Physicochem. Probl. Miner. Process. 48(1), 2012, 149–158

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

Physicochemical Problems of Mineral Processing

ISSN 1643-1049 (print)

Received April 29, 2011; reviewed; accepted July 26, 2011

GRINDING KINETICS OF GRANITE CONSIDERING MORPHOLOGY AND PHYSICAL PROPERTIES OF GRAINS

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Abstract. The article presents the results of studies on the kinetics of grinding of granite taking into consideration the morphology and mechanical properties of particular size fractions of the feed. The study was conducted in a mill on a semi-technical scale. Milling was carried out periodically using several sets of grinding media. The output fraction of the ground material was of size 3-5 mm. The granulometric analysis of the raw material was carried out in a multiple manner. The granulometric composition of milling product was analyzed every 30 minutes. Simultaneously, ground material was subjected to an analysis of the shape of grains and microscopic analysis of morphology and chemical composition. Strength tests of grains were performed applying selected fractions of particle size ranges. The change of particle breakage rate function *S*i, for selected particles size ranges, was described with the Austin-Gardner expression. The influence of destructive force on kinetics of grinding was defined.

keywords: ball mill, specific grinding rate, grain morphology, contact points

1. Introduction

The grinding mechanism comes down to the division of solid particles into the grains of smaller size and that this process is evoked by the action of external loads, exceeding the limit of endurance and can damage the atomic or molecular bonds (Blumenauer and Pusch 1981). Since each rupture of the material in each zone of load precedes deformation, the implementation of the process of grinding requires provision of the necessary amount of energy. This amount being conditioned with the size of deformation, elastic properties of deformed material and the type of load.

Simultaneously, uneven internal structure of the material to be ground, numerous micro and macro cracks weaken the cohesion forces between particles forming a crystallographic network of grain. Destruction of the internal cohesion of the grain, cracking the grains into smaller sized items, requires exceeding the required levels of cohesion force distribution (under the action of external forces). The described phenomenon may be caused by normal stretching or shearing stresses (Mostafa 2003).

The grinding in ball mills is determined by a complex nature of the impact of grinding media on the ground raw material. Main geometrical dimensions of drum grinding mill and the size and type of motion affect the speed of the grinding process as well as the final composition of grinding. The grinding is performed primarily through a complex interaction of grinding media on the ground material being located between them or between the inner surface of grinding media. Grains of material to be ground that will be in these areas are mainly abraded and thinned, with the possibility of participation of the crushing mechanism (Lynch 1974; Shipway and Hutchings 1993). Energy transfer is conditioned by the energy level of the working parts of the mill. The basic energy level assumed in the potential energy of the Earth's gravity conditions. A measure of the energy level grinding is therefore the ratio of the dynamic forces to the forces of gravity or kinetic energy into potential energy of grinding media (Cole and Peters 2007).

Practically low efficiency of the grinding process forces engineers to look for process parameters being optimal from the point of view of energy inputs to obtain the shortest possible milling time. Considering this point of view, examined the effects of grinding in a ball mill, taking into account the analysis of the results, the morphological structure and chemical composition of grains, and their resistance to normal stresses.

The objective of the investigation was to determine the effect of a variable number of grinding media for grinding process, taking into account the individual properties of particles such as yield strength for normal forces and the shape of the grain (Hornga et al., 2009). Mechanical properties of the grain may determine the change in value of breakage rate function S_i in the corresponding size frictions of the grains. The study was conducted for granite. Due to the morphology of particles of granite, which is characterized by a very heterogeneous structure, it is expected that the fragmentation process takes place in such a way that it provides very different grain size particles, and substantially different shape. The observed diversity of the feed may determine the value of parameters in the Austin-Gardner equation (Eq. 1), and the specific numerical values may depend on process parameters such as number and size of grinding media.

2. Process parameters

The grinding process was conducted under dry conditions. Kinetic studies of milling were carried out for a semi-technical mill. Basic technical information concerning the mill is shown in Table 1

Granite was subjected to crushing in a ball mill. This is a solid, acidic magma-deep rock, medium or thickly-crystalline of overtly-crystalline structure distinguished by a clear symmetry planes, usually in three orthogonal directions (Cappell and White 2001). The bulk density of granite, was determined after a freely drop and after 10 minutes of shaking of the measurement sample. Bulk density was, respectively, equal to 1394 kg/m^3 and 1410 kg/m^3, and its average value was equal to 1402 kg/m^3.

Material used for milling was from 5 to 8 mm in size. Filling the mill with grinding media with a feed accounted for 30% of the total capacity of the mill.

Milling process was carried out in a batch mode using several sets of balls. The total mass of the balls used for milling was about 41 kg. Sampling of the feed was measured every 30 minutes, taking a mass of about 0.6 kg for analysis. Milling was performed using four sets of balls, labeled sequentially I, II, III and IV. Size and weight of balls for each measurement series are provided in Table 2. Furthermore, the statistical estimated number of contact points for each set of balls was determined (Mort 2003).

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

Table 2. Number composition and ball mass for particular series

Series	I	II	III	IV
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	-	-	-
Sum	40 / 512	40.6 / 50611	41 / 14432	41 / 13475

3. Analysis of results

Samples were subjected to granulometric, morphological, chemical and strength analyses. The chemical composition, determined by the number of atoms of different elements included in the composition of chemical compounds and grain morphology, were examined using a scanning electron microscope. The analysis of the shape of grains and grain composition was performed using Analyzer 3D AWK made by Kamika Instruments. Furthermore, a fractional sieve analysis was carried out to rule out a measurement error associated with the testing method applied. The results of the analysis allowed to determine the granulometric composition of milled material at particular moments of grinding time. To determine the shape of particles fraction analysis according to Zingg (1935) was used.

Table 3 shows the chemical composition and atomic fractions of particular chemical elements of particular chemical elements for chosen size fraction of grains.

In combination with a chemical composition analysis, an optical grain analysis was carried out. With this aim in mind, a scanning microscope was utilized. Figures 1 and

2 show a selected granite surface for a size fraction of 1.6 – 2.0 and 0.2 – 0.3 mm.

Selected grains from each size fraction were subjected to strength examinations. Single grains were exposed to shearing stresses. Crushing tests were performed with INSTRON 3300. To make the results uniform, for each grain size fraction multiple tests were conducted to exclude the measurement error. The results of strength analyses, that is the values of compression forces and destructive stresses evoked by them, are summarized in Table 5.

Table 3. Atomic fractions of elements present in the chemical compound composition associated with the structure of granite

A chemical compound / element	Grain size fraction				
	1.6 – 2.0	1.25 – 1.4	0.8 – 1.0	0.4 – 0.5	0.2 – 0.3
	Atomic fractions, %				
$CaCO_3$ / C	4.58	4.82	11.52	9.91	8.39
SiO_2 / O	64.72	65.77	56.36	63.05	66.85
Allbite / Na	1.71	1.87	1.78	0.63	1.43
MgO / Mg	0.52	0.64	0.38	0.24	0.31
Al_2O_3 / Al	4.66	4.60	5.29	1.39	2.91
SiO_2 / Si	19.78	17.51	18.63	23.56	18.2
Feldspar / K	1.81	1.91	1.83	0.56	0.81
Wollastonite / Ca	0.53	0.50	0.96	0.12	0.3
/ Ti	0.18	0.23	0.26	-	0.09
/ Fe	1.54	2.14	2.92	0.54	0.70

Basing on the granulometric composition changes, disintegration rates of particular size fractions using authors' computer program were calculated (Olejnik 2009, 2010). For calculations, Eq. 1 of Gardner and Austin was applied for discrete values of fractions, assuming ideal mixing of the milled material:

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

where

$b_{i,j,t}$ – particle size distribution function in time

S_i, S_j– specific grinding rate (distribution parameter) of particles in fraction i or j

T – grinding time, min

Δt – time increment

w_i – the mass of grains from size grade i

w_j – the mass of grains from size grade j

$\Delta w_i(t)$ – increment of the mass of grains from size grade i.

For better presentation of results, we defined also the mean geometrical grain size by using Eq. 2:

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

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

The rate coefficients S_i for particular size fractions are shown in Table 4. For particles of granite, characterized by distinct cracks and fissures, devastating impact of grinding media causes a rapid change in the particle size. Granite used in the study is characterized with a high susceptibility to grinding being reflected in a high value of distribution parameter (Table 4) for all tested grain size ranges.

Strength tests were performed for selected grains, with the appropriate fraction size ranges. To eliminate measurement error, the sample test was repeated several times, averaging the results while calculating the average measurement error and standard deviation.

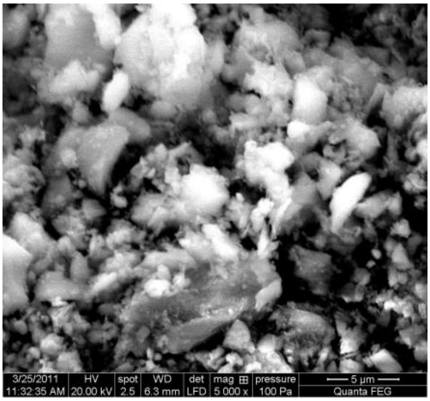

Fig. 1. Granite grain, size fraction of 1.6 – 2.0 mm. Magnification about 5000x

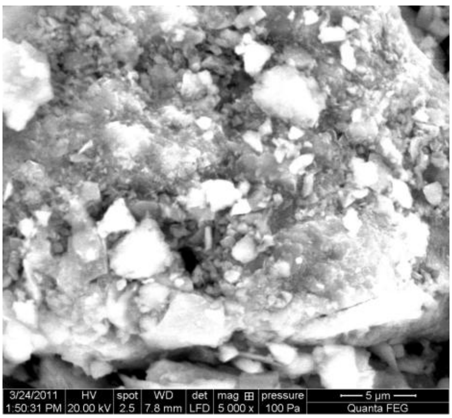

Fig. 2. Granite grain, size fraction of 0.2 – 0.3 mm. Magnification about 5000x

Table 4. Disintegration rates S_i (distribution parameter) of grain fractions d_s for investigated series

d_s	$S_{i(I)}$, min^{-1}	$S_{i(II)}$, min^{-1}	$S_{i(III)}$, min^{-1}	$S_{i(IV)}$, min^{-1}
2.5	0.00244	0.0115	0.00517	0.00781
1.8	0.00221	0.015	0.00806	0.01208
1.5	0.00115	0.017	0.00911	0.01018
1.32	0.00372	0.0165	0.0147	0.0147
1.13	0.00306	0.0169	0.0163	0.0203
0.9	0.00291	0.0197	0.0224	0.0128
0.4	0.0198	0.0356	0.0071	0.0211

Table 5. The values of normal forces and destructive stresses

Grain size fraction, mm	Mean destructive force, N	Mean destructive stresses, MPa
3 ÷ 2	279.4	14.01
1.6 ÷2.0	135	13.27
1.25 ÷ 1.4	126.4	22.93
0.8 ÷ 1.0	57.66	22.67
0.4 ÷0.5	64.98	48.72

For a size fraction of granite grains between 2 and 3 mm, there are the highest average grain destructive forces. Their value is more than 270 N. In the course of destruction tests, there was a tendency to reduce the medium destructive forces with decreasing average grain size. For the smallest particles in the range of 0.5 to 0.8 mm, destructive forces were approximately 60 N.

Simultaneously, with the decreasing grain size, the opposite trend was observed concerning the normal stress. For the largest particles, the destructive stress was around 14 MPa, and increased to a value of about 50 MPa, for the smallest ones. The observed trend may be elucidated by the morphology of the grains. From the physico-chemical analysis – the zone investigated with the application of a scanning electron microscope it may be inferred that the change in grain size does not entail a change in the atomic composition and indirectly, chemical composition (Table 3). Simultaneously, Zingg's analysis points to the fact that the grains in the whole range of variation of its size, have a shape resembling a sphere. The example results of analysis of samples taken at 30th and 210th minute after the start of grinding, for series I are given respectively in Fig. 3 and 4.

The observed tendency concerning the growth of destructive stresses at a simultaneous reduction of the size of the load can be explained by the increase in deformation of the grain structure without losing the cohesiveness of the material. While for the larger particles it is possible to obtain the presence of a soft matrix, weakening the structure of the material, then for smaller particles subjected to fragmentation one obtains a homogeneous material. However, the analysis of image of the surface of grains does not confirm this assumption.

For large and small grains, we have similar elemental compositions, which is tantamount to saying that for the investigated range of variation of grain size of granite, there occur the same chemicals. And if so, the grains should have similar mechanical properties. Even more interesting conclusions can be drawn by analyzing the rate of grinding balls for different compositions of balls. The observed differences in susceptibility of the tested materials to grinding can lead to a differentiated composition and size, and hence, masses of balls.

For relatively large particles, a crucial mechanism causing fragmentation of the granite will be crushing. Grinding effect for the smallest particles can be determined by abrasion. For large particles the grinding media should have a sufficiently large kinetic energy that is apt to overcome the internal forces of cohesion within the grain. If the milling is conducted for a composition of balls of large diameter, increased energy of balls will occur for the largest grains. In this case, wearing of large grains causes the formation of the smallest fraction but not necessarily a transition of destroyed grain to a fraction of finer grains. Only long-time wear can reduce the grain size large enough to make it over into a smaller size ranges.

An analysis of grinding speed leads to the conclusion on the mechanism of crushing that the impact grinding occurs at the initial stage of grinding. The effect of grinding is greater for larger particles and smaller broken grains are mainly ground by the mechanism of wear. This is due to the fact of a greater probability of finding the grain in the area between grinding media. While the impact effect on large grains increases with increasing weight of the grinding media, so for small particles a decisive meaning is played by abrasive action grinding occurring between the grinding media and feed.

The shortest times of grinding needed to obtain a suitable granulation product were attained for two measurement series I and II. This corresponds to two different configurations of the balls. For series I there occurs a small number of theoretical contact points (512). On the other hand, for series II, one has the greatest number of all contact points (Table 2). Considering the economic criterion, the two compositions of balls are justified, however, the analysis of disintegration rate of individual size fractions indicates more favorable conditions for the milling of series II (Table 4, refer to column S_i(II)).

Grains with relatively small size in comparison to the size of balls, have a smaller chance of being in the area of impact grinding (Georgalli and Reuter, 2008). Therefore, from the grinding efficiency point of view, the most important is point contact of the particles with the balls. This is when replace of large grinding media with smaller media. Changing the size of balls, is changed the number of contact points. Due to the fact that the rate of milling of small size fractions increases with the number of contact points can describe mathematically the size of grinding media most appropriate for the economy grinding process. The expression for mathematical models will be possible after examination of the grinding process of other minerals with a different morphology.

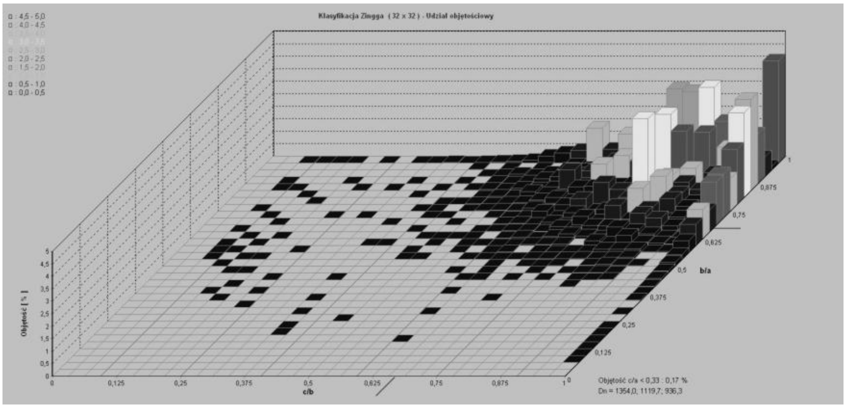

Fig. 3. Distribution of granite grain shape obtained after 30 minutes of milling. Measurement series I

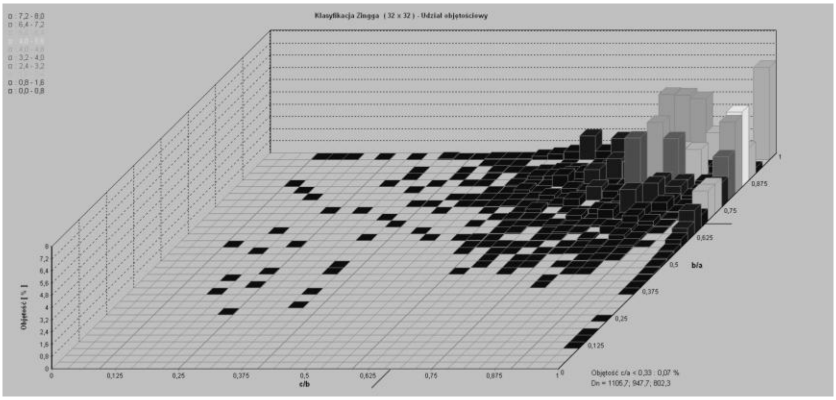

Fig. 4. Distribution of granite grain shape obtained after 210 minutes of milling. Measurement series I

Economic aspects of milling is shown in Fig. 5 containing curves of the average grain size changes in time using different sets of grinding media. Therefore, the change of the characteristic (diameter) grain size is accompanied by a change in grain cross-section. The mathematical expression describing the relationship between these values is changed to the second power of linear dimension. Considering the state of stress in the two grains of granite differing significantly in terms of characteristic size, it is possible with the application of weaker destructive power, in favor of smaller grains. Trends of decreasing normal forces and the corresponding increase of destructive stress for smaller grains are shown in Table 5.

For measurement series II, there are greater milling rates of small size fractions (of the order from 0.0197 to 0.0356 min^{-1}). Thus, the theoretical total decay time of size fraction of 0.9 mm is circa 50 minutes for measurement series II and until 341 minutes for Series I. The difference in the time of the disappearance of size fractions illustrates the positive impact of increased number of contact points on the process kinetics for the small size fractions.

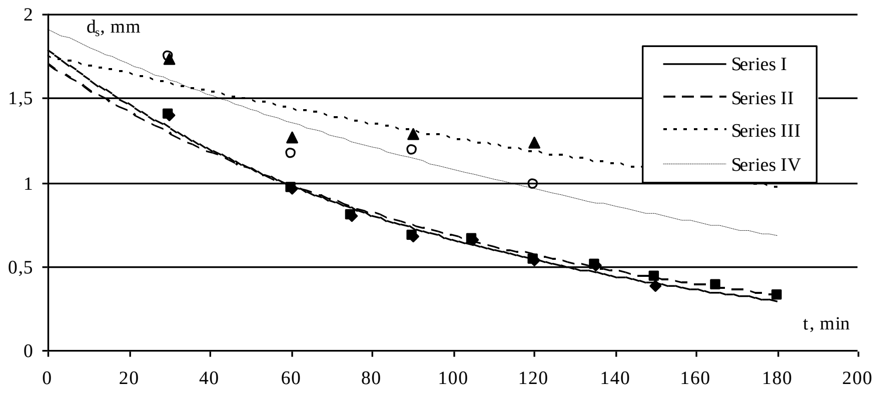

Fig. 5. The curves of change in time of the mean grain size of granite for four compositions of balls

4. Conclusions

Basing on the results, the following conclusions can be drawn. The kinetics of milling is determined by the strength of the stress-destructive particles depending on the morphology of the shredded material. Variation in size of balls may significantly affect the dominant mechanism of grinding of the grain. It is feasible to attain the required granulometric composition through the selection of the size of grinding media.

Acknowledgments

The project was financed within the framework W-10/1/2011 Dz. St. of the Faculty of Process and Environmental Protection, Technical University of Lodz.

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