Liberability: A new approach for measuring ore comminution behavior

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Abstract

Crushability and grindability are traditionally used to describe the material properties in comminution. These parameters neglect the main objective of ore comminution, the mineral liberation and therefore information is incomplete. A new concept called liberability: *the easiness of mineral liberation in comminution* is introduced to fill the gap. Establishing a liberability map of a deposit requires grindability tests and liberation measurements for the grinding product. The liberability curve shows the degree of liberation of the mineral against grinding energy and offers better baseline for resource optimization than the grindability curve.

A case study with a magnetite iron ore from Malmberget, northern Sweden, shows that certain shortcuts can be applied to keep the experimental effort reasonable which is important, particularly when applying the liberability in a geometallurgical program. In Malmberget the liberability is depending on the grade and grain size of magnetite. A significant difference between grindability and liberability can be observed.

1 Introduction

In comminution it is common that grindability is used to describe the easiness or hardness of an ore to grind. This parameter measures average grams per number of revolution of a tumbling mill passing 100 µm as defined by Bond (1962). This parameter does not take into account the liberation properties of the mineral in question which is necessary for efficient mineral separation in downstream processing. Liberability, introduced by Mwanga (2014), is an extension of grindability and a new approach of measuring the easiness of an ore to liberate the mineral of interest by comminution processes. Liberability as a parameter is therefore defined as **''relative ease of liberate minerals by comminution" and more exactly "a mass proportion of fully liberated mineral in the particle population per kWh of energy used to change the progeny size distribution in comminution''**. The approach relates the liberation characteristics of an ore and applied comminution energy for mapping variations of mineral liberation within an ore body for the geometallurgical purposes.

Even the term liberability is new, the concept of comparing grindability and liberation has been used before. Philander and Rozendaal (2011, 2013) used both grindability and liberation of zircon at Namakwa Sands mine in their geometallurgical program. Within this approach a template model was used to quantify the detrimental minerals in the concentrate and mineral recoveries without considering comminution energy.

Mineral liberation is a prerequisite for successful ore beneficiation. It should be regarded as a driver for energy efficient comminution and quality of final product in the extraction of minerals. The degree of liberation required for certain product quality with each technology alternatives existing is a question to be answered during the flowsheet development. To finally select the technology and flowsheet among different options requires knowledge on how much energy is required for that and in addition how this will vary within the ore body. Presumably the most optimal economic operation point is not at fixed particle size distribution neither at fixed liberation. Increasing the degree of liberation of the mineral comes with a cost related to energy required to grinding fine particles. As this means decrease in the throughput it must come with improvement in recovery.

The question of how much energy is needed to achieve the required liberation size when feed composition or mineral texture is varying is crucial and important for building up a suitable geometallurgical model. Liberability is proper way to describe the multi-dimensional problem since it combines mineral liberation, grinding energy and particle size relationships.

State-of-the-art comminution models provide a forecast of particle size distribution, grinding energy and throughput dependency but they are not capable of forecasting neither how the mineral grade varies by size nor the liberation distribution of the products. Before a comminution test method can be linked to a process simulation reliable mineral by size and mineral liberation models for comminution need to be investigated and developed.

Liberability and comminution modelling that combine mineral by size and liberation by size are also considered as an alternative way of building up a geometallurgical program based on modal mineralogy, mineral textures and liberation properties of an ore. This study provides a new approach through liberability for assessing ore comminution behavior for geometallurgical purposes. A case study for the Malmberget iron ore, Northern Sweden, is used to demonstrate the approach.

2 Materials and methods

2.1 Samples

The samples for the study come from the Malmberget iron ore deposit located in Northern Sweden. In the Malmberget iron ore field more than 20 separate ore bodies are known and production is coming from several different underground operations (Lund, 2013). Ore is processed in the Malmberget concentrator in two lines: one for magnetite dominated ore (FAR) and another for hematite dominated ore (HAR). The first geometallurgical classification of the ore body based on modal mineralogy and mineral textures was developed by Lund (2013), see also Lund (2012), Lamberg et al. (2013), and Lund et al. (2013). This model, however, did not take into account comminution properties. According to Lund (2013), textural classification for the Malmberget ore has two dimensions: magnetite grain size (fine/coarse) and the mass proportions of melanocratic and leucocratic parts. Melanocratic material is rich in magnetite while the leucocratic breccia shows an albite-orthoclase-rich magnetite-poor matrix. The textural types are by increasing magnetite grade (Table 1) 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 distinction between fine and coarse grained texture is put to 100 microns (the average grain size of magnetite). Besides the above listed minerals the samples usually also includes actinolite, albite, biotite and apatite. Most of the samples are classified as fine grained.

Table 1. Mineralogical, mineral texture and comminution properties of characterized samples.

Sample	1F	2F	3F	4F	5F	6F	7C	8F	8C	FAR	HAR
Main Fe mineral	Mgt*	Mgt*	Mgt*	Mgt*	Mgt*	Mgt*	Mgt*	Mgt*	Mgt*	Mgt*	Hmt*
Texture type	1.0	2.0	3.0	4.0	5.0	6.0	7.0	8.0	8.0	-	-
Grain size	F	F	F	F	F	F	C	F	C	-	-
FeO wt.%	5.5	10.0	22.0	28.0	57.0	55.0	55.0	80.0	80.0	62.9	51.1
Mgt grain size (µm)	44.0	75.0	95.0	61.0	64.0	74.0	106.0	32.0	180.0	-	-
Modal composition %											
Magnetite		14.8		54.6		59.1		84.4	90.5	87.6	2.7
Hematite										0.5	70.8
Albite		53.7		28.0		29.9		1.8	1.1	2.0	4.6
Actinolite		15.8		7.5		5.8		3.2	4.8	2.6	0.0
Apatite		0.0		0.2		0.1		0.7	0.9	1.2	4.4
Orthoclase		2.3		6.2		1.5		0.4	0.1	1.6	2.6
Biotite		0.0		0.0		0.0		0.0	0.0	2.5	5.2
Others										2.0	5.5
Rock mechanics 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	-	-
Grindability properties											
F80 of the test (µm)	2822	2115	2456	1893	2609	1983	2221	2237	2065	2980	1033
P80 of the test (µm)	109	125	113	132	127	127	N/A	130	140	258	977
Estimated Bond work index(kWh/t)	9.0	9.3	10.1	9.5	10.0	10.4	N/A	10.3	11.0	10.9	13.5

Mgt*= magnetite, **Hmt***= hematite

Two types of samples were used. Small drill core pieces of samples from different textural types of the Malmberget ore as classified by Lund (Koch, 2013; Lund, 2013) represent typical samples for a geometallurgical program. Two composite magnetite (FAR) and hematite (HAR) ore were collected from the Malmberget processing plant in 2012. These samples represent sample types and sample sizes normally used in comminution characterization. For more information of the Malmberget process and flow sheet see Alldén Öberg et al. (2008), Tano et al. (1999) and Öberg and Pålsson (2004).

2.2 Comminution test

The comminution experiments were carried out by using a short cut testing method developed by Mwanga (2014). The method is a simplification of the Bond grindability test that was scaled down to use about 220 g of sample and it was changed to a single pass.

The grinding test was performed by using the Capco jar mill 337SS with ball charge 1.3 kg and average ball diameter ϕ 28 mm. The target P80 should align with the Bond tests and therefore 17 minutes grinding time was used for the samples studies. This must be defined individually for each geometallurgical program.

After grinding, the material was sized and the results were calculated: 80% passing particle size, estimated Bond work index and the Rosin-Rammler distribution parameters. The size distribution was determined using a sieve series from 3.35 mm down to 38 µm following the $\sqrt{2}$ series.

2.3 Sample assays

The chemical composition of the samples and size fractions was determined by X-ray fluorescence at LKAB using their standardized method. The modal composition was calculated with element-to-mineral conversion technique by using the HSC Chemistry 7.1 software and calculation routine developed by Lund et al. (2013). Mineral liberation analyses were conducted with Merlin SEM - Zeiss Gemini (FESEM, Luleå University of Technology, Sweden) with Oxford Instrument EDS detector and IncaMineral (Liipo et al, 2012). For sound statistical representations at least ten thousand (10 000) particles were analysed and used to establish the information about liberation distribution.

3 Assessing comminution efficiency

3.1 Grindability

Traditionally comminution efficiency is assessed on the basis of the achieved progeny size distribution against applied mechanical energy. Even the sample set has a wide variation in iron grade, modal mineralogy and mineral texture the grindability measured by Bond Work Index has narrow variation.

Figure 1 shows breakage properties of the magnetite sample fractionated at four different size classes; where each size class was ground separately. The curves in figure 1 have different angles which demonstrate different breakage behavior in different particle size classes. This indicates that breakage is not controlled by particle size alone.

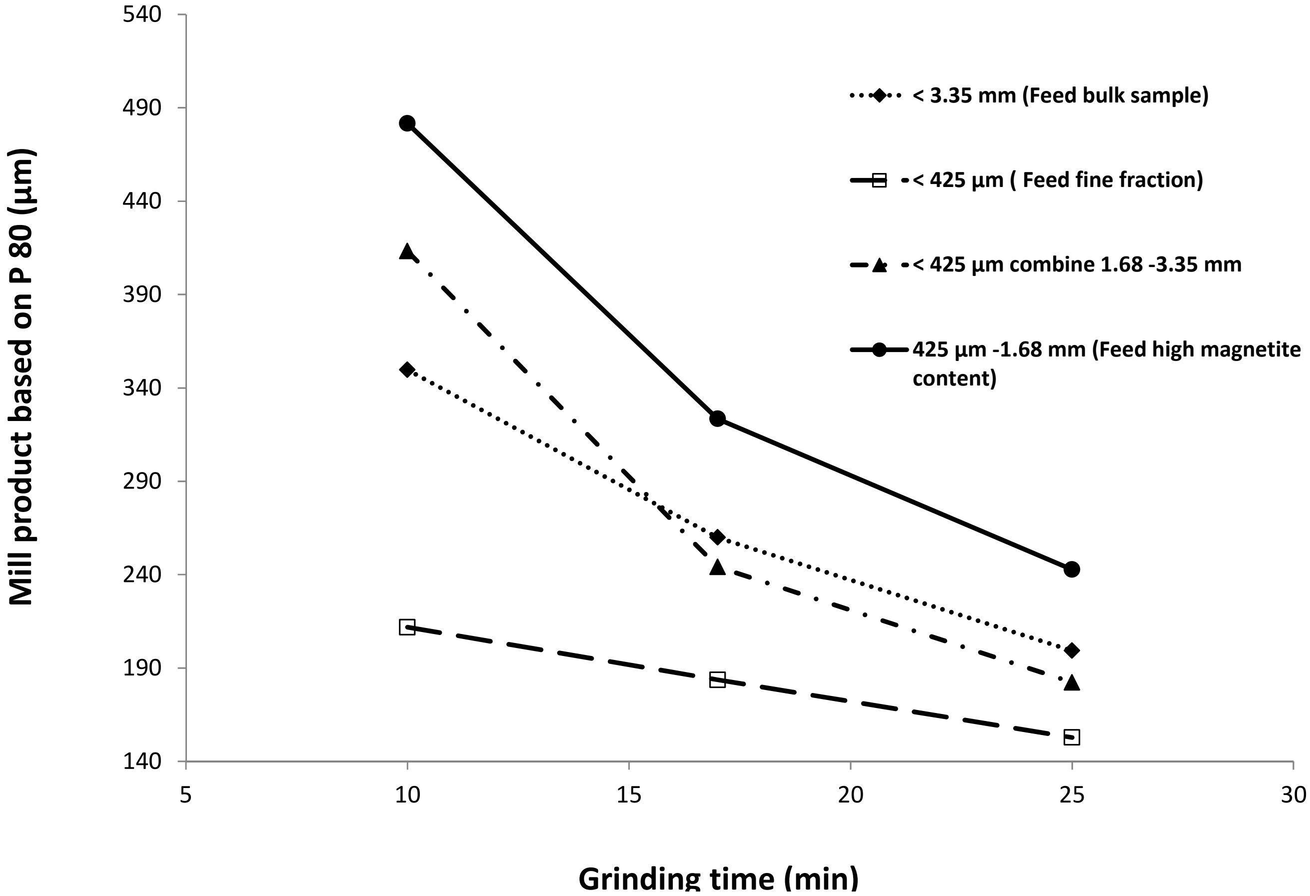

Figure 1: Comminution properties for FAR sample characterized by P80 of mill product.

3.2 Modal mineralogy level

Table 2 and 3 summarize and Figure 2 illustrates the modal composition of the FAR and HAR samples by particle size fractions.

Table 2. Modal composition of different size fractions for magnetite ore (FAR) from Malmberget.
In the table: ***Ab*** *=Albite,* ***Act****=Actinolite,* ***Ap****=Apatite,* ***Bio****=Biotite,* ***Hm****=hematite,* ***Mgt****=Magnetite,* ***Or****= Orthoclase,* ***Qtz****= Quartz,* ***Dio****= Diopside,* ***Ilm****=Ilmenite,* ***SG****= specific gravity of a mineral.*

		Modal mineralogy										
		Ab %	Act %	Ap %	Bio %	Hm %	Mgt %	Or %	Qtz %	Dio %	Ilm %	SG
Bulk		**1.3**	**0.7**	**0.8**	**2.6**	**5.2**	**83.1**	**0.5**	**0.0**	**0.9**	**0.9**	**4.9**
Size fraction (µm)	Sample name											
2380 – 3350	Crushed ore (mill feed)	0.7	2.1	1.1	2.3	3.5	86.1	0.0	0.0	1.8	1.9	4.9
1680 – 2380		0.7	0.7	0.7	2.1	1.5	90.2	0.0	0.0	1.6	1.8	5.0
1190 – 1680		0.7	0.0	0.3	1.5	0.6	94.2	0.0	0.0	0.6	1.4	5.0
850 – 1190		0.7	0.0	0.2	1.2	0.0	95.8	0.0	0.0	0.2	1.1	5.1
600 – 850		0.7	0.0	0.2	1.1	0.5	95.8	0.0	0.0	0.1	0.8	5.1
425 – 600		0.7	0.0	0.2	0.8	0.4	96.4	0.0	0.0	0.2	0.6	5.1
300 – 425		0.7	0.0	0.4	2.1	0.0	94.5	0.0	0.0	0.8	1.0	5.0
212 – 300		0.7	1.9	0.7	2.1	0.2	91.4	1.2	0.0	0.3	0.8	4.9
150 – 212		4.2	1.4	1.6	4.7	2.0	81.8	1.6	0.0	1.7	1.0	4.6
106 – 150		4.1	6.2	2.8	6.5	0.4	73.6	4.1	0.2	0.0	1.2	4.3
75 – 106		5.0	8.1	4.0	8.2	2.4	62.5	5.6	0.4	0.0	1.5	4.1
0 – 75		8.1	11.7	5.3	9.5	3.2	49.3	7.4	0.0	0.0	2.6	3.8
Bulk	**Milled ore (product)**	**1.5**	**2.2**	**1.2**	**3.4**	**1.0**	**86.6**	**1.3**	**0.0**	**0.6**	**1.1**	**4.8**
2380 - 3350		0.7	0.0	0.2	1.2	1.8	93.2	0.0	0.0	0.3	1.8	5.1
1680 - 2380		0.7	0.0	0.1	1.1	2.3	92.2	0.0	0.0	0.6	2.1	5.1
1190 - 1680		0.7	0.0	0.1	1.3	1.5	94.2	0.0	0.0	0.1	1.3	5.1
850 - 1190		0.7	0.0	0.1	1.2	2.1	93.2	0.0	0.0	0.1	1.7	5.1
600 - 850		0.7	0.0	0.1	1.4	1.7	93.1	0.0	0.0	0.4	1.8	5.1
425 - 600		0.7	0.0	0.1	1.5	0.6	94.9	0.0	0.0	0.0	1.4	5.1
300 - 425		0.7	0.0	0.1	1.8	0.9	94.8	0.0	0.0	0.0	0.9	5.1
212 - 300		0.7	0.0	0.2	1.7	0.1	95.5	0.0	0.0	0.2	0.9	5.0
150 - 212		0.7	0.0	0.4	2.5	0.9	93.2	0.1	0.0	0.9	0.8	5.0
106 - 150		1.6	0.8	0.8	2.8	1.9	89.4	0.6	0.0	1.0	0.9	4.9
75 - 106		2.1	2.6	1.3	2.8	1.6	86.5	1.4	0.0	0.4	1.0	4.8
0 – 75		2.2	5.6	2.3	5.0	0.5	76.9	3.2	0.1	0.0	1.7	4.5

Table 3. Modal composition by size of hematite ore (HAR) from Malmberget. In the table: ***Ab*** *=Albite****, Act****=Actinolite,* ***Ap****=Apatite,* ***Bio****=Biotite,* ***Hm****=hematite,* ***Mgt****=Magnetite,* ***Or****= Orthoclase,* ***Qtz****= Quartz,* ***Dio****= Diopside,* ***Ilm****=Ilminite,* ***SG****= specific gravity of a mineral.*

		Modal mineralogy										
		Ab %	Act %	Ap %	Bio %	Hmt %	Mgt %	Or %	Qtz %	Dio %	Ilm %	SG
Feed Bulk		**4.6**	**0.0**	**4.4**	**5.3**	**71.5**	**2.6**	**3.8**	**3.2**	**0.0**	**0.1**	**4.4**
Size fraction (µm)	Sample name											
2380 - 3350	Crushed Hematite ore (mill feed)	15.6	11.4	1.9	2.0	30.0	2.6	19.6	5.9	0.0	0.6	3.3
1680 - 2380		14.5	6.0	2.2	1.6	46.8	3.4	13.5	4.4	0.0	0.4	3.7
1190 - 1680		5.4	2.5	1.3	2.1	75.2	2.2	5.3	2.1	0.0	0.0	4.5
850 - 1190		2.3	0.6	1.2	2.2	84.4	1.3	2.4	1.4	0.0	0.0	4.8
600 - 850		0.7	0.6	1.2	1.1	90.1	1.4	2.4	1.2	0.0	0.0	4.9
425 - 600		0.8	0.2	1.9	1.9	87.4	2.2	2.4	1.6	0.0	0.0	4.9
300 - 425		4.1	0.0	3.4	4.3	79.6	2.4	2.0	2.0	0.0	0.1	4.6
212 - 300		5.5	0.0	5.8	5.8	69.2	2.0	3.0	3.5	0.0	0.2	4.3
150 - 212		6.8	0.0	8.4	8.5	56.4	3.4	4.1	5.5	0.0	0.4	4.0
106 - 150		7.1	0.0	9.5	9.6	50.4	3.8	5.0	5.9	0.0	0.5	3.9
75 – 106		7.8	0.0	10.5	11.1	45.7	5.0	5.7	5.8	0.0	0.6	3.8
0 – 75		8.5	0.0	10.8	13.4	43.5	2.7	7.2	5.0	0.0	0.4	3.7
Product bulk	**Milled hematite ore (product)**	**5.9**	**0.0**	**4.2**	**5.3**	**70.9**	**3.9**	**2.8**	**2.7**	**0.0**	**0.1**	**4.4**
2380 - 3350		18.5	1.6	0.8	0.0	37.4	6.3	17.5	5.5	4.9	0.4	3.5
1680 - 2380		7.9	1.9	0.5	0.0	67.3	3.6	11.0	2.4	2.5	0.2	4.2
1190 - 1680		2.1	1.0	0.3	0.0	83.3	3.6	5.2	1.2	0.9	0.0	4.8
850 - 1190		1.5	1.6	0.3	0.7	87.8	4.0	2.4	0.7	0.0	0.0	4.9
600 - 850		0.8	1.1	0.2	1.0	88.8	4.2	2.2	0.6	0.0	0.0	5.0
425 - 600		0.7	0.8	0.1	3.2	89.3	4.0	1.2	0.3	0.0	0.0	5.0
300 - 425		0.7	0.3	0.3	4.3	90.4	1.9	1.4	0.5	0.0	0.0	5.0
212 - 300		2.3	0.3	1.0	4.1	87.3	1.8	1.3	1.1	0.0	0.0	4.8
150 - 212		4.5	0.0	2.8	4.3	76.7	3.2	2.0	2.4	0.0	0.1	4.6
106 - 150		6.4	0.0	4.7	4.8	69.7	3.0	2.8	3.4	0.0	0.2	4.4
75 - 106		7.5	0.0	6.0	5.2	64.2	4.1	3.4	3.7	0.0	0.2	4.2
0 – 75		8.9	0.0	7.1	7.3	57.7	6.2	3.8	3.3	0.0	0.2	4.1

Both magnetite and hematite ore show grade by size pattern where the highest magnetite / hematite grade is found in the middle size range, i.e. between 250 and 1200 microns. The pattern can be divided into three particle size ranges, accordingly. The coarse range from 1200 to 2400 microns represents hard particles and in magnetite ore they are compositionally close to the average ore whereas in hematite ore they are rich poor in hematite but rich in actinolite, orthoclase and albite. The middle range between 250 to 1200 microns is enriched in magnetite and hematite and corresponds to extremely hard material to fracture. The third size range, below 250 microns represents a soft component.

The grade patterns are due to heterogeneous breakage phenomena related to mineralogical characteristics (i.e. modal composition and grain size of minerals) of the bulk sample and individual particles.

Even though the extremely hard particle size range is rich in magnetite the mineral is not fully liberated (see figure 3). For a high quality magnetite concentrate higher degree of liberation is needed and extremely hard component (particles) must be further comminuted. The grinding efficiency is higher for gangue than for magnetite minerals as observed also by Wiegel (1975). This is probably an indication of liberation inefficiency and size fraction 53-75 µm is presumably relevant fraction for measuring the degree of liberation.

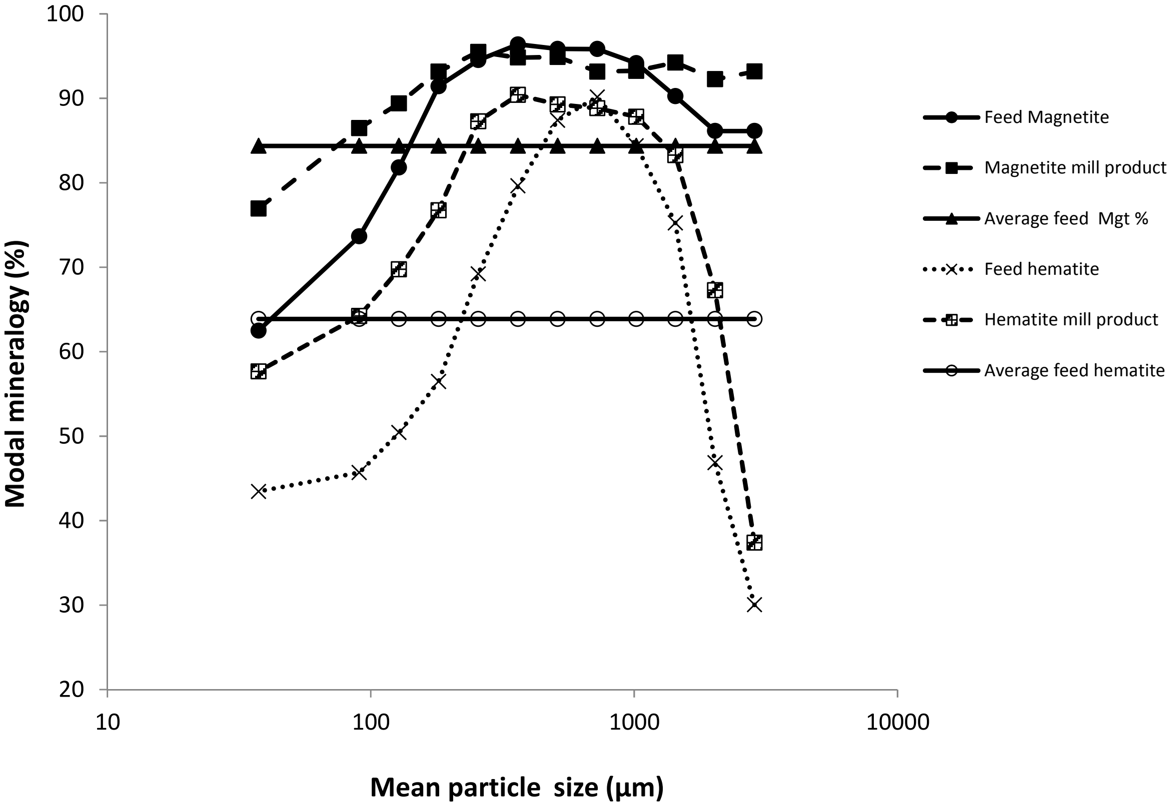

Figure 2: Grade of hematite / magnetite by size in the mill feed and the product.

Looking on mineralogical parameters, the degree of mineral liberation depends on the particle composition and can change the target size of the progeny size distribution. Besides liberation also the fraction of hard minerals may affect the efficiency of a comminution system and this can easily happen when the mineral composition is known. 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 mineral grade varies by size neither the liberation distribution of the products. Before the testing method can be linked with process simulations reliable mineral by size and mineral liberation models on comminution needs to be investigated and developed.

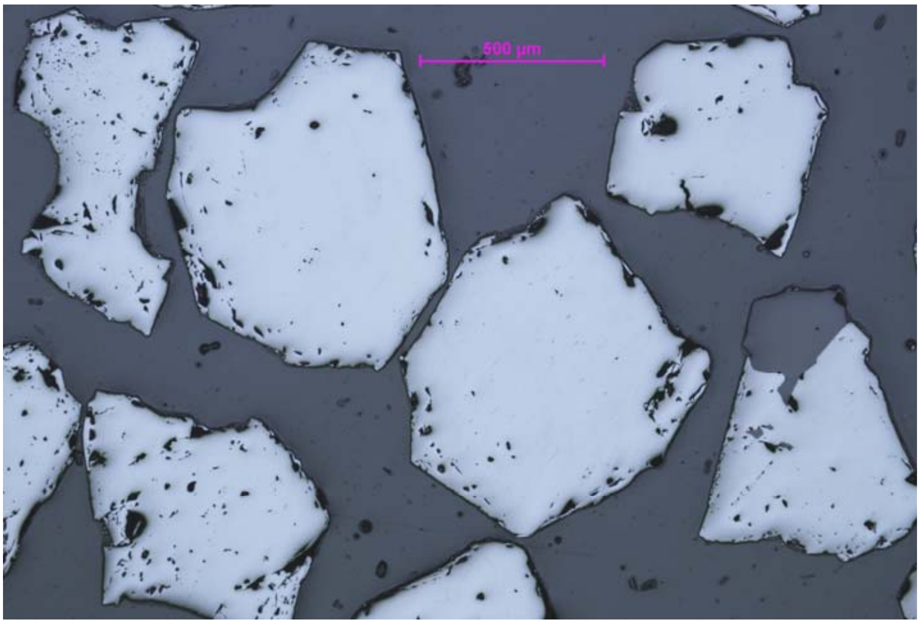

Figure 3: In size fraction > 420 µm the magnetite particle is still binary with gangue minerals under the optical microscope.

For different mineral texture also a texture class with high magnetite content showed high resistance for grinding (see figure 4). 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 partly used 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 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 the term liberability is introduced: It is defined as the relative ease with which an ore mineral can be liberated by grinding and it is elaborated more in section 3.3 and 3.4.

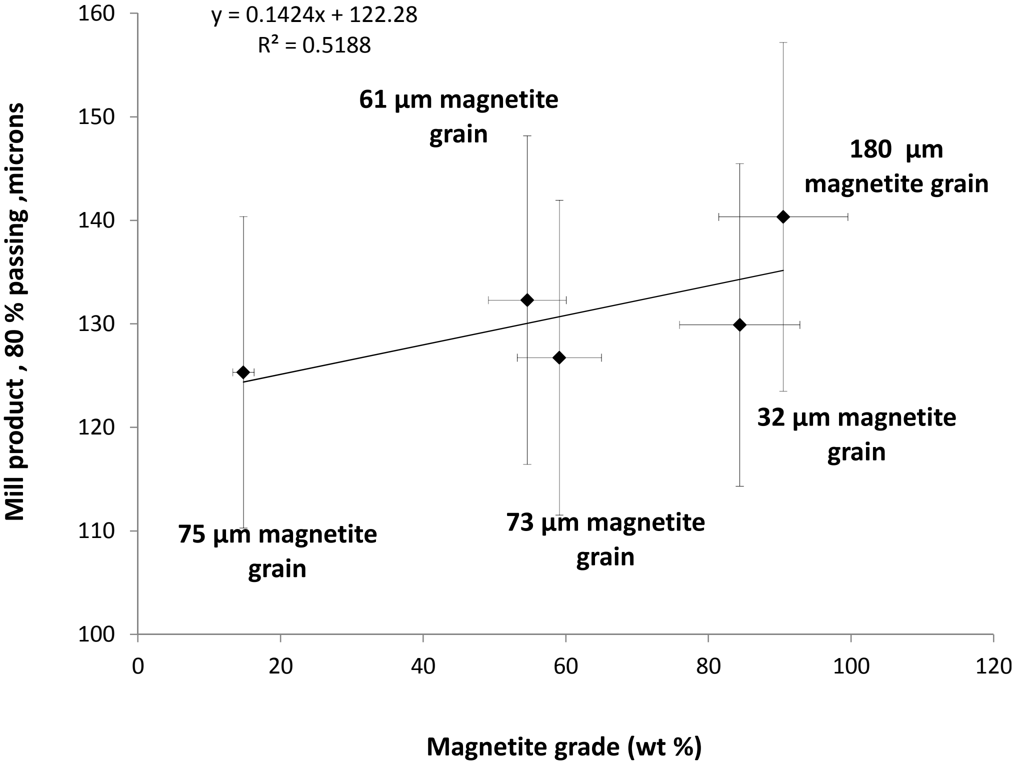

Figure 4. Mill product size P80 after grinding in small –scale ball mill at the same conditions.

3.3 Mineral liberation level

For the geometallurgical context both grindability and liberability of the material are required since for different material the degree of liberation of the mineral can be different (see table 4). Therefore modal mineralogy, mineral texture and grain size are becoming more important when considering liberability and comminution models for proper geometallurgical modelling and ore body mapping. 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 5). 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 this 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 the expected liberation size and for the Malmberget ore a size fraction of 53-75 microns was selected.

A compromise on energy required to liberate mineral particle can be made by combining liberation information data and energy consumption from comminution (Larson and Rule, 1995).

Table 4. Parameters for the determination of degree of liberation considering mineralogical composition of samples from Malmberget.

Sample	2F	4F	6F	8F	8C
Texture type	2	4	6	8	8
Grain size	Fine	Fine	Fine	Fine	Coarse
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

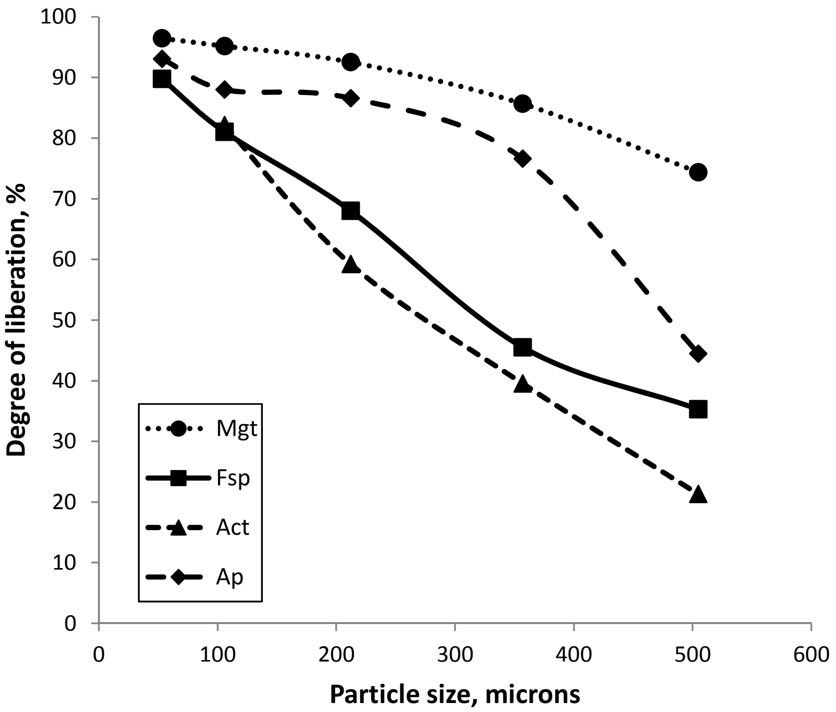

Figure 5. Particle size versus degree of liberation of the main minerals in Malmberget, sample Fabian Fsp ore type (Lund, 2013)*. Mgt = magnetite, Fsp = feldspar (albite + K-feldspar), Act = actinolite, Ap = apatite.*

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 from Malmberget (analyzed by Lund, 2013; Figure 5) the estimated degree of liberation in the bulk sample differs only 1% from the measured one.

3.4 Liberability

The grinding test gave a certain particle size distribution, which was measured by sieving. The degree of liberation for the bulk sample was estimated as described in section 3.3. To estimate how the liberation changes with grinding energy a simple approach was used (a-f in the following refer to the worked example given in Table 5). 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.

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

In the 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 6.

The received P80 (b) was converted to a full particle size distribution by using the Rosin-Rammler equation and taking the parameter describing the variance 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 by least squares fitting. 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 degree liberation vs. specific grinding energy is shown in Figure 7.

Table 5. Worked example of how the grinding energy to degree of liberation relationship was established. meas = measured, calc = calculated; for (a)-(h) see text.

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

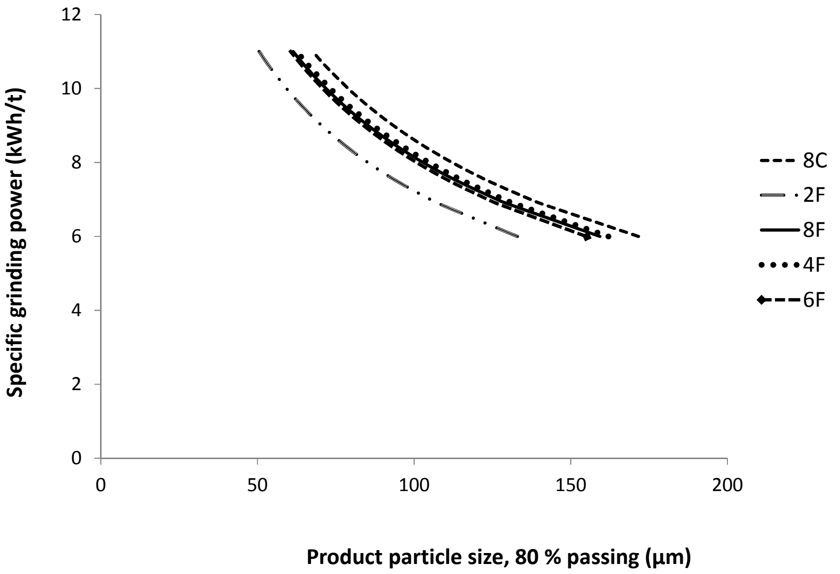

Figure 6. Specific power prediction for target size for magnetite liberation from five different mineral texture classes of Malmberget iron ore deposit.

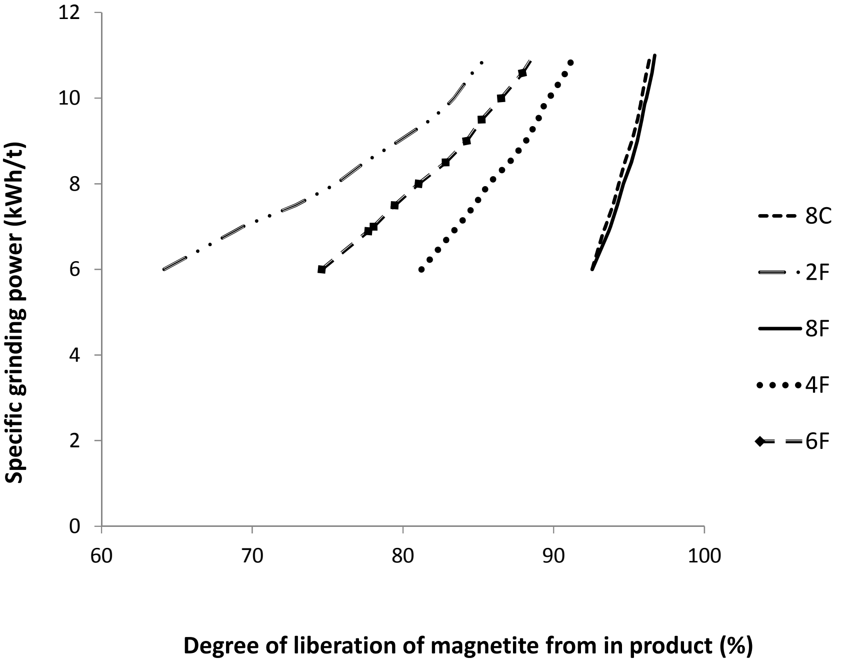

Figure 7. Specific power prediction for degree of liberation of magnetite ore of Malmberget iron ore from five different mineral texture classes.

Significant difference is observed between the liberability and the grindability (see Figure 6 and Figure 7).

3.5 Applications of liberability for mapping ore body in geometallurgy

By comparing liberation properties of different texture classes at the same applied grinding energy level significant texture class can be identified in terms of liberability: i.e. how easy it is to liberate a mineral in question. 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. 2011; Hunt et al. 2008). If the picture is available then limitations comes in the assumption of non-preferential breakage, limitation to binary systems (i.e. two minerals: valuable and others) or requirement of Kernel function (King, 1998).

It may happen within an ore body that one ore texture class has similar liberability and different grindability (see table 4, figure 6 and 7). For example texture class 8 has the same degree of magnetite liberation (95 %) but different mill product sizes 140 µm and 130 µm for coarse and fine grain textural class, respectively. This emphasizes that for proper geometallurgical mapping of an ore body, both information about grindability and liberability are required to be able to manage the resource in an optimal manner. When the liberation properties of the minerals are known, domains of similar liberability can be identified for strategic purposes of geometallurgical modelling.

Many approaches used in geometallurgy have focused on hardness of ore (crushability and grindability) or mapping mineralogical variability of an ore separately. For example Kojovic et al (2010) developed a test method for mapping hardness of an ore and throughput based on crushability index with no emphasis on mineralogical and liberation properties. Likewise Vatandoost's (2010) work on petrophysical properties of a rock on ore comminution behavior emphasising on measuring the hardness of a rock. Bonnici et al (2008) provided detailed characterization of a porphyry copper ore mainly based on mineralogical variability within a deposit by showing a qualitative correlation between textural parameters and liberation properties of an ore.

Associated minerals are another parameter that affects liberation and grinding properties of an ore as observed by Bonnici et al (2008). Mineral associations affect the type of particles that may be recovered in the concentrate, which has been observed by Petruk (1990) as an important part of better minerals separations. These parameters are very important but very challenging to quantify. Lund and Lamberg (2010) developed a method to quantify associated minerals in a magnetite ore based on archetype textural classes. This means that the approach presented here does not fully answer the questions on the modelling part. It rather provides an insight and directions for the quantification of mineralogical parameters with respect to comminution and provides a platform for proper integration between mineralogical and comminution parameters in the context of geometallurgical modelling and simulation.

4 Summary and Conclusions

Liberability is a new concept to quantify comminution energy required for mineral liberation. The liberability can be measured within a small scale comminution test developed by Mwanga (2014). This offers an inexpensive way to collect information on grindability and liberability properties of an orebody for geometallurgical mapping and modeling.

The implication of the experimental results is that samples with similar grindability and modal mineralogy may have different liberability. Such ores are distinguished from each other by mineral textures, and the mineral grain size seems to be the most important parameter in that. Including liberability in the deposit model enables energy efficient production planning. The overall conclusion is that modal mineralogy, grain size and liberation properties (liberability) of an ore are necessary for comminution and geometallurgical modelling and efficient resource utilisation.

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