 kg/M^3) and mill volume. The steel ball size distributions used in the experiments ranges from four to 50 per cent for smallest and biggest steel ball diameter sizes (mm), respectively (Table 3).
Figure 1. Laboratory mills of different sizes used in the study.

Table 3. Size distribution of steel grinding media used in Bond ball mill grindability test and in down-scaled test with a small mill.

<table>
<thead>
<tr>
<th>Size of the steel ball (mm)</th>
<th>Distribution by weight (%)</th>
<th>Number of balls in a small mill</th>
</tr>
</thead>
<tbody>
<tr>
<td>36.0</td>
<td>15</td>
<td>1</td>
</tr>
<tr>
<td>28.5</td>
<td>51</td>
<td>7</td>
</tr>
<tr>
<td>21.8</td>
<td>29</td>
<td>9</td>
</tr>
<tr>
<td>15.0</td>
<td>4</td>
<td>5</td>
</tr>
</tbody>
</table>

Mineralogical analyses on modal composition and liberation distribution were made using scanning electron microscope (SEM) based automated mineralogy. Zeiss Merlin SEM and IncaMineral system (Liipo et al., 2012) for automated mineralogy were used. In modal and liberation analyses minerals were identified and classified using back-scattered electron image and EDS analysis. Magnetite grain size was estimates were done by optical microscopy (Lund, 2013).
4. Downscaling the Bond ball mill test for geometallurgy

The starting point selected for the new grindability test was the Bond ball mill grindability test (Figure 2). The test is a locked cycle test which simulates a closed continuous comminution circuit (Figure 2). The test starts with 0.7 liters sample, corresponding to 3.4 kg FAR (iron ore sample), and the test is repeated until steady state is reached; normally this takes at least six grinding-screening cycles. The test aims for 250% circulating load at a defined cut screen size close to 100 μm. After each grinding step, the mill product is sized, and material passing 100 microns screen is removed and replaced by equal amount of a fresh feed material to maintain 3.4 kg sample in the tumbling mill. The grinding time is adjusted after each round to reach 250% circulation load and a steady-state condition.

![Figure 2. Schematic flowsheet of the Bond ball mill grindability test. Test needs more than 10 kg sample.](image)

The average mass per number of revolution of the undersize materials of the last three cycles of the grinding test is used to determine the grindability and the work index according to the Bond formula in equation 1. Totally the test uses about 10 kg of sample and it takes usually at least one working day to be completed. Figure 3 shows how steady state was reached with the magnetite ore sample (FAR).

\[ BWI = 1.1 \times \frac{44.5}{P_i^{0.23} \times G_{bp}^{0.822} \times \left( \frac{10}{V_i} - \frac{10}{V_F} \right)} \]

(1)

Where:

- BWI = Bond work index, kWh/t
- \( G_{bp} \) = Average mass in gram of undersize material produced per number of revolution for the last three cycles.
- \( P_i \) = cut screen size (100 μm)
\( F_i = \) Particle size 80 \% passing of fresh feed, wt \%

\( P_i = \) Particle size 80 \% passing final undersize (passing cut screen size), wt \%

**Figure 3.** Grindability curve of the Bond ball mill grindability test with the Mamberget iron ore sample (FAR).

To be applicable for geometallurgy the test should be faster and it should use smaller sample (< 2 kg). Therefore a solution was searched by doing the test in single pass with electrical energy measurement, similarly to the Mergan test (Niitti, 1970) but with a significant smaller mill and sample size.

In downscaling the Bond ball mill grindability test, the principle was to keep the impact effects similar in the Bond and in a smaller mill (Table 4). Therefore ball sizes and their size distribution was kept constant. The total ball charge was defined by keeping the ball charge filling fixed (19\%). The target was to minimize the sample size and therefore to find the smallest possible mill fulfilling the conditions on similar impact effect. The diameter vs. length of the mill was not fixed because the aim was to find a suitable commercially available laboratory mill and length of mill does not affect the impact of ball charge inside a mill. To maintain similar type of stress and ball hitting location inside a tumbling mill, ball trajectories and ball impact velocities were calculated based on throw angle and tangential velocity of rotating mill. Calculations showed that a CAPCO laboratory 1.4 l stainless steel ball mill model 2 variable speed (Ref. 337SS, www.capco.co.uk) with 115 mm mill internal diameter gives similar conditions as the Bond mill with similar critical speed. The sample size was defined by keeping the proportion between ball and sample weight similar for both mills. The mill speed was maintained at 91\% of the critical speed.
Table 4. Parameters for downscaling the Bond ball mill test.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Condition for downscaling</th>
<th>Standard Bond ball mill</th>
<th>Small ball mill</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Mill dimensions</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 Diameter (mm)</td>
<td>To be changed</td>
<td>305</td>
<td>115</td>
</tr>
<tr>
<td>2 Length (mm)</td>
<td>To be changed</td>
<td>305</td>
<td>132</td>
</tr>
<tr>
<td><strong>Ball charge</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3 Percentage mill volume fillings</td>
<td>Fixed</td>
<td>19</td>
<td>19</td>
</tr>
<tr>
<td>4 Average ball size (mm)</td>
<td>Fixed</td>
<td>27</td>
<td>27</td>
</tr>
<tr>
<td>5 Ball charge (kg)</td>
<td>Scaled by filling (3)</td>
<td>21.9</td>
<td>1.33</td>
</tr>
<tr>
<td><strong>Sample</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6 Sample to balls ratio (w/w)</td>
<td>Fixed</td>
<td>0.16</td>
<td>0.16</td>
</tr>
<tr>
<td>7 Sample size (kg)</td>
<td>Scaled by ratio (6)</td>
<td>3.4</td>
<td>0.220</td>
</tr>
<tr>
<td>8 Sample particle size distribution</td>
<td>Fixed</td>
<td>&lt;3.5</td>
<td>&lt;3.5</td>
</tr>
<tr>
<td><strong>Operational conditions</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9 Speed, vs. critical (%)</td>
<td>Fixed</td>
<td>91</td>
<td>91</td>
</tr>
<tr>
<td>10 Grinding time (minutes)</td>
<td>To be changed</td>
<td>10.5</td>
<td>17.0</td>
</tr>
<tr>
<td>11 No of revolutions/minute</td>
<td>To be changed</td>
<td>70</td>
<td>114</td>
</tr>
<tr>
<td>12 Test type</td>
<td>To be changed</td>
<td>Locked cycle</td>
<td>Single pass</td>
</tr>
<tr>
<td>13 Mill product sizing</td>
<td>Fixed</td>
<td>Standard sieve series</td>
<td>Standard sieve series</td>
</tr>
</tbody>
</table>
The Bond mill gives bigger impact because of its large diameter compared to the small ball mill. By prolonging the grinding time in the small ball mill the material experiences higher number of impacts. Sample FAR was used to find the grinding time in the smaller mill giving identical particle sized distribution in the mill discharge compared to the Bond test. It was found that 17 minutes grinding time in single pass gives similar particle size distribution for the mill discharge (80% passing size, P80 = 259 μm) as the Bond test procedure in the steady state (see Figure 4). This was therefore selected as a standard condition for further testing in the small ball mill.

By shifting the Bond grinding conditions to the small ball mill the kinetics are changed because of the differences in geometry. Another thing to consider is the change from a closed circuit test to single pass test. Therefore a scale factor is needed to equalize the results with the Bond test. From geometrical relationship the scale factor (square root of the ratio of the diameter of large to small ball mill) between the Bond and the small mill is 1.63. The reason for using square root is because of the proportion of impact velocity between Bond mill and small ball mill is defined as:

\[
\text{Impact velocity by Bond mill} = \sqrt{\frac{\text{Diameter of Bond mill}}{\text{Diameter of small ball mill}}} \text{ Impact velocity by Small ball mill}
\]

With the FAR iron ore sample the measured specific energy with 17 minutes grinding time is 10.56 kWh/t. The Measured Bond Work Index with full Bond test gave

Figure 4. Comparison of particle size distribution of the product from small ball mill for different grinding time vs. Bond test procedure. Sample: FAR.
10.6 kWh/t. By applying back calculation with the Bond energy equation the calculated work index with the small mill is 10.87 ± 0.42 kWh/t (28). This confirms that scale-down factor of 1.63 from the geometry can be applied and is used in this study for the estimation of the Bond Work Index.

\[
BWl = \frac{E}{k \times Ef1 \times Ef2 \times Ef3 \times Ef4 \times 10 \times \left( \frac{1}{\sqrt{P80}} - \frac{1}{\sqrt{F80}} \right)}
\]

(2)

Where

BWl = Bond Work Index (estimated),

E = measured specific energy in the small mill,

P80 = the product 80% passing size (microns),

F80 = the mill feed 80% passing size (microns) and

k = scale factor defined by square root of the ratio of the diameter of Bond to small ball mill equal (1.63)

Ef1 = correction factor for dry grinding (1.3; Rowland and Kjos, 1978; Mular et.al., 2002).

Ef2 = correction factor efficient diameter (1.842) (Rowland and Kjos, 1978; Mular et.al., 2002).

Ef3 = Ball mill efficient factor (0.835) (Rowland and Kjos, 1978; Mular et.al., 2002).

Ef4 = Efficient factor for fineness (0.95) (Rowland and Kjos, 1978; Mular et.al., 2002).

Four different samples of known Bond work indices were used to validate the developed test method (Figure 5). It can be clearly seen that there is strong correlation between BWI of standard grindability test and BWI obtained from the small ball mill with small amount of sample. It implies that the BWI of the small ball mill with fixed grinding time describes relative grindability correctly.
5. Linking comminution properties and mineralogy with special reference to mineral liberation

Grindability, expressed as estimated Bond Work Index, doesn’t appear to correlate with crushability, expressed crusher reduction ratio (Figure 6). Looking against mineralogical parameters it can be found that the higher the content of magnetite the higher is the reduction ratio (easy to crush) while in grinding the opposite is the case: the higher the magnetite content the higher is the P80 of the grinding product (and therefore the harder it is to grind). When applying multivariate statistics for the small mill data set it can be found that the mill product size (P80) is controlled by the magnetite grade and the magnetite grain size according to following empirical equation 3 (see also Figure 7).

\[
P80(\text{microns}) = 0.139 \times \text{Mgt (wt%)} + 0.054 \times \text{Mgt grain size (microns)} + 118
\]

Direct relationship means that the higher is the grain size of magnetite the higher is the P80 and therefore the harder is the material to grind. As the P80 is between 110 and 140 microns in coarse grained materials, where the magnetite grain size is >100 microns, the grinding action is used partly to break individual magnetite grains and presumably this is why the material appears to be very hard to grind. The purpose of ore grinding is to liberate and with the coarse grained sample the particle size in the mill product is already well below the average magnetite grain size and most probably also of the liberation size, i.e. the size where the mineral occurs liberated enough for the downstream processes. For the geometallurgical context the grindability of the material is not exactly the proper measurement since for different material the degree of liberation of the mineral may be
very different. Therefore the grindability is here extended to mineral liberation and term liberability is introduced: It is defined as *relative ease with which an ore mineral can be liberated by grinding*.

![Figure 6. Crushability vs. grindability of Malmberget samples. Weak positive correlation indicates that samples easy to crush (having high size reduction ratio) seem to be difficult to grind (high work index).](image)

In Malmberget the degree of liberation (i.e. mass proportion of mineral in particles containing more than 95% of mineral in question) shows inverse relationship with particle size, as expected (Figure 8). The relationship is close to linear and passes through the point 0 microns particle size and 100% liberation. It is not very practical to introduce a liberability term in geometallurgy if it means that for each sample after grinding several size fractions must be analyzed for liberation. Therefore an alternative approach was developed. Firstly, a key size fraction was selected for liberation measurement. This should be close to expected liberation size and in Malmberget a size fraction of 53-75 microns was selected. The liberation characteristic of the size fraction was measured with automated mineralogy. Based on the measurement on the selected size fraction the degree of liberation of magnetite was estimated in the other size fractions by applying a linear equation which passes through the measured point and the point (0,100). The degree of liberation in the bulk sample was calculated from the size fractions as weighed average. In the Fabian Fsp sample (analyzed by Lund, 2013; Figure 8) estimated degree of liberation in the bulk sample differs only 1% from the measured one.
The degree of liberation for the bulk sample was estimated as described above. To estimate how the liberation changes with grinding energy a simple approach was used (a–f in the following refer to a worked out example given in Table 6). Calculations were done for each sample individually. Firstly a set of grinding energies were selected and for each of them (a) the P80 (b) was estimated by using the Bond equation (Equation 4). In calculation the Bond Work Index received from the tests (c) and fixed (d) F80 were used. The energy vs. particle size relationship for different textural types of Malmberget is shown in Figure 9.

\[
E = 10 \times BWI \times \left( \frac{1}{\sqrt{P80}} - \frac{1}{\sqrt{F80}} \right)
\]

The received P80 (b) was converted to full particle size distribution by using the Rosin-Rammler equation and taking the parameter describing the spread of the distribution (e) from the 17 minutes grinding product (Table 5). A new D63.2 parameter (f) to give identical P80 as received from the Bond equation was searched with Excel Solver. Finally to get an estimate on the degree of liberation of magnetite it was assumed that the degree of liberation within the narrow size fractions remains constant (g) and the overall value is a product of each size fraction by their mass proportions (h). The liberability graph, i.e. the liberation degree vs. specific grinding energy is shown in Figure 10.
Figure 8. Particle size versus degree of liberation of the main minerals in Malmberget, sample Fabian Fsp ore type (Lund, 2013).

Table 5. Parameters for the determination of degree of liberation considering mineralogical composition of samples from Malmberget.

<table>
<thead>
<tr>
<th>Sample</th>
<th>2F</th>
<th>4F</th>
<th>6F</th>
<th>8F</th>
<th>8C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Texture type</td>
<td>2</td>
<td>4</td>
<td>6</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>Grain size</td>
<td>Fine</td>
<td>Fine</td>
<td>Fine</td>
<td>Fine</td>
<td>Coarse</td>
</tr>
</tbody>
</table>

Size fraction 53-75 microns

| Magnetite wt% | 13.3 | 88.6 | 59.0 | 85.0 | 90.2 |
| Magnetite Lib% | 78.0 | 88.6 | 85.2 | 94.5 | 95.3 |

Grinding test product

| 80% passing | 125.3 | 132.3 | 126.7 | 129.9 | 140.3 |
| Rosin-Rammler D63.2 | 81.2 | 96.6 | 93.4 | 96.3 | 103.5 |
| Rosin-Rammler alpha | 1.7 | 1.7 | 1.7 | 1.7 | 1.7 |
Figure 9. Specific power prediction for target size for magnetite liberation from five different mineral texture classes of Malmberget iron ore deposit.

Figure 10. Specific power prediction for degree of liberation of magnetite ore of Malmberget iron ore from five different mineral texture classes.
Table 6. Worked out example how the grinding energy to degree of liberation relationship was established. Meas = measured, calc = calculated; for (a)-(h) see text.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Measured with grinding test (t=17 min)</th>
<th>Forecasted for given energy (example 9 kWh/t)</th>
</tr>
</thead>
<tbody>
<tr>
<td>E kWh/t</td>
<td>10.6 (meas)</td>
<td>9.00 (a)</td>
</tr>
<tr>
<td>BWI kWh/t</td>
<td>11.0 (c, calculated)</td>
<td>11.04 (c)</td>
</tr>
<tr>
<td>F80 microns</td>
<td>2065 (d, meas)</td>
<td>2065 (d)</td>
</tr>
<tr>
<td>P80 microns</td>
<td>72.0 (meas)</td>
<td>93.36 (b)</td>
</tr>
<tr>
<td>Rosin-Rammler D63.2 microns</td>
<td>53.6 (meas)</td>
<td>68.36 (f)</td>
</tr>
<tr>
<td>Rosin-Rammler alpha</td>
<td>1.7 (e, meas)</td>
<td>1.7 (e)</td>
</tr>
<tr>
<td>Size fraction</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bulk</td>
<td>96.2 (calc)</td>
<td>95.2 (h)</td>
</tr>
<tr>
<td>0-38 microns</td>
<td>43.0 98.0 (calc)</td>
<td>31.1 98.0</td>
</tr>
<tr>
<td>38-53 microns</td>
<td>19.6 96.7 (calc)</td>
<td>16.8 96.7</td>
</tr>
<tr>
<td>53-75 microns</td>
<td>20.2 95.3 (meas)</td>
<td>21.0 95.3</td>
</tr>
<tr>
<td>75-106 microns</td>
<td>12.9 93.4 (calc)</td>
<td>18.7 93.4</td>
</tr>
<tr>
<td>106-150 microns</td>
<td>3.9 90.6 (calc)</td>
<td>10.0 90.6</td>
</tr>
<tr>
<td>150-212 microns</td>
<td>0.4 86.7 (calc)</td>
<td>2.2 86.7</td>
</tr>
</tbody>
</table>

Significant difference is observed between the liberability and the grindability (see Figure 9 and Figure 10). For example, grindability indicates that two high grade samples, 8F (fine grained) and 8C (coarse grained), require quite different grinding energy but when the mineral liberation is set as a target the ores appear to be very similar. Because the main purpose of grinding is to achieve required liberation the liberability information
will clearly tie technical and economical way how to utilize the resource in an optimal manner. This has potential to change the plants in their operational principles from targeting a certain particle size to defined mineral liberation.

6. Novel small scale comminution test

Based on the work done a small-scale test method for mapping variation of ore comminution properties in geometallurgy was established and the flow sheet is shown in Figure 11. The test includes a separate crushability stage. For the crushability the procedure is optional and preliminary and must be further tested.

The test is designed for drill core samples and each sample is ideally a 30 cm long piece of a drill core half (Step 1, Figure 11). In magnetite ore this equals to about 500 g sample. In the sample preparation stage (2) the drill core is cut to about 2x2 cm pieces. (3) The pieces are then crushed by laboratory jaw crusher at closed side setting 3.35 mm. (4) If also crushability is to be determined then after one pass crushing, the crusher product is sized. (5) Otherwise the crusher product is split with 3.35 mm sieve and oversize is crushed again. This is continued until all passes the 3.35 mm sieve. This
should give a product with 80% passing close to 1 mm. (6) Crushed sample is split to 2-3 parts. (7) One is used for sieving to obtain F80. (8) One part is used for the grinding test. The grinding test is performed as described in chapter 4. When using the Capco jar mill 337SS the sample size is 220 g and the ball charge is 1.3 kg with diameters as given in Table 4. Grinding time of 17 is suggested but should be verified for each ore body separately. With these conditions electrical energy meter is not required because the reading will be identical in all the tests. The target P80 should align with the Bond tests and therefore some other grinding time might be used. But the idea of the test is to use fixed time for a given ore body and geometallurgical program. (9) After grinding, the material is sized and the results are calculated: 80% passing, estimated Bond Work Index and the Rosin-Rammler parameters). One size fraction slightly coarser to the expected liberation size is used to determine the degree of mineral liberation and mineral associations. The size distribution is determined using a sieve series form 3.35 mm down to 38 µm following the $\sqrt{2}$ series.

The designed comminution test can be suited with normal sample preparation scheme used for chemical assays. The crusher product can be split and one part can be used for determining the bulk chemical composition of the sample e.g. with X-ray fluorescence. For the modal mineralogy element to mineral conversion method can be applied (Lund et al., 2013, Whiten, 2007) but one may need to use additional techniques like X-ray diffraction (A2, Lamberg et al. 2013; Parian and Lamberg, 2013)) and SEM based automated mineralogy (A3).

In the grinding test (8) the used sample size is defined by mass rather than volume as in the Bond test. Therefore the volume of the sample can be varying significantly in e.g. massive sulphide and iron ores. However, this is considered as one part of material properties in this methodology.

The outcome of the test results when combined with chemical assays are then:

A. Chemical composition of the sample
B. Crushability index as a reduction ratio (F80/P80)
C. Grindability index as P80 and calculated BWI
D. Degree of liberation for the key minerals and their association indices (Lamberg et al. 2012; Lund, 2013)
E. Modal mineralogy.
F. Liberability curves (Figure 10 and Figure 12)

To be cost effective geometallurgical program one might come to a solution where chemical assays are done for all samples, crushability and grindability for 50% of samples and liberation analysis for 10% of samples.
7. Discussion

The developed test method aims to characterize the essential comminution properties of small samples in a single (combined) test. This is an ambitious goal since most of the geometallurgical programs use different tests for different particle sizes. It is common to do separate characterization tests for crushing, SAG grinding and ball mill grinding (e.g. Bulled and Lozano, 2009; Bergholtz and Schreder, 2004; Flores et al., 2005; Keeney et al. 2011; Montoya et al., 2011; Harbort et al. 2013). Even though the Bond Work Index generally speaking has a positive correlation with SAG grindability indexes like A*b (e.g. Bulled and Lozano, 2009) the difference is so significant that it is rare to use Bond test only as an estimate for the full grindability in geometallurgical programs (Oyarzún and Arévalo, 2011; Philander and Rozendaal, 2011b). Vatandoost (2009, 2010) developed petrophysical methods to be used for proxies for comminution characterisation. This approach is very practical for geometallurgical mapping but it misses important information about mineral liberation.

In geometallurgical programs comminution characterization aims to provide reliable model to be used to forecast plant throughput. As the comminution circuits consists of several different type of comminution units like crushers, SAG mills and ball mills also the models must be capable in to treat these units separately but in a circuit. Parameters like scat handling (e.g. does the circuit includes a pebble crusher), transfer size between the SAG and the ball mill and handling of slimes may be more important for the throughput than the actual grindability. This addresses that methodology developed here can’t provide all this important information needed for reliable forecasting. Rather the
developed test is designed to be used in early project stages for identification of variability in the comminution properties. This information is to be used in geometallurgical domaining. After this, the sampling and testing can be done in larger scale to economically and efficiently serve circuit design, sizing of the unit operations and to model and simulate the throughput. This ensures the health of the process as circuit configurations are based on material properties and their variations as given by the geometallurgical program.

Linking of the liberation and comminution characteristics in geometallurgy is not very common. Philander and Rozendaal (2011a, 2011b) compared grindability and liberation of zircon at Namakwa Sands mine resulting in a successful expansion program. Instead many different kinds of liberation models have been developed before geometallurgy was known (e.g. Gay, 1999; King and Schneider, 1998; King, 1979; Wei and Gay, 1999, Gay 2004). Most of the liberation models require a good quality textural picture to start with. This is a limitation when thinking of geometallurgical programs. Scanning drill holes with pixel sizes of some microns would be required and with currently available techniques this is impossible or at least very slow and costly (Leichliter et al. 2012; Hunt et al., 2008). If picture is available then there are additional limitations like the existing liberation models assume non-preferential breakage, they can be used only in binary systems (i.e. two minerals: valuable and others) and they require ore specific Kernel function (King, 1967).

Methodology proposed here requires validation for each deposit to prove that assumptions lying behind the test do hold. These are that (i) the bulk liberation can be estimated only using one size fraction and that (ii) the assumption that liberation within a narrow size fractions is constant regardless of particle size distribution of the bulk material (Vizcarra et al. 2010). How to combine liberation and size reduction in comminution models is also an open question. Current crusher and grinding models provide forecast on particle size distribution, grinding energy and throughput dependency but they are not capable to forecast how the grade varies by size neither the liberation distribution of the products. Before the developed test method can be linked with process simulations reliable mineral by size and mineral liberation models on comminution needs to be developed.

The question how much energy is needed to achieve required liberation when the feed composition (texture) is changing is crucial and important for production planning. Interesting observations from this study is that, there is a significant difference between grindability and liberability at the same grinding energy when the mineral texture is different. It implies that domaining an ore body based on grindability (hardness) may mislead the ore classification and may result to ineffective resource utilization. Therefore it is important to collect information on mineral liberation, grinding energy and particle size relationships before the geometallurgical domains are defined.

Mineral liberation may not be sufficient information because associating minerals and type of particles is important for downstream processes to produce salable product. Lamberg and Lund (2012) and Lund (2013) developed a methodology how to
incorporate full liberation information into geometallurgical model but the concept was missing grindability. The developed methodology has potential to fill this gap. Comminution mechanisms and texture characteristics should be seen as drivers for the prediction of the liberation properties of minerals. The possibility of using different breakage mechanisms on different mineral texture has a potential to improve resource efficiency.

8. Summary and Conclusions

Comminution test method commonly used in geometallurgy require large samples and they are time demanding and expensive. Small scale comminution test is needed to be applied early in the ore characterization for collecting information on variability of crushability and grindability for proper geometallurgical domaining. Review of existing rock fracture testing showed that none of the available methods fulfills the criteria set for proper geometallurgical tests. The most promising ones were found to be small scale Bond ball mill test, instrumented drop weight test and rotary breakage tester (RBT).

Bond test method was selected for a basis because it is simple, repeatable, it is industrial standard method for determine the grindability and there is established practices how to use Bond Work Index in modeling and simulation of comminution circuits. The Bond grindability test was scaled down to use about 200 g of sample and it was changed to single pass. It was complemented with crushability test and with mineral liberation measurement on one selected size fraction for establishing quantitative information on the relationship of grindability and mineral liberation, i.e. liberability curves.

Developed method is still a prototype and before applying it routinely in geometallurgical programs following studies is suggested:

- Study how accurate the estimated Bond Work Index is compared to full scale Bond grindability test.
- Study can the crushability test be used for estimating SAG characterization parameters like A*b.
- Study if the degree of liberation can be estimated reliably for the bulk samples based on one size fraction also with other ore types.
- Study if the observation and assumption that liberation in narrow size fractions is independent on overall particle size distribution holds.
- Study how the mineral grade varies by size and how big effect it has for evaluating the degree of liberation for full sample based on analysis on one size fraction.
- Study how grindability and liberation information can be combined in process simulations using the concept proposed by Lamberg and Lund (2012) and Lund (2013).
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