

TEXTURAL DESCRIPTORS FOR MULTIPHASIC ORE PARTICLES

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ABSTRACT

Monitoring of mineral processing circuits by means of particle liberation analysis through quantitative image analysis has become a routine technique within the last decades. Usually, liberation indices are computed as weight proportions, which is not informative enough when complex texture ores are treated by flotation. In these cases, liberation has to be computed as phase surface exposed to reactants, and textural relationships between minerals have to be characterized to determine the possibility of increasing exposure. In this paper, some indices to achieve a complete texture characterization have been developed in terms of 2D phase contact and mineral surfaces exposure. Indices suggested by other authors are also compared. The response of this set of parameters against textural changes has been explored on simple synthetic textures ranging from single to multiple inclusions and single to multiple veins and their ability to discriminate between different textural features is analyzed over real mineral particles with known internal structure.

Keywords: image analysis, linear intercepts method, mineral liberation, mineral processing, texture characterization.

INTRODUCTION

Ores are complex assemblages of mineral phases, some being economically valuable and others being considered as uneconomic, gangue material or even as penalties. The main objective of mineral processing is to separate the valuable fraction from the gangue material by making use of contrasted properties such as density, magnetic susceptibility, hydrophobicity, etc.

The most efficient separation techniques operate on monomineralic particles obtained after crushing and grinding, but obviously this ideal situation can hardly be achieved and most often multiphasic or so-called unliberated particles are present in the process. Usually, these composite particles are treated in a regrinding stage with the aim of producing liberated particles. However, size reduction not always leads to a significant increase in mineral liberation, because size is not the only factor that determines liberation: textural relationships between mineral phases that make up particles play an important role in the possibilities of achieving liberation. Hence, a complete characterization of particles should include not only mineral liberation quantification and size characterization, but also an adequate textural characterization, which is essential for mineral processing control, and consequently for increasing mineral recoveries.

MINERAL CHARACTERIZATION

In the last decades, sophisticated techniques for automatic mineral characterization have been developed based on the use of digital images provided by scanning electron microscopy or optical microscopy (Pirard *et al.*, 2008, proposed multispectral imaging in the visible and near-IR realms; Castroviejo *et al.*, 2010, applied it to a fully automated system). The use of these techniques allows for analyzing a huge quantity of particles and a great variety of mineral properties, which would be impossible to measure accurately by manual methods.

Mineralogical analysis performed by automatic techniques includes qualitative and quantitative data about composition, grain size and mineral liberation, which is one of the most useful parameters for metallurgists. Liberation can be expressed in different ways, being weight proportion the most frequently used. However, when it deals with flotation, liberation must also be expressed in terms of exposed surface proportion. Nevertheless, when complex textures are present in the ore, both values of liberation differ (Lastra, 2002) and a complete characterization of texture is required to establish the possibility of liberation by physical or chemical means.

TEXTURAL DESCRIPTORS DEFINITION

Based on the parameters described above, some indices have been developed with two main purposes: to quantify the most relevant mineralogical features for mineral processing, and to provide textural information discriminating between different types of intergrowth. Some of these indices satisfy both conditions, while others (like those computed from linear liberation) have been developed because of their expected discriminating power. Along with these descriptors, the most relevant intergrowth indices proposed by other authors (Gurland, 1958; Amstutz and Giger, 1972; Jeulin, 1981) are analyzed.

Before describing textural descriptors it is convenient to make some comments on the notations used for their formulation. As mentioned before, the phase of interest is represented by α while the remaining phases in the particle are named with β, γ, δ . To refer to all the phases in the particle φ is used as a generic symbol, \circ represents the background (resin in real sections) and finally, \bullet represents all phases, including background. Founded on this notation, indices are formulated for the POI's (α) and they are classified according to their metallurgical significance and origin.

CLASSICAL LIBERATION INDICES

Usually, mineral liberation is expressed by two different parameters: weight ratio and exposure ratio. In single particles, the former indicates the weight proportion of one mineral with regard to the total particle weight, while the latter quantifies the proportion of exposed perimeter occupied by this mineral. Both of them are essential for the characterization of mineral particles, because they indicate the value of the particle and the possibility for recovery by flotation, respectively. Weight proportion is obtained from Eq. 10 multiplying by mineral density, while exposed perimeter proportion is derived from Eq. 11, dividing exposed perimeter of α by total exposed perimeter of the particle. Both perimeters are calculated using Barbier's formula and the notation used is explained in Fig. 3.

$$A_A(\alpha) = \frac{\sum_i L_i^\theta(\alpha)}{\sum_i L_i^\theta(\varphi)}, \quad (10)$$

$$B_B(\alpha) = \frac{\sum_\theta \sum_i N_i^\theta(\alpha, \theta)}{\sum_\theta \sum_i N_i^\theta(\varphi, \theta)}. \quad (11)$$

PHASE CONTACT INDICES

This group of indices quantifies the degree of contact between phases within particles by means of different S_V ratios. In this group, the indices proposed by other authors (Gurland, 1958 (Eq. 15); Amstutz and Giger, 1972 (Eq. 13); Jeulin, 1981 (Eq. 14)) are included, after being adapted to the special case of particle-by-particle analysis instead of analyzing a multiphase material aggregate. Along with them, an additional index (Eq. 12) has been developed. For each index, both formulae based on surface area density (S_V) and its simplification based on intercept counts (Eq. 8) are shown.

Phase contact index. Ratio between the surface density of the $\alpha\beta$ intergrowth surface and the surface density of the particle exposed surface.

$$I_C(\alpha\beta) = \frac{S_V(\alpha\beta)}{S_V(\varphi\circ)} = \frac{\sum_i N_i^\theta(\alpha\beta)}{\sum_i N_i^\theta(\varphi\circ)} \quad (12)$$

Intergrowth index (Amstutz and Giger, 1972). The so-called intergrowth or locking index is a numerical value which indicates how much of each phase is intergrown with all other phases. It is a ratio between the surface density of the intergrowth surface between two phases and the total surface density in the particle.

$$I_{A-G}(\alpha\beta) = \frac{S_V(\alpha\beta)}{S_V(\varphi\bullet)} = \frac{\sum_i N_i^\theta(\alpha\beta)}{\sum_i N_i^\theta(\varphi\bullet)}. \quad (13)$$

Coordination index (Jeulin, 1981). Indicates the probability of the $\alpha\beta$ contact in a multiphase system.

$$\begin{aligned} I_J(\alpha\beta) &= \frac{S_V(\alpha\beta) \times S_V(\varphi\bullet)}{S_V(\alpha\bullet) \times S_V(\beta\bullet)} = \\ &= \frac{\sum_i N_i^\theta(\alpha\beta) \times \sum_i N_i^\theta(\varphi\bullet)}{\sum_i N_i^\theta(\alpha\bullet) \times \sum_i N_i^\theta(\beta\bullet)} \end{aligned} \quad (14)$$

Contiguity Index (Gurland, 1958). Originally this index was defined to compute the fraction of the total interface area of a phase that is shared by particles of the same phase. Its derivation for multiphase systems is given in Eq. 15.

$$I_{CG}(\alpha\beta) = \frac{S_V(\alpha\beta)}{S_V(\alpha\bullet)} = \frac{\sum_i N_i^\theta(\alpha\beta)}{\sum_i N_i^\theta(\alpha\bullet)} \quad (15)$$

TEXTURE COMPLEXITY INDEX (I_{TC})

One last index has been developed based on intersection counts to give an idea of the texture complexity.

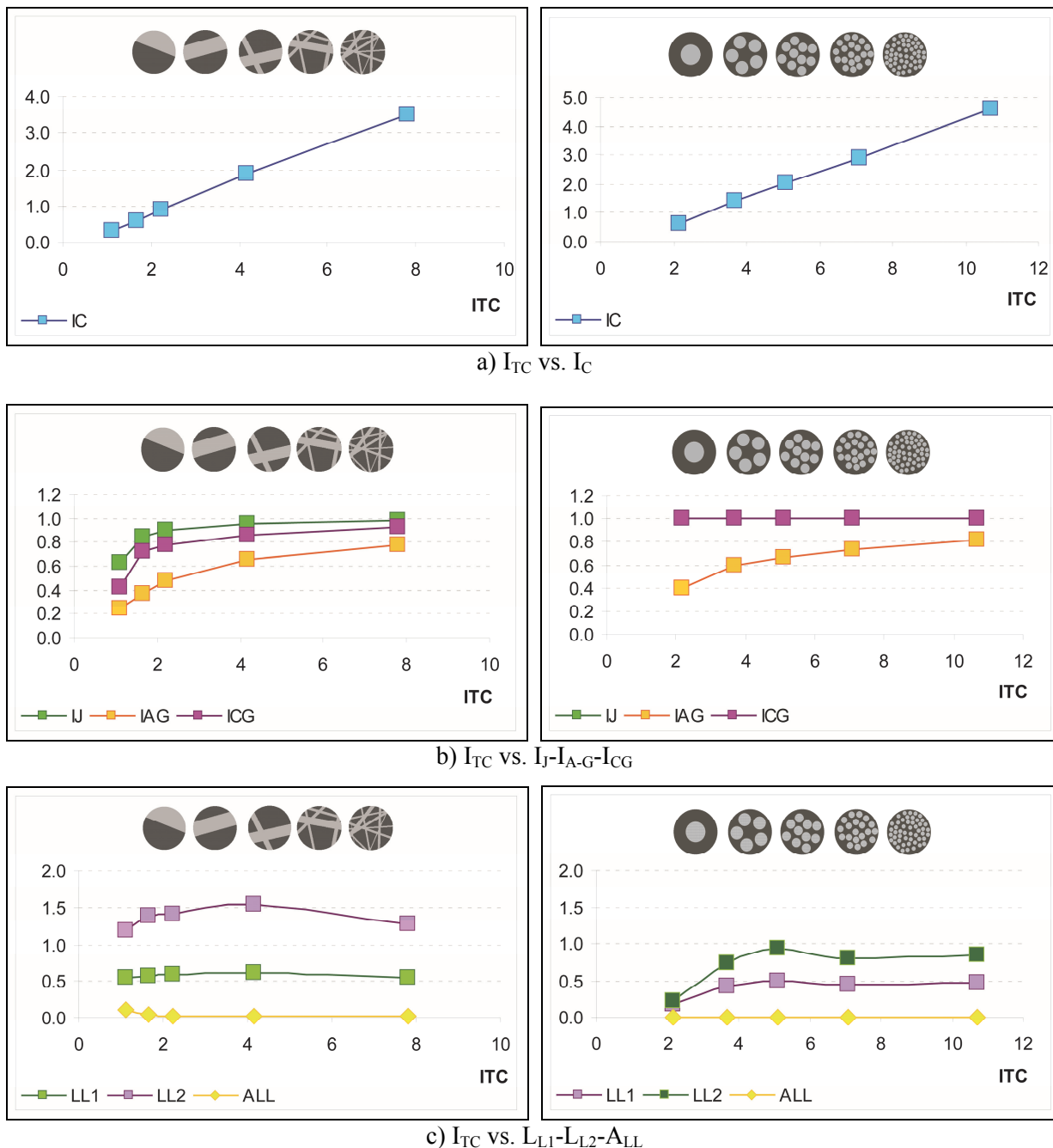


Fig. 4. Evolution of textural descriptors (ordinates) against texture complexity Index (I_{TC} , abscissas) for the bright phase in particles ranging from simple texture to stockwork (left column), and from coated to emulsion (right column). In Fig 4b-right, curves for I_j and I_{CG} are superimposed.

This behavior against texture changes indicates that most of the proposed indices might be used to distinguish between different types of intergrowth. To establish which ones are the most effective a discriminant analysis has been carried out over a total of 77 real mineral particles from different samples. These particles have been selected according to their internal structure, so that one of the types of intergrowth shown in Fig. 2 can be easily recognized in any of their constituents. Some examples of these particles are shown in

Fig. 5. As they are processed as biphasic particles, the initial four types of intergrowths are in fact seven possible types. Thus, in particles belonging to type *a*, the phase of interest may be in the form of a single inclusion coated by a rim or it may be the rim itself. In the case of particles type *b*, the POI may be the emulsion or the matrix that contains the emulsion and the same can be said about particles of type *c*. Finally, the intergrowth in particles of type *d* is considered as simple. Working with biphasic particles also implies

that for each particle there are two possible intergrowths (one for each phase), so the initial 77 cases considered are actually 154 cases to be processed by discriminant analysis.

For both phases present in the particles, indices in Eqs. 10–20 were computed and correlations among them were evaluated in order to select the most efficient ones and to limit redundancy in the variables. The correlation matrix shows that a strong correlation exists between I_C and I_{TC} , I_C and I_{A-G} , L_{L1} and L_{L2} . Therefore, in each pair, the index with the lowest discriminant power was discarded. This analysis has been carried out with a discriminant function analysis and the classification is performed by the minimum Mahalanobis distance criteria. Results show that 95.5% cases were correctly classified using the following four indices: I_J , I_{CG} , I_{TC} and L_{L1} . As shown in Table 2, phases belonging to the groups simple, emulsion and emulsion matrix were 100% correctly classified. Incorrectly classified cases are shown in Table 3.

Table 2. *Classification results*

	% Correct
Simple	100.0
Stockwork Matrix	86.7
Stockwork	80.0
Emulsion	100.0
Emulsion Matrix	100.0
Inclusion	96.2
Rim	96.2
Total	95.5

Each row in this table contains a particle in which the inter-growth type of at least one of the phases has been incorrectly classified. For each phase (bright and dark phase) the observed intergrowth type (OC) and the intergrowth type given by discriminant analysis (DAC) are shown. Moreover, the Mahalanobis distance to the group into which each phase has been classified (DAD)

and the Mahalanobis distance to the group into which the phase should have been classified (OCD) are also given. As shown in Table 3 the higher error occurs for the stockwork and stockwork matrix intergrowth types. However, for these intergrowth types, little difference exists between Mahalanobis distance to the observed classification group and Mahalanobis distance to de discriminant analysis classification group.

TEXTURAL DESCRIPTORS AS MINERAL PROCESSING INDICATORS






Although the main objective of these indices is the discrimination between different types of mineral intergrowths, the assessment of their mineralurgical meaning is also important. The first two indices that have to be computed are A_A and B_B . The first one quantifies the amount of phase borne by each particle, which for real mineral particles means mineralogical value. However, a particle that carries the POI but has very low surface exposure to reactants (low B_B) would not be recovered by flotation in spite of having a high mineralogical value. So, both of these indices have to be computed and if they differ, a textural analysis will be required to establish the possibilities of acting on the particle in order to increase its liberation.

In addition to B_B , there are two more indices that show evidence of locking: I_{CG} and I_J . Both of them are equal to 1 when there is a locked phase in a biphasic particle. However, while the first one is calculated for each phase in the particle and specifies which phase is included, the second one just indicates the existence of locking in the particle. For those cases in which a high degree of locking has been detected by one of the three indices (B_B , I_{CG} , I_J) the degree of intergrowth and the intergrown surface irregularity has to be analyzed in order to assess the possibility of increasing liberation. The intergrowth index proposed by Amstutz and Giger (1972) (Eq. 13) is a good estimator of the former, while the latter can be estimated by the I_{TC} (Eq. 16).



Fig. 5. *Some examples of real particles used for discriminant analysis.*

Table 3. *Incorrectly classified cases. OC: Observed classification (real intergrowth type). OCD: Mahalanobis distance to the observed classification group. DAC: Discriminant Analysis classification (intergrowth type given by discriminant analysis). DAD: Mahalanobis distance to the discriminant analysis classification group.*

	Bright Phase				Dark Phase			
	OC	OCD	DAC	DAD	OC	OCD	DAC	DAD
	Stockwork Matrix	22.5	Stockwork	18.3	Stockwork	17.0	Stockwork	17.0
	Stockwork Matrix	1.5	Stockwork	1.4	Stockwork	1.9	Stockwork Matrix	1.1
	Stockwork Matrix	2.1	Stockwork Matrix	2.1	Stockwork	2.5	Stockwork Matrix	2.3
	Stockwork Matrix	4.9	Stockwork Matrix	4.9	Stockwork	6.4	Stockwork Matrix	6.3
	Inclusion	6.3	Emulsion	3.6	Rim	5.9	Matrix Emulsion	3.0

CONCLUSIONS

The automated characterization of the intergrowth type of mineral phases within mineral particles is possible using the new methodology proposed. This methodology is supported by a set of descriptors based on stereological parameters, which have been developed using the linear intercepts method. Comparison with some indices proposed by other authors to quantify the type of contact between mineral phases shows that the efficiency of these as discriminant variables is improved if complemented with the descriptors proposed in this work. Furthermore, assessment of their mineralurgical meaning shows their potential for practical application to geometallurgical purposes.

Discriminant analysis results show the capability of these indices to classify mineral phases according to their intergrowth type. This analysis shows that 95.5% of cases analyzed were correctly classified using four indices: I_J , I_{CG} , I_{TC} and L_{L1} . It also indicates that three mineralurgical parameters appear as significant for texture identification: locking grade (quantified by indices proposed by Gurland (1958) and Jeulin (1981)), texture complexity (quantified by I_{TC} , this work) and the shape of linear liberation grades distribution (expressed with index L_{L1} , this work). The 95.5 % success rate found

appears as reasonable, taking into account that the morphology of complex intergrowths shows features that may be transitional to different types and tends to be ambiguous even for a human observer.

The results discussed in this paper show the potential of the proposed methodology to discriminate between the intergrowth types considered and to provide the mineralogical information required to achieve a complete mineralogical characterization regarding particles behavior during mineral processes. However, further tests have to be performed in order to improve the classification and to extend the methodology for the discrimination between new types of intergrowth. The tests performed suggest that, in some cases, textural analysis may require the use of different parameters to optimize the results for particular textures.

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