Particle Impact Energy Variation with the Size and Number of Particles in a Planetary Ball Mill

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Abstract To investigate the mechanical energy applying to the particles in a grinding process using a planetary ball mill, the impact energy of particles was estimated by simulating the behavior of the particles and grinding balls using the discrete element method (DEM) under different conditions of the size and number of particles, corresponding to their variations during milling. As the impact energy contributing to the particle breakage, we focused on the particle impact energy generated at particle-to-grinding ball/wall and particle-to-particle collisions. The particle size and the number of particles affected the level of particle impact energy at a single collision and the number of collisions of particles, respectively, resulting in an increase of the total impact energy of particles with decreasing particle size and increasing number of particles. The result suggests that milling conditions such as the size of grinding balls should be adjusted appropriately based on the variation of the size and number of particles so that the particles can receive large amounts of the impact energy during milling.

1 Introduction

Dry powder grinding is an important unit operation in many industries, such as mining, food, fine chemical and pharmaceutical, ranging from coarse mineral ore to submicrometer-sized fine drug powder. Recently, ultrafine dry grinding processes with high energy milling (Chen *et al.*, 2015; Guzzo *et al.*, 2015; Kleiv and Thornhill, 2007; Guzzo *et al.*, 2019), which can produce fine particles with improved properties and/or enhanced performance, have attracted much attention. In ultrafine dry grinding processes, planetary ball mills have often been employed since the particles receive remarkably high impact energy at collisions with the grinding balls and the mill pot wall. The impact energy can vary depending strongly on the milling conditions and lead to breakage of particles, resulting in decreasing the particle size and increasing the number of particles. Therefore, the impact energy alters the produced particle properties, such as size distribution, specific surface area and microscopic structure. Accordingly, for producing the particles with controlled properties, the impact energy must be appropriately adjusted.

In the ultrafine dry grinding, due to the high impact energy applied to the particles, the particle size and number of particles drastically varies during milling (Kleiv and Thornhill, 2007; Chen *et al.*, 2015; Guzzo *et al.*, 2015; Guzzo *et al.*, 2019), which can change the type and amount of the impact energy of particles. Therefore, as a fundamental study for adjusting the impact energy, it is necessary to investigate the variation of the impact energy with the size and number of particles.

In some studies, variations of the impact energy with the revolution speed of the mill pot (Minagawa *et al.*, 2018) and the loading masses of the particles and grinding balls (Ashrafizadeh and Ashrafizaadeh, 2012; Geissbuhler and Sawley, 2013) were obtained using the discrete element method (DEM) simulation of behavior of the particles and balls. However, to the best of our knowledge, no studies have focused on the impact energy variation with the size and number of particles.

In this paper, in order to provide criteria for adjusting the impact energy in accordance with the progress of particle breakage, we estimated the impact energy by simulating the behavior of the particles and grinding balls in a planetary mill under different conditions of the size and number of particles using DEM. To study in detail the effects of the size and number of particles on the impact energy, the impact energy was analyzed separately by classifying the impact energy of a particle into two collision categories, i.e., particle-to-particle and particle-to-grinding ball/wall collisions.

2 Methods

To obtain the impact energy of the particles, the behavior of the particles and grinding balls in a planetary mill under dry conditions was simulated (Hirosawa *et al.*, 2019) using DEM (Cundall and Strack, 1979), which is a reliable method for simulations of solid particle behaviors (Horabik and Molenda, 2016; Tang *et al.*, 2018). In this work, the simulation method proposed by Tsuji *et al.* (1992) was employed. The simulation

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parameters, such as the density, Poisson's ratio, Young's modulus of particle, ball and wall materials, and the restitution coefficient and friction coefficient of particle-to-particle, particle-to-ball/wall and ball-to-ball/wall collisions, were the same as those used by Capece *et al.* (2014), as listed in Table 1. In order to obtain the variation of the impact energy of particles with respect to the particle breakage, both the particle size and the number of particles were changed independently as shown in Table 2. The variation of the size and number of particles was expressed by a diameter ratio D_b/D_p, where D_b and D_p are the diameters of a ball and a particle, respectively. The ball-to-particle filling mass ratio (BPR) was kept at 30 regardless of the size and number of particles.

In order to evaluate the energy spent for the particle breakage by impact milling, the impact energy E of particles is defined by the energy dissipated through a particle collision, according to Govender *et al.* (2015), Santhanam and Dreizin (2012) and Cleary and Morrison (2011). The impact energy is calculated by integrating the normal and tangential contact forces, F_n and F_t, of a particle with respect to its overlaps, δ_n and δ_t, over the contact period t_c in the case of no sliding at the contact, as expressed in Eq. (1).

$$E = \int_0^{t_c} (F_n \mathrm{d}\delta_n + F_t \mathrm{d}\delta_t) \qquad (1)$$

Table 1. Parameters used in the simulation

Number:	
Grinding ball	18
Particle	18–3724
Ball/particle filling mass ratio	30
Ball/particle filling volume ratio	16
Diameter:	
Grinding ball	10.0 mm
Particle	4.0–0.67 mm
Density*:	
Grinding ball	4000 kg/m^3
Particle	2150 kg/m^3
Poisson's ratio*	0.3
Young's modulus*	1×10^7 Pa
Coefficient of restitution*	0.75
Sliding friction coefficient*	0.75
Rolling friction coefficient*	0.02
Pot volume	45 mL
Pot diameter	40 mm
Pot depth	35.8 mm
Revolution speed	10.0 s^{-1}
Revolution radius	67 mm
Rotation-to-revolution speed ratio	–1
Time step	200 ns

* Capece *et al.* (2014)

Table 2. Particle sizes and numbers of particles in the simulation

Particle size, D_p [mm]	Number of particles [–]	D_b/D_p [–]
4.0	18	2.5
2.7	59	3.75
2.0	140	5
1.6	273	6.25
1.3	476	7.5
1.0	1120	10
0.80	2188	12.5
0.67	3724	15

D_b = Ball size (10 mm)

When the contacting particle slides, the impact energy E in the tangential direction is calculated by integrating the product of the contact force F_t, i.e., the frictional force, and the tangential velocity v_t, over the contact period t_c.

$$E = \int_0^{t_c} (F_n \mathrm{d}\delta_n + F_t v_t) \qquad (2)$$

The total impact energy E_t was obtained by summing up E for all collisions of the particles. Additionally, the total particle impact energies, E_{tb} and E_{tp}, at the particle-to-ball/wall collisions and the particle-to-particle collisions, respectively, were also investigated, of which the relationship was expressed by Eq. (3).

$$E_t = E_{tb} + E_{tp} \qquad (3)$$

3 Results and Discussion

Figure 1 illustrates the snapshots of the particles and grinding balls in the mill pot at different D_b/D_p values corresponding to different stages of the particle breakage. Regardless of D_b/D_p, the balls were packed densely near the wall of mill pot because of high centrifugal accelerations induced by the planetary motion of the mill pot. Smaller particles also tended to gather near the wall. Therefore, the smaller particles may receive large amounts of the impact energy at particle-to-ball/wall collisions near the wall.

Figure 2 shows the impact energy distributions of the particles at different D_b/D_p values. Smaller impact energies increased at high values of D_b/D_p. The energy distributions, except for a case at D_b/D_p = 2.5, were approximately bimodal, consisting of high and low energies. The higher and lower impact energies could be generated at particle-to-ball/wall and particle-to-particle collisions, respectively. At all D_b/D_p values, the most of the impact energy generated at the particle-to-ball/wall collisions exceeded a threshold energy of the particle breakage (Capece *et al.*, 2014), determined by the material and size of the particles. On the other hand, more than half of the impact energy generated at the particle-to-particle collisions was lower than the threshold energy. Therefore, the particle breakage may strongly depend on the collision types of the particles determining the level of impact energy.

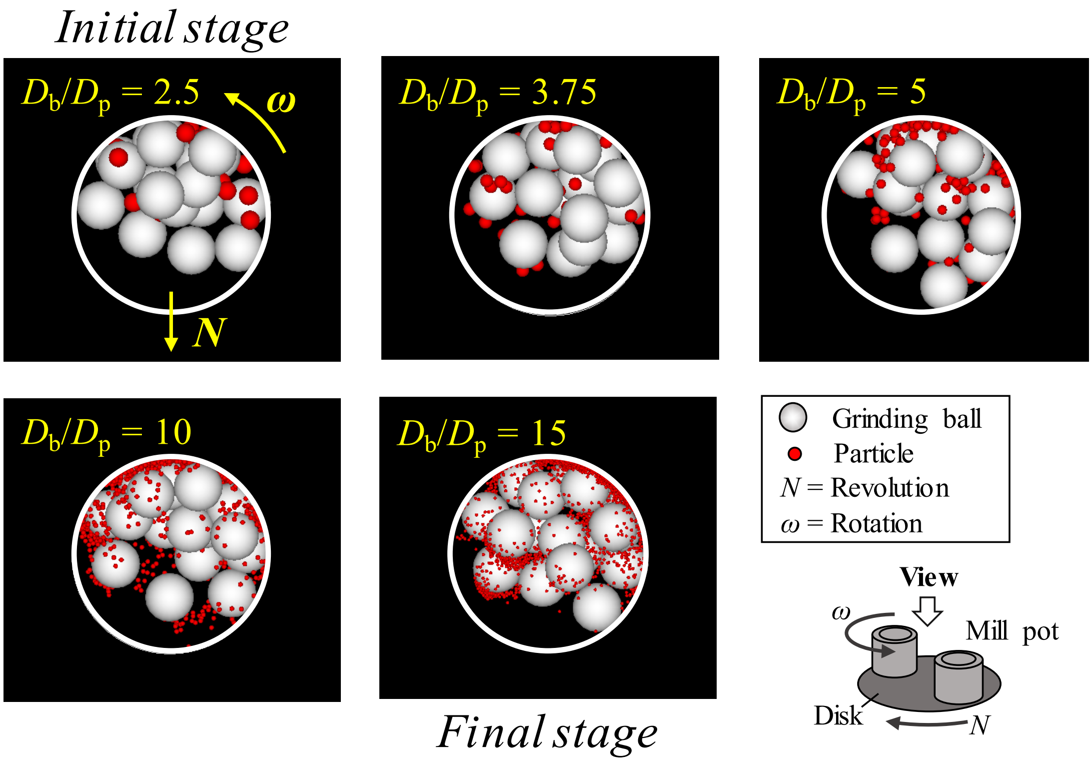

Figure 1. Snapshots of particles and grinding balls in planetary mill at different stages of particle breakage

In order to investigate the effect of collision types on the impact energy variations with the size and number of the particles, we calculated the impact energy separately at the particle-to-ball/wall and particle-to-particle collisions. The effect of the particle size on the impact energy of particles was expressed by a median impact energy corresponding to the 50% value of the accumulated impact energy representing a representative of the impact energy at a single collision. Figure 3 shows the change in the median impact energy with the mass of a single particle at each collision type. The median impact energy at the particle-to-ball/wall collisions was almost constant regardless of the mass of a particle and much higher than that at the particle-to-particle collisions, showing that the impact energy at the particle-to-ball/wall collisions can greatly affect the particle breakage. However, at the particle-to-particle collisions, the median impact energy showed a tendency to remarkably increase with increasing mass of a particle in comparison with that at the particle-to-ball/wall collisions. Subsequently, the effect of the number of particles on the impact energy at each collision type was studied based on the number of collisions of particles, as shown in Figure 4. The numbers of particle-to-ball/wall collisions increased linearly with increasing number of particles. On the other hand, at the particle-to-particle collisions, the number of the collisions exponentially increased due to the drastic increase in the number of particles.

For investigating the amount of impact energy applied to the particles during milling, the total impact energies, E_t, E_{tb} and E_{tp}, were calculated, as illustrated in Figure 5. The total impact energies increased with increasing D_b/D_p values, i.e., decreasing particle size and increasing number of particles simultaneously at a constant filling mass of the particles, because the number of particles greatly affected on the impact energy in comparison with the particle size. E_{tb} was remarkably higher compared with E_{tp}, and close to E_t at low D_b/D_p values. However, the influence of E_{tp} on E_t gradually increased with increasing D_b/D_p, implying that the amount of impact energy contributing to the particle breakage may relatively decrease at extremely high D_b/D_p values.

4 Conclusion

The variation of particle impact energy with the particle size and number of particles in a planetary ball mill was investigated by simulating the behavior of the particles and grinding balls using DEM. The median impact energy at a single collision decreased with reduction of the particle size. However, the number of collisions of the particles drastically increased with an increase in the number of particles. Comparing to the particle size reduction, the increase of the number of particles greatly affected the particle impact energy, resulting in an

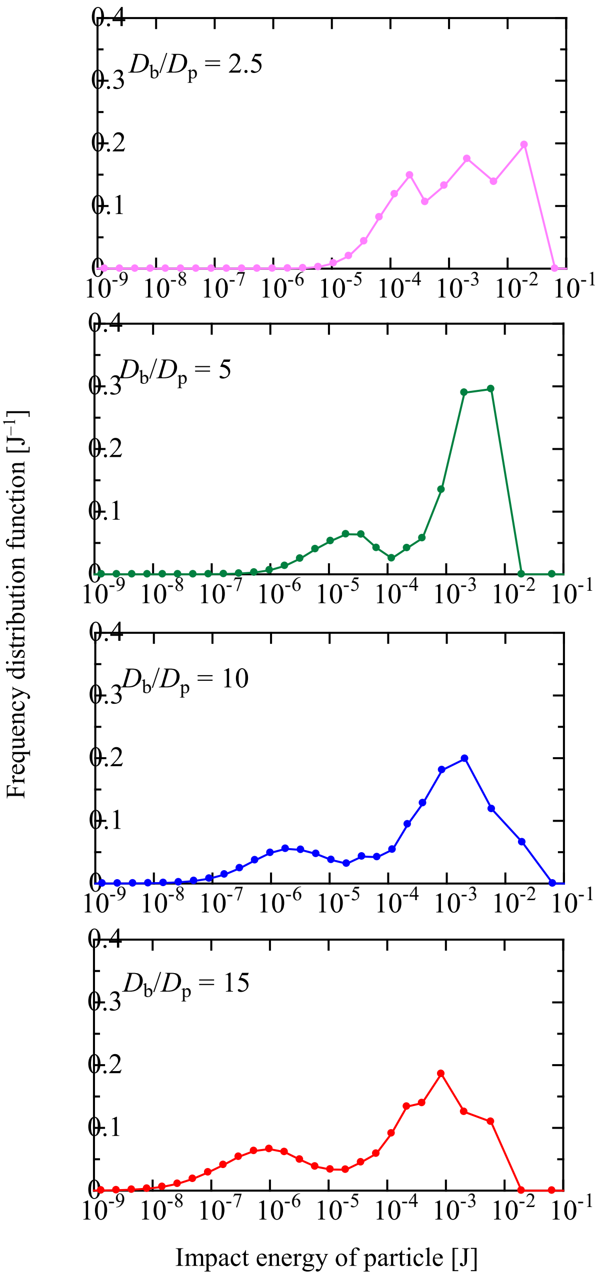

Figure 2. Effect of D_b/D_p on impact energy distribution of particles

increase of the total impact energy contributing to the particle breakage. The result suggests that the size of grinding balls should be adjusted appropriately based on the variation of the size and number of particles so that the particles can receive large amounts of the impact energy during milling.

Acknowledgement

This work was supported by JSPS Research Fellowships for Young Scientists, and JSPS KAKENHI Grant Number JP18J21860.

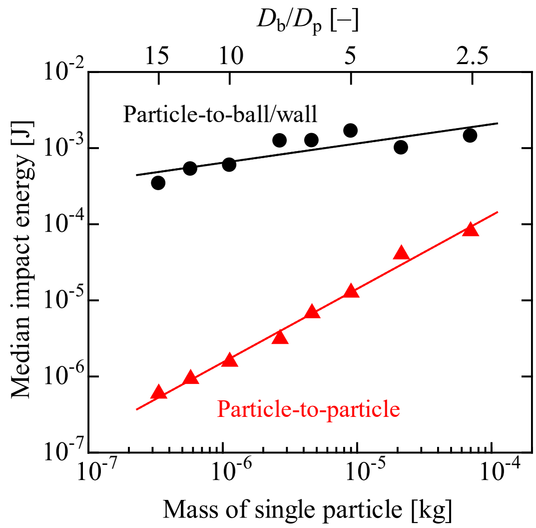

Figure 3. Effect of collision types on median impact energy variation with mass of single particle.

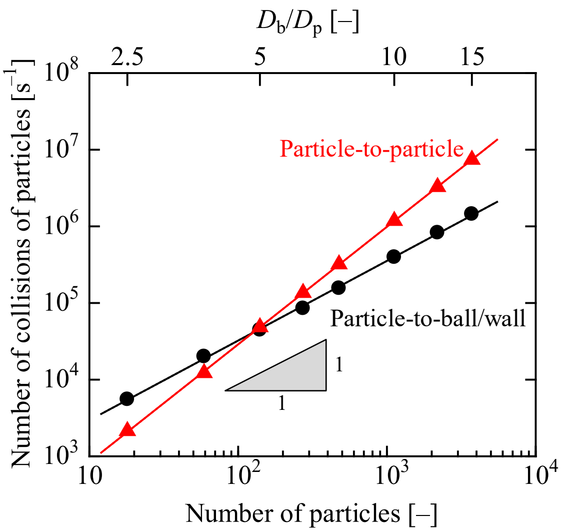

Figure 4. Effect of collision types on change in number of collisions with number of particles

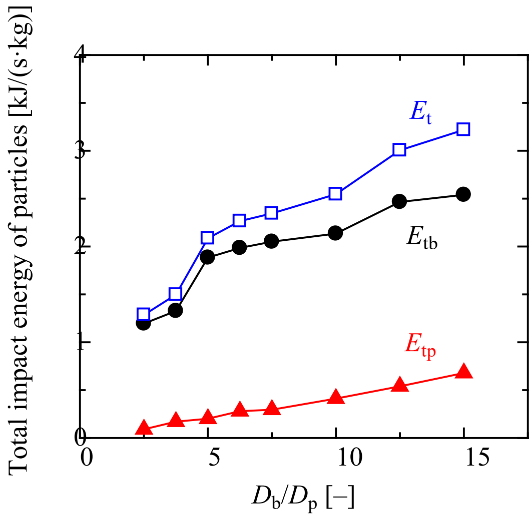

Figure 5. Effect of collision types on total impact energy variation with D_b/D_p

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