GOSPODARKA SUROWCAMI MINERALNYMI

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Aspects of comminution flowsheets design in processing of mineral raw materials

Introduction

Comminution circuits constitute the integral part of raw material processing and also the basis of mechanical processing of ore. The efficiency of ore pretreatment circuits in fact determines the effectiveness of the whole concentration process because it enables the suitable liberation of useful minerals from ore. The useful mineral liberation is caused by achieving the comminution degree, suitable for a given type of material, together with aiming at avoiding the feed over-grinding. To make the designed circuit efficient from the technological and economic point of view, two key issues need to be considered: the material characteristics and the suitable selection of modern crushing devices. A crucial role here is played by the type of material because its physical-mechanical properties determine entirely the run of comminution process and the technological circuit should be adjusted to those feed properties. Comminuting devices are significant for their technological efficiency, measured by weight recoveries of respective size fractions of crushing products, and the economic one that can be determined with the use of energy-consumption of a single crusher or an entire circuit.

Considering the above, in basic investigations over pretreatment circuits of ore concentration technology, the following aspects should be taken into consideration:

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a) the multi-stage comminution circuit should be investigated, and the configuration of stages increases the performance efficiency, (products quality), leading to decreasing of the energy consumption and waste generation,
b) HPGR devices will be operating on the second or third crushing stage in the circuit. Other energy-efficient crushing devices can be also considered for application, for example in aggregate production circuits,
c) Physical-mechanical parameters of the material and the methods of further industrial utilization of obtained products will be also considered.

Energy considerations. Industrial comminution processes are energy consuming. In the United States approximately 30% of total energy costs consumed in mining industry are used up for comminution (indices for 2005). It causes that the comminution energy makes around 0.39% of total national energy consumption. In Canada, in turn, the respective index comes to nearly 2%, similarly in the Republic of South Africa. In Australia comminution consumes roughly 1.5% of total national energy (Thromans 2008; Maxton et al 2003). It should be pointed out that the countries mentioned above are the leaders in the application of modern mining technology. In recent years the values of energy consumption indices have generally decreased as a result of the application of modern processing technologies and devices, especially in ore preparation circuits. In many other countries the ore pretreatment is based on the older technologies which causes the increased energy consumption by comminution processes. As a result of the above, it is estimated that industrial comminution processes can absorb from 3 to 5% of global electric energy consumption.

The article presents the issues concerning modeling and simulation of comminution circuits performance in beneficiation processes of mineral raw materials.

1. Problem identification

Comminution is the subject of many scientific and industrial investigations all over the world. Their main aims are the proper selection of modern crushing devices for processing of mineral raw materials and waste treatment and the replacement of outdated equipment, in order to obtain the best possible products together with the highest technological and economic benefits. In recent years a larger interest in raw materials, especially coming from low grade ore bodies, can be observed. It enforces a need of suitable arrangement of scientific research over comminution processes which should produce a considerable amount of results in the field of optimization during the modernization of recent circuits or designing the new processing plants.

For the most of mineral raw materials a widely understood comminution (including the washout process) consists in the operation starting the feed pretreatment process for its further utilization in downstream processes. Considering the material petrographic and mineralogical structure and technological aims of the crushing process one should head towards decreasing the energy consumption, which is enormous in comminution operations.

Finally, the optimal utilization of material, understood as avoiding the overgrinding or insufficient liberation of useful minerals, needs to be achieved as well. The above statement is based on two important facts, confirmed theoretically and experimentally:

- within the scope of primary micro-cracks formation in downstream processes of crushing and grinding, the activated material comminutes with lower energy consumption,
- the finer material consumes less milling energy, achieving the desired particle size (energetic balance according to the Bond scheme).

The general comminution circuit is presented in Fig.1. Each crushing stage is preceded by a classification operation, which reduces the material mass stream directed to the crushing, and as a result the energy demand also decreases. On next crushing stages there are machines that were selected taking into account material properties.

Devices listed in Fig. 1 are examples of possible applications. Utilization of HPGR for the Polish ore concentration technology is a proposal that has not been industrially implemented so far, but should be considered and investigated thoroughly. The HPGR technology has many advantages, like increased micro-crack generation, lower energy-consumption, finer products, that will be commented in the next paragraphs, together with the characteristics of comminuted material.

The desired performance of the comminution circuit is an issue, and the aim could be achieved utilizing mathematical modeling and simulation techniques. One of methods of

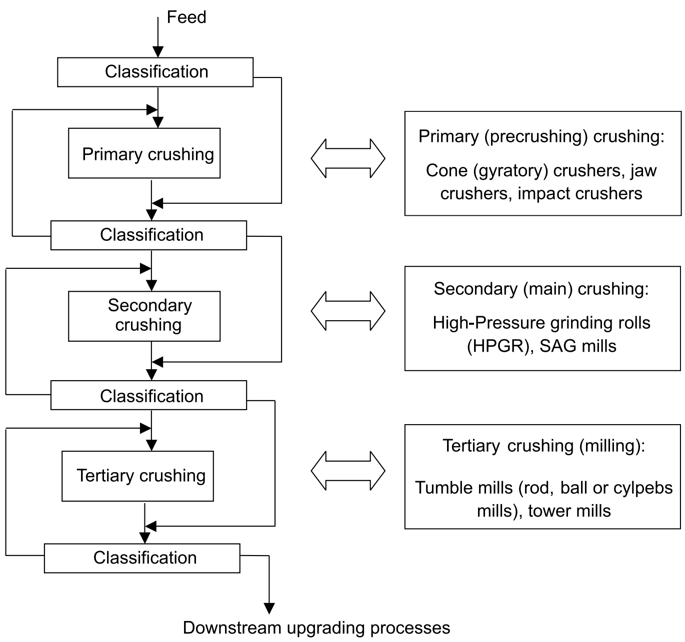

Fig. 1. Overall flowsheet of the comminution circuit

Rys. 1. Ogólny schemat technologicznego układu rozdrabniania optimal solution searching, i.e. the selection of technical and technological parameters of devices, can be constituted by the evolutionary programming (Tumidajski et al. 2009). Other optimizational software can be also utilized, especially based on the non-linear programming theory (Skorupska et al. 2007; Skorupska, Saramak 2005).

2. Basic characteristics of material grindability

The mineral raw material is described with different resistance (Poisson number, Young module) and grindability (Bond's and Protodiakonov's index) indices that are connected mainly with the particle size and petrographic and mineralogical structure. The single particle crushing test analysis can determine basics for designing the mathematical models of the comminution process. Chosen issues of the problem are then presented below.

Internal stresses, occurring in a particle as a result of crushing forces influence, lead to grain disintegration, after exceeding the critical value. The disintegration resistance of the particle, which is pressed pointwise, equals:

$$\sigma = k_\sigma \frac{P}{d^2} \tag{1}$$

where:
P – value of disintegration force,
d – particle diameter,
k_σ – proportionality coefficient.

Specific comminution energy corresponding to the mass unit of the particle is defined as the elasticity energy accumulated in the grain during the compression until the particle disintegration, and is defined by the following formula:

$$W = \frac{0.897}{\rho} \pi^{2/3} \left(\frac{1-v^2}{E} \right)^{2/3} \sigma^{2/3} \tag{2}$$

where:
ρ – particle density.

While measuring the particle disintegration resistance, huge scatter of results can be observed, moreover, theoretical resistance, resulting from disintegration of atomic bonds in the perfect crystal, is 10^2–10^4 times larger than real resistance. In order to explain that, Griffith presented a hypothesis that in each solid a primary micro-crack exists that weakens the sample durability. The resistance of the solid weakened by a lenticular crack with length $2a$ equals:

$$\sigma = \sqrt{\frac{2E\gamma}{\pi a}} \tag{3}$$

where:

γ – free surface specific energy.

For stresses σ larger than critical, the crack increases and the particle is disrupted. In fact, for the disruption, a more than one single crack should exist in a particle. Moreover, in each particle or sample the distribution of crack's size, can be observed. A crack influencing the sample durability at a given stress is called the active crack. For the above reasons, the disintegration resistance is the random variable with Weibull's distribution.

From the authors' experience, gained at single particle compressing comminution of limestone and porphyry grains (Brożek 1996; Brożek, Tumidajski 1996), it results that when the distribution of disintegration resistance for particles of the same mineral is presented in relationship $\sigma/\overline{\sigma}$, i.e.:

$$P_r = 1 - \exp\left[-c\left(\frac{\sigma}{\overline{\sigma}}\right)^m\right] \tag{4}$$

then distribution is not the function of the praticle size. In formula (4) m denotes so-called Weibull's modulus, $\overline{\sigma}$ – the average resistance of particles in given size fraction empirically connected with Weibull's modulus (Brożek, Oruba-Brożek 2003), and c is the constant, connected by analytic relationship with Weibull's modulus. The experiment shows that the particle size distribution in the single grain crushing tests in the press can be approximated with high accuracy by means of the following function (Brożek, Tumidajski 1996; Brożek 1996):

$$F(x) = ax^b e^{kx}$$

where x is a variable determining the relationship of the product grain size d to the arithmetical average from the border feed grain size D, namely $x = d/D$, while a, b, k are empirical parameters dependent on grain's disintegration resistance. Then, on the basis of comminution results, it is possible to predict the particle size distribution and the energy consumption in the model of stratified comminution. Next, if the HPGR is utilized for mechanical activation of the material (micro-cracks formation), then it is also possible to predict the process efficiency and to estimate the energy savings.

The process of slow compression of the material layer is analogical to the crushing process in HPGR. The analysis results of this stratified compression to some extent enable the assessment of the HPGR process, especially when they are additionally combined with other indices (like Bond's or Protodiakonov's index). Standard energy index is determined by the Bond's work index W_i (Lowrison 1974l Brożek et al. 1995). In industrial conditions, grindabilities of various raw materials show huge scatter of values. In the carbonate flour production sector both relatively soft limestones, with W_i value about 7 kW·h/Mg, and hard clinkers, with W_i value reaching 20 kW·h/Mg, occurs. It involves a distinct approach for each case. A supplementary description can be made with the use of other indices like Poisson's number or Young's modulus. Additionally, the mineralogical composition, abrasiveness, or useful mineral liberation degree are significant. HPGR products demonstrate a reduction of Bond's work index value which leads to the decrease of the grinding process energy consumption.

3. Basics of HPGR

From the point of view of physical-mechanical particle properties, the most efficient process of decreasing in its particle size takes part when the material is subjected to a pressure, whose volume is increased slowly (not rapidly) and steadily. Such a manner of pressure application causes that in the first stage the liberation of rock particles which build the ore takes place. Further increasing in pressure volume causes a compression of the material and crack formations in bigger particles along their structure. In the last phase (highest volume of pressing force) the micro-crack formations within the particle structures can be observed. In such a comminution process a significant disorder of the particle structure takes place, yet the unfavourable phenomena of feed overgrinding and the generation of undesirable in downstream beneficiation operations (like flotation) the size fraction under 0.063 mm, are not observed. Additionally, the energy loss is minimized and the noise and heat emissions are considerably reduced. The described manner of comminution takes place exactly in roller presses, it is then essential to introduce the high-pressure grinding technology to comminution processes. This technology has been present in ore concentration circuits since mid nineties and the development of HPGR industrial application is the worldwide trend. The investigations over crushing technology constantly improve and current devices reached their technical development at the beginning of the present century (Morley 2003). The HPGR technology is nowadays the most efficient method of crushing hard ores of base and precious metals within the scope of energy-consumption.

The theoretical bases of the phenomenon occurring during a high-pressure comminution were precisely defined and worked out in the literature (i.e. Schoenert 1988), but a more common application of the technology in harder ores processing had to wait until the presses were technologically modernized. Up to date HPGR optimizational projects treated marginally or passed over issues of physical-mechanical properties of the feed. A relatively small amount of optimizational works can be found in the literature in English. The paper (Schneider et al. 2009) deals with the problem of HPGR crushing results modeling with the use of four-parametric distributions. In the work the feed influence was not generally considered. Some works summing up the results of the HPGR industrial application in specific mines (Maxton et al. 2003), where the presented investigations usually concern the individual conditions of the processing plant. In Polish in recent years a few scientific papers were produced, concerning high-pressure technology in ore comminution (Saramak 2010; Naziemiec, Saramak 2009; Gawenda 2009; IMMB investigations 1999). In the plant scale there are problems with achieving the satisfactory level of throughput level and desirable products quality, like in some Polish cement processing plants (Naziemiec, Gawenda 2006).

The HPGR industrial application in mineral raw materials comminution is beneficial from the technological and economic scope, considering the following issues:

- lower unit energy consumption in comparison to tumble mills for roughly 10 to 40%, according to different investigations (Rule et. al 2008; Pahl 1993; Fuerstenau et. al 1991),
- lower running costs of HPGR, also lower capital cost compared to conventional circuits (i.e. the circuit: crusher-screen-classifier-rod mill-ball mill) as well as to SAG and AG mills (due to the low footprint of the installation), (Morrel 2008),
- a selective ore comminution, which eliminates the overgrinding effect for coarser mineralized useful components, otherwise the overgrinded minerals usually pass to tails,
- a selective grinding of carbonate raw materials, preventing the overgrinding for flour production in the narrow size fraction from 0.4 to 1.2 mm,
- high efficiency of the grinding process (greater comminution effect),
- easily maintained stable throughput level and the capacity of the device,
- possible wet and dry comminution.

Significant energy savings can be obtained by the application of the HPGR instead of tumble mills or by combining the roller press with the ball mill. The principle of operating of such system lies in the two-stage grinding, utilizing the fact that the smaller particle size of the ball mill feed, the lower grinding energy consumption. The energy savings in roller press, in turn, result from comminuting under the high-pressure exerted by counter-rotating rollers on the material's layer. HPGR's are also very efficient devices from a technological point of view. In roller presses the most favourable mass recovery of product fraction size (0.1–1.0 mm) can be obtained, as compared to the other crushing devices. It is a very desirable feature of the product, both in the ore processing industry (limitation the material overgrinding) and the carbonate flour manufacturing, used as fillers in plaster mass production. HPGR's have a lower index of the unit energy consumption, as compared not only to the tumble mills (rod or ball mills), but also to the tower mills (Kalinowski 2006; Kurdowski 1998).

High-pressure grinding roll presses can be easily applied both in modernized comminution circuits and in newly built plants, where they can be used for secondary or tertiary crushing. Amongst many advantages of HPGR application, apart from the energy savings, the following ones should be mentioned: easy adaptation to different crushed materials (variable pressure and roller speed values), beneficial particle size distribution of the product, relatively small footprints, low noise emission, low dust emission. Beyond the application in hard ore comminution, roller presses can be also used in carbonate flours production, cement and lime industry and others. Their common recent application in cement industry (like Russia, Turkey, India, Egypt, Lithuania, Bulgaria and others) is caused by the fact that the press crushing products have considerably increased the grindability value, what makes the growth in operating efficiency and decrease in grinding energy in ball mill the next crushing stage (Kalinowski 2006).

4. Flowsheet modeling

The proper design of the pretreatment circuit involves the investigation leading towards the circuit work optimization through working out suitable mathematical models. These models, based on technological work parameters of crushing devices and the material characteristic indices (mainly grindability), will determine the values of technological parameters for the circuit performance. It is possible by the application of multistage statistical analyses and evolutionary algorithms, especially genetic algorithms (Tumidajski et al. 2009).

The main aspects of mathematical comminution models should include:

- Conditioning the choice of the specific process (or device) on the feed characteristics.
- Making the determination of operations and devices sequence dependent on ore properties and technological aims.
- Performance optimization of individual devices, processes and the total technological circuit.
- Overall work assessment (optimization) of designed multi-stage comminution circuit.

The elaborated models should enable the optimization of raw material pretreatment circuits performance in downstream processes to be carried out from the scope of:

- Energy consumption.
- Technological aim executing (suitable qualitative and quantitative characteristics of products).
- Environmental protection demands (rational resources economy, minimising of tailings generation, utilization of human or process waste deposits).

The optimization of HPGR comminution circuit performance should be then assessed from the technological (mass recovery of the product with desired graining), economic (specific energy consumption of the HPGR/circuit) and environmental (the rational resources economy) points of view.

Summary

After designing the mineral raw material pretreatment circuit in downstream processes, its performance assessment (King 2001) should be done as well. The assessment performed with the use of the work simulation should include the mathematical model implementation which takes into account technical and technological parameters of machines. The work simulation enables the assessment (verification) of performance results to be done with the use of determined target function, considering energetic, technological and environmental scopes. The approach helps us to find optimal operating conditions by means of evolutionary algorithms (Tumidajski et al. 2009). Helpful in the matter would be the worked out principles of prediction the grain composition of crushers' comminution products, considering weight recoveries of given size fractions and irregular grain contents. The predictions will be based on making the parameters in the particle size distribution approximation formula dependent on both material and crushing device characteristics. For a jaw crusher, for example, the following parameters can be considered: working chamber filling level, the width of gap, jaw jump and frequency, type of jaw grooving, while for the roller press – the operating pressure and speed of rollers.

Optimizational investigations on comminution circuits are constantly conducted, and the results contribute to better understanding of the comminution issues and more common implementation of roller presses or other energy-efficient devices into a plant scale. Adjusting the crushing devices into existing operating conditions and material properties includes determination the economic threshold of implementation and their position in downstream pretreatment circuit (i.e. roller presses for secondary or tertiary crushing, tumble mills for tertiary crushing or grinding etc.). The determination of all relationship is mainly connected with characteristics of feed and comminution products. High-pressure grinding rolls can be especially applied into base and precious metal ores processing, cement industry or carbonate flour production sector.

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ASPEKTY PROJEKTOWANIA UKŁADÓW ROZDRABNIANIA W PRZERÓBCE SUROWCÓW MINERALNYCH

S ł o w a   k l u c z o w e

Układy rozdrabniania, modelowanie, optymalizacja, prasy walcowe

S t r e s z c z e n i e

Proces przygotowania rud do wzbogacania opiera się na odpowiednim rozdrobnieniu nadawy w celu uwolnienia minerałów użytecznych. Przemysłowe rozdrabnianie jest procesem najbardziej energochłonnym w całym układzie wzbogacania, determinuje uzyskiwane efekty technologiczne, zatem odpowiednio zaprojektowany układ rozdrabniania ma kluczowe znaczenie z punktu widzenia m.in. ekonomiki zakładu przeróbczego. Odpowiednio zaprojektowany układ opiera się na nowoczesnych urządzeniach rozdrabniających, w szczególności na wysokociśnieniowych prasach walcowych. Analizując układy rozdrabniania ze względu na dobór maszyn autorzy nadają także kluczową wagę kwestii charakterystyki nadawy do procesu przeróbki ponieważ obydwa aspekty są podstawą doboru układu rozdrabniania do realizacji konkretnego zadania technologicznego. Autorzy w artykule rozważają wszystkie możliwe problemy nowoczesnego podejścia do zagadnień modelowania i optymalizacji układów rozdrabniania surowców mineralnych w celu maksymalizacji efektów technologicznych (odpowiednia jakość produktów), energetycznych (redukcja energochłonności procesu) i środowiskowych (optymalne wykorzystanie surowca).

ASPECTS OF COMMINUTION FLOWSHEETS DESIGN IN PROCESSING OF MINERAL RAW MATERIALS

K e y   w o r d s

Comminution circuits, modeling, optimization, high-pressure grinding rolls

A b s t r a c t

The ore pretreatment process is based on suitable comminution of feed in order to liberate the useful minerals from ore. Industrial comminution is the most energy-consuming process in the entire concentration flowsheet which determines the obtained overall technological effects. The properly designed comminution circuit is therefore of crucial importance from the point of view of the economics of the concentrator. The suitably designed system is grounded on modern comminuting devices, particularly on high-pressure grinding rolls (HPGR). Together with the examination of the comminution circuit from the point of view of devices selection, the authors give a key-role to the feed characteristics issues, because these both aspects are the basis of the selection of the comminuting circuit ready to carry out the technological task. The authors take into consideration all possible aspects of a modern approach to modeling and optimization of mineral raw materials comminution flowsheets in order to maximize the technological (desired quality of the product), energy (reduction of energy-consuming of the process) and environmental (optimal utilization of the raw material) effects.