Physicochemical Problems of Mineral Processing, 39 (2005), 189-198
Fizykochemiczne Problemy Mineralurgii, 39 (2005), 189-198

Andrzej HEIM[*], Tomasz P. OLEJNIK[*], Agnieszka PAWLAK[*]

RATE OF CERAMIC BODY GRINDING IN A BALL MILL

Received March 15, 2005; reviewed; accepted May 15, 2005

The paper presents results of studies whose aim was to determine the effect of the number of contact points of grinding balls on the rate of grinding in a ball mill. Experiments were carried out in a pilot-plant batch mill. The process was performed in a water suspension with the addition of antiemulsifiers, using raw materials that are typically applied in a commercial-scale production of ceramic tiles. The grinding process was analysed for three compositions of grinding balls and two values of mill filling. Grinding rates were determined for particular size grades. Changes in the size distribution of ground material in time were analysed and the effect of ball size, degree of filling the mill with feed and the number of grinding balls on the process rate was reported. This rate varies during grinding, and the effect of the above listed factors is different on subsequent stages of the process.

Key words: ball mill, point of contacts, grinding rate, ceramics

INTRODUCTION

Grinding in ball mills is determined by a complex character of the interactions between grinding balls and material being ground. Geometric dimensions of the mill and the size and type of grinding balls affect grinding rate and final composition of the ground product. Feed is comminuted mainly due to the interaction of grinding balls and additionally between grinding elements and inner drum surface. Material which is between the surfaces of adjacent balls moving against each other, is abraded and sheared but it can also be crushed [Drzymała 1992, Mattan 1971].

These mechanisms of grinding occur mainly when grinding balls move like an avalanche. When the balls move like a cascade, there is additionally a stroke mechanism induced by collisions of balls that fall down on the bed of material on the drum bottom [Lynch 1974, Lowrison 1974]. The type of motion at which the stroke

---

[*] Technical University of Lodz, Department of Process Equipment, 90-924 Lodz, Stefanowskiego 12/16, Poland

mechanism prevails, occurs at the frequency of mill rotations close to a critical frequency. This phenomenon is very desirable because of grinding intensity, but dimensions of industrial ball mills, and consequently, inertia forces, reduce the character of mill operation at velocities close to the critical one [Shipway 1993, Hutchings 1993].

For this reason, at smaller frequencies of mill rotations, the contribution of individual grinding mechanisms can be changed by changing the size and number of grinding balls. It is obvious that at the same volume of the bed of grinding balls, i.e. the same degree of mill filling with balls, the bigger are the balls, the smaller is their number. When bigger balls are used, the mass of a single ball is bigger and the interacting forces are higher. This causes that less balls are used, so the points of contact are fewer which means that there is a limited number of mini-regions where stresses destroying ground material particles can occur in a given moment. Selection of ball diameters depends both on the strength of ground material and its particle diameters. For bigger particles that require higher destructive forces, bigger balls should be used, while for smaller particles as well as the materials of lower mechanical strength, better results will be obtained when the number of contact points of the balls is increased, so when their number grows at the cost of their diameters.

The process of comminution can be intensified by increasing the kinetic energy of balls which can be done by increasing the height from which the balls fall down onto the bed. This effect can be obtained by decreasing the total mill filling with feed.

A simple construction of the mill is not in keeping with process efficiency. Low efficiency of the grinding process makes technologists look for such a composition of balls and mill filling for which the mean particle size is reduced the fastest. This enables a more economical use of the mill working time.

Taking this point of view, the effects of grinding in the mill with a different number and diameters of balls as well as for different total mill filling with feed, were analysed. Ceramic body masses were wet ground.

PARAMETERS OF THE GRINDING PROCESS AND EQUIPMENT

Changes of particle size distribution in time were investigated in a pilot-plant mill. Technical data of the mill are given in Table 1.

Table 1. Main parameters of a pilot-plant mill

Inner diameter [m]	0.5
Total volume [m^3]	0.118
Frequency of rotations n [min^{-1}]	31
n/n_{kr}	0.54

The process of comminution was performed in a water solution with the addition of antiemulsifiers. A feed were the mixtures of rock material, mainly feldspars and clay. Two different feed components were used in the experiments. A difference was due to product applicability. This is related to the use of ground product in the production of ceramic materials that should satisfy strictly specified users' demands. In production technology of ceramic floor tiles an increased contribution of hard components (feldspars) is planned. In the production of wall tiles, this fraction is limited to minimum. Table 2 presents compositions of the feed that is ground in the tested mill for two products, i.e. wall and floor tiles, for 100% and 50% mill filling, respectively. Mill filling was calculated on the basis of a technical documentation for ceramic body mass grinding in an industrial mill. 100% filling denotes identical feed composition as in the industrial mill. The 100% filling with the feed corresponds to 45% water capacity of the mill.

Table 2. Feed composition used in the production of wall and floor tiles. 100% and 50% filling of the mill

	100%		50%	
	Wall tiles	Floor tiles	Wall tiles	Floor tiles
Solid components [kg]	66	66	32.5	32.5
- incl. feldspars, [kg]	18	36	9	18
- clay [kg]	29	25	14.5	12.5
- quartz, [kg]	11	5	5.5	2.5
- carbonates, [kg]	8	-	4	-
Liquid components [kg]	19.7	19.7	9.85	9.85
- incl. water [kg]	19.5	19.5	9.75	9.75
- trisodium (poly)phosphate, [kg]	-	0.2	-	0.1
- water glass, [kg]	0.2	-	0.1	-

Filling of the mill with grinding balls was assumed to be 45% water capacity of the mill for full feed and 22.5% water capacity of the mill for half of the feed mass. Additionally, the ceramic body masses were ground with balls of changing composition. Mass fractions and dimensions of balls for every experimental series are given in Table 3. To differentiate between grinding runs according to ball composition, they were marked as A, B and C.

Table 3. Composition and diameters of grinding balls

	100 %			50 %		
Series	A	B	C	A	B	C
Ball diameter, [mm]	Ball mass, [kg]					
10	12.4	2	-	6.2	1	-
20	24.6	25	22.6	12.3	12.5	11.3
30	24.6	25	29.4	12.3	12.5	14.7
40	20.4	30	30	10.2	15	15
Total, [kg]	82	82	82	41	41	41

Grinding was a batch process. After feeding raw material to the mill, at specified time intervals (every 1000 mill revolutions) samples were taken for the analysis of particle size distribution. The analyses were using ANALYSETTE 22 laser particle analyser (FRITSCH).

Table 4 gives results of the analysis of particle size distribution of the ceramic body mass used in the production of wall tiles, for series A at 100% feed load.

On the basis of analysis of the particle size distribution, grinding rates for particular size fractions were calculated. Gardner and Austin's equation (1) in the differential form for discrete fractions was used in the calculations, assuming an ideal mixing of the ground material:

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

Rate coefficient S_i in equation (1) for grinding of ceramic body mass used in the production of wall tiles for series A, B and C is shown in Table 5. Data in Table 5 present calculated values for the full and 50% filling of the mill. Similar calculations of rate coefficient S_i in equation (1) were made for grinding of the ceramic mass used for floor tile production, for three ball compositions and full and 50% filling of the mill.

At known particle size distribution, also mean particle size was calculated from the formula

$$d_{śr} = \sum_{i=1}^{n} d_i \cdot x_i \tag{2}$$

Using Statistica®, correlation equations of changes in grinding rate as a function of particle size distribution $d_{śr}$ were determined. This enabled a graphic representation (Fig. 1) of grinding kinetics in the form of a relation of rate change S_i for size fractions depending on filling the mill with feed and grinding balls.

As a correlation equation the function in the form was selected:

$$S_i = a \cdot d_i^b \tag{3}$$

Coefficients a and b for each measuring series are given in Table 6.

Table 4. Particle size distribution of individual fractions for series A, 100% filling of the mill with feed
Ceramic body mass for wall tiles

Size fraction i, [μm]		Number of mill rotations, [min^{-1}]										
		1000	2000	3000	4000	5000	6000	7000	8000	9000	10000	11000
		Size fraction w_i, [%]										
1	617.14÷791.42	1.06	0.73	0.88	0.91	0.77	0.88	0.83	0.81	0.76	0.72	0.81
2	473.09÷617.14	1.33	0.92	1.11	1.14	0.97	1.1	1.04	1.02	0.97	0.95	1.04
3	362.67÷473.09	1.78	1.23	1.5	1.54	1.32	1.49	1.41	1.4	1.33	1.32	1.44
4	278.01÷362.67	2.43	1.69	2.08	2.15	1.87	2.08	2	1.97	1.88	1.88	2.03
5	213.12÷278.01	3.19	2.23	2.76	2.86	2.5	2.76	2.67	2.63	2.51	2.54	2.73
6	163.38÷213.12	3.82	2.67	3.32	3.44	3.03	3.33	3.24	3.2	3.05	3.09	3.32
7	125.24÷163.38	4.3	3	3.76	3.88	3.44	3.77	3.68	3.64	3.46	3.53	3.78
8	96.01÷125.24	4.54	3.17	3.98	4.1	3.65	4.01	3.91	3.89	3.68	3.78	4.03
9	73.60÷96.01	4.55	3.17	4	4.11	3.67	4.04	3.94	3.95	3.72	3.84	4.08
10	56.42÷73.60	4.44	3.1	3.92	4.03	3.6	3.97	3.89	3.91	3.68	3.8	4.01
11	43.25÷56.42	4.42	3.11	3.94	4.06	3.63	4.01	3.95	3.98	3.76	3.84	4.03
12	33.16÷43.25	4.7	3.35	4.27	4.42	4	4.36	4.36	4.38	4.19	4.19	4.38
13	25.42÷33.16	5.27	3.82	4.9	5.13	4.72	5.06	5.13	5.13	4.98	4.88	5.1
14	19.48÷25.42	5.67	4.21	5.43	5.84	5.42	5.72	5.88	5.9	5.73	5.61	5.85
15	14.94÷19.48	5.56	4.29	5.53	6.27	5.78	6.02	6.27	6.36	6.07	6.07	6.32
16	11.45÷19.94	5.19	4.22	5.46	6.63	6.02	6.22	6.53	6.75	6.3	6.52	6.73
17	8.78÷11.45	4.98	4.3	5.61	7.21	6.49	6.7	7.1	7.45	7	7.31	7.43
18	6.73÷8.78	4.89	4.53	5.89	7.73	7.02	7.36	7.88	8.28	8.12	8.31	8.2
19	5.16÷6.73	4.76	4.75	6.05	7.94	7.36	7.86	8.47	8.81	9.23	9.05	8.61
20	3.95÷5.16	4.66	5.07	6.3	8.28	7.82	8.37	9.09	9.14	10.2	9.64	8.83
21	3.03÷3.95	2.67	3.84	4.7	5.13	5.46	5.12	5.33	4.48	5.41	5.37	4.54
22	2.32÷3.03	2.7	5.27	5.19	2.1	4.72	3.27	2.23	1.78	2.45	2.42	1.61
23	1.78÷2.32	3.71	8.46	5.4	0.28	3.63	1.34	0.41	0.36	0.69	0.59	0.33
24	1.37÷1.78	3.63	9.96	2.54	0.01	1.53	0.26	0.03	0.03	0.1	0.07	0.04
25	1.05÷1.37	2.52	6.73	0.47	0	0.41	0.03	0	0	0.01	0.01	0
26	0.8÷1.05	1.03	1.25	0.04	0	0.09	0	0	0	0	0	0
27	0.62÷0.8	0.43	0.09	0	0	0.04	0	0	0	0	0	0
28	0.47÷0.62	0.27	0	0	0	0.07	0.02	0	0.01	0.01	0.01	0.01
29	0.36÷0.47	0.19	0	0.02	0	0.1	0.04	0	0.02	0.02	0.03	0.02
30	0.28÷0.36	0.17	0.01	0.13	0.01	0.07	0.02	0.01	0	0.01	0.01	0
31	0.21÷0.28	0.22	0.15	0.01	0	0.09	0.03	0	0.01	0.01	0.01	0.01

Table 5. Rate coefficients S_i for grinding of ceramic body mass for wall tile production for series A. B and C. Full and 50% filling of the mill

	100% feed			50% feed		
Ball composition	Series A	Series B	Series C	Series A	Series B	Series C
d_i	S_{iA}	S_{iB}	S_{iC}	S_{iA}	S_{iB}	S_{iC}
617.14÷791.42	0.0005250	0.006010	0.00188	0.000503	0.000130	0.000045
473.09÷617.14	0.0007200	0.000118	0.00487	0.000438	0.000146	0.000143
362.67÷473.09	0.0010900	0.002840	0.00803	0.000864	0.000647	0.000021
278.01÷362.67	0.0019900	0.005120	0.00653	0.001770	0.000775	0.000019
213.12÷278.01	0.0019000	0.002910	0.00369	0.002010	0.000668	0.000244
163.38÷213.12	0.0007050	0.000067	0.00223	0.001800	0.000043	0.000575
125.24÷163.38	0.0003160	0.000167	0.0012	0.001170	0.000016	0.000728
96.01÷125.24	0.0002650	0.000196	0.000647	0.000630	0.000004	0.000689
73.60÷96.01	0.0002220	0.000179	0.00043	0.000310	0.000007	0.000522
56.42÷73.60	0.0001270	0.000108	0.00045	0.000202	0.000002	0.000365
43.25÷56.42	0.0000198	0.000015	0.000313	0.000122	0.000050	0.000186
33.16÷43.25	0.0000368	0.000574	0.000119	0.000043	0.000012	0.000036
25.42÷33.16	0.0000532	0.000731	0.000129	0.000035	0.000011	0.000009
19.48÷25.42	0.0000650	0.000798	0.000165	0.000025	0.000056	-0.000007
11.45÷19.94	0.0000713	0.000083	0.000307	0.000021	0.000009	-0.000014
8.78÷11.45	0.0000714	0.000081	0.000566	0.000025	0.000001	-0.000014
6.73÷8.78	-0.0000660	0.000069	0.000742	0.000034	0.000000	-0.000010
5.16÷6.73	-0.0000606	-0.000053	0.000728	0.000041	-0.000001	-0.000005
3.95÷5.16	-0.0000594	-0.000040	0.000599	0.000045	-0.000003	-0.000003
3.03÷3.95	-0.0000605	-0.000032	0.00043	0.000044	-0.000005	-0.000002
2.32÷3.03	-0.0000577	-0.000027	0.00027	0.000036	-0.000007	-0.000003
1.78÷2.32	-0.0000496	-0.000026	0.000156	0.000024	-0.000008	-0.000004
1.37÷1.78	-0.0000399	-0.000025	0.000088	0.000013	-0.000009	-0.000006
1.05÷1.37	-0.0000316	-0.000024	0.000047	0.000005	-0.000010	-0.000007
0.8÷1.05	-0.0000255	-0.000023	0.000022	0.000000	-0.000011	-0.000009
0.62÷0.8	-0.0000215	-0.000023	0.000004	-0.000003	-0.000013	-0.000010
0.47÷0.62	-0.0000190	-0.000024	-0.000011	-0.000004	-0.000015	-0.000011
0.36÷0.47	-0.0000195	-0.000028	-0.000019	-0.000001	-0.000019	-0.000012
0.28÷0.36	-0.0000212	-0.000035	-0.000026	0.000007	-0.000025	-0.000012
0.21÷0.28	-0.0001000	-0.000122	-0.000034	0.000037	-0.000075	-0.000039

Table 6. Comparison of coefficients a and b in equation (2)

	100% mill filling		50% mill filling	
Series	a	b	a	b
A	0.05229	0.49953	0.08068	0.43149
B	0.08221	0.49999	0.00905	0.60458
C	0.16146	0.48957	0.04787	0.2927

DISCUSSION AND RESULTS

Based on the coefficients in equation (3) that describes the change of grinding rate for size fractions. for different measuring series the highest values of coefficient S_i were observed in equation (2) for series C 100 in the whole range of particle changes (Fig. 1). Series C is characterised by the largest number of balls with the biggest diameters. They determine the highest destroying forces necessary to comminute the material. Grinding rates for series B 100 are much smaller and for size fraction below 20 μm they are almost the same as for the other series. For series A 50 and A 100, differences in coefficients S_i for the whole range of size fractions are small irrespective of the tested series. For series A 50 comminution is by several percent faster as compared to series A 100. Series A is characterised by the highest percentage of balls with small diameters. An increased number of small balls and decreased drum filling cause growing energy of the falling grinding balls. A longer distance that the grinding balls must pass before getting in contact with the feed free surface causes that the grinding balls attain high kinetic energy which in turn has a positive effect on the grinding rate in the whole range of size fractions of the ground product. The least favourable grinding conditions (low rates S_i) were obtained for series B 50 and C 50.

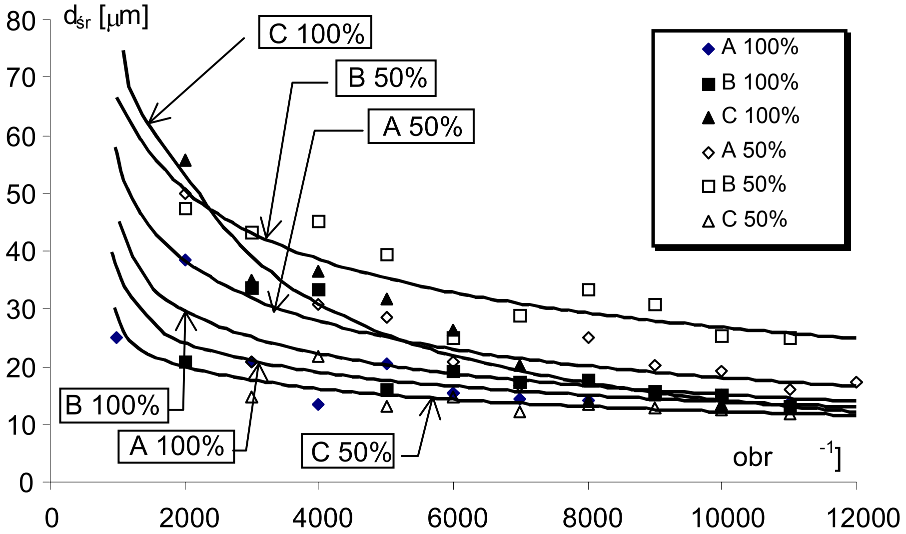

Fig. 1. Change of grinding rate of ceramic body mass for wall tile production at full filling of the mill

These series are characterised by a large number of balls with the biggest diameters and despite this, the interactions of the grinding balls and feed do not cause an increase of S_i. The ball energy increase induced by a longer distance from the free feed surface has no effect on an increased grinding rate either.

After about 6,000 revolutions of the mill, which corresponds to grinding time of 200 min, the mean particle size for all measuring series, is smaller than 35 μm. The smallest change of mean particle size occurs in series C for decreased filling of the mill. The rates of decay of size fractions between 790 and 96 μm are the highest for series C (Table 5) at 100% filling reaching about 0.005 rev^{-1}. For half of the mill filling and the same ball composition, the calculated grinding rate of the same size fractions is several times lower and ranges from 0.000021 to 0.000728 rev^{-1}.

A worse result was obtained for series B at 50% filling, because after the same number of revolutions, $d_{śr} = \sim 30$ μm, the rate S_{iB} for big size fractions (791.42 to 96.01 μm) for series B is much lower than the rate S_{iC} for the same fractions in mill C. Variability of S_{iB} ranges from 0.000004 to 0.0007575 rev^{-1}. For series B and 50% mill filling, it is not possible to attain a mean particle dimension like the one obtained for series C and 100% after 11,000 drum revolutions.

These results can be explained by two factors. The first one is the size and number of grinding balls. The biggest balls in series B are 40 mm in diameter. For series C, the biggest ball diameter is identical to that in series B but the mass of balls is bigger. This caused that the energy of grinding balls in series C was the highest, while in series B the energy was definitely the lowest. For these reasons, there are so big differences between the series in the first period of grinding at high process rates.

In the second period of grinding, illustrated in Fig. 2, which starts when the mean dimension of ground material particle reaches about 20 micrometers, the process rate is determined not by the size of balls but their number. An increase of the number of balls leads to an increased number of contact points. Probability that ground material particle will occur in the region where it is destroyed, hence in the zone of contact of two balls, is proportional to the number of these points of contact. For series A, the number of balls is the biggest (an increased fraction of balls 10 and 20 mm in diameter) which causes an increased rate of grinding of particles smaller than a dozen micrometers. For a smaller size fraction, the main factor affecting the grinding rate is the mentioned number of contact points. For all measuring series and the smallest particle sizes, the grinding rates are similar.

For the smallest size fractions (below 15 μm), negative rates of grinding S_i were observed. This can be explained by agglomeration of the smallest feed particles caused by intermolecular interactions. This is a disadvantageous phenomenon that has a negative effect on grinding of bigger fractions. The smallest fractions can stick to the grinding balls and decrease in this way the impact of grinding balls on the material.

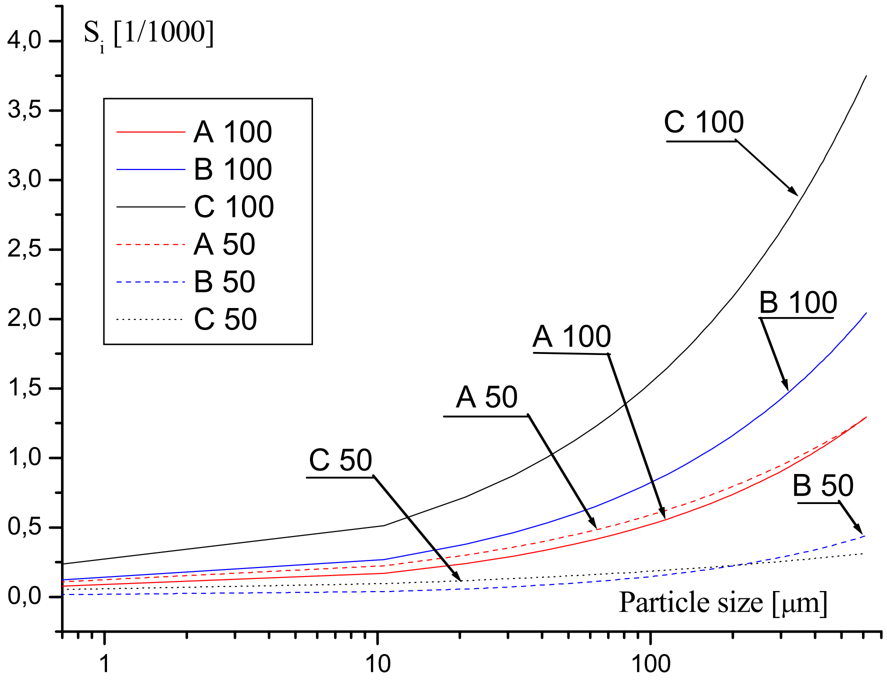

Fig. 2. Change of the grinding rate S_i for specific particle size in the size range *i* of ceramic body mass for wall tile production for tested series

CONCLUSIONS

The following conclusions can be drawn from results presented in this paper:

1. In the first period of grinding in the ball mills, when raw material particles are relatively big, the process depends to a large extent on ball size and mill filling which determine the forces of ball interactions.
2. In the second grinding period, when particle size of the ground material is much smaller, we can observe the impact of the number of balls, and consequently, contact points between the grinding balls.
3. The highest grinding rates for big fractions of the feed were obtained for the balls of the biggest diameters. A decrease of the number of balls with big diameters and replacing them with grinding balls of smaller diameters much reduces the grinding rate and causes that this parameter does not change a lot in the whole size range of the ground product.

NOMENCLATURE

a, b – parameter in the equation, constant
$b_{i,j}$ – distribution function defined as this part of ground material from size range *j*,
d_i – particle size in the size range *i*
$d_{śr\ i}$ – mean (arithmetic) particle size in the size range *i*
S_i, S_j – specific grinding rates for particles from size range *i* or *j*, respectively, called also distribution parameters, which passes to size range ,.
$w_i(t)$, $w_j(t)$ – weight fraction of particles *i* or *j* after grinding time *t*,
x_i – mass fraction of particles from size range *i.*

ACKNOWLEDGEMENTS

This study was carried out within research project no. 3T0C 005 23 financed by the Polish State Committee for Scientific Research in the years 2002-2005.

REFERENCES

DRZYMAŁA Z. i inni. (1992), *Badania i podstawy konstrukcji młynów specjalnych*. PWN. Warszawa.
LOWRISON G. C. (1974), *Crushing and grinding*. Butterworth, London.
LYNCH A.J. (1974), *Mineral crushing and grinding circuits*. Amsterdam, Oxford, New York.
MATTAN J.: (1971), *How to step up ball mill efficiency*. Rock Products, Nr 5.
SHIPWAY P. H., HUTCHINGS I. M. (1993), *Attrition of brittle spheres by fracture under compression and impact loading*. Powder Tech. 76, 23-30.
SHIPWAY P. H., HUTCHINGS I. M. (1993), *Fracture of brittle spheres by fracture under compression and impact loading. I. Elastic stress distribution*. Phil. Magaz. A, 67, 1389-1404.

Heim A., Olejnik T.P., Pawlak A., *Szybkość przemiału mas ceramicznych w młynie kulowym,* Physicochemical Problems of Mineral Processing, 39 (2005) 189-198 (w jęz. ang)**.**

W pracy przedstawiono wyniki badań, których celem było określenie wpływu liczby punktów kontaktu mielników na szybkość mielenia w młynie kulowym. Badania prowadzono dla młyna o działaniu okresowym pracujących w skali półprzemysłowej. Przemiał prowadzono na mokro (w zawiesinie wodnej z dodatkiem antyemulgatorów) dla typowych surowców mających zastosowanie w przemysłowej produkcji płytek ceramicznych. Zbadano przebieg procesu mielenia dla trzech składów kul oraz dwóch wartości wypełnienia młyna. Dla badanych przemiałów określono szybkość rozdrabniania poszczególnych klas rozmiarowych. Analizowano zmianę w czasie składu granulometrycznego mielonego materiału, stwierdzając wpływ na szybkość procesu wielkości kul, wielkości wypełnienia nadawą młyna oraz liczby mielników. Szybkość ta jest zmienna w czasie mielenia, a wpływ w/w czynników jest różny w poszczególnych okresach procesu.