Physicochem. Probl. Miner. Process. 46(2011) 145-154

journal homepage
www.minproc.pwr.wroc.pl/journal/

Physicochemical Problems of Mineral Processing

Index No. 32213X ISSN 1643-1049

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MILLING KINETICS OF CHOSEN ROCK MATERIALS UNDER DRY CONDITIONS CONSIDERING STRENGTH AND STATISTICAL PROPERTIES OF BED

Received May 15, 2010; reviewed; accepted July 15, 2010

The article presents the results of investigations concerning the analysis of milling kinetics of chosen rock materials taking into consideration their strength properties. Investigations were carried out for a mill operating on a semi-industrial scale. Milling was conducted in a periodical mode using grinding media differing in diameters. Mineral raw materials differing in terms of crystallographic structure were subjected to grinding. The process of milling was carried out for quartzite, granite and greywacke. Input fraction of ground material was of size 5 – 8 mm. Grain strength from particular size fractions and its influence on the process kinetics were determined. Grinding rate of particular size fractions and basic parameters used in the theory of statistical moments were calculated.

keywords: ball mill, specific grinding rate, moments theory

1. INTRODUCTION

The mechanism of grinding is based on division of solid grains into grains of smaller size and the process is caused by internal or external loadings, exceeding the strength limit and damaging atomic and molecular bonds (Blumenauer and Pusch, 1981). As each material cracking in the zone of loading precedes deformation, the process of grinding requires a supply of indispensable quantities of energy, this quantity being conditioned by deformation, tensile properties of deformed material and the type of loading. Grain cracking requires overcoming cohesive forces in cracking planes (exposed to external forces) and increasing the distance between elementary particles. The phenomenon under scrutiny may be brought about by

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normal stresses – tensile or tangential stresses.

The process of grinding in ball mills is determined by a complex character of grinding media influence on the ground material. The main geometrical dimensions of mill's drum, grinding media size and the type of their movement have an impact on grinding rate and final composition of grinding products. The process of grinding takes place due to the complex interaction of grinding media with ground material being located between those media and the internal surface of the drum. Grains of ground material located in those areas are ground and sheared with an opportunity of a crushing mechanism (Lynch, 1974; Shipway and Hutchings, 1993). Conditions of energy transfer from grinding media to grains are defined by the energy level of mill's working elements. Potential energy is regarded as a basic energy level under the Earth gravity. Therefore, a measure of grinding media energy level is the ratio of their dynamic forces to gravity forces or the ratio of kinetic to potential energy. A complex mechanism of grinding media interaction with feed determines the course of a grinding process and the final grain size product composition. Using mathematical tools, which are applied to the theory of statistical moments, one may describe the influence of ball composition change on the change of skewness and flattening coefficients (Heim and Olejnik 1997). Thus, there is a possibility of grain size product composition and the grinding time to be predicted based on percentage fraction of balls of appropriate diameters. Change of process conditions determining the change of milling products grain size composition may shorten substantially the milling time. The situation under scrutiny is desirable due to a purely economical aspect of grinding process and each action shortening the time necessary for obtaining the required product graining has a direct influence on the costs of the whole process. Low practical efficiency of a milling process, forces to search for optimal process parameters considering the energy input to obtain shortest milling time. The effects of milling in a ball mill were analyzed from such a point of view and taking into account grain resistance to normal stresses and statistical moment distributions in the analysis of the results.

The aim of investigation was to compare the influence of process condition and properties of raw material on specific grinding rate. Grain size distribution function, determined by process parameters, has a key impact on main factors used in statistical moment theory. A relationship between statistical parameters and process conditions may carry on to simpler expression describing milling process.

2. PROCESS AND EQUIPMENT PARAMETERS OF MILLING

The process of milling was carried out under dry conditions. Milling was conducted for three mineral materials: quartzite, greywacke and granite. Raw material came from the Lower Silesia region. Quartzite is a dense, hard, metamorphic rock composed almost exclusively of quartzite grains. Silica content (SiO_2) in this rock is more than 99%. This is the so-called typical quartzite. Greywacke is a sedimentary clastic multi-component rock rich in chippings of various finely crystalline rocks (above 25% of dendrite material). Granite is a lithic, acidic, magmatic-intrusive rock, medium or thickly crystalline rock of clearly crystalline structure displaying a visible joint in three perpendicular directions. These three raw material differed in mechanical properties and grain structure. Investigations of milling kinetics were carried out for a semi-industrial mill. Basic technical data about the mill is summarized in Table 1. Basic data concerning feed mass and physical properties of ground materials are summarized in Table 2. Raw materials of graining from 5 to 8 mm were used for milling.

Table 1. Basic parameters of a semi-industrial mill

Internal diameter, m	0.5
Total capacity, m^3	0.112
Rotation frequency n, min^{-1}	31
V/V_{mill}, - (feed volume/mill capacity)	0.30
n/n_{kr}, -	0.54

Table 2. Basic feed properties

Raw material	Bulk density kg/m^3	Bulk density after thickening kg/m^3	Mean feed density kg/m^3	Feed mass kg
Quartzite	1236	1298	1267	45
Greywacke	1268	1324	1296	45
Granite	1394	1410	1402	45

Charge of the mill (grinding media and feed) was determined for circa 30% of mill capacity. The process of milling was conducted in a periodical mode using balls of different diameters. Ball sets, differing in diameters, are presented in Table 3. Total mass of balls applied for milling was about 41 kg. Feed sampling was performed every 30 minutes, collecting mass of about 0.6 kg for the grain size analysis. The samples were subjected to a grain size analysis using a laser grain size analyzer ANALYSETTE 22 (FRITSCH). Additionally, a screen analysis was carried out.

Table 3. Ball specification for particular compositions

Series	A	B	C	D
Ball diameter, mm		Ball mass, kg / Number of contact points		
10	-	6 / 27588	1 / 6424	-
20	-	12.3 / 11176	12.5 / 11363	11 / 9999
30	-	12.3 / 2035	12.5 / 2068	15 / 2475
40	-	10 / 671	15 / 1001	15 / 1001
60	40 / 512	-	-	-
Total	40 / 512	40.6 / 50611	41 / 14432	41 / 13475

3.RESULT

Based on the grain size analysis, grinding rates of particular size fractions were calculated using the author's computer program. To perform calculations, Gardner and Austin's formula (Eq. 1) was applied for discrete values of fractions assuming an ideal mixing of ground material (Lowrison, 1974; Heim and Olejnik, 2006).

$$\frac{\Delta w_i(t)}{\Delta t} = -S_i w_i(t) + \sum_{j=1,i>1}^{i-1} S_j b_{i,j,t} \cdot w_j(t)\,, \tag{1}$$

where $w_i(t)$, $w_j(t)$ are weight fraction of particles i or j after grinding time t; S_i, S_j specific grinding rate (distribution parameter) of particles in fraction i or j, s^{-1}; $b_{i,j,t}$ particle size distribution function and t is time grinding, s.

Based on the knowledge of grain size composition, mean grain size was calculated using the following formula:

$$d_s = \sum_{i=1}^{n} d_{si} \cdot x_i\ , \tag{2}$$

where d_{si} denotes mean (arithmetic) particle size in size fraction i, mm; x_i is mass fraction of particles in size fraction i.

The example values of rate coefficients Si of particular size fractions for ball set A are summarized in Table 4. The results of grain size analysis were used for calculation of skewness and flattening of distributions, applying for this purpose the tools utilized in the theory of statistical moments (Heim and Olejnik, 1997). Equations defining modified flattening coefficients K_{1m} and skewness coefficients K_{2m}, were defined using Eqs 3 and 4.

$$K_{1m} = \frac{M_4 - (M_2)^2}{M_4}\,, \tag{3}$$

$$K_{2m} = \frac{M_3}{M_2^{3/2} + |M_3|}\,. \tag{4}$$

Central moments M of the second, third and fourth order (k) present in Eqs 3 and 4 were derived as follows:

$$M_k = \sum_{i=1}^{n} (d_{xi} - d_s)^k \cdot x_i\,. \tag{5}$$

Selected grains of particular size fractions were subjected to a destructive test in which compressive loading was applied. Crushing tests were performed using an INSTRON device. The data containing the values of crushing forces and grain deformations during tests were processed statistically. Example values of compressive forces and resulting destructive stresses in grains of ground minerals are shown in Table 5.

Table 4. Grinding rates of particular grain size fractions for milling with ball set A

	Quartzite	Greywacke	Granite
d_s	S_{ik} [min^{-1}]	S_{is} [min^{-1}]	S_{ig} [min^{-1}]
2.5	0.00267	0.00244	0.0215
1.8	0.0095	0.00221	0.0151
1.5	0.015	0.00115	0.0172
1.32	0.044	0.00372	0.017
1.13	0.045	0.00306	0.0174
0.9	0.0563	0.00291	0.0201
0.4	0.101	0.0198	0.0457

Analyzing the process of grinding of chosen mineral materials, one may notice a considerable influence of their structure on the process kinetics. For granite, characterized by a clear joint, a detrimental influence of grinding media causes a rapid change of mean grain size. The consequence of this fact is obtaining high values of grinding rate (Table 4) for all the investigated grain size ranges. For the size fraction of granite between 2 and 3 mm, the greatest mean forces destroying grains existed. Their value is equal to more than 270 N. In the course of granite grain destructive tests, mean destructive forces and mean grain size tended to decrease. For the smallest grains from the range of 0.5 to 0.8 mm the destructive forces were equal to slightly more than 26 N. Simultaneously, for the whole range of grain size variability, the approximate values of destructive stresses were measured. The value of above–

mentioned stresses was in the range from 13.27 MPa (for grains from the range 1.6 to 2 mm) and to 48 MPa for the smallest size fractions. Different values of destructive forces and corresponding destructive stresses were observed for quartzite and graywacke.

Table 5. Values of destructive forces and stresses of investigated raw materials

Grain size class mm	Mean destructive force, N	Mean destructive stresses, MPa	Raw material
	244.1	12.44	Quartzite
3 ÷ 2	279.4	14.01	Granite
	412	21.01	Greywacke
	144.8	14.24	Quartzite
2 ÷1.6	135	13.27	Granite
	348	34.2	Greywacke
	94.62	13.39	Quartzite
1.6 ÷ 1.4	118	16.7	Granite
	132.3	18.73	Greywacke
	60.71	11.01	Quartzite
1.4 ÷ 1.25	126.4	22.93	Granite
	124.6	17.46	Greywacke
	45.49	11.45	Quartzite
1.25 ÷ 1.0	108.9	27.4	Granite
	71.22	18.31	Greywacke
	34.46	13.55	Quartzite
1.0 ÷ 0.8	57.66	22.67	Granite
	84.86	33.37	Greywacke
	26.39	19.88	Quartzite
0.5 ÷ 0.8	74.98	48.72	Granite
	36.13	27.45	Greywacke

For the analyzed process conditions, grinding rates S_i, are for granite by one order greater when compared to quartzite and greywacke. After milling time equal to 200 minutes, mean grain size was equal to less than 0.5 mm.

Quartzite has a different composition. This is a clastic rock composed of quartzite grains very densely packed and silica bound. Therefore, the rock is characterized by a low susceptibility to grinding. In the investigated range of grain size (Table 5), very similar values of destructive stresses were obtained. For coarse grains (up to 1 mm) the values were equal to 12.44 MPa whereas for grains below 1 mm destructive stresses increased to the value above 19 MPa. A constant decrease of normal force values causing destructive stresses is intriguing. For the greatest grains from the range of 2 to 3 mm, the destructive force is equal to 244.1 N. A decrease of the grain size causes a decrease of destructive force to the value of 26.39 N for grains from the range of 0.5 to 0.8 mm. The increase of destructive stresses accompanied by a simultaneous decrease of loading may be elucidated by an increase of grain structure deformations without loosing material cohesion. For greater grains, it is possible for a soft binder to occur, weakening material structure, then, a very homogenous material is obtained for smaller grains subjected to the grinding process.

The observed diversification, in terms of susceptibility of investigated raw materials to grinding, may inspire one to apply a differing composition and size as well as ball mass. Quartzite, composed of hard grains, depending on size fraction, displays a different susceptibility to grinding. Therefore, grain size has a relevant meaning for achieving an appropriate state of destructive stresses. For coarse grains, the main mechanism causing crushing of raw material will be impact reaction of grinding media whereas for the smallest grains tangential forces may decide about the grinding rate. For greater fractions grinding media should display appropriately high kinetic energy, capable of overcoming internal cohesive forces acting between grains of the raw material. When grinding is carried out with balls that have the same diameter, then greater values of specific grinding rate occur for the smallest grains. In such a case, grinding media of a considerable size and mass in comparison with the smallest grain size fraction may evoke tangential destructive stresses being appropriately high. In the case of greywacke being very similar to sandstones in terms of structure, destructive stresses obtained for the investigated size fractions attain similar values.

The analysis of grinding rate inspires to state that the mechanism of impact grinding occurs in case of all investigated raw materials. However, its effect is greater in the case of greater grains, whereas smaller grains are ground mainly by means of a grinding mechanism.

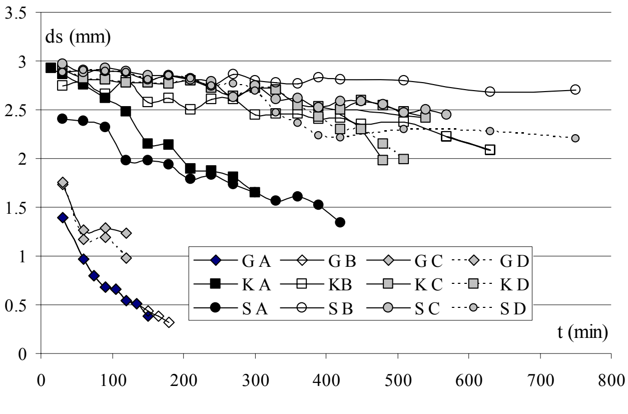

Fig. 1. Change of mean grain size d_s with in time: granite – G, quartzite – K and greywacke - S for four ball compositions (A, B, C, and D)

As a matter of fact, grinding of large grains causes the formation of the smallest fraction but it does cause the movement of destroyed grains to the finest grain fraction. Grinding, which is longer in time may decrease the size of coarse grains to such an extent that they move to the neighbouring size fraction. The consequence of the grain strength change accompanied by their mean size change was that varying milling time was necessary. For the investigated raw materials, grinding times and corresponding change of mean grain size d_s, are shown in Fig. 1. The application of balls of series A, for all raw materials contributed to a considerable shortening of the grinding time. For quartzite displaying a more homogenous structure, when compared to greywacke and granite, diversification of ball composition produced no considerable influence on the change of mean grain size. In spite of change of the mean size, quartzite grains are of similar strength. For raw materials containing soft, hard and resistant inclusions and soft binder, a change of ball compositions brings about an increase of destructive interactions for balls of smaller diameter. Distribution of skewness coefficients K_{2m} and flattening coefficients K_{1m}, is shown in Figure 2.

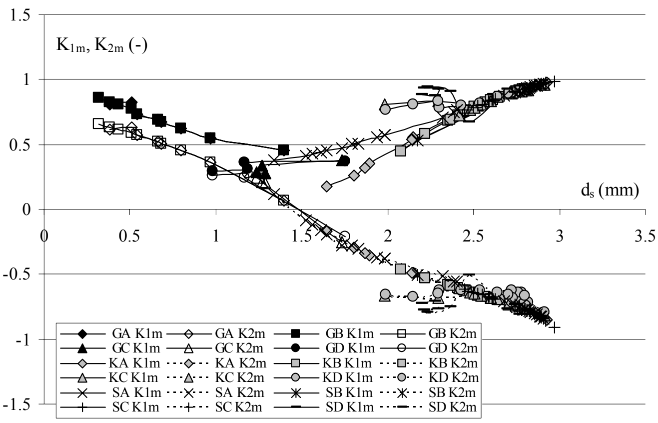

Fig. 2. Change of values of modified flattening coefficient K_{1m} and skewness coefficient K_{2m} for investigated raw materials. Symbols: G - granite, K – quartzite and S – greywacke. A, B, C and D denote ball compositions

The application of changing ball compositions contributes to the fact, that for certain mean grain size, one may obtain distributions similar to a normal distribution and grains are more monodispersive. Obtaining small grinding times for granite and, what is connected with this, a rapid change of the mean grain size causes high changeability of skewness and flattening coefficients. This is reflected in occurrence of a considerable number of grains differing in terms of size and causing the fact that grain distributions are characterized by high changeability (skewness). Obviously, the analysis of process kinetics as well as its influence on statistical distributions should consider destructive ball interactions and bed strength properties changing in the course of milling. The aforementioned problem should be a subject of further investigations.

4. CONCLUSION

Based on the results obtained in this work the following conclusions can be drawn:

– grinding rate of chosen size fractions may depend on the magnitude of normal forces occurring at the contact point of grinding media with ground raw materials
– grinding kinetics is determined by grain resistance to destructive stresses depending on the structure of ground raw material
– differing ball size may influence substantially predominant mechanisms of grain grinding
– ball composition has a considerable impact on the values of skewness and flattening coefficients of grain size distributions.

ACKNOWLEDGMENTS

This study was carried out within research project no. N N208 0773 33, financed by the State Committee for Scientific Research in the years 2007-2010.

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Artykuł przedstawia rezultaty badań kinetyki mielenia, wybranych materiałów skalnych, z uwzględnieniem ich własności wytrzymałościowych. Badania prowadzono dla półprzemysłowego młyna kulowego. Przemiał realizowano w trybie okresowym, używając mielników o zróżnicowanych wymiarach. Materiał skalny różnił się budową krystalograficzną. Mielenie przeprowadzono dla kwarcytu, granitu oraz szarogłazu. Nadawa charakteryzowała się początkową frakcją rozmiarową z przedziału 5 – 8 mm. Zbadano wytrzymałość ziarn, należących do poszczególnych frakcji rozmiarowych, oraz jej wpływ na kinetykę procesu. Obliczono szybkość przemiału poszczególnych frakcji rozmiarowych oraz rozkłady wielkości matematycznych, wykorzystywanych w teorii momentów statystycznych.

słowa kluczowe: młyn kulowy, szybkość właściwa rozdrabniania, teoria momentów