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# THE EFFECT OF THE NUMBER OF CONTACT POINTS BETWEEN GRINDING ELEMENTS ON THE RATE OF GRINDING IN BALL MILLS

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Results of studies aiming at the determination of the effect of the number of contact points of grinding media on the rate of grinding in ball mills are discussed in the paper. Studies covered batch mills operating in industrial conditions. Wet grinding in a water solution with the addition of anti-emulsifiers was carried out for typical raw materials applicable in industrial production of ceramic tiles. The process of grinding was investigated for three industrial ball mills with different numbers and sizes of corundum grinding media. In the tested mills the rate of grinding of particular size groups was specified. The change of ground material particle size distribution in time was analysed, and the effect of ball size, frequency of drum revolutions and the number of grinding media on the process rate was reported. This rate is variable during grinding and the effect of the above mentioned factors is different in consecutive periods of the process.

*Key words: ball mill, point of contacts*

## INTRODUCTION

In ceramic industry, advantage is most often taken of grinding equipment whose operating principles are based on the use of free energy of grinding media. The simplest design solution are ball mills with steel or corundum grinding media. Grinding of material particles in these mills proceeds mainly between grinding elements and to a lesser extent between grinding media and the inner drum surface [Drzymała 1992, Mattan 1971]. Particles of the ground material which are between the surfaces of adjacent balls moving against each other (this motion may result from both translational motion and rotations of the balls) will be mainly abraded and sheared with possible crushing [Lynch 1974, Lowrison 1974]. In the cataract motion of balls

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(very desirable in ball mills), the striking mechanism of falling balls will be involved additionally [Shipway, Hutchings 1993]. Moreover, the particular mechanisms of grinding are affected by the size of balls and their number. It is obvious that at the same volume of the bed of balls (the same degree of drum filling with balls) the bigger are the balls the smaller is their number. Bigger balls mean a bigger mass of a single ball and higher forces of interactions. A related smaller number of balls means a fewer points of contact, hence a decrease of mini-regions in which in a given moment there can be loads breaking the particles of material being ground. Selection of ball diameters depends on the strength of material being ground and the diameter of raw material particles. In general, for bigger particles, which require bigger forces to be destroyed, bigger balls should be used, while in the case of smaller particles (of weaker materials) better results are obtained when the number of the points of ball contact increases, hence when this number grows at the cost of diameter. Results of grinding in three industrial ball mills operating in the plants that manufacture ceramic tiles were analysed from this point of view.

Simple construction of the mill does not correspond with grinding efficiency. Low efficiency of the process makes technologists search for such ball composition in which mean particle diameter decreases most quickly. This will enable the mill operation time to be more economical.

## PROCESS AND EQUIPMENT PARAMETERS OF GRINDING

Changes of particle size distribution of ground material in time were investigated in three industrial mills. Mills A, B and C, were characterised by similar size and kinematic parameters (Table 1). The process of wet grinding was carried out in a water suspension with the addition of anti-emulsifiers. The feed consisted of a mixture of minerals, mainly feldspar and clay. Tables 2 to 4 show the compositions of feed ground in the tested mills.

Table 1. Main parameters of industrial mills

| Industrial mills | A | B | C |
|---|---|---|---|
| Inner diameter, [m] | 3 | 2.5 | 3.15 |
| Total volume, [$m^3$] | 34 | 38 | 38 |
| Frequency of rotations, n[$min^{-1}$] | 13 | 12.65 | 13 |
| Critical frequency, $n_{cr}$ [$min^{-1}$] | 24.43 | 26.76 | 23.84 |
| $n/n_{cr}$ | 0.53 | 0.47 | 0.54 |
| Number of grinding balls, [thousand] | 620 | 400 | 400 |

Slight differences in feed composition for the tested mills followed from different technologies of production. This was related to the application of ground product in manufacturing of ceramic materials that would meet special requirements. The ground product from each of the three mills was used in the production of two types of ceramics. Wall tiles are burnt from a material called monoporosis (mill A, B) and silica (mill C). In the production of floor tiles quarry tiles are used (mills A, B and C).

Table 2. Feed composition for silica quarry tiles in mill A.

| | Monoporosis | Quarry tiles |
|---|---|---|
| Solid components, [kg] | 18 000 | 18 000 |
| - including feldspar, [kg] | 5 220 | 9 540 |
| - clay, [kg] | 7 740 | 7 020 |
| - quartz, [kg] | 2 880 | 1 440 |
| - carbonates, [kg] | 2 160 | - |
| Liquid components, [kg] | 1 095 | 1 064 |
| - including water, [kg] | 1 000 | 1 000 |
| - sodium tripolyphosphate, [kg] | 15 | 24 |
| - water glass, [kg] | 80 | 40 |

Table 3. Feed composition for monoporosis and quarry tiles for mill B.

| | Monoporosis | Quarry tiles |
|---|---|---|
| Solid components, [kg] | 21 300 | 22 000 |
| - including feldspar, [kg] | 3 834 | 11 660 |
| - clay, [%] | 11 502 | 7 700 |
| - dolomite, [%] | 1 704 | 1 980 |
| - calcium carbonate, [%] | 1 704 | - |
| - scrap metal, [%] | - | 660 |
| Liquid components, [kg] | 2 100 | 2 600 |
| - including water, [kg] | 2 051 | 2 550 |
| - sodium tripolyphosphate, [kg] | 49 | 50 |

Table 4. Feed composition for silica and quarry tiles in mill C.

| | Silica | Quarry tiles |
|---|---|---|
| Solid components, [kg] | 20 000 | 20 000 |
| - including feldspar, [kg] | 6 000 | 10 000 |
| - clay, [kg] | 14 000 | 10 000 |
| Liquid components, [kg] | 1 500 | 1 500 |
| - including water, [kg] | 1 422 | 1422 |
| - flumix, [kg] | 20 | 20 |
| - water glass, [kg] | 68 | 68 |

Filling of mills with grinding media, in all three mills equal to ca. 45% batch-wise, was composed of corundum balls of different sizes. Particular ball size fractions in the tested mills are presented in Table 5.

Table 5. Composition of balls and their sizes

| Mill | A | B | C |
|---|---|---|---|
| Ball diameter, [mm] | Mass of balls, [kg] | | |
| 19,05 | 1700 | - | 925 |
| 22,23 | 2750 | - | 1625 |
| 25 | - | 4000 | - |
| 25,4 | 4150 | - | 2500 |
| 30 | - | 8000 | - |
| 31,75 | 8000 | - | 5050 |
| 38,1 | 1800 | - | 1400 |
| 40 | - | 8000 | - |
| 44,45 | 3050 | - | 2300 |
| 45 | - | 6500 | - |
| 50,8 | 4550 | - | 3450 |
| 63,5 | - | - | 5750 |
| Altogether | 26000 | 26500 | 23000 |

The grinding was a batch process. After feeding the mill with raw material, in determined intervals (every 60 min) samples were taken for analysis of particle size distribution. The analyses were made using a FRITSCH laser particle size analyser ANALYSETTE 22. Table 6 gives examples of the results of particle size analysis for quarry tiles in mill A.

On the basis particle size analysis the rate of grinding of particular size fractions was calculated. In the calculations, equation (1) proposed by Gardner and Austin was used in the differential form for discrete values of fractions, under the assumption of 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 coefficients $S_i$ in equation (1) for grinding of quarry tiles in mills A, B and C are given in Table 7.

Table 6. Particle size composition of quarry tiles for mill A

| Size fraction i, [μm] | | Grinding time, [min] | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | 60 | 120 | 180 | 240 | 300 | 360 | 420 | 480 |
| | | Size fraction $w_i$, [%] | | | | | | | |
| 1 | 0,21÷0,28 | 0,73 | 0,69 | 0,67 | 0,64 | 0,64 | 0,65 | 0,66 | 0,68 |
| 2 | 0,28÷0,36 | 0,95 | 0,92 | 0,89 | 0,86 | 0,86 | 0,88 | 0,91 | 0,92 |
| 3 | 0,36÷0,47 | 1,33 | 1,31 | 1,28 | 1,25 | 1,25 | 1,28 | 1,33 | 1,35 |
| 4 | 0,47÷0,62 | 1,91 | 1,90 | 1,87 | 1,84 | 1,85 | 1,9 | 1,96 | 2 |
| 5 | 0,62÷0,8 | 2,59 | 2,61 | 2,56 | 2,55 | 2,56 | 2,62 | 2,72 | 2,78 |
| 6 | 0,8÷1,05 | 3,18 | 3,22 | 3,16 | 3,16 | 3,18 | 3,26 | 3,39 | 3,47 |
| 7 | 1,05÷1,37 | 3,66 | 3,72 | 3,66 | 3,67 | 3,70 | 3,79 | 3,94 | 4,04 |
| 8 | 1,37÷1,78 | 3,97 | 4,04 | 3,98 | 4 | 4,04 | 4,14 | 4,31 | 4,42 |
| 9 | 1,78÷2,32 | 4,13 | 4,21 | 4,15 | 4,18 | 4,24 | 4,33 | 4,52 | 4,63 |
| 10 | 2,32÷3,03 | 4,22 | 4,31 | 4,26 | 4,31 | 4,36 | 4,46 | 4,66 | 4,78 |
| 11 | 3,03÷3,95 | 4,37 | 4,50 | 4,46 | 4,54 | 4,58 | 4,68 | 4,91 | 5,04 |
| 12 | 3,95÷5,16 | 7,73 | 4,96 | 4,92 | 5,03 | 5,07 | 5,2 | 5,45 | 5,62 |
| 13 | 5,16÷6,73 | 5,25 | 5,64 | 5,60 | 5,75 | 5,83 | 6 | 6,31 | 6,56 |
| 14 | 6,73÷8,78 | 5,5 | 6,09 | 6,08 | 6,24 | 6,46 | 6,69 | 7,07 | 7,42 |
| 15 | 8,78÷11,45 | 5,16 | 5,93 | 5,97 | 6,12 | 6,60 | 6,86 | 7,33 | 7,80 |
| 16 | 11,45÷19,94 | 4,54 | 5,48 | 5,60 | 5,74 | 6,50 | 6,77 | 7,34 | 7,92 |
| 17 | 14,94÷19,48 | 4,16 | 5,29 | 5,54 | 5,72 | 6,57 | 6,88 | 7,49 | 8,13 |
| 18 | 19,48÷25,42 | 4,15 | 5,46 | 5,98 | 6,33 | 6,81 | 7,22 | 7,60 | 8,01 |
| 19 | 25,42÷33,16 | 4,37 | 5,87 | 6,81 | 7,49 | 7,07 | 7,55 | 7,32 | 7,02 |
| 20 | 33,16÷43,25 | 4,71 | 6,53 | 7,91 | 8,91 | 7,51 | 7,87 | 6,83 | 5,48 |
| 21 | 43,25÷56,42 | 3,1 | 4,65 | 5,51 | 5,24 | 4,53 | 3,78 | 2,57 | 1,21 |
| 22 | 56,42÷73,60 | 3,44 | 4,35 | 4,78 | 3,60 | 3,04 | 1,68 | 0,68 | 0,13 |
| 23 | 73,60÷96,01 | 5,33 | 3,95 | 3,03 | 1,85 | 1,49 | 0,62 | 0,11 | 0,01 |
| 24 | 96,01÷125,24 | 6,2 | 2,56 | 0,69 | 0,37 | 0,42 | 0,16 | 0,01 | 0 |
| 25 | 125,24÷163,38 | 4,8 | 0,98 | 0,06 | 0,03 | 0,09 | 0,03 | 0 | 0 |
| 26 | 163,38÷213,12 | 1,98 | 0,15 | 0 | 0 | 0,02 | 0,01 | 0 | 0 |
| 27 | 213,12÷278,01 | 0,52 | 0,01 | 0 | 0 | 0,01 | 0,03 | 0,01 | 0 |
| 28 | 278,01÷362,67 | 0,11 | 0 | 0 | 0 | 0,04 | 0,03 | 0,1 | 0 |
| 29 | 362,67÷473,09 | 0,06 | 0,01 | 0 | 0 | 0,06 | 0,04 | 0,1 | 0 |
| 30 | 473,09÷617,14 | 0,15 | 0,06 | 0 | 0,02 | 0,03 | 0,03 | 0 | 0 |
| 31 | 617,14÷791,42 | 0,12 | 0,02 | 0 | 0 | 0,06 | 0,04 | 0,01 | 0 |

Table 7. Rate coefficients $S_i$ for grinding of quarry tiles in mills A, B and C

| Mill A | | Mill B | | Mill C | |
|---|---|---|---|---|---|
| $d_i$ | $S_{iA}$ | $d_i$ | $S_{iB}$ | $d_i$ | $S_{iC}$ |
| 617,14÷791,42 | 0,000713 | - | - | - | - |
| 473,09÷617,14 | 0,000859 | - | - | 473,09÷617,14 | 0,0165 |
| 362,67÷473,09 | 0,00107 | - | - | 362,67÷473,09 | 0,0313 |
| 278,01÷362,67 | 0,00187 | 278,01÷362,67 | 0,00709 | 278,01÷362,67 | 0,0481 |
| 213,12÷278,01 | 0,00219 | 213,12÷278,01 | 0,0167 | 213,12÷278,01 | 0,0464 |
| 163,38÷213,12 | 0,00194 | 163,38÷213,12 | 0,0212 | 163,38÷213,12 | 0,0353 |
| 125,24÷163,38 | 0,0016 | 125,24÷163,38 | 0,0238 | 125,24÷163,38 | 0,0264 |
| 96,01÷125,24 | 0,00121 | 96,01÷125,24 | 0,0242 | 96,01÷125,24 | 0,0178 |
| 73,60÷96,01 | 0,000703 | 73,60÷96,01 | 0,0198 | 73,60÷96,01 | 0,0119 |
| 56,42÷73,60 | 0,000428 | 56,42÷73,60 | 0,0144 | 56,42÷73,60 | 0,00997 |
| 43,25÷56,42 | 0,000266 | 43,25÷56,42 | 0,0127 | 43,25÷56,42 | 0,00694 |
| 33,16÷43,25 | 0,000101 | 33,16÷43,25 | 0,0041 | 33,16÷43,25 | 0,00262 |
| 25,42÷33,16 | 7,53E-03 | 25,42÷33,16 | 0,002 | 25,42÷33,16 | 0,00187 |
| 19,48÷25,42 | 4,48E-03 | 19,48÷25,42 | 0,0015 | 19,48÷25,42 | 0,00134 |
| 11,45÷19,94 | 2,16E-03 | 11,45÷19,94 | 0,00123 | 11,45÷19,94 | 0,00107 |
| 8,78÷11,45 | 1,09E-04 | 8,78÷11,45 | 0,00105 | 8,78÷11,45 | 0,000835 |
| 6,73÷8,78 | -6,06E-04 | 6,73÷8,78 | 0,000982 | 6,73÷8,78 | 0,000649 |
| 5,16÷6,73 | 6,75E-04 | 5,16÷6,73 | 0,00088 | 5,16÷6,73 | 0,000525 |
| 3,95÷5,16 | 2,00E-04 | 3,95÷5,16 | 0,00068 | 3,95÷5,16 | 0,000475 |
| 3,03÷3,95 | 1,60E-04 | 3,03÷3,95 | 0,000513 | 3,03÷3,95 | 0,000448 |
| 2,32÷3,03 | -2,14E-04 | 2,32÷3,03 | 0,000419 | 2,32÷3,03 | 0,000346 |
| 1,78÷2,32 | -2,67E-04 | 1,78÷2,32 | 0,000384 | 1,78÷2,32 | 0,000198 |
| 1,37÷1,78 | -5,08E-04 | 1,37÷1,78 | 0,000305 | 1,37÷1,78 | 7,41E-05 |
| 1,05÷1,37 | -7,01E-04 | 1,05÷1,37 | 0,000236 | 1,05÷1,37 | -0,00011 |
| 0,8÷1,05 | -8,38E-04 | 0,8÷1,05 | 0,000134 | 0,8÷1,05 | -0,00025 |
| 0,62÷0,8 | -8,97E-04 | 0,62÷0,8 | 8,00E-04 | 0,62÷0,8 | -0,00044 |
| 0,47÷0,62 | -8,74E-04 | 0,47÷0,62 | 5,80E-05 | 0,47÷0,62 | -0,0005 |
| 0,36÷0,47 | -6,61E-04 | 0,36÷0,47 | 0,000621 | 0,36÷0,47 | -0,00059 |
| 0,28÷0,36 | -1,84E-05 | 0,28÷0,36 | 0,000199 | 0,28÷0,36 | -0,00068 |
| 0,21÷0,28 | 0 | 0,21÷0,28 | 0,00144 | 0,21÷0,28 | -0,00134 |

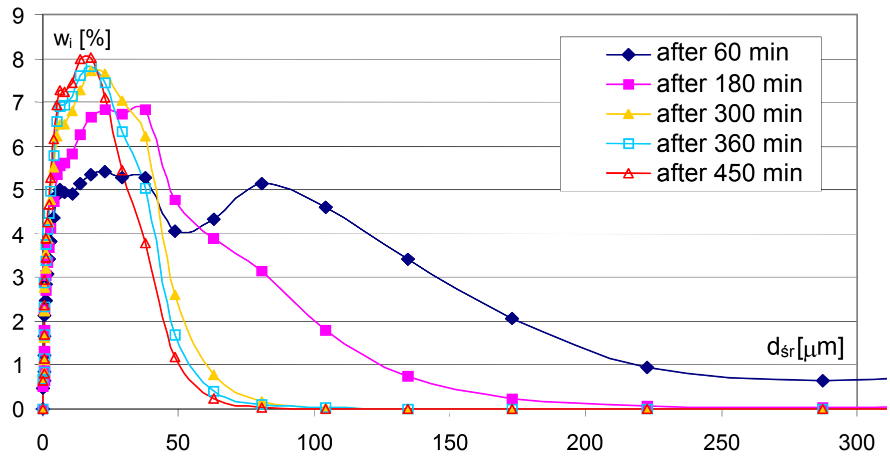


Fig. 1. Change of particle size composition of material ground in mill A in time

Knowing the particle size composition, mean particle size was calculated from the formula

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

This enabled a graphical representation (Fig. 2) of grinding kinetics in the form of a relation between mean particle size and grinding time: $d_{śr} = f(t)$.

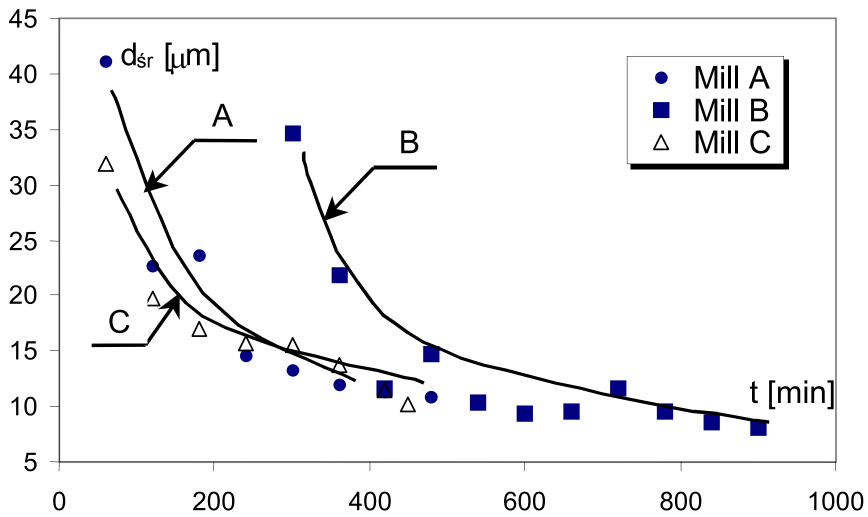


Fig. 2. Change of mean particle size $d_{śr}$ during grinding

## RESULTS AND DISCUSSION

Diagrams in Fig. 2 show clearly that in the first period of grinding, when raw material particles are big, the process of grinding is the fastest in mill C. Already, after 60 min of grinding, the mean size of particles ground in this mill is about 32 μm. Decay rates of size fractions between 699 and 109 μm are the biggest for mill C (Table 7) reaching about 0.04 $min^{-1}$. A worse result was achieved in mill A, because after the same time $d_{śr} = \sim 41$ μm. Rate $S_{iA}$ for so big size fractions (362,67 to 73.6 μm) in mill B is almost twice as small as rate $S_{iC}$ for the same fractions in mill C. For the mentioned size range the mean value of $S_{iB}$ for mill B is around 0.02 $min^{-1}$. To obtain a mean size of particles of ground material $d_{śr} = 45$ μm, the process should be carried out in mill B for 300 min. These results can be explained by two factors. The first one is the size of grinding balls. The biggest balls in mill B had the diameter 45 mm, while in mill A the balls had the diameter 50.8 mm, and in mill C even 63.5 mm. Another parameter is the relative frequency of drum rotations which in mill B was much lower than in the two other mills (Table 1). This made that the energy of grinding balls in mill C was the highest (the highest relative rate and the biggest balls), while in mill B this energy was definitely the lowest. For these reasons, with big particles in the first period of grinding the process rates are so differentiated in particular mills. In the second period of grinding, shown in Fig. 2, which starts when the mean particle size of ground material reaches dozen micrometers, the process rate is determined not by the size of balls but their number to which the number of points of contact between balls is proportional. As was reported above, the probability that a particle of ground material can appear in the region where it is destroyed, thus in the region near the contact point of two balls, is proportional to the number of these contact points. In mills B and C the number of balls is the same and a time-dependent change of the mean particle size proceeds in a similar way. The values of $S_{iB}$ and $S_{iC}$ for the size fraction below 5.84 μm are similar (Table 7) and are equal to around 0.0004 $min^{-1}$. In mill A filled with a bigger number of balls (a bigger number of contact points) the rate of decreasing the mean particle size is bigger in the second period of grinding when only small particles occur.

## CONCLUSIONS

The following conclusions can be drawn from the results discussed above:

1. In the first period of grinding in ball mills, when raw material particles are relatively big, the process depends on ball size and rotational speed of the mill, which determines the forces with which balls act on each other.
2. In the second period of grinding, when particle size of the ground material is much smaller, the effect of the number of balls and consequently the number of the points of contact of grinding elements between which material particles are comminuted, becomes more evident.

## LIST OF SYMBOLS

$d_{śr}$ – mean (arithmetic) particle size in size interval i
$x_i$ – mass fraction of particles from the size interval i
$w_i(t)$, $w_j(t)$ – weight fraction of particles from interval *i* or *j* after grinding time *t*,
$S_i$, $S_j$ – specific rate of grinding of particles from interval *i* or *j* called also the distribution parameter,
$b_{i,j}$ – distribution function defined as this part of ground material from size fraction *j*, which passed to size interval *i*.

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W pracy przedstawiono wyniki badań, których celem było określenie wpływu liczby punktów kontaktu mielników na szybkość mielenia w młynach kulowych. Badania prowadzono dla trzech młynów o działaniu okresowym pracujących w warunkach przemysłowych. Młyny posiadały zbliżone wymiary geometryczne. Przemiał prowadzono na mokro (w zawiesinie wodnej z dodatkiem antyemulgatorów) dla typowych surowców, mających zastosowanie w przemysłowej produkcji płytek ceramicznych, którymi były mieszaniny skalenia oraz iłów w odpowiednich udziałach masowych. Zbadano przebieg procesu mielenia dla trzech przemysłowych młynów kulowych, różniących się liczbą i wielkościami mielników korundowych. Dla każdego z przemiałów, co 60 minut pobierano próbki do analizy granulometrycznej. Określono szybkość rozdrabniania poszczególnych klas rozmiarowych w oparciu o równanie Gardnera Austina. Analizowano zmianę w czasie składu granulometrycznego mielonego materiału, stwierdzając wpływ na szybkość procesu wielkości kul, częstości obrotowej bębna oraz liczby mielników. Szybkość ta jest zmienna w czasie mielenia, a wpływ w/w czynników jest różny w poszczególnych okresach procesu.

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