SELECTIVE COMMINUTION - AN EXAMPLE OF QUANTITATIVE MICROSTRUCTURAL ANALYSIS AS SUPPORT IN ORE BENEFICIATION

M. Hesse[1], O. Popov[1] and *H. Lieberwirth[1]

[1]Technical University Bergakademie Freiberg
Institute for Mineral Processing Machines
Lampadiusstr. 4
09599 Freiberg, Germany
*(*Corresponding author: holger.lieberwirth@iam.tu-freiberg.de)*

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ABSTRACT

Selective comminution exploits differences in the comminution behavior of the various minerals an ore comprises. The wider the difference in a material property to be exploited the better the components accumulate in different fractions of the comminution product. The waste portion can be rather easily excluded from further mineral processing by classification.

A suitable technology for selective comminution, considering the specific kind of loading generated by each type of crushers and mills, can be chosen on the basis of a quantitative microstructural analysis. Based on an ore analysis and its mathematical formulation, key parameters can be calculated in the form of mathematic values oriented to terms in geology.

KEYWORDS

Selective comminution, Quantitative Microstructural Analysis, Impact Comminution

INTRODUCTION

The world population will continue to grow until it might eventually peak at around 10 billion people after 2050. Resource consumption will by far outpace this growth, however, since it is closer linked to GDP growth than just to that of population (Haberl, 2012; Krausmann, 2009). While population growth rates shrink since the 1960s the GDP grows at accelerating speed (Figure 1). It is expected that the global population will grow from presently around 7.1 billion to around 8.7 billion in 2035 (BP p.l.c., 2015). In the same period, GDP is forecasted to more than double. It is remarkable how this GDP growth is reflected especially by rising per person income in non-OECD countries in Asia. Those rising incomes will trigger increased resource consumption.

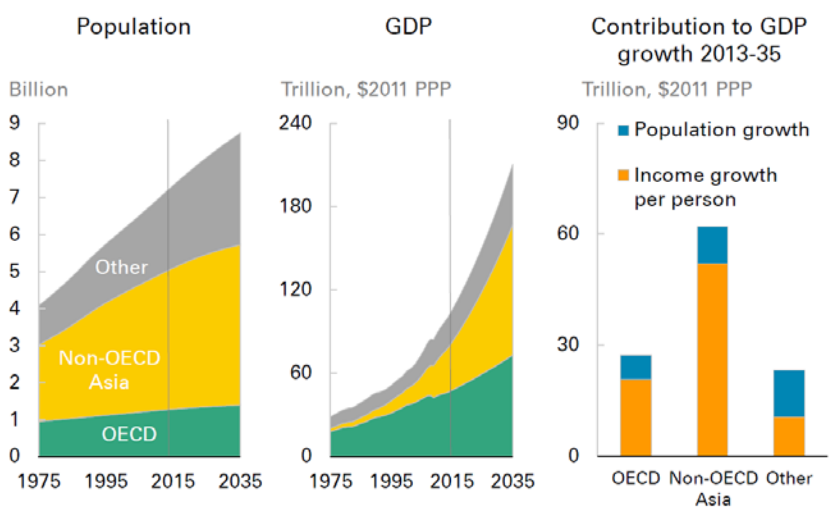


Figure 1 – Global population and increase in income per person (BP p.l.c., 2015)

While recycling may eventually replace refurbishing and reuse in those countries as it did in developed economies it cannot cater for the absolute increase in consumption. New deposits have to be discovered and extracted. As figures from the past indicate new deposits were always found if required, yet often smaller in size, lower in grade and located in more remote areas than the depleted ones which they shall replace (Schodde, 2010).

Increased consumption and lower ore grades lead to larger volumes to be processed. Already at the present level of consumption, about 2 % of the electrical energy generated worldwide is spent on comminution processes (Napier-Munn, 2014). Reducing the specific energy consumption in mineral processing seems to be an obvious task, looking at resource economics as well as at the environmental impact of the mineral processing industry.

Selective comminution is a promising way to reduce the specific energy consumption in comminution. Properly applied, it allows removing a portion of the material at an early comminution stage. If this portion is constituted by gangue material, as in most cases involving selective comminution, the energy which would have been usually spend on grinding this portion to final product size, can be saved.

While selective comminution was occasionally applied in processing ores and industrial minerals already in the past (Puffe, 1955), a systematic investigation on the process is still missing. A realistic prognosis for new plants is therefore still difficult. There are many, sometimes contradictory definitions and applications of the term selective comminution in the literature. This article aims to provide a general definition, which considers known material properties as well as comminution parameters.

First promising results of research, conducted on the topic at the Institute of Mineral processing machines of the TU Bergakademie Freiberg, in the combination of comminution process research and Quantitative Microstructural Analysis (QMA) are presented. For the influence of certain material properties on selectivity in comminution examples will be given.

SELECTIVE COMMINUTION

Selective comminution is a property of a comminution system (Hesse, 2014). It is based on the different comminution behaviors of the various minerals of a feed material at the same load. Selectivity may be supported by the focused application of a specific comminution procedure selected to meet the characteristics of the feed material. The use of selective comminution is mostly limited to pre-concentration processes, because there it has the highest efficiency. The pre-concentrate from a selective comminution contains very often still intergrown particles and bigger amounts of waste mineral. Pre-concentration processes usually relieve the downstream steps in mineral processing and thus increase process efficiency. Since selective comminution in combination with subsequent classification is a particularly cost-effective way of generating pre-concentrates it is also a promising method for the treatment of low-grade ores and old tailing dumps.

A sufficiently large difference in the separation criterion between the minerals to be separated is decisive when choosing a suitable separation process. For a variety of ores, such a criterion is given in the comminution behavior. The comminution itself realizes only a differentiation in the size of comminution products, no separation. A downstream separation step is always necessary for the separation of the different materials. In the simplest case this is a classification.

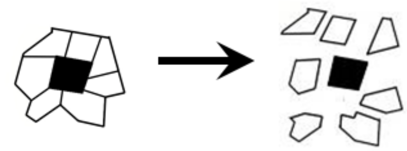
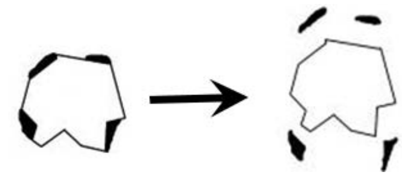
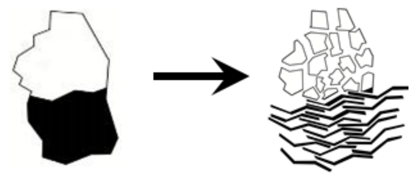
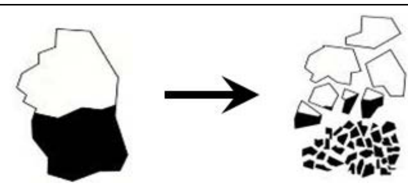
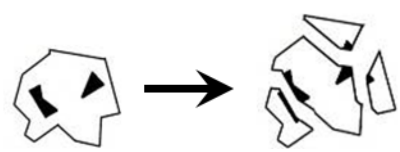
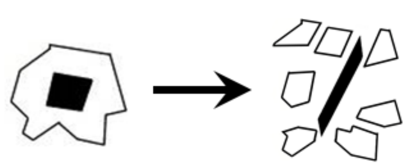
However, in addition to the material characteristics, a suitable processing technology is fundamental for selective comminution. Design and operational parameters such as the kind of loading, the loading frequency, velocity and energy take decisive influence on the comminution system, too. Their appropriate combination to the given material properties facilitates selective comminution and the subsequent separation of the various comminution products. Selective comminution can be expected only if both, material properties and comminution technology are suitable (see Table 1). If this is the case, selective comminution can be applied to separate various constituents of an ore. This may refer to separation of valuable minerals from waste, ore from bed rock or different ore varieties of a deposit from each other.

Table 1 – Relation between material properties and the characteristics of the applied comminution technology for selective comminution of a raw material

Suitability of the comminution technology for selective comminution	**Suitability of material properties for selective comminution**	
	Suitable	*Not suitable*
Suitable	**selective comminution**	non-selective comminution
Not suitable	non-selective comminution	non-selective comminution

When selecting a comminution procedure knowledge on crack propagation within the feed material is essential. Cracks may propagate in the ore structure in fundamentally different ways, either through the mineral phases, called preferential breakage or along the phase boundaries, also known as interfacial breakage. The properties of the material phases as well of the phase boundaries mainly determine the way of propagation. Processing parameters may influence the cracking behavior determined by the material properties to a certain extent. An overview about various application options of selective comminution is shown in Table 2.

Table 2 – Application examples of selective comminution

	Target	Graphical example
	High degree of liberation	
Grain or phase boundary fractures (interfacial breakage)	Removal of superficially adhering components	
	Comminution into fragments with different particle shapes	
	Selective comminution with enrichment by classifying	
Grain or phase fractures (preferential breakage)	Liberation of valuable materials at the surface	
	Selective comminution with reshaping	

EVALUATING SELECTIVE COMMINUTION

Selective comminution in combination with a separation process can be considered as a sorting process. Different methods for measuring the effect of selective comminution have to be used depending on the kind of selective comminution and the separation process. The probably most common case of selective comminution can be detected as a different distribution of valuable and waste mineral in dependence on the particle size or fraction. Thus, particle size is the most important parameter for the evaluation of the selective comminution. The following three examples focus on the particle size for evaluating the selective comminution.

Integration method with cumulative passing distributions

This integration method is independent of any separation cuts and provides only one evaluating parameter, which makes it easy to compare results from various test series.

Material components to be separated by selective comminution are subsequently named V for valuable material and W for waste (index V and W respectively). For each component a cumulative passing distribution Q3 can be calculated with the mass md of each particle size class d and the content cd of the component in each particle size class, see Figure 2 a) and Equation (1.1).

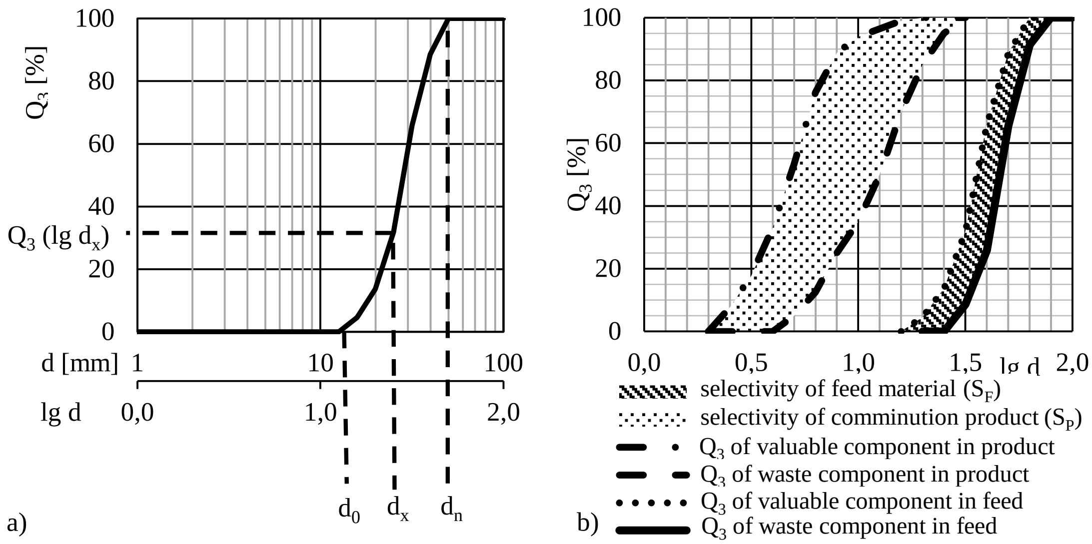


Figure 2 – a) Example of cumulative passing distribution Q_3; b) Example of Q_3 with selectivity of the feed material and comminution product between the valuable and waste material

$$Q_3(\lg d_x) = \frac{\int_{d=d_0}^{d_x} m_d \cdot c_d}{\int_{d=d_0}^{d_n} m_d \cdot c_d} \cdot 100\% \qquad (1.1)$$

The selectivity S of two components describes the difference in a considered class feature (here particle size) of these two components as a quantitative value. It is calculated as the area between the cumulative passing distributions of the two components and may for example be described for the comminution product (index P) with Equation (1.2). In this case S_P (light shaded area in Figure 2b)) is the area between the Q_3 functions of the waste ($Q_{3,WP}$ in Equation (1.2), dashed line in Figure 2b)) and the valuable component ($Q_{3,VP}$ in Equation (1.2), dot-dash line in Figure 2b)).

$$S_P = \frac{\left(\int_{g=1}^{n} Q_{3,VP}(\log d) - \int_{g=1}^{n} Q_{3,WP}(\log d) \right)}{\log d_{g=n} - \log d_{g=1}} \tag{1.2}$$

It should be noted when evaluating the selectivity of a comminution process that even in the feed material (index F) the components V and W may exhibit differences in the cumulative passing distributions and reflect a selectivity of the feed material S_F (Figure 2b), dark shaded area). If this selectivity of the feed material S_F remains unchanged in the comminution product S_P, no selective comminution occurred. The magnitude of the change, the SZ is a quantitative value for the selective comminution, Equation (1.3), (1.4).

$$SZ = S_P - S_F \tag{1.3}$$

SZ can be determined inserting Equation (1.2) for S_P and the respective term for S_F in Equation (1.3). For the discretization in cumulative passing distributions from sieve analyzes, the values g and f are the numbering of the screening cuts, ascending with larger mesh size.

$$SZ = \frac{\left(\int_{g=1}^{n} Q_{3,VP}(\log d) - \int_{g=1}^{n} Q_{3,WP}(\log d) \right)}{\log d_{g=n} - \log d_{g=1}} - \frac{\left(\int_{f=1}^{m} Q_{3,VF}(\log d) - \int_{f=1}^{m} Q_{3,WF}(\log d) \right)}{\log d_{f=m} - \log d_{f=1}} \tag{1.4}$$

SZ is positive in the example shown in Figure 2 b), despite V is already slightly enriched in the fine fractions of the feed material, since this enrichment in the fine fractions further increases with comminution. Selective comminution can also be used to homogenize a material if the components occur in different particle size distributions in the feed material and are equally distributed in the comminution product. An interpretation of SZ and conclusions with regard to beneficiation processes should therefore always take into account the selectivity of the feed material (S_F) and the comminution product (S_P).

Ore separation degree η_{ore}

Another option for characterizing a selective comminution effect is the ore separation degree η_{ore}, Equation (1.5).

$$\eta_{ore} = \frac{(c_F - c_W) \cdot (c_P - c_F) \cdot 100\%}{c_F \cdot (100 - c_F) \cdot (c_P - c_W)} \cdot 100\% \tag{1.5}$$

The parameters are c_F - concentration in the feed material, c_P - concentration in the product and c_W - concentration of the valuable material in the waste material, respectively as percentage. Concentrate and waste will be divided by the separation cut d_t, see Figure 3a). The c_W and c_P changes in dependence on d_t, see Figure 3b). With this dependence on d_t it is simple to find the maximum value for the ore separation degree $\eta_{ore,max}$ and with them the best fit for a separation , see Figure 3 c), (Hesse, & Lieberwirth, 2014; Hesse, 2014). This calculation method can also be applied to the feed material. The difference of η_{ore} between the initial state and the comminution product can be used to evaluate the selective comminution.

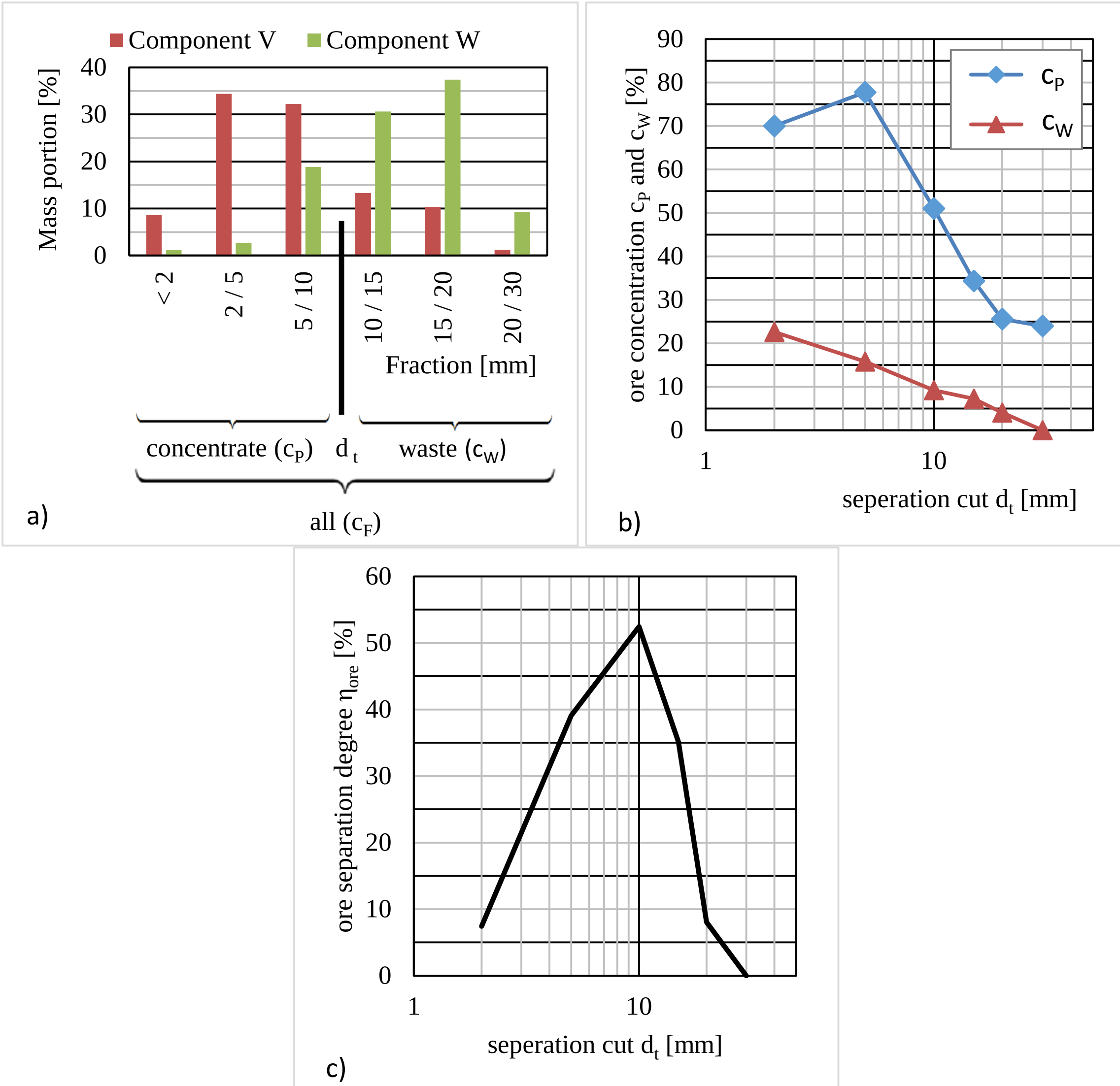


Figure 3 – a) Example for distribution of the mass portions for a component V and W; b) distribution of the ore concentration from a) in the concentrate c_P and in the waste c_W in dependence of the separation cut; c) Graph of the ore separation degree η_{ore} for example a)

Recovery plots

A further method for evaluating the selective comminution is to use the Fuerstenau upgrading diagram in recovery plots (Leißner, 2014; Reichert, 2015). For the application of this method the selectively comminuted material is separated into two fractions, a fine fraction and a coarse fraction. The recovery of the valuable ore mineral and the waste mineral can be plotted in a diagram for various separation cuts d_t, see Figure 4. Decision is to be made if the calculation is done for the fine or coarse fraction. Figure 4 shows the results for the fine fraction for example. A linear diagonal line would indicate that there is no selectivity in the particle size distribution (line 3 in Figure 4). An enrichment of the ore mineral in the fine fractions can be seen if the recovery curve for the fine fraction is above the diagonal line (line 1 in Figure 4). An enrichment of the waste mineral in the fine fractions can be seen if the recovery curve for the fine fraction is under the diagonal line (line 2 in Figure 4). In this case the enrichment of the ore mineral is in the coarse fraction. This evaluating method has similar advantages and disadvantages as the ore separation degree η_{ore}. However, different parameters can be derived from these functions (Leißner, 2014).

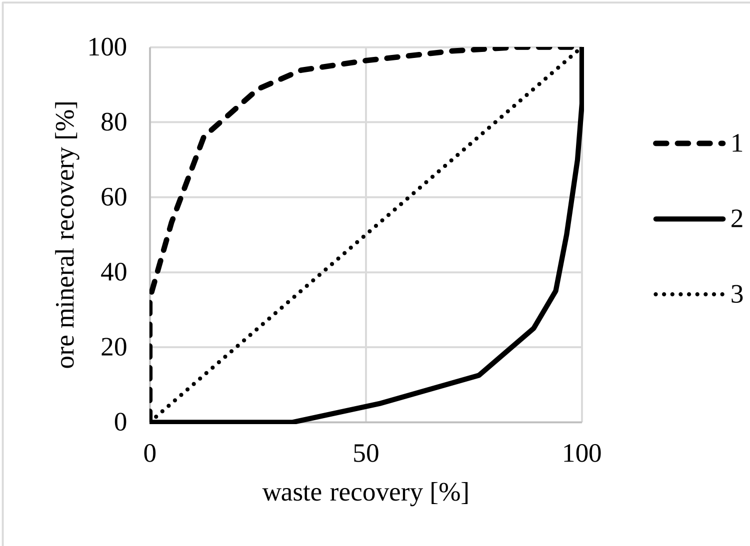


Figure 4 – Recovery plot as Fuerstenau upgrading curve (if applied for the fine fraction: Line1: selective comminution with enrichment of the ore mineral in the fine fraction; Line 2: selective comminution with enrichment of the ore mineral in the coarse fraction; Line 3: no selectivity in the particle size distribution

APPLICATION EXAMPLE OF SELECTIVE COMMINUTION

The following examples show some results of selective comminution tests with a lead-zinc-ore (Stöhr, 2012; Hesse, 2015). The comminution investigations are designed to find out the effect of selective comminution at different kinds of load: impact load, compressive load and shear load. A pneumatically operated shoot apparatus is used to execute the single particle comminution with impact load. A double roll crusher is used for the compressive load investigation. A disk mill is used to comminute the single ore particles mainly with shear load.

The ore originates from the marble mine Hermsdorf in the Erzgebirge Mountains, Germany. Six separated calcite/dolomite horizons are located in the deposit. The mainly dolomitic, partly calcitic horizon K1 contains a larger, concordant lead-zinc-mineralisation consisting of two types of ore. One type is banded, the other type is as brecciated as a part of the dolomite in the K1-horizon. The brecciation leads to a coarser recrystallization of a part of the ore mineralisation. The wall rock is phyllite. The whole deposit contains a lot of bigger dislocations. Marble had been mined in the deposit since the 16th century. In 1956 lead-zinc ores were sent to the smelter in Freiberg. An intensive prospection of the lead-zinc-mineralisation took place in the years 1958, 1960 and 1963. The high variability of the thickness of the ore layer and the relatively low amount of ore prevented a separated ore mining. The lead-zinc-mineralisation is largely triaged by the marble mining (Hoth et al., 2010).

Some results of the investigations with the brecciated ore type are shown below. The focus of this work is on the lead-zinc-mineralization. The texture and structure properties were determined with the QMA (Popov, 2007) on polished sections, see Figure 5. The galena and sphalerite are mostly fine crystalline grains in a calcitic matrix. The average grain size is about 0.21 mm for sphalerite and 0.25 for galena. The calcite grain size could not be evaluated from the polished section. The literature gives values of 0.03-0.1 mm (Hoth et al., 2010).

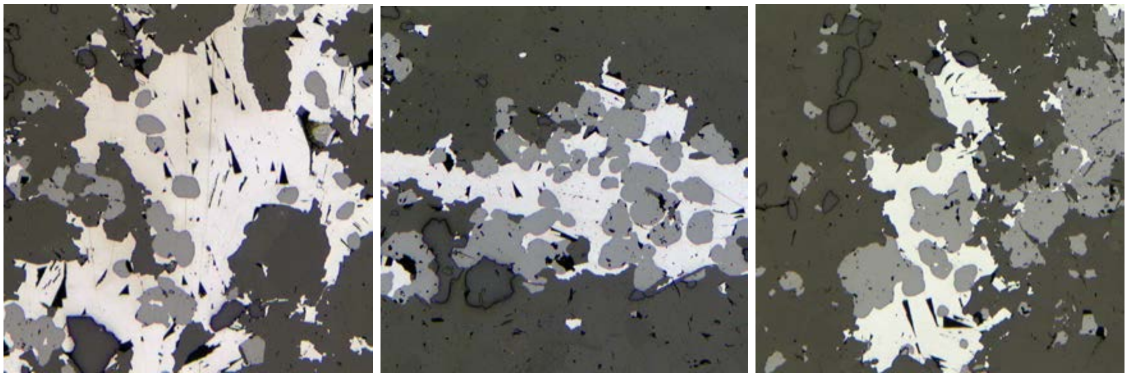


Figure 5 – Polished sections of the brecciated concordant lead-zinc-mineralization in the K1-horizon, Hermsdorf marble deposit, Erzgebirge mountains, Germany; light grey: galena; middle grey: sphalerite; dark grey: calcite; image width: 1.6 mm

The Vickers hardness number and fracture toughness were measured to quantify the difference in the comminution properties, see Table 3. The fracture toughness was derived from the crack length. Cracks could be generated with the Vickers indenter only in the calcite. The low hardness indicates calcite. The unconfined compressive strength of the ore is in average 101 MPa and was calculated from the point-load-index $I_{S(50)}$ = 4.04 MPa (Broch & Franklin, 1972; Brook, 1985; Chau & Wong, 1996; ISRM, 1985). The variation coefficient is 23.5 %. The density of the ore is about 2.84 g/cm^3. The ore content is about 4.7 % for sphalerite and 0.4 % for galena.

Table 3 – Properties of sphalerite, galena and dolomite; Average ± Standard deviation

Mineral	Content [%]	Grain size [mm]	Vickers hardness number (0,025 HV) [N/mm^2]	Specific surface [mm^2/mm^3]	Roughness [%]	Fracture toughness [MN/m$^{3/2}$]
sphalerite	4.7 ± 0.12	0.25 ± 0.36	195 ± 21	30	56	-
galena	0.4 ± 0.08	0.21 ± 0.31	75 ± 4	31	71	-
calcite	~95	0.03 – 0.1	159 ± 11	-	-	0.53 ± 0.06

The minimum amount of sample mass was calculated according to Schubert (Schubert, 1984). The confidence level was set at 80 % to reduce the experimental effort. Finally, the representative sample was generated with a sample divider. The fraction 10/12.5 mm was chosen for the tests. The narrow fraction guarantees a feed material without selectivity.

Some results from the investigation with single particle impact comminution in a shoot apparatus will be shown first. The sample contains 499 particles. The particles were comminuted in a pneumatically operated shoot apparatus by perpendicular impact load at 60 m/s against a hard metal plate. The comminution product of all particles was classified (see Figure 6) and the lead and zinc content was determined. The ore separation degrees were calculated separately for galena and sphalerite according to Equation (1.5).

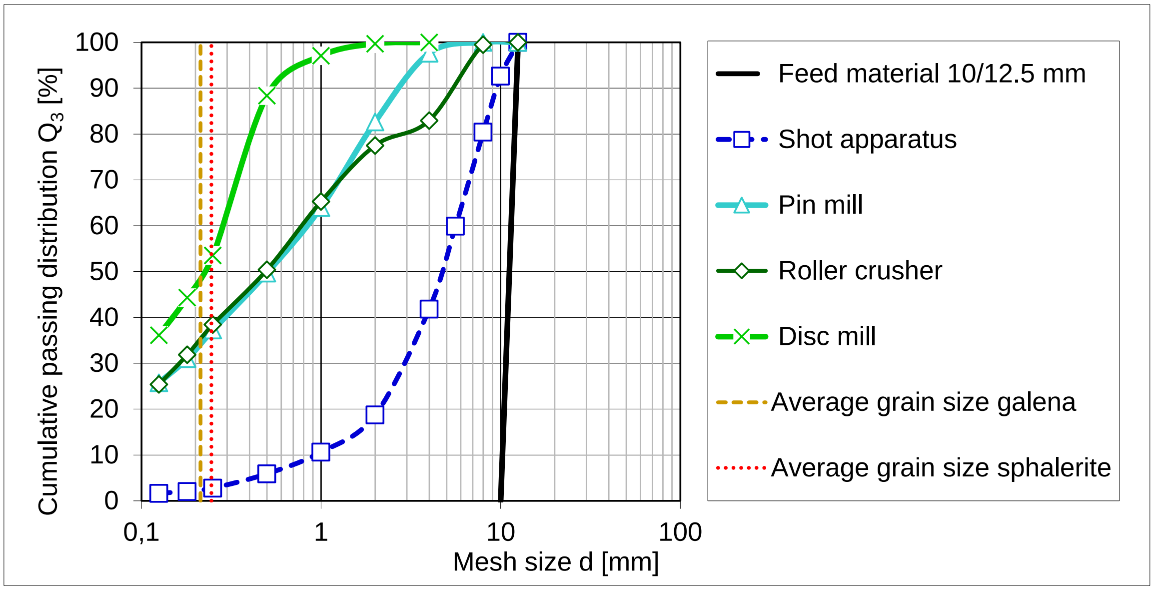


Figure 6 – Particle size distribution of the comminution products from different machines, brecciated ore

Further tests were conducted with the same material on a double roll crusher (compressive load), pin mill (impact load with high loading frequency) and disc mill (shear load with subordinated compressive load). The samples for the tests on the other machines were prepared in the same way as for the shoot apparatus. The gap of double roller crusher was set to 0.25 mm and the peripheral velocity to 2.7 m/s. The smooth rollers have a diameter of 0.45 m. The pin mill has one rotating plate with two lines of 4 pins each. Between and outside of the rotating pin lines are grizzlies with the smallest mesh size of 10 mm. The peripheral velocity at the outer pin line is 32 m/s. The gap between the discs was set to 0.3 mm and the relative velocity of the disc mill at the outer rim of the 200 mm discs was 4.5 m/s.

The reduction ratio ε is defined with mesh size d_{50} respectively at 50 % of the Q_3-functions of the feed material (F) and the comminution product (P), see Figure 2a).

$$\varepsilon = \frac{d_{50,F}}{d_{50,P}} \tag{1.6}$$

For the comminution with the shoot apparatus ε is about 2. Thereby, only about 5% (mass) of the comminution product is in the same range as the grain size of galena and sphalerite, see Figure 6. The comminution at the other machines generates a more finely disperse product. The products from the roll crusher and the disc mill show a similar particle size distribution. The finest product comes from the disc mill. The selective comminution leads to a high increase of the lead content from 0.4 % in the feed material to 4.3 % in the fractions < 0.125 mm in the product of the shoot apparatus. Here, the fraction < 0.125 mm contains only 2 % (mass) of the product, but 18 % of the galena. The coarsest fraction > 4 mm in this product contains only 0.14 % galena but still 58 % of the mass. This clear displacement of the galena into the fine fractions leads to the high ore separation degree η_{ore} shown in Figure 7 b).

The best ore separation degree for the galena enrichment can be reached with the shoot apparatus in coarse fractions (at d_t=4 mm, Figure 7b). The selective comminution effect at the pin mill starts also already at coarse fractions, increases continuously with decreasing d_t and reaches a maximum at the finest fraction, Figure 7b). The roll crusher shows a similar development, but at much lower values. All three distributions show no significant change near the grain size of the galena (Table 3). Two interpretations are possible: First, the selective comminution effect comes mainly from preferential breakage. Hence, the selective comminution leads to preferred crack propagation in the galena. In the coarse fractions dominates case 5 from Table 2. This changes with smaller fractions where case 4 dominates. This interpretation can be explained by the relative low hardness, the low toughness, the higher roughness and the big mineral clusters of the galena. Second, this kind of breakage is highly depending on the kind of load. This explains the significant differences in the ore separation degree curves for the different testing machines, which realize different kinds of load. Only the ore separation degree of the disc mill product shows a significant change in the range of the galena grain size and a constant level at smaller separation cuts. The gap between the discs (0.3 mm) seems to prevent a further comminution of the galena. Thus, a higher portion of interfacial breakage may be possible.

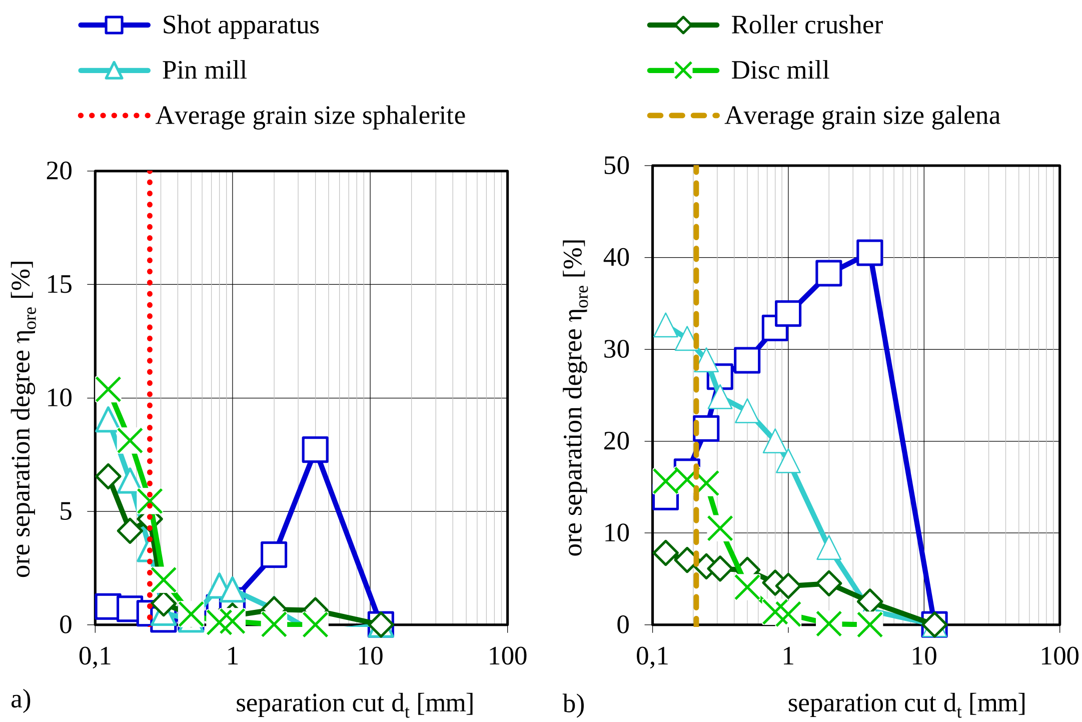


Figure 7 – Ore separation degree η_{ore} for the brecciated ore a) sphalerite; b) galena

The selective comminution effect for sphalerite is much smaller; η_{ore} reaches a maximum of 10 % only, Figure 7 a). One reason is certainly the much lower difference of the Vickers hardness value between sphalerite and calcite. The biggest changes of η_{ore} and in parallel in the effect of selective comminution can be seen in the range of the sphalerite grain size. There are again 2 interpretations: First, the selective comminution of sphalerite seems to come mostly from interfacial breakage. This can be explained by the highest hardness (Table 3) among the three minerals, the high toughness and the well rounded grain shape, quantified with a lower roughness (Table 3). The Vickers hardness difference between sphalerite and galena is much bigger than between sphalerite and calcite. That results in a much better interfacial breakage for the sphalerite in the galena in contrast to the sphalerite in the calcite. This leads to the sharp increase of η_{ore} with a decreasing d_t below the sphalerit average grain size. The sphalerite seems to need a higher liberation for selective comminution. In the range of the grain size the case 1 of Table 2 may dominate. With smaller particle sizes the case 4 may become more and more important. Secondly, the effect is nearly independent from the kind of load. The maximum of the η_{ore} for sphalerite at the shoot apparatus came from the intergrown sphalerite in the galena. The sphalerite is also enriched in the fractions (1 till 4 mm) with the selective comminution of the galena. If the sphalerite intergrown in the galena would be neglected, the distribution would be similar to the other ones in Figure 7a). The best result from the disc mill is achieved in the finest fraction.

Finally, Figure 8 gives an overview about further investigations conducted with different lead-zinc ores. Only the results for the lead enrichment are shown. The tests were done with similar machine parameters. The influence of the ore characteristics can be seen by comparing the results of the same kind of load but from different ores. For ore 1 and 3 the impact load in the shoot apparatus is the most suitable load for selective comminution with a distinct distance to the other kinds of load. Ore 2 shows no distinct difference for the results for disk mill, roller crusher and shoot apparatus. Only the pin mill affects a slightly higher value. Ore 4 is the same as already shown more detailed in Figure 7.

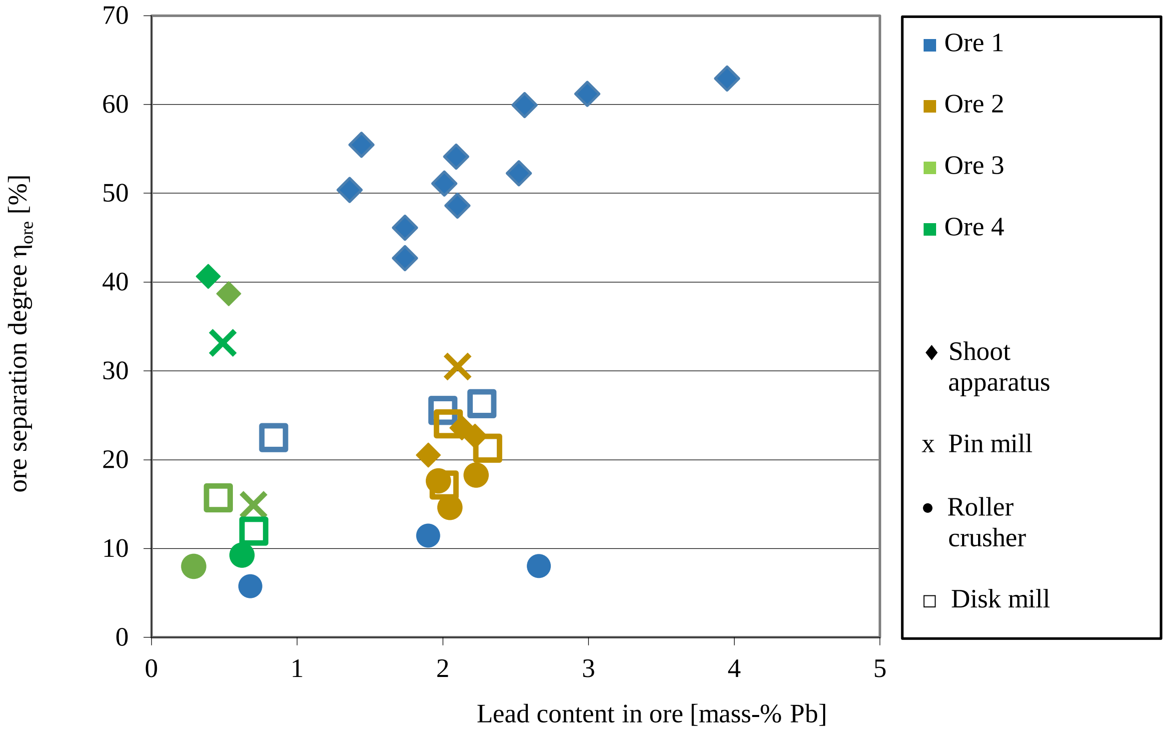


Figure 8 – Results for selective comminution from different lead-zinc ores, evaluation with maximum for ore separation degree

MATHEMATICAL-PETROGRAPHIC ORE CHARACTERIZATION

In-depth knowledge of properties of the minerals an ore comprises seems to be essential for the understanding of processes in selective comminution. Geologists use verbal descriptions of texture and structure of to interpret ore formations. Microstructural descriptions are obtained by petrographic analysis including thin or polished sections. This method has limitations as it describes the ore structure usually two-dimensional only. Moreover, until now the microstructure of raw materials (including ores) is usually still described qualitatively, whereas the search for systematic relations between relevant processing parameters and product characteristics and inherent textural attributes requires quantification of the microstructure description of raw materials. Therefore, Quantitative Microstructural Analysis (QMA) was developed to support the process engineer in selecting the appropriate type and size of machine and determining the proper operation parameters to obtain the best results (liberation, recovery, energy consumption, wear etc.) for a certain ore.

QMA is a collective term for a large number of methods for analyzing geometry and mechanical properties of microstructural constituents of an ore. Microstructural characteristics are often used for the classification of rocks. Methods for microstructural assessment have long been part of rock research, rock testing and production monitoring. The widening range of possible applications, among those for selective comminution, and the development of theoretical principles (stochastic geometry, digital image processing) have led to QMA becoming a separate field of science.

A microscope analysis of thin or polished sections is normally the basis of the QMA of an ore sample. As ore-forming minerals and ore microstructures mostly have a complex three-dimensional structure, the information that can be derived from two-dimensional cut surfaces is often insufficient for spatial quantitative characterization of the minerals and microstructures of geological materials. The three-dimensional reconstruction of minerals and ore microstructures allows a quantitative characterization of complex spatial structures typical of geological materials. The results of mathematical-petrographic ore characterization are the precondition for predicting the relationships between ore characteristics and relevant product properties or system characteristics, such as selectivity in comminution using mathematic-statistic models (Lieberwirth, Popov, & Folgner, 2014).

An analysis of the most common textures and structures of various ore types has shown that an ore microstructure can be characterized by determination of the volume percentages, the grain size distribution, grain shape, roughness, orientation, distribution and space filling (Figure 10). Based on the known stereological measurement processes in metallography, QMA as a mathematical-petrographic method for quantification of ore microstructures was developed at the Institute of Mineral Processing Machines of the TU Bergakademie Freiberg (see Figure 9) (Popov, 2007).

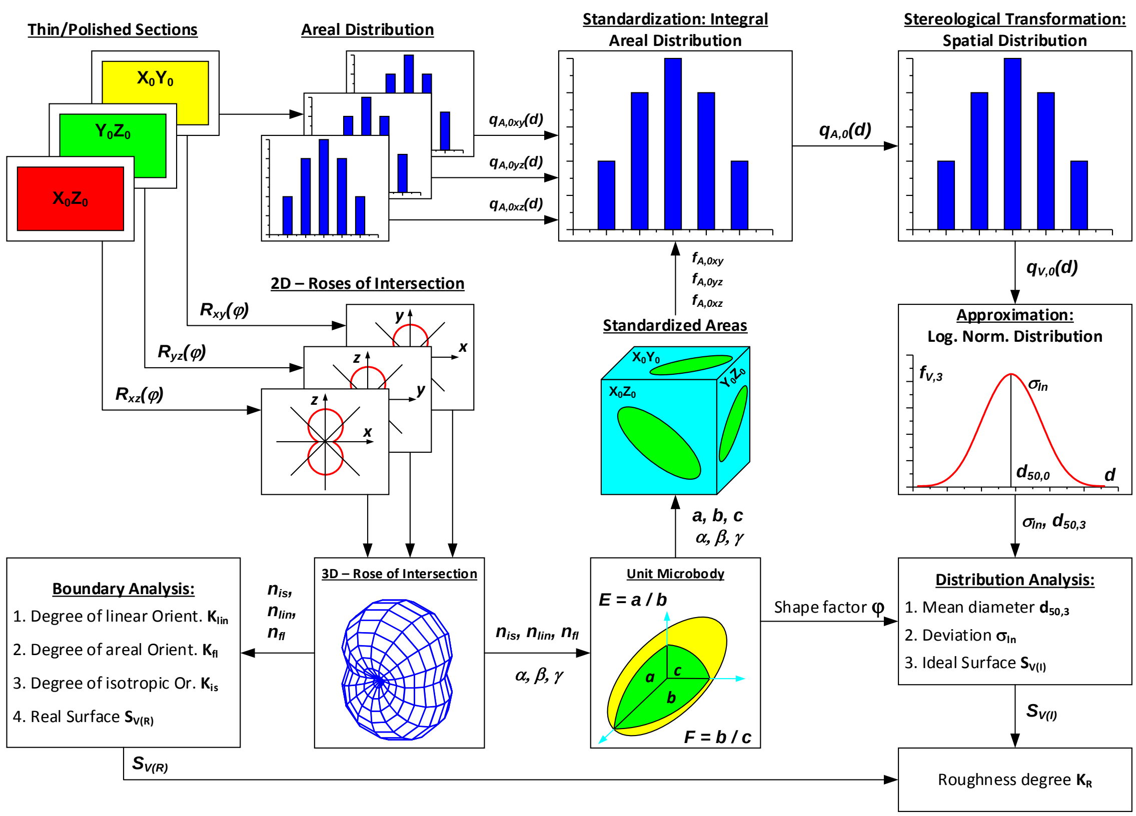


Figure 9 – Determination of mineral characteristics using QMA (Process flow-chart)

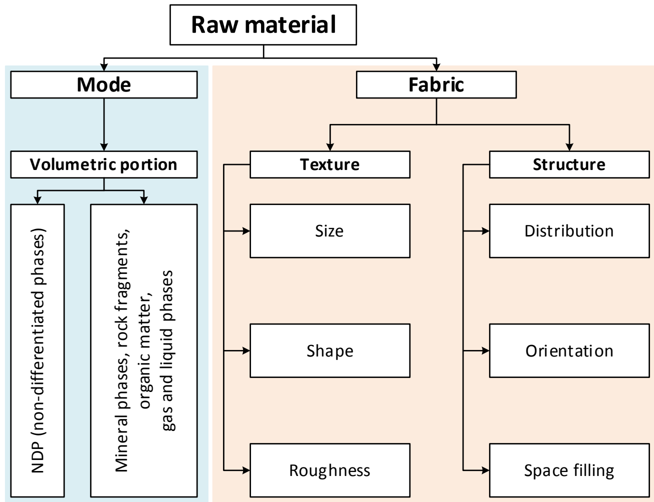


Figure 10 – Characterization of ores

It is based on the analysis of light microscopic photomicrographs of oriented thin sections cut from carefully oriented hand specimen collected from exposures in the field. Out of each hand specimen three orthogonally orientated thin sections (Figure 11) or polished sections are prepared and investigated using stereological methods.

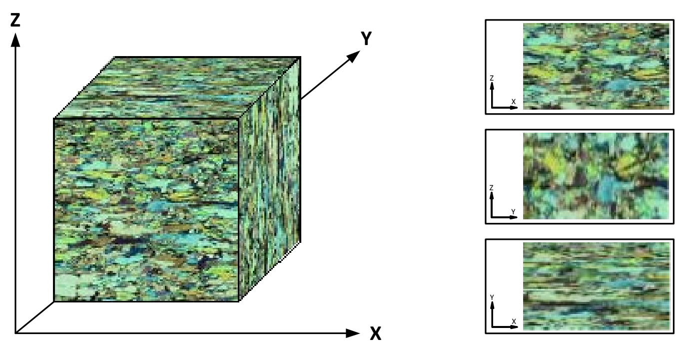


Figure 11 – Preparation of thin sections

The starting points for the quantitative microstructural analysis are the thin sections of individual samples. When a thin section is placed on the stage of a standard light microscope, the first objective of any examination is usually the identification of the minerals present. A variety of properties exhibited by each phase can be studied using the microscope.

The photomicrographs are analyzed in successive steps utilizing point counting, linear analysis (the number of intersections per unit length in different directions) as well as areal analysis (Figure 12). The data obtained for each of the three thin sections are used to establish area distribution histograms as well as so called "intersection rose diagrams". The latter represent the distribution of the number of intersections per unit length in different directions. On the basis of the 2-dimensional information of the three thin or polished sections of one hand specimen it is possible to synthesize a 3-dimensional model by a mathematical transformation and approximation. This way, one receives phase related histograms of area distributions, number of points and intersection rose diagrams for further mathematical processing of each thin section. In this manner, the microstructure of the material is quantified.

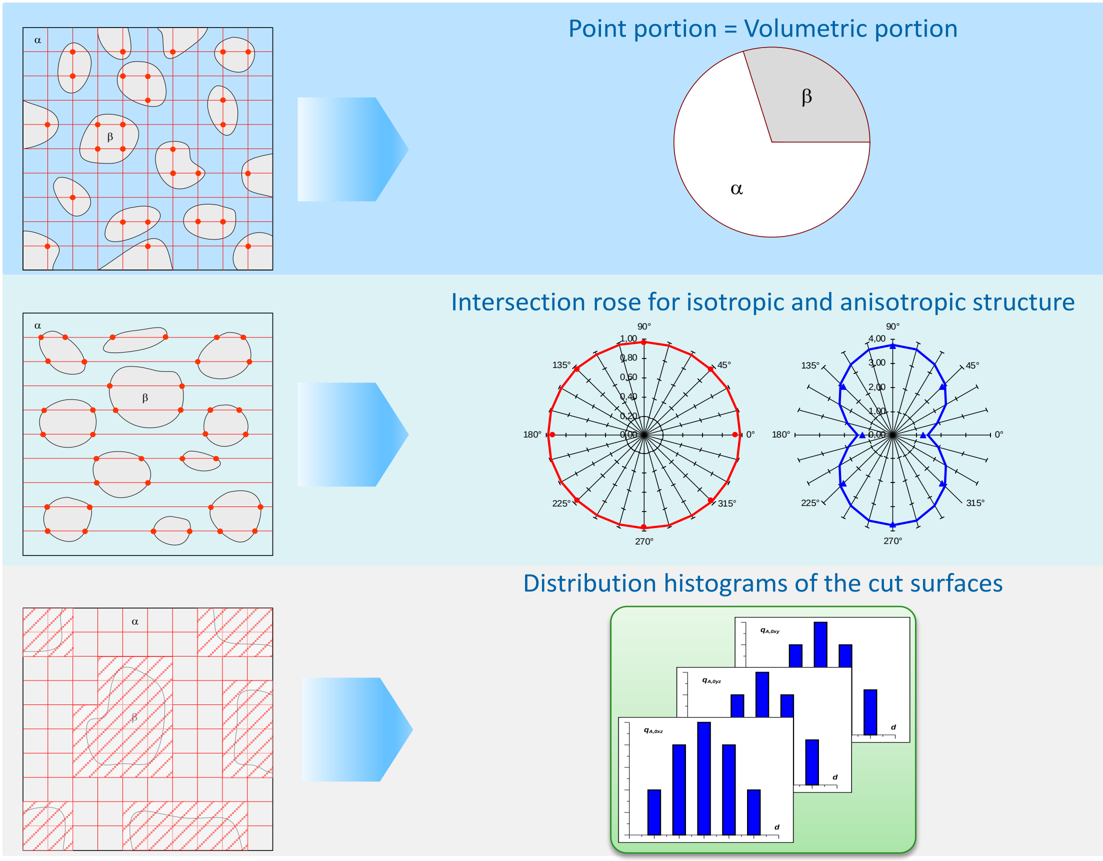


Figure 12 – Stereological methods (a – point counting, b – linear analysis, c – areal analysis)

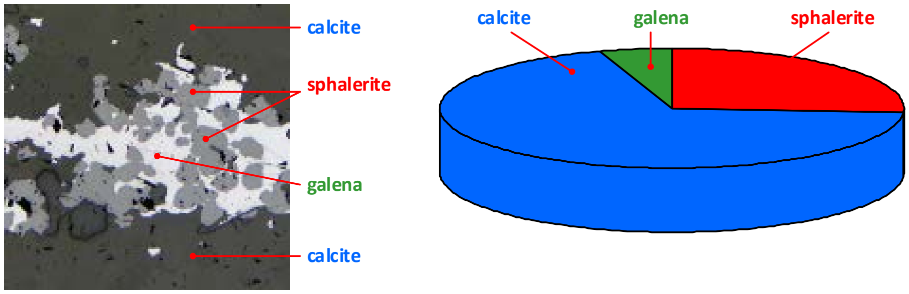
Based on the ore analysis and its mathematical formulation, ore characteristics can be calculated in the form of characteristic values oriented to terms in geology. For the characterization of the ore, characteristic data of the mode (phase, volume percentages of the phases), the phase- and ore-related characteristic data of the texture (size, shape, roughness) as well as the structure (orientation, distribution, space filling) are used.

A quantitative analysis of the ore microstructure prior to breakage can provide valuable information regarding the types of textures and mineral assemblages that are likely to produce various particle sizes and characteristics that are favorable or unfavorable for mineral processing.

Volume percentages of the phases – starting point for the evaluation of selectivity

The volume percentage of a mineral group is defined as the quotient of the sum of the volume of the individual mineral grains in the sample and the sample volume and can be most easily determined with the help of the point counting method (Glagolev, 1934). The percentages of the constituents are generally shown in the form of a table (Figure 13).

Volume percentage or derived mass percentage of the ore constituents before a certain comminution step serve as reference for any evaluation of selectivity achieved. Even comminution products may be investigated using this method after embedding the particles in epoxy.

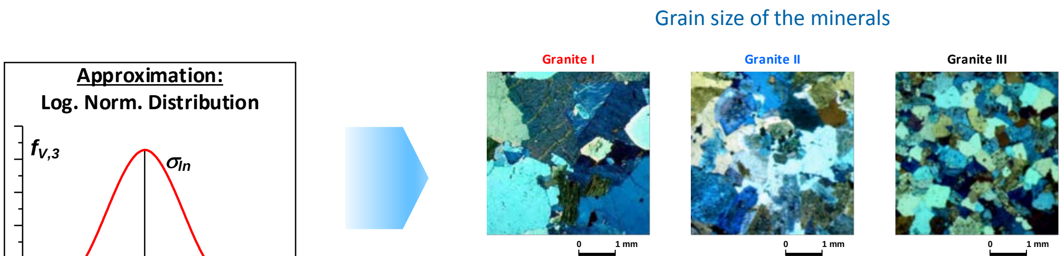


Phases	Kind	Unit	sphalerite	calcite	galena	Gas	NDP
Volumetric Portion	ε_V	%	4.7	94.9	0.4	0	0

Figure 13 – Mineral composition (e.g. granite from Meissen, Germany)

Grain size

Knowledge on the grain sizes in an ore is essential for judging the potential for selective comminution since differences in particle size after comminution are usually the simplest way to separate an enriched fraction by simple classification. The individual microbodies are polydispersed in the ore microstructure so that the size of the micro bodies has to be approximated with a size distribution function. Accordingly, the distribution density of the microbody diameter d of a logarithmic normal distribution function can be described with a median $d_{50.3}$ and a scatter parameter σ_{ln} (Figure 14).



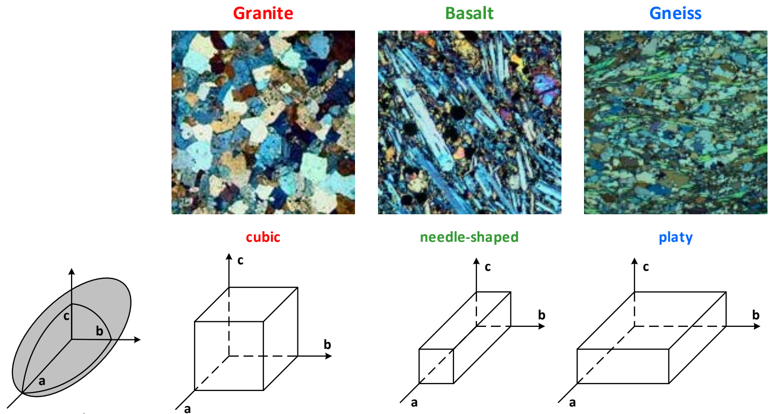
Rock characteristic features				Phase related features		
				Granite I	Granite II	Granite III
Size	Mean diameter	$d_{50,3}$	mm	2,837	1,494	0,551
	Standard deviation	σ_{ln}	-	0,433	0,373	0,259

Figure 14 – Grain size of the minerals (e.g. granites)

Grain shape

The shape is a geometric particle characteristic, i.e. a characteristic that has to take all three dimensions into account (Unland & Folgner, 1997). The shape of a micro body can be regarded approximately as an ellipsoid with the main axes a, b and c, where $a \geq b \geq c$. The relationships of the main axes to each other describe the form of the micro body (Figure 15).

For the consideration of selectivity in comminution the grain shape may have an impact on the sensitivity of an ore constituent against certain loads during comminution. A mineral forming mainly platy particle might preferably be ground by applying shear loads supporting the platy shape. Then, an air classifier could support the selectivity in classification, of course considering constraints which may be imposed by the density of the various minerals.



E=a/b

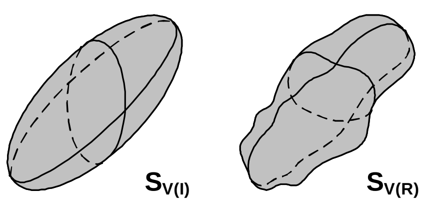
F=b/c

Rock characteristic features			Phase related features		
			Granite	Basalt	Gneiss
Elongation	E	-	1,095	3,908	1,000
Flatness	F	-	1,061	1,365	1,834

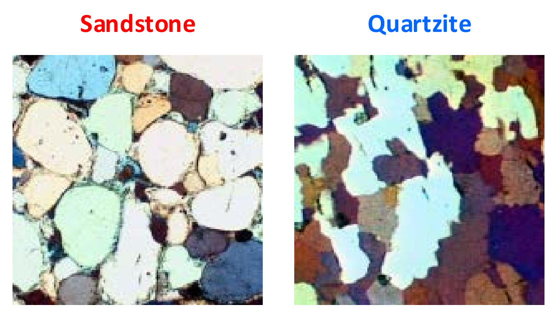
Figure 15 – Different grain shapes, variation of the main axes

Roughness

The roughness can be recorded statistically in thin sections and characterized with indices. The roughness K_R is defined as the ratio of the difference between the "real" surface area $S_{V(R)}$ and the "ideal" surface area $S_{V(I)}$ to the "real" surface area $S_{V(R)}$ of the individual phases (Figure 16). The calculation of the "ideal" surface area $S_{V(I)}$ is based on the microbody size distribution with consideration of the microbody shape and the phase volume percentage. The "real" surface area $S_{V(R)}$ is calculated from the 3-dimensional rose of intersections.



$$K_R = \frac{S_{V(R)} - S_{V(I)}}{S_{V(R)}}$$



Rock characteristic features			Phase related features	
			Sandstone	Quartzite
Quartz	Qtz	%	100	100
Mean diameter	$d_{50,3}$	mm	0,289	0,388
Roughness degree	K_R	%	5	29

Figure 16 – Degree of roughness of the minerals

The surface area per unit volume is especially useful as it is concerned with the determination of contacts between phases within ore. This parameter is easily calculated from the number of intersections per unit length of test line applying one of these stereological relationships.

The outer shape of the microbodies largely determines the character of the microstructure. In selective comminution, roughness may play an important roll through its influence on the shear strength of an ore, in particular along the grain boundaries.

Orientation

The linear analyses have to be done with varying angles (usually by turning the thin section by rotating the stage clockwise by 15 degrees with each step). With every new position all the intersections of lines with grain boundaries have to be counted. The result contains very valuable information in the form of 2D-intersection roses

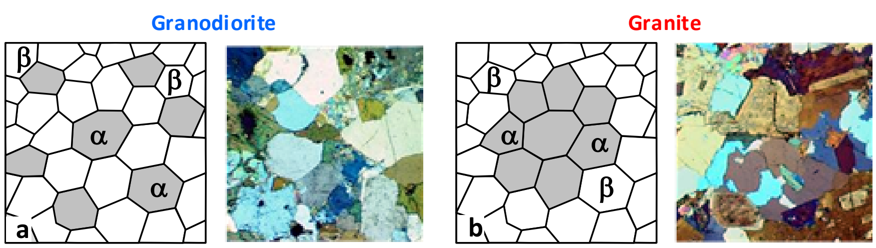
From three 2D-roses of intersections orthogonal to each other, with an approximation, the parameters of a spatial rose of intersections (n_{is}, n_{lin} and n_{fl}) and their orientation angle in the space (α, β and γ) are calculated. The spatial rose of intersections:

- of an ideally isometric boundary surface system is a sphere with the diameter n_{is},
- of an ideally linear-oriented system is a toroid with the diameter n_{lin} and
- of an ideally area-oriented system is a double-sphere with the diameter n_{fl}.

A spatial rose of intersections of an oriented microstructure is the superposition of the roses of intersection of ideal boundary surface systems. From the parameters of the spatial rose of intersections, the orientation degrees (K_{is}, K_{lin} and K_{fl}) of a spatial arrangement (percentages of linear- and area-oriented as well as non-oriented boundary surfaces) can be derived.

Distribution

Micro bodies of a phase can be evenly distributed in the space, but they can also form clusters in which the micro bodies of a phase share boundary surfaces (Figure 17). The degree of clustering C is defined as the quotient of the sum of the boundary surfaces between the grains of the same mineral group and the total boundary surface of this mineral group. The degree of clustering can be calculated with the help of linear analysis. In selective comminution the knowledge on clustering is important to predict the size fraction which might show an enrichment of a certain ore constituent.



Rock characteristic features			Phase related features	
			Granodiorite	Granite
Quartz	Qtz	%	35	32
Feldspar	Fds	%	41	55
Mica	Mc	%	24	13
Mean diameter	$d_{50,3}$	mm	0,518	0,437
Degree of clustering	C	%	16	49

Figure 17 – Distribution of the microbodies

After evaluation of all mineral groups present in the ore, the results of the evaluation were summarized in the data sheet "Ore characteristics" (Table 4). QMA permits mathematical derivation of ore characteristics in the form of characteristic values. These ore characteristic values are first determined independently and for all applications, and can then be interpreted for use with the specific application. The big advantage of this method is that the quantitative characteristic values of an ore sample always remain the same, only their application specific interpretation changes.

Table 4 – Data sheet "Ore characteristics", brecciated ore type

Raw Material		Kind: Sphalerite-galena				Phase related features			Raw material features
		Deposit: Hermsdorf		Location: Saxony, Germany					
Mode		Phases		Kind	Unit	galena	sphalerite	calcite	Σ Microbodies
		Content	Volumetric Portion	ε_V	%	0.4	4.7	94.9	100
Fabric	Texture	Size	Mean diameter	$d_{50,3}$	mm	0.213	0.245	-	0.232
			Deviation	σ_{ln}	-	0.314	0.360	-	0.341
		Grain surface	Specific surface	S_V	mm^2/mm^3	31.460	30.470	-	30.880
		Shape	Elongation	E	-	1.371	1.365	-	1.367
			Flatness	F	-	1.000	1.000	-	1.000
		Roughness	Roughness degree	K_R	%	71	56	-	62
	Structure	Orientation	Degree of linear orientation	K_{lin}	%	23	22	-	15
			Degree of areal orientation	K_{fl}	%	0	0	-	0
			Degree of isotropic orientation	K_{is}	%	77	78	-	85
		Distribution	Degree of clustering	C	%	0	0	-	0
		Space filling	Space filling degree	ε_{VF}	%	-	-	-	100

The test results deliver mathematical-statistical relationships between the ore properties (e.g. grain size, grain shape, mineral intergrowth, etc.), selected machine parameters (e.g. stress loading rate) and the achievable product parameters (particle size and particle shape distribution). Not only could a weighting of the influence of the different ore characteristic values on individual target values be established, mathematical statistical relationships between selected target values and the various design and operating parameters could be proven as well. The ore characteristic values permit an estimation of the ore with respect to selectivity in comminution, crushability, product particle shape, wear, and energy consumption.

CONCLUSIONS

The main aim of selective comminution in pre-concentration is the separation of valuable ore constituents from waste mineral particles, thereby relieving the subsequent beneficiation process. The different comminution behaviour of ore constituents is exploited to generate a product which shows an enrichment of the valuable component in certain fractions. With particle size being often the preferred parameter to differentiate these fractions, a simple classification step may be sufficient in those cases to separate a waste fraction and produce a pre-concentrate.

In order to select the appropriate kind and magnitude of load to be applied and thus the most suitable comminution machine, the mineral has to be investigated. With the QMA the paper presents a proven scientific approach to characterise ores in a mathematic way oriented to the terms of geology to predict their comminution behaviour. By determining the texture (grain size, grain shape, roughness, specific surface) of the minerals and their structure (orientation, clustering) in an ore in combination with further parameters such as Vickers hardness, toughness, $I_{s(50)}$ strength index or density, a model is generated to support the selection of the comminution machine and the operation parameters of the system.

First results in this new field of scientific investigation into selective comminution are presented. Parameters are defined to quantify selectivity S and ore separation degree η_{ore}. The selective comminution factor SZ quantifies the change in selectivity between feed and product materials.

Test results with lead-zinc-ores confirm that selective comminution requires a system approach, comprising the comminution behavior of the ore under a certain load, the type of comminution machine and a number of operation parameters of the system. The approach is a starting point. Further investigation is required to better understand the influence of certain ore characteristics on its comminution behaviour under various loads or to relate the new parameter sets to indices widely used in the resource industry nowadays such as UCS or the various Bond indices. The new approach was applied and tested with a number of ores already. Future investigations with materials from other sources, however, will certainly help to refine the model.

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