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MINERAL LIBERATION AND ENERGY SAVING STRATEGIES IN MINERAL PROCESSING

A thorough knowledge of ore textures will significantly allow the mineral technologist to predict the performance of the ore during a treatment operation and this could lead to improvements of the design of treatment processes. The characterization of textural properties of minerals is closely related to the process of their respective liberation. High probability prediction methods of the given mineral liberation have been applied to micrometric measurement results for textural characteristics of ore-contained minerals in the processes of ore grinding. The distribution of linear intercept lengths on polished sections of the parent ore gives a very useful characterization of the mineralogical texture such as grain and crystal aggregate sizes, specific surface areas, proximity index, contiguity index, etc. Frequency distribution, classified intercept lengths and sample means are provided, based on the identified lognormal distribution and the use of Gauss–Laplace integral probability function. The prediction of particle size to which ore should be ground for the desired mineral liberation, is given. Size ranges and percentages of liberated particles within these ranges were estimated by the probability calculus.

INTRODUCTION

Most industrial plants for mineral processing use mainly electric power. The principal concentration operations are virtually all physical in nature and involve: crushing and grinding, surface conditioning, physical separation (concentration) of minerals and de-watering processes such as thickening, filtering and drying. According to Cohen (1983), the total motive power consumption is in the range from 10 to 25 kW h/t made up roughly as follows: crushing 0.2 to 1.0 kW h/t, grinding 2.5 to 8.5 kW h/t, concentration 1.0 to 2.5 kW h/t and pumping 0.5 to 1.0 kW h/t. Crushing and grinding usually account for more than 30 to 50% of the total power used in the concentration process, but this can rise to as high as 70% for hard and/or finely dispersed and intergrown ores. Crushing is relatively cheap in energy terms, but grinding is the most energy-consuming step in mineral processing and the least efficient.

Mineral processing technologies are continuously improved, because deposits of rich ore bodies have been limited, mineral concentrations depleted or, in other words, the complexity of lower grade ore is growing in terms of extremely fine mineral dispersions and very complex intergrowths. Therefore, liberation of minerals from a low

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grade and texturally complex ore requires very fine grinding and, consequently, very high energy consumption. It has been estimated (Lowrison 1974) that only about 0.6% of the total electrical energy supplied to rod and ball mills actually is turned into the production of new mineral surface in grinding and, clearly, there is a big chance for significant improvements in grinding efficiency.

Figure 1 (after Kaplan 1987) shows the dramatic increase of grinding energy as the product size required for liberation decreases below about 100 μm.

The main purpose of grinding is mineral liberation from complex ores but for as large a grain size as possible.

Comminution (crushing and grinding) of an ore is an energy-consuming operation and it must be performed to achieve two goals:

1. To have the product not finer than necessary for the desired liberation.
2. To ensure that liberated product will not be further ground, that it is to be removed from further grinding.

Obviously it is very difficult directly to assess the mineral liberation percentage, but the desired particle size can be predicted as early as in the flowsheet design, because the product size directly depends on the grain size of the ground ore.

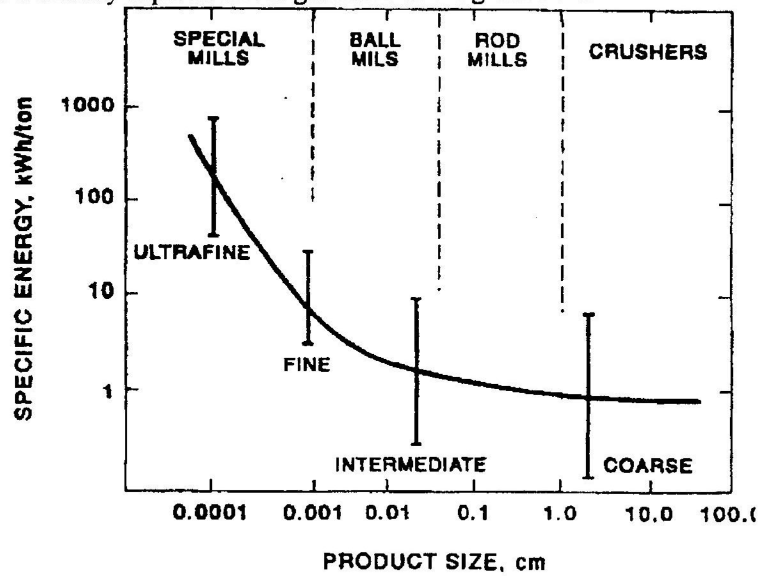

Fig. 1. The effect of product size on the specific energy required for comminution (Kaplan 1987)

EXPERIMENTAL WORK

While studying the feasibility of magnetite concentration from new small iron ore deposits, the major problem was how to eliminate appreciable amounts of accessory sulphides.

Magnetite mineralization of skarn included, along with fissures and fine cracks, the intergrowths of a later mineralization product: pyrrhotite and a significant quantity of undesirable arsenopyrite, interesting chalcopyrite, and insignificant lead and zinc sulphides. Another problem, besides this paragenetic mineral association unsuitable for processing, were complex intergrowths and textures. It was a fine grained magnetite mineralization in petrogenic, skarn minerals later intergrown with complex and likewise fine-grained sulphide veinlets.

This work aims to show micrometric measurements and to present the texture characterizations expressed in numerical data, unlike the descriptive methods used earlier, all aimed at a better understanding of the ore complexity and the elucidation of feasible mineral liberation for certain grinding grain size.

For quantification of various mineral properties, modern QEM*SEM image analyzer can be used, well equipped ore microscope fitted with an M.P.V. photometer or some other type of image analyzer.

MICROSCOPY – TEXTURE CHARACTERIZATION

For a satisfactory separation of mineral product (magnetite, chalcopyrite) from the ore, it is necessary, before crushing, to identify in the parent rock the characteristic of associated minerals: their size, crystal aggregate size, shape, type of growth, density and complexity of adjacent surfaces of mineral pairs, and other textural properties, percentage, and the like.

The Rosiwal–Schand method of examination was used in this work. The information resulting from measurements of linear intercepts of each mineral along a dense set of lines is the following:

- sum of intercept lengths across the grain of mineral A,
- total number of intercepts (grains) of mineral A,
- total traverse length across the specimen,
- total number of contacts between minerals A and B (areas of contact surfaces of associated minerals).

The information on linear intercept distribution, directly recorded during the experimental work on two-dimensional surfaces of polished sections, was used in equivalent stereological transformation into volumetric values of the given ore. It allowed the calculation of the following magnitudes:

- volume (and mass) percentage of identified minerals,
- morphology of grains or crystal aggregates,
- size of the crystal aggregates,
- specific surface area of the mineral,
- contiguity index (proximity index) of any two minerals in paragenesis,
- general textural characteristics of minerals in the ore.

MINERAL ASSOCIATION PROBABILITIES

Textural characterization of minerals contained in ore can be performed and represented by descriptive and accurate numerical data which is commonly more convenient for engineering purposes.

For a mineral liberation prediction based on microscopic examinations of the textural-structural properties of the ore, one must determine: the mode and degree of mineral intergrowth; the minerals which intergrow with useful minerals in the technological process, when the ore contains deleterious components.

Associations of the selected pairs of minerals may be expressed by the "contiguity index" or, as termed by some authors, "intergrowth or proximity index" which is approximately the same as the connectivity (Amstutz and Giger 1972). Where ground ore is concerned, this index is closely related to the free surface area of the selected mineral and its relationship with other associated minerals. The contiguity index relates the given grain surface area of the selected mineral and its total surface. This parameter is useful for parent ore, as the input processing material, to predict the mineral liberation, and even more for the analysis of liberation from comminuted ore to characterize the intergrown grains.

The coordination number has been extensively used in textural characterizations of various rocks (Amstutz and Giger 1972) and their classifications. Thus, the coordination number between A_i and A_k phases is given by the relation:

$$K_{(A_i,A_k)} = \frac{N_{(A_i,A_k)} N}{N_{(A_i)} N_{(A_k)}}$$

where

$N_{(A_i,A_k)}$ – number of contacts between A_i and A_k,
N – total number of investigated grains,
$N_{(A_i)}$ – number of grains A_i,
$N_{(A_k)}$ – number of grains A_k.

Contiguity index of mineral A to mineral B can be written (Jones and Barbery, 1975) as:

$$V_{A/B} = S_{A,B}/S_A = S_{V(A,B)}/S_{V(A)}$$

or

$$P_{A/B} = S_{A/B} \cdot 100/S_A \quad (\%)$$

where

$V_{A/B}$ – proximity index,
$S_{A/B}$ – surface area of A in contact with B,
S_A – total surface area of mineral A,
$S_{V(A,B)}$ – specific surface area of A in contact with B (i.e. the contact area per unit volume of A),
$S_{V(A)}$ – specific surface area of A,
$P_{A/B}$ – proximity index of minerals A and B (%).

The specific surface area of mineral is calculated from the relation

$$S_{V(A)} = S_{(A)}/V_{(A)} = 4/\bar{L}_{(A)}$$

where

$S_{V(A)}$ – specific surface area of mineral A,
$S_{(A)}$ – total surface of mineral A,
$V_{(A)}$ – volume of A,
$\bar{L}_{(A)}$ – mean intercept length on mineral A.

Along a set of parallel lines across the surface of an ore polished section, volume percentages of minerals were measured and their textures characterized, and the number of contact points, both internal and external, on the set lines was registered. The number of transitions from one phase to another, or one mineral into another, was registered with the purpose of defining mineral association across the contact areas of mineral grains in the analyzed material.

Sizes of contact areas of this association mineral pairs, as an important textural characteristic, are expressed by the contiguity index. A statistical processing of results (density of contact points) was used to calculate areas of direct contacts between mineral pairs in the analyzed ore. The measured frequencies of direct contact surface areas are given in Tab. 1.

Table 1. Intergrowth index of minerals contained in ore

	Fe_3O_4	FeS	$CuFeS_2$	FeAsS	Gangue min.	S, %
Fe_3O_4		4.41	0.61	0.67	94.31	100
FeS	16.5		8.21	5.22	70.52	100
$CuFeS_2$	18.18	66.67			15.15	100
FeAsS	14.94	32.18			52.88	100
Gangue min.	80.92	16.62	0.44	2.02		100

The results given in Tab. 1 show the following: magnetite intergrowth with pyrrhotite is 4.41%; magnetite intergrowth with chalcopyrite is 0.61%; magnetite intergrowth with arsenopyrite is barely 0.67%; and magnetite intergrowth with gangue is the highest, 94.31%. Likewise, other mineral proportions in the ore can be read from Tab. 1. Quite indicative are chalcopyrite intergrowth with pyrrhotite of 66.67% (pyrrhotite concentrate should therefore have the highest chalcopyrite percentage), or arsenopyrite with gangue of 52.87% (which indicates a feasible removal of this deleterious material together with the gangue).

The calculated contiguity indices suggest the behaviour of the ore in crushing and grinding, the behaviour of each mineral during its liberation, and the effects of processing on the concentrate.

From the measurements on polished sections, the percentages of minerals contained in ore and their respective contiguity indices, the following can be deduced:

– upon the size reduction to the desired grinding fineness and the magnetite liberation, the highest intergrowth content in magnetite concentrate is that of magnetite–gangue, which decreases with the finer particle grinding; the same goes for pyrrhotite,
– intergrowth occurrence is much lower with arsenopyrite,
– intergrowths with chalcopyrite are fewer.

The contiguity index for magnetite/arsenopyrite intergrowth is very low due to the absence of a direct contact (genetic bond) of the two minerals. The new quantities of sulphide minerals (arsenopyrite and chalcopyrite) provided by sulphidization along fissures in magnetite do not come in contact with magnetite.

MINERAL LIBERATION PREDICTION

The known value of the contiguity index for the given mineral can be used to deduce other ore characteristics. The empirical expression relating the *degree of liberation for the given (selected) mineral phase* (α) and the *specific surface area* (Steiner 1975) is the following:

$$L_\alpha(D) = 1 - S_{V_\alpha}^{(i)}(D)/S_{V_\alpha}^{(e)}(D)$$

$$S_{V_\alpha}^{(e)}(D) > S_{V_\alpha}^{(i)}(D)$$

where

$L_\alpha(D)$ – proportion of α that is liberated at particle size (D),

$S_{V_\alpha}^{(i)}(D)$ – interfacial α/β area per unit volume of α for particles of size (D),

$S_{V_\alpha}^{(e)}(D)$ – external surface area of α per unit volume of α for particles of size (D).

Most of these (free) areas in the above relation can be estimated from either linear or planimetric measurements as mentioned earlier. It may be used to estimate the liberation by stereologic method following the expression (Steiner 1975):

$$L_\alpha(D) = 1 - B_\alpha^{(i)}(D)/B_\alpha^{(e)}(D) = 1 - I_\alpha^{(i)}(D)/I_\alpha^{(e)}(D)$$

where

$B_\alpha^{(i)}(D)$ – boundary length of α/β interfaces measured on sections through particles of size (D),

$B_\alpha^{(e)}(D)$ – boundary length of α/matrix interfaces measured on sections through particles of size (D),

$I_\alpha^{(i)}(D)$ – number of intersections of a test line with α/β interfaces for particles of size (D),

$I_\alpha^{(e)}(D)$ – number of intersections of a test line with α/matrix interfaces for particles of size (D).

King's prediction method has been used, as a comparison method, in this paper. Through a mathematical analysis he claimed that the proportion of particles that are liberated is equal to the probability that the largest possible probe through the particles is liberated. The fractional liberation of minerals (Tab. 3) was calculated using King's equation

$$L_m(D) = 1 - 1/\mu_m \int_0^{D_m} \{1 - N(l/D)\} \{1 - F_m(l)\} dl \tag{1}$$

IDENTIFICATION OF THE DISTRIBUTION LAW

To be able to identify the law of linear intercept lengths of magnetite grain size distribution, principal statistical values had to be calculated for the arranged and classified sets. Based on the values obtained for mathematical expectations, central moments, asymmetry and excesses, the distribution of intercept lengths or magnetite grain sizes corresponded to the log-normal distribution law. This may help us to calculate, using the theory of probability calculus and applying Gauss–Laplace function, the probability of free magnetite grain occurrence in each size class, from ore ground to the desired fineness.

Statistical processing of linear intercepts, expressed in the logarithmic form, is summarized in Tab. 2.

Table 2. The analysis of linear intercepts length across magnetite

Intercept category μm	Number of intercept f_i	Class limits l_{lg}	Class centre $\hat{l}_{lg}$	$\hat{l}_{lg} \cdot f_i$	$\Delta l^2 \cdot f_i$	$\Delta l^3 \cdot f_i$	$\Delta l^4 \cdot f_i$
4–6.3	2	0.6–0.8	0.7	1.4	1.805	–1.715	1.629
6.3–10.1	38	0.8–1.0	0.9	34.2	21.375	–16.031	12.023
10.1–15.9	81	1.0–1.2	1.1	89.1	24.5	–13.476	7.412
15.9–25.2	284	1.2–1.4	1.3	369.2	34.79	–12.177	4.262
25.2–40.0	281	1.4–1.6	1.5	421.5	6.323	0.948	0.142
40.0–63.4	186	1.6–1.8	1.7	316.2	0.465	0.023	0.001
63.4–100.5	284	1.8–2.0	1.9	539.6	17.75	4.438	1.109
100.5–159.0	138	2.0–2.2	2.1	289.8	27.945	12.575	5.659
159.0–252.4	94	2.2–2.4	2.3	216.2	39.715	25.815	16.78
252.4–400.0	18	2.4–2.6	2.5	45	13.005	11.054	9.396
400.0–633.95	1	2.6–2.8	2.7	2.7	1.102	1.158	1.216
633.95–1004.75	1	2.8–3.0	2.9	2.9	1.562	1.953	2.441
Σ	1408	[redacted]	2327.8	[redacted]		12.668	62.07

Statistically processed results of linear intercept measurements for magnetite and the identified distribution law gave the following parameters: mean chord length (grain size) $\bar{l}_{lg} = 1.65$ ($l = 45$ μm); standard deviation $\sigma^2_{lg} = 0.3678$ ($\sigma = -2.33$ μm); variation $V_{lg} = 1.33238$ ($V = 2.50\%$); the third central moment $m_{3\,lg}$ 0.0089975 ($m_3 = 1.0209$);

skewness $A_{lg} = 0.181$ $A/\sigma_A^3 = 2.718 < 3$, ($A = 1.5171$); the fourth central moment $m_{4\,lg} = 0{,}044084$ ($m_4 = 1.1067$); kurtosis $E_{lg} = m_4/s^4 = -0.591$; $E/\sigma_E = 2.263 < 3$, ($E = 0.25666$).

The intercept length distribution for magnetite was identified as log-normal distribution.

Magnetite grain size distribution in the parent ore was identified using the distribution of linear intercepts for magnetite (calculation of mean geometric value of grain diameter, central moments, asymmetry, excesses and the set tests) as equivalent to the log-normal distribution. This would be used further besides employing the theory of probability and using Gauss–Laplace function of normal distribution to evaluate the probability of free magnetite grain occurrence in each size class of the ore ground to the desired fineness. The selected size, on which the liberation degree is to be predicted, is the mean geometric value of the magnetite crystal size or ore grain size.

Measurements on a set of ore polished sections by Rosiwal–Schand method and statistical processing of linear intercept of magnetite grain size distribution gave principal data on textural characteristics (average grain size, frequency and types of intergranular mineral contacts) of the parent ore.

PREDICTION MODEL

A prediction of mineral liberation in ore grinding was possible on the basis of the identified distribution law (distribution of linear intercept) and modelling the mineral texture.

Table 3 summarizes data processing on the example of the main ore mineral, magnetite, and the use of Gauss–Laplace probability function for magnetite grain size measurement results.

For the prediction given in Tab. 3, the probability function used was the following

$$F(d) = \left[\exp \left\{ -\left(\log d - \log \bar{d} \right)^2 /2(\log \sigma)^2 \right\} \right] / \left\{ \log \sigma \, (2\pi)^{1/2} \right\} \tag{2}$$

where

$F(d)$ – normal distribution (probability) function,

d – grain size diameter,

$\bar{d}$ – geometric mean intercept ($d = 1$),

σ – standard deviation.

For an average magnetite grain diameter of 66.45 μm, or the ore ground to the same or similar mean diameter (D_c), the expected magnetite liberation is 100% for grain size less than 6.3 μm; 79% for all grains up to 10.1 μm; 72% for sizes up to 25 μm; 41% for sizes up to 63.4 μm; and only 1% for grain sizes exceeding 634 μm.

The above data refer to *complete grain liberation* of magnetite crystal aggregates.

This concept of mineral liberation prediction model estimates free magnetite grain occurrence probability for any mean grain diameter. A predicted high probability of

Table 3. The prediction of mineral liberation

Grain size µm	Frequency Σf_i	Z-trans-formation Z_i [1*]	Normal distribution $F(Z_i)$ [2*]	Probability $P_{l<Dc}$ [3*]	Probability $P_{l>Dc}$ [3*]	Inverse probability $q = 1-P_l$ [4*]	Theoretical probable number of liberated grains	Observed number of ore grains that are liberated	The expected proportion of magnetite that is probably liberated at particle size D_c = 66.72 µm	King's (1979) fraction liberation Equation (1)
4.0–6.3	2	−3.05682	0.4988	0.0012	0.9988	0.0012	2/1408	2/1408	100%	0.97
6.3–10.1	40	−2.51303	0.4939	0.006	0.9939	0.006	8/1408	40/1408	79%	0.91
10.1–15.9	121	−1.96923	0.4756	0.0244	0.9756	0.0234	34/1408	121/1408		0.83
15.9–25.2	405	−1.45544	0.4222	0.0778	0.9222	0.0778	109/1408	403/1408	72%	0.71
25.2–40.0	686	−0.88164	0.2106	0.2894	0.7106	0.2894	407/1408	686/1408		0.58
40.0–63.4	872	−0.33785	0.1331	0.3669	0.6331	0.3669	516/1408	872/1408	41%	0.42
63.4–100.5	1156	−0.20595	0.0832	0.4169	0.5832	0.5832	587/1408	1156/1408	29%	0.27
100.5–159.0	1294	0.74974	0.2734	0.2266	0.7734	0.7734	1089/1408	1294/1408	15%	0.15
159.0–252.4	1388	1.29354	0.3015	0.1985	0.8015	0.8015	1128/1408	1388/1408	18%	0.08
254.4–400.0	1406	1.83733	0.4671	0.0329	0.9671	0.9671	1362/1408	1406/1408	3%	0.05
400.0–633.9	1407	2.38112	0.4913	0.0087	0.9913	0.9913	1396/1408	1407/1408	1%	0.03
633.9–1004.7	1408	2.92492	0.4982	0.0018	0.9982	0.9982	1405/1408	1408/1408	0%	0
Σ	1408									

1* $Z_i = (\hat{l}_{lg} - \bar{\hat{l}}_{lg}) / \sigma_{lg}$

2* Normal distribution function $F(Z_i)$

3* Probability values $P_{l>a} = 0.5 - F(Z_i)$; $P_{l<a} = 1 - P_{l>a}$; $a \subset D_c$

4* Inverse probability $q = 1 - P_l$

5* Mean chord length D_c (66.72 µm)

magnetite liberation will thus be possible for any size (D_c) at varied grinding fineness. The total magnetite liberation will certainly be much higher, and consequently the efficiency of concentration should also be higher, but the product will be of a lower grade due to the intergrown magnetite grains.

The predicted magnetite liberation probabilities, for different grinding sizes, have been verified by experiments on a Davis magnetic analyzer for separation of high magnetic minerals.

The magnetic fraction contained free grains of magnetite and pyrrhotite as well as magnetite or pyrrhotite grains intergrown with other minerals. This is so because separation in the magnetic field is dependent on the magnetic susceptibility of grains, not on the grain mineral composition or its being free or intergrown.

The analysis on a Davis analyzer was in terms of the grinding grain size. Five separation tests were performed for grinding sizes of 19.79%; 42.79%; 56.24%; 79.20%; 90.99% of class –41+0 μm. The obtained percentages of magnetic and nonmagnetic fractions per size classes ascertained a high proximation of the predictions.

CONCLUSIONS

Mineral liberation is accomplished by grain size reduction (ore grinding) until the grain (crystal aggregates) of the desired mineral have become separated and free from accessory minerals in the degree to be efficiently concentrated into a product of specific qualities and for a satisfactory utilization.

A significant liberation will begin only when the mean size of particles has become of the same or lower magnitude than the mean size of grains (crystal aggregates) in the ore.

At present, mainly extremely fine grinding of ore is needed requiring large quantities of energy. Therefore, the size reduction should be achieved for two purposes:

a) to avoid reduction greater than necessary for the desired degree of liberation, and

b) to assure that liberated material will not be further reduced, i.e. to have the liberated materials removed as quickly as possible from the process of further grinding.

Keeping the grain sizes as large as possible was tested in various treatments of metallic ore for the best result of mineral liberation and other advantages of the process.

It has been stated (Lowrison 1974) that only about 0.6% of the electrical energy supplied to rod and ball mills actually goes into the production of new mineral surface in grinding and, clearly, there is room for significant improvements in grinding efficiency.

The strategy of energy saving in mineral processing operations calls for prediction of the liberation percentage at the given grinding fineness, based on the textural characterization data (contiguity index, liberation prediction), as early as the flowsheet design or optimization and process control.

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Rzetelna wiedza o strukturze mineralogicznej rud pozwala technologom przeróbki kopalin przewidywać efekty kontroli procesów przeróbki. Uwalnianie minerałów jest ściśle związane ze strukturą mineralną rud. W pracy przedstawiono metodę, dzięki której można przewidzieć efekty uwolnienia minerałów, charakteryzuje się ona wysokim stopniem prawdopodobieństwa. W metodzie tej użyto wyników pomiarów mikrometrycznych własności strukturalnych minerałów zawartych w rozdrabnianej rudzie. Zauważono, że rozkład długości odcinków liniowych na zgładzie macierzystej skały daje bardzo użyteczną charakterystykę tekstury mineralogicznej, obejmującą wielkości ziarn i agregatów krystalicznych, powierzchnię właściwą, współczynniki bliskości współczynnik sąsiedztwa. Rozkłady długości odcinków oraz średnich w próbce opisano rozkładem logarytmo-normalnym i Gaussa–Laplace'a. Wykazano, że można przewidzieć wielkości ziarn, do których powinno doprowadzić rozdrabnianie dla żądanego uwolnienia minerałów. Zakres wielkości ziarn i stopień ich uwolnienia wewnątrz tych zakresów zostały oszacowane za pomocą rachunku prawdopodobieństwa.