Application of DEM Simulation to drum type agitation mill for appropriate comminution

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Abstract

A computer simulation using discrete element method (DEM) was applied to a comminution/detachment process of waste printed circuit boards (PCBs). Recycling of PCBs is an important subject not only from the treatment of waste but also from the recovery of valuable metals. However, direct simulation method to investigate a comminution/detachment process of PCBs has not yet been established. We have already published an indirect simulation using the general spherical particle model to discuss the mechanism of parts detachment and board breakage.

This study prepared simulant PCBs on which some capacitors were solder-mounted and used for the comminution test to compare with simulation results. In order to calculate the behavior and comminution/detachment process of PCBs, a PCB was constructed many fine particles and particle based rigid body model was also included to the simulation. This simulation could directly represent the behavior of PCBs in the drum typed agitation mill. Simulation results successfully corresponded to comminution experimental results using drum type mill with agitator.

Keywords: DEM, Particle based rigid body, Comminution, Recycling

Introduction

The amount of electronic waste, commonly known as e-waste, waste electrical and electronic equipment (WEEE) is increasing at a rate of 3-5 % per annum [Herat 2007]. In order to reduce final waste volume and decline environmental burden, it has been expected that the recycling system of e-waste is established. A printed circuit board (PCB) is one of the most important components of e-waste, and contains many electronic components such as resistors, capacitors, relays, semi-conductors and IC chips. These components have not only many valuable metals but also many hazardous chemicals. Although their composition varies slightly depending on the grade, usage and manufacturing year, PCBs represent a useful source of recoverable material values. Efficient recycling and appropriate material treatment will ensure that non-renewable resources are recovered and environmental pollution is prevented.

The computer simulation is an important means of scientific research. The Discrete Element Method (DEM) predicts the behavior of the whole particles from the motion of individual particles (Cundall and Strack 1979). Therefore, in order to analyze the behavior of particle flow and investigate phenomena of powder particles, the DEM is widely used and has been applied to powder simulation such as fluid bet, ball mill, slope failure, and so on. On the other hand, in order to apply DEM to breakage phenomenon, there are some methods which construct an object by bonding many fine particles, analyze contact force of constituent particles, and break the bonds between fine particles if contact forces became over a threshold level. However, it has not been investigated which models are adequate for the grinding process.

The objective of this study was to apply DEM simulation to comminution process in drum type agitation mills and to investigate the mechanism of mechanical detachment to remove electronic components from printed circuit boards (PCBs). In addition to the conventional model, in this study, two DEM simulation models were constructed. One is the particle breakage model. The other is the particle-based rigid body model. Simulation results were compared with experimental results using test PCBs. And then we investigated whether simulation results successfully corresponded to comminution experimental results or not.

Comminution experiment

Preparation of test PCBs

A test PCB was prepared to stabilize comminution experimental results. A double side glass epoxy PCB (FR-4, Picotec International, Taiwan) and, 10 μF and 35 V of several ceramic condensers (GP075F106Z, Taiyo Yuden, Japan) were used for a test PCB. Nine ceramic condensers were solder-mounted at regular intervals on a PCB. A PCB was 210×155 mm and weighed 92.8 g. A ceramic condenser weighed 0.14 g.

Drum-typed impact agitation mill

Two types of drum-typed impact agitation mill (Parts separator, Hirata corporation, Japan) were used for comminution tests. The mill is a cylinder, 0.86 m diameter and length. The cylinder axix is inclined at 30° from the vertical, and a mechanical stirrer is installed in the bottom of the drum. There are two projections on the surface of the stirrer and the wall. There is a slight difference between two types of agitation mill. Type A has bigger mechanical stirrer than Type B. These simulation models of the agitation mill constructed in DEM simulation are shown in Figure 1.

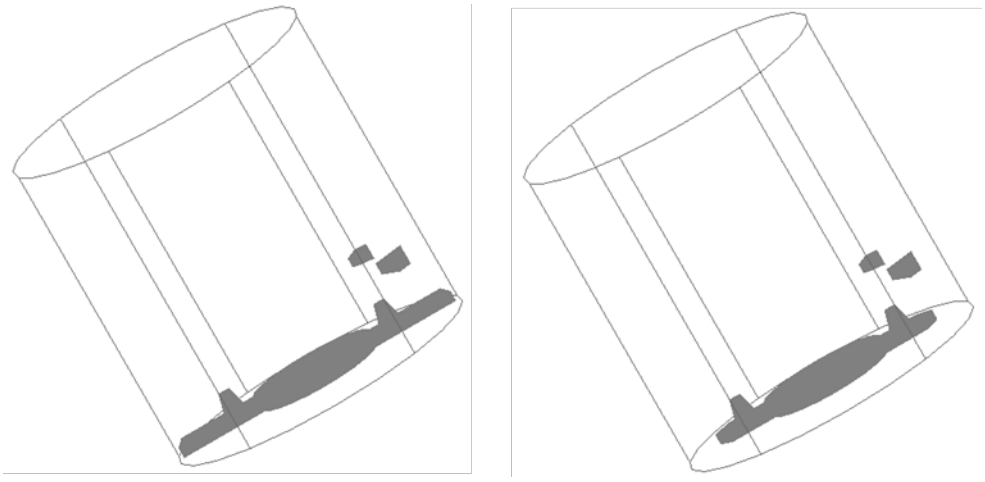

Figure 1 Schematic of drum-typed impact agitation mill represented in the DEM simulation (Left : Type A, Right : Type B)

Comminution test

In the parts detachment test, the grinding time was fixed at 30 s. The rotation speed was changed from 300, 500, 1000, or 1500 rev/min. The mill was charged with 5 – 100 pieces of PCBs. All of comminution products were collected and weight of each PCB and number of remaining parts on PCBs were counted.

DEM simulation method

Spherical particle model

A spherical particle model is based on the original DEM concept proposed by Cundall and Strack. Contact between particles and between a particle and a wall is modeled using a Voigt model consisting of a spring and a dashpot in normal and tangential directions. A slip model defined by the friction slider is included in the tangential force. Table 1 gives parameter values used in the spherical particle model.

Table 1 DEM simulation conditions in the spherical particle model

Spring constant	5.0×10^{6} N/m
Coefficient of restitution	0.10
Coefficient of friction	0.27
Diameter of a particle	0.1 m
Number of particles	5 - 100
Weight of a particle	92.8 g

Particle breakage model

In the particle breakage model, PCBs and parts geometry were constructed consisting of many fine bonded particles. A phenomena of parts detachment was modeled by breaking the bonds between fine particles if contact forces became over a threshold level. An anchoring concept was developed as a new bonding model to avoid displacement of the bonding point between particles. In this case, torque and bonding force between bonded two particles, *i* and *j*, were calculated as follows.

$$\mathbf{T}_i = \mathbf{T}_{Di} + \frac{\pi a^4}{4}\mathbf{K}_0 \begin{pmatrix} \Delta\psi_x \\ \Delta\psi_y \\ 2\Delta\psi_z \end{pmatrix} \quad (1)$$

$$\mathbf{T}_j = \mathbf{T}_{Dj} + \frac{\pi a^4}{4}\mathbf{K}_0 \begin{pmatrix} \Delta\psi_x \\ \Delta\psi_y \\ 2\Delta\psi_z \end{pmatrix} \quad (2)$$

$$\mathbf{K} = \pi a^2 \mathbf{K}_0 \quad (3)$$

Where $\mathbf{T}_i$ and $\mathbf{T}_j$ were the torque vectors between two bonded particles, *i* and *j*, and $\Delta\psi_x$, $\Delta\psi_y$ and $\Delta\psi_z$ were the difference in rotation angles between two bonded particles around the x, y and z-axis. In this case, the contact point between two bonded particles was set at the origin, the normal direction was set as the z-axis and the tangential direction were set to the x and y axes. $\mathbf{T}_{Di}$ and $\mathbf{T}_{Dj}$ were the torques calculated in an original DEM model without particle breakage. **K** was the spring constant vector in the original DEM model without particle breakage. *a* was the anchoring area between two bonded particles.

The connection between two particles was considered to be broken if the bonding force calculated from DEM rose above a set threshold level. The threshold level was determined from tensile tests. The DEM parameter used for the particle breakage model are shown in Table 2.

Table 2 DEM simulation conditions in the particle breakage model

Diameter of configuration particles per a PCB	0.15 m
Diameter of anchoring area	1.5 mm

Particle-based rigid body

Since the shape of waste PCBs is complicated, waste PCBs cannot be directly simulated in the original DEM. In order to investigate the behavior of these waste PCBs in the agitation mill, a particle-based rigid model was included into the original DEM.

The motion of a rigid body is computed by dividing motion into two parts: translation and rotation. Translation describes the motion of the center of mass, whereas rotation describes how the rigid body rotates around the center of mass. A detailed explanation is reported by Baraff (1997).

In this method, the shape of waste PCBs and the collision detection are based not on the polygons that represent the rigid bodies, but on particles, as done by the authors (Bell, 2005; Tanaka et al., 2006). A waste PCB is represented by a set of fine particles that are spheres of identical size.

The calculation conditions of a waste PCB represented in this model were shown in Table 3. The diameter of constituent particle was set at 5 mm. These particles were aligned in the shape of a lattice. Snapshot of a waste digital camera in this model was shown in Figure 2.

Table 3 Calculation condition of a waste PCB in Particle-based rigid body model

Particle diameter	5 mm
Number of particles constructed board	41 × 32
Number of particles constructed part	2
Number of parts	9
Mass of a PCB	92.8 g

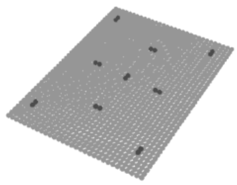

Figure 2 Snapshot of PCBs constructed of particle-based rigid body model

Collision energy

Breakage of PCBs is caused by collision between PCBs, a PCB and drum wall or agitator. Calculation of the damping energy generated during the collision would be crucial to investigate the mechanism of comminution process. In this study, we counted damping energy during collision of PCBs in order to grasp collision energy of them. Dumping energy was calculated from consuming energy in dashpot and friction slider of the Voigt model during collision. This is given by:

$$E_{loss} = \int P_{dashpot} dt + \int P_{friciton} dt \quad (4)$$

where $\boldsymbol{E_{loss}}$ was damping energy, $\boldsymbol{P_{dashpot}}$ and $\boldsymbol{P_{friction}}$ were respectively the rates of energy dissipation in dashpot and friction slider.

Results and Discussion

Experimental results of comminution test

Experimental snapshots of test PCB before/after comminution are presented in Figure 3. After comminution test, most parts were detached from the boards, as shown in snapshots (b) and (c). A part of PCBs was broken like snapshots (c) while most PCBs were unbroken like snapshots (b). Detached parts were unbroken like snapshots (d).

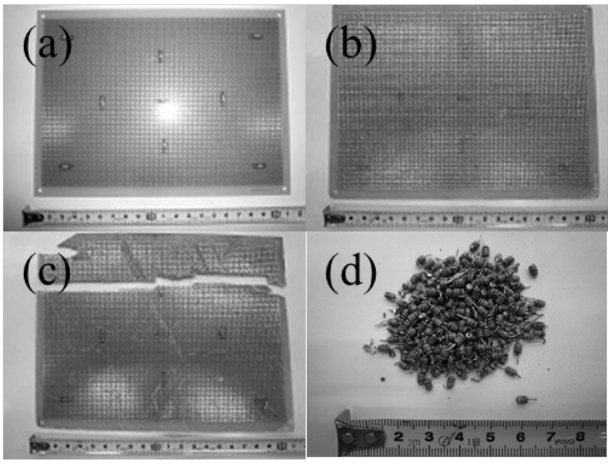

Figure 3 Result of comminution experiment for test PCB using drum-typed impact agitation mill: (a) test PCB before comminution test, (b) unbroken PCB, (c) broken PCB, (d) detached parts

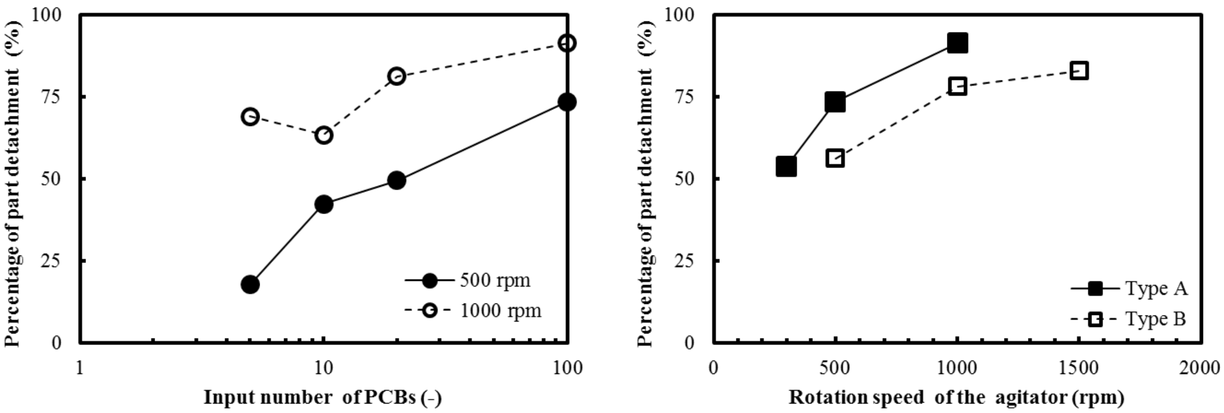

Figure 4 Result of comminution experiment for test PCB using drum-typed impact agitation mill: (left : relationship between input number of PCBs and part detachment, right : relationship between rotation speed and part detachment)

Figure 4 shows the result of comminution experiment for test PCBs. The left graph shows that the relationship between percentage of part detachment and number of PCBs in the mill charge. In this comminution tests, the rotation speed was fixed at 500 or 1000 rpm. As shown in the left graph of Figure 4, the percentage of part detachment was increased with the number of PCBs. These results suggested that interaction between PCBs became more frequent and parts detachment from the board was accelerated. The more input of PCBs is better to achieve parts liberation from the board. On the other hand, the right graph of Figure 4 shows the relationship percentage of part detachment and rotation speed. In these comminution tests, 100 pieces of PCBs were charged in the mill par a batch. As shown in the right graph of Figure 4, the percentage of part detachment increased with rotation speed. The percentage of part detachment in drum type A was larger than that of part detachment in drum type B at each rotation speed. These results indicated that the stress became high when the edge of agitator was narrow, and that the shape of agitation at the bottom of the mill affected the part detachment.

Simulation results of the particle breakage model

Figure 5 shows a snapshot of DEM simulation using the particle breakage model. In this simulation results, rotational speed was 500 rev/min and the mill was charged with 20 PCBs. The

PCBs were agitated by the stirrer, and part detachment process in the mill could be directly represented in this simulation result. In this simulation, the connection between two particles was considered to be broken if the contact force between bonded particles calculated from DEM rose above a set threshold level. The threshold level for the connection between the part particle and the board particle was set as 750 times less than that for the connection between particles inside the board, by reference to experimental results of the breakage energy for parts detachment and board breakage.

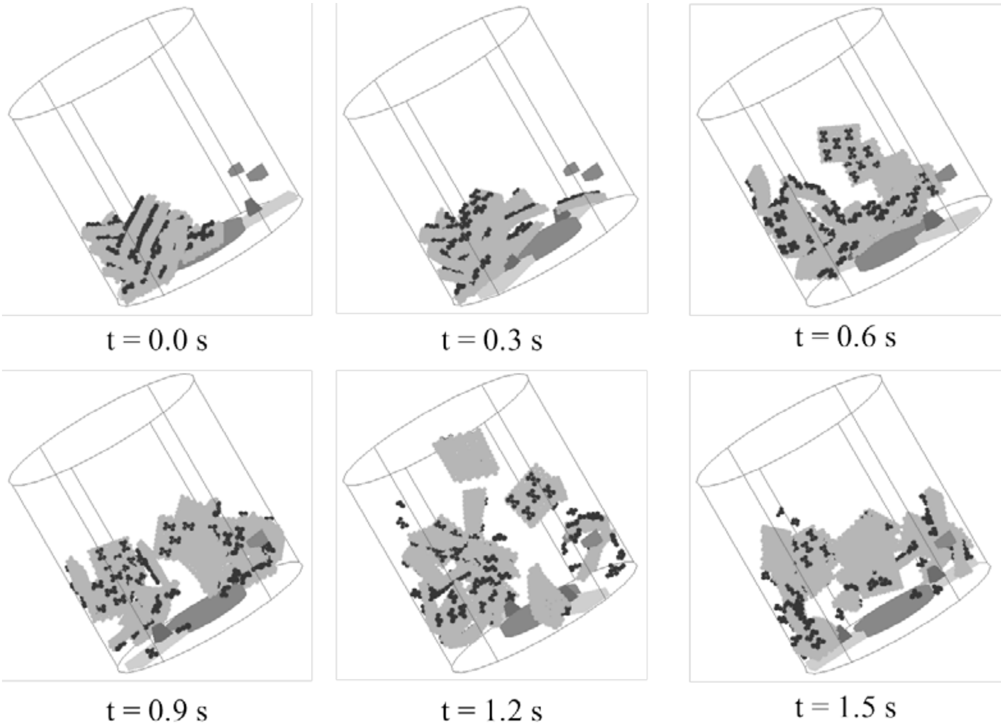

Figure 5 Snapshots of DEM simulation results using the particle breakage model

Figure 6 shows the percentage of parts detachment of the board calculated from DEM simulation results. When compared with experimental results for parts detachment, upward trend for the percentage of parts detachment to the rotational speed of agitation accorded well with experimental results. These results indicated that this particle breakage model was one of the adequate models to simulate the behavior of PCBs and represent parts detachment of the boards.

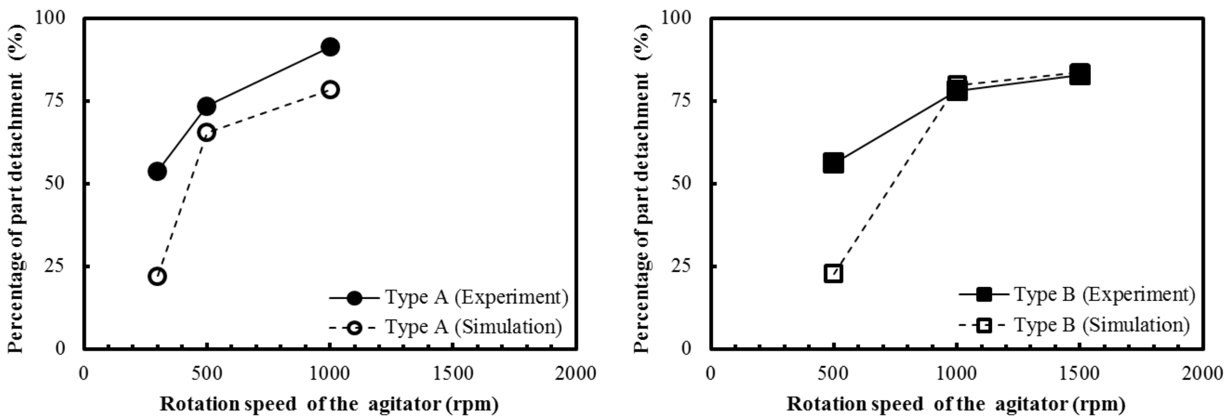

Figure 6 Comparison of parts detachment between DEM simulation and experiment (Left : Type A, Right : Type B)

Simulation results of the particle-based rigid model

Figure 7 shows the relationship between each rotational speed of the agitator and collision energy calculated from the particle-based rigid model simulation. As the rotational speed of the agitation was increased, collision energy was also increased. The collision energy between the particle and the agitation or the drum wall were much larger than the collision energy between particles. While the collision energy between the particle and the agitation or the drum wall were dramatically changed with rotational speed, the collision energy between particles was gradually increased with rotational speed. These results indicated that the comminution process of PCBs mainly was promoted by the collision of the agitation and the drum wall.

In order to conduct a detailed investigation of the collision energy, Figure 8 shows the collision energy distribution. In this simulation results, rotational speed was 500 rev/min and the mill was charged with 50 PCBs. As shown in Figure 8, the number of collisions between particles was much larger than that of collision between particles and the drum wall, the agitator or the projection. Although the number of collisions between particles was large, the collision energy between particles was smaller.

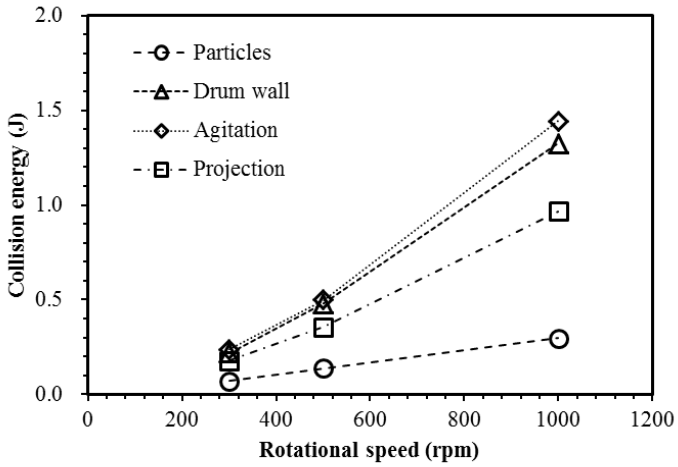

Figure 7 Relationship between rotational speed and collision energy in type A simulation

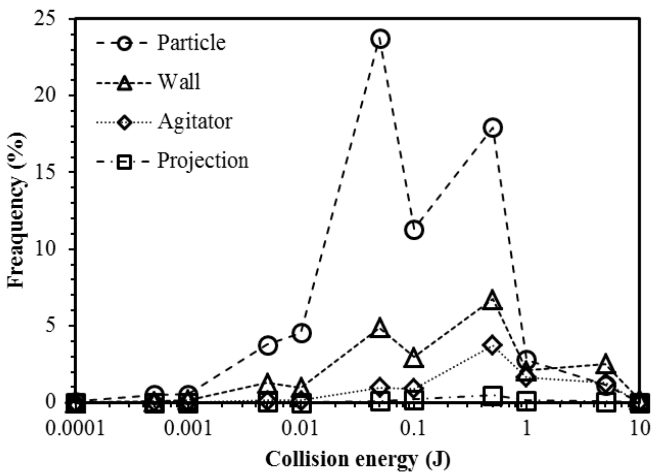

Figure 8 Collision energy distribution (Type A, Rotational speed : 500 rpm)

Conclusion

Mechanism of part detachment of PCBs by comminution in two drum type agitation mills was investigated from both of the experimental approach and simulation. Comminution experiments using glass-epoxy double side printed circuit boards soldered with nine ceramic condensers were carried out. The comminution process of PCBs was also investigated by two types of DEM simulation.

Experimental results showed that the percentage of parts detachment of the board increased with input number of PCBs and rotation speed. The interaction between PCBs affected parts detachment. Although only an indirect study was possible for part detachment and the behavior of PCBs using an original DEM simulation model, DEM simulation with particle breakage model and particle-based rigid model could directly represent the behavior of PCBs. The relationship between part detachment and rotation speed of the agitation simulated by a DEM model with particle breakage qualitatively corresponded to experimental observations of comminution using test PCBs. The result of DEM simulation with particle-based rigid model showed although the number of the collisions between PCBs was larger than others, the collision energy between PCBs was smaller than others.

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