R&D NOTE

Correlation of Grinding Rate of Gibbsite with Impact Energy of Balls

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Ball mills such as tumbling, vibrating, and planetary mills have been widely and frequently used as grinding devices in the field of chemical, materials, and recycling industries. Particularly, tumbling mills are employed in grinding processes because of low cost in operation and comparatively easy scale-up for practical use. The operational conditions in tumbling milling are generally determined experimentally (Ito et al., 1996). In order to determine the effective operational conditions such as ball size, ball filling ratio, mill diameter, rotational speed of mill, considerable effort and time is needed. If a method for determining the effective conditions were established without experimenting, it would be convenient for choosing the operational conditions and for determining the mill design. Under such circumstances, the authors (Kano et al., 1997) have proposed a novel method for simulating the motion of balls under the presence of powder on the basis of the particle element method (PEM) or discrete element method (DEM) (Mishra and Rajamani, 1990; Yokoyama et al., 1991; Ryu et al., 1992). It was reported that the grinding rate of the talc powder ground by a planetary mill could be correlated with the simulated impact energy of balls (Kano and Saito, 1998a; Kano et al., 1999a). This would extend to the case of the grinding rate of a powder in mills with different ball-filling ratios.

This article discusses the effects of the ball-filling ratio and mill scale on the correlation of grinding rate of a gibbsite powder with the ball impact energy simulated by the PEM.

Experimental Studies

The sample used in this experiment was a gibbsite powder ($Al(OH)_3$, CHP340s), which was supplied by Sumitomo Chemical Co. Ltd., Japan. The median diameter (50% particle diameter) of the starting sample D_o is 34.4 μm.

Grinding devices used in this experiment were tumbling ball mills made of stainless steel. The mill diameter was varied from 78 to 199 mm. Media balls made of steel were loaded into the mill at ball-filling ratio of 20, 30, 40, 60, and 80% of the mill volume. The sample was charged at a half of the ball-filling ratio. The mill was run under dry atmospheric condition, and the grinding time was varied from 15 to 180 min. A small amount of the ground sample was taken from the mill at the prescribed grinding time for the characterization. Other experimental conditions were tabulated in Tables 1 and 2.

Particle-size distributions of the starting and the ground samples were characterized using a laser diffraction particle-size distribution analyzer (Laser Micronsizer, LMS-30, Seishin Enterprise, Co. Ltd., Japan). The median diameter D_t of the sample ground at arbitrary time was employed as an indicator of grinding process in this work.

Simulation of Balls Motion by PEM

The PEM is essentially the same as the DEM, which is a popular simulation method of solid particle behavior, and is capable of describing the motion of media balls in a mill (Mishra and Rajamani, 1990; Yokoyama et al., 1991; Ryu et al., 1992).

Table 1. Experimental Conditions

Mill diameter	121, mm
Mill length	142, mm
Critical rotational speed	121.5, rpm
Ball diameter	10.2, mm
Grinding time	15, 30, 45, 60, 90, 120, 180, min

Table 2. Milling Conditions

Ball-filling ratio (%)	No. of balls	Sample wt. (kg)
20	312	0.150
30	468	0.225
40	624	0.300
60	936	0.450
80	1248	0.600

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Table 3. Material Properties and Physical Constants for the PEM Simulation

Young's modulus	1.0×10^{9} (Pa)
Poisson's ratio	0.28
Frictional coefficient	0.82
Coefficient of restitution	0.16
Density of particle	7.8×10^{3} (kg/m)
Time step	1.0×10^{-5} (s)

Three-dimensional motion of the balls in the mill under the presence of the sample could be simulated by determining relevantly the frictional coefficient of balls and mill wall. The frictional coefficient was assumed as 0.82, which was determined by a parameter fitting method (Kano et al., 1997). Furthermore, a smaller value of Young's modulus of the ball than the real datum was used in order to shorten the calculation time. This convenience, however, does not influence on the behavior of motion of the balls in a mill. Physical properties employed in the simulation are tabulated in Table 3. The motion of the balls was simulated for 5 s.

Results and Discussion

Figure 1 shows the particle-size distribution curves of the sample ground for various times at 40% in ball-filling ratio and the critical rotational speed. The distribution curves shift continuously towards the finer side as the grinding progresses, and this is a predominant range of the size reduction.

Figure 2 shows the normalized median diameter D_t/D_o of the ground sample at the critical rotational speed of the mill ($D = 121$ mm) as a function of grinding time with a parameter of the ball-filling ratio. The marked values denote experimental ones, and the solid lines correspond to the calculated ones derived from the following equation,

$$\frac{D_t}{D_0} = \left(1 - \frac{D_l}{D_0}\right) \exp(-K_P t) + \frac{D_l}{D_0} \quad (1)$$

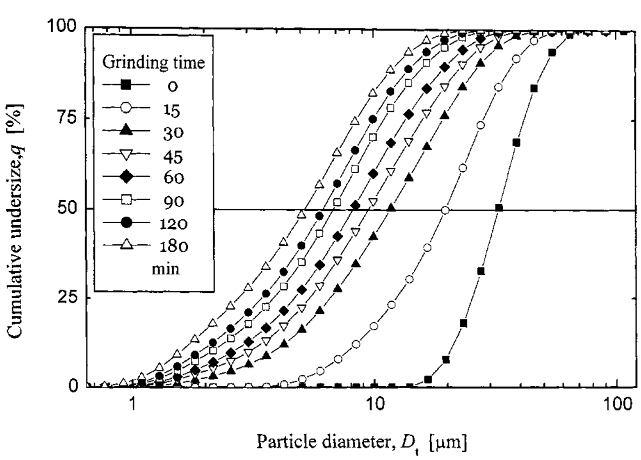

Figure 1. Particle-size distribution curves of the sample ground for various times by the 121 cm diameter mill driven at the critical rotational speed.

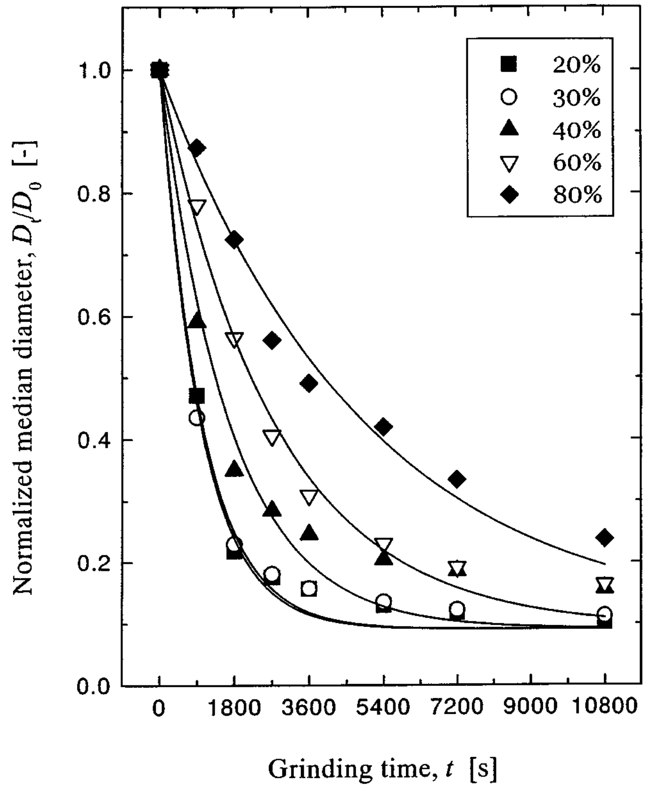

Figure 2. Relation between normalized median diameter and grinding time at the critical rotational speed.

where D_l denotes the median diameter at grinding limit. K_P is the grinding rate (s^{-1}) of the sample. D_t/D_o decreases rapidly in the initial stage of grinding. Subsequently, it tends to level off as the grinding progresses. In addition, D_t/D_o reduces as the ball-filling ratio decreases when compared at the same grinding time. Most of the experimental values are traced by the calculated lines. The same trend was seen in the relation between D_t/D_o and t for other rotational speeds of the mill with different sizes. Therefore, K_P in Eq. 1 is a representative value in the grinding processes.

Figure 3 shows a relation between K_P and the relative rotational speed of the mill ($D = 121$ mm) N/N_c with a parameter of the ball-filling ratio. N and N_c denote the rotational speed (s^{-1}) and the critical rotational speed (s^{-1}) of the mill, respectively. K_P increases with an increase in N/N_C. The value, however, rapidly falls over the rotational speed showing a maximum value of K_P at not more than 30% ball-filling ratio, while it slowly falls at not less than 40% ball-filling ratio. The rotational speed at the maximum K_P shifts to higher side as the ball-filling ratio decreases, and K_P accordingly becomes large. Rapid decrement in K_P at 20% and 30% in ball-filling ratios, respectively, is attributed to the rolling motion of balls. While, in the cases of 40%, 60% and 80% in ball-filling ratio, K_P decreases gradually due to cascading or cataracting of balls, although a part of the balls move together with the mill wall.

On the other hand, the impact energy of balls E_W (J/(kg·s)) can be calculated from the balls motion, as follows (Kano

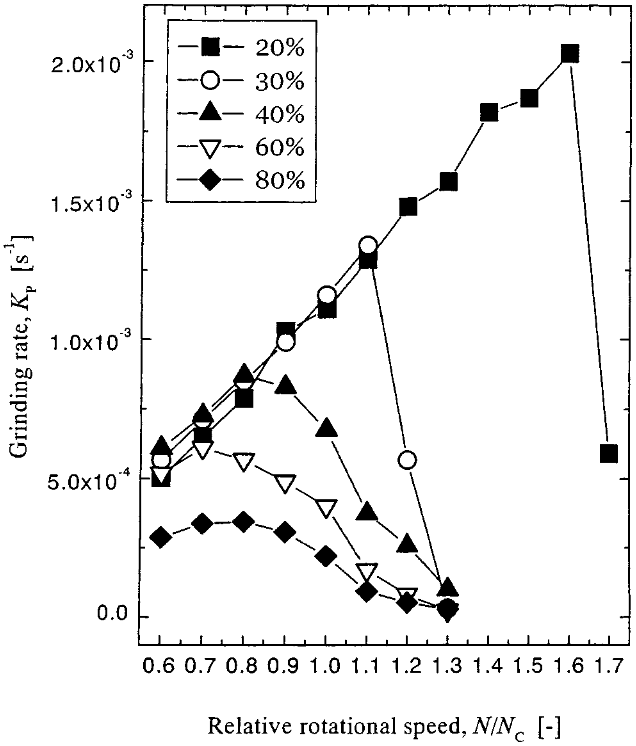

Figure 3. Relation between grinding rate and relative rotational speed.

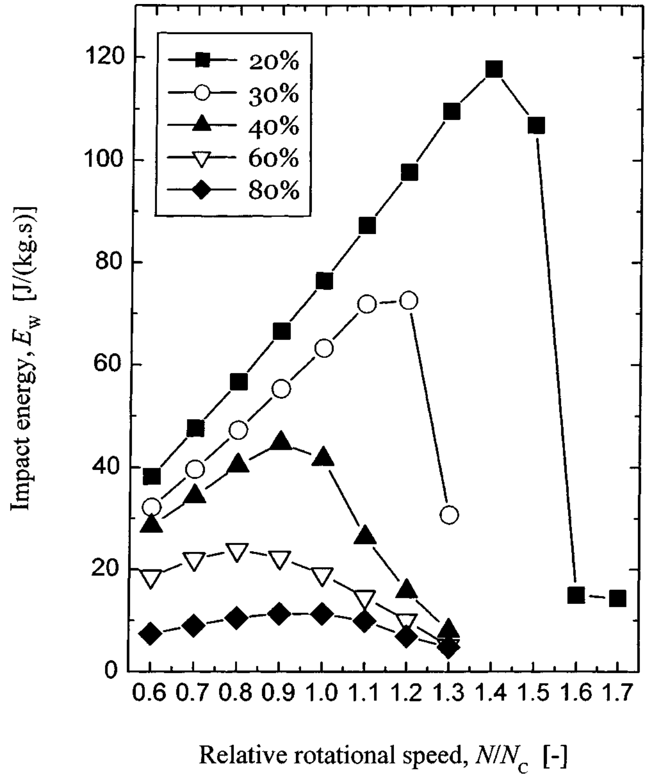

Figure 4. Relation between impact energy and relative rotational speed.

and Saito, 1998b)

$$E_W = \sum_{j=1}^{n} \frac{1}{2W} m v_j^2 \tag{2}$$

where m is the mass (kg) of the ball, n and v_j^2 denote the number of collision of a ball against another ball or the mill wall within a second and square of relative speed of the balls, respectively. W denotes the weight (kg) of sample charged in the mill.

Figure 4 shows relation between E_W and N/N_C with a parameter of the ball-filling ratio ($D = 121$ mm). E_W increases with an increase in N/N_C. The value rapidly falls down over the rotational speed showing a maximum value of E_W at not more than 30% ball-filling ratio, while it slowly falls down at not less than 40% ball-filling ratio. The rotational speed at a maximum E_W shifts to higher side as the ball-filling ratio decreases, and E_W accordingly becomes large. These tendencies are quite similar to the experimental results shown in Figure 3, and understood as follows: When the mill is operated at not more than N/N_C showing a maximum E_W, the balls behave in a cascading or cataracting motion. However, when N/N_C is over that speed, the motion of balls shifts to the rolling motion, which is ineffective for the grinding.

Correlation of K_P with E_W in the mill ($D = 121$ mm) obtained under whole conditions is shown in Figure 5. It is noticed that K_P is fairly correlated with E_W. A part of the data for 20% and 30% in ball-filling ratios is extremely outlying from the straight line due to the inconsistency of the speed

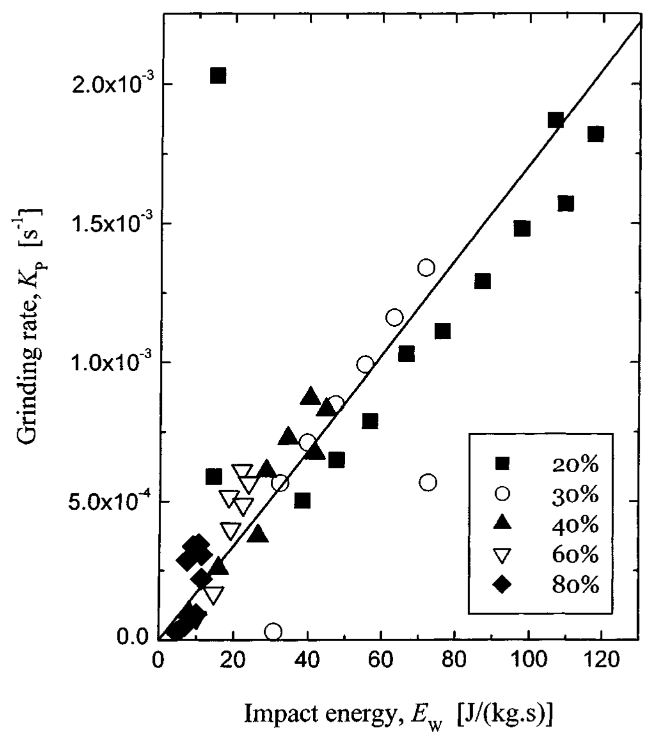

Figure 5. Relation between impact energy and grinding rate.

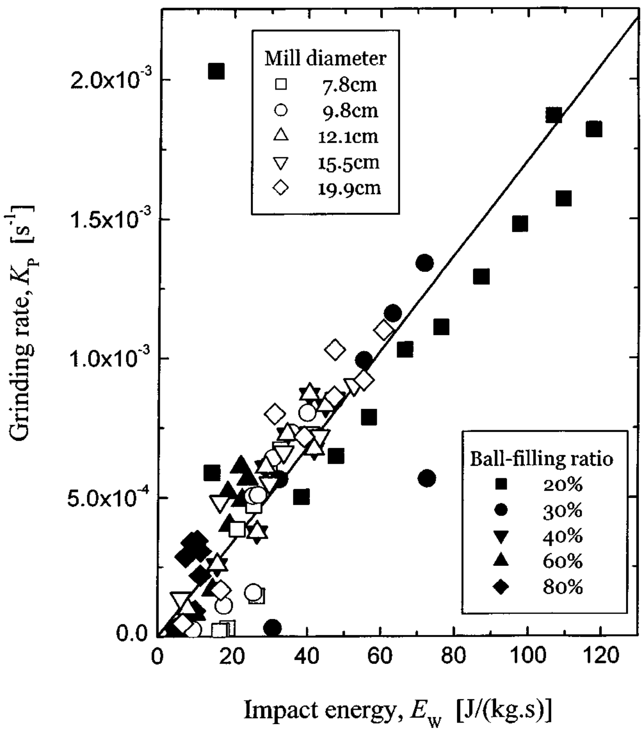

Figure 6. Relation between impact energy and grinding rate with parameters of ball-filling ratio and mill diameter.

showing a maximum value of K_P with that of E_W. In any case, we concluded that K_P is proportional to E_W regardless of the ball-filling ratio.

Figure 6 shows the grinding rate of the gibbsite powder ground by tumbling mills with different diameters at 40% in ball-filling ratio as a function of the impact energy (Kano et al., 1999b). Most of the data are scattered around the same straight line regardless of the mill diameter and ball-filling ratio, so that the relation is expressed by Eq. 3

$$K_P = kE_W \tag{3}$$

The value k is the grinding resistant, which is dependent on the material and initial size. This implies that the effective grinding conditions can be determined by this relationship.

Conclusion

In this article the effects of the ball-filling ratio on grinding rate of the gibbsite sample determined experimentally were investigated in correlation with the impact energy of balls simulated by the PEM. Here is a summary of this work.

(1) The grinding rate of the sample increases with increasing rotational speed of the mill. The rate rapidly falls over N/N_C showing a maximum K_P at not more than 30% ball-filling ratio, while it slowly falls at not less than 40%. The rotational speed at a maximum value of K_P shifts to higher side as the ball-filling ratio decreases, and according the grinding rate becomes large.

(2) The same trend (as the fact described above) can be seen in the relation between the impact energy of balls E_W and the relative speed N/N_C regardless of the ball-filling ratio and the mill diameter.

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Notation

D_t = 50% passing particle size at arbitrary grinding time, μm
D_l = 50% passing particle size at the grinding limit, μm
D_0 = 50% passing particle size at initial stage, μm
t = grinding time, min
v_r = relative speed of balls, m/s

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