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Investigation and evaluation of the detachment of printed circuit boards from waste appliances for effective recycling

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ABSTRACT

To establish an effective recycling process for waste appliances, the process of recovering printed circuit boards (PCBs) containing valuable elements in comminution was investigated and evaluated. The present study performed comminution tests using three different types of waste appliances: smartphones, microwave ovens and electrical rice cookers. Comminution tests showed that a drum-type agitation mill operated at a mid-range rotation speed could achieve a relatively high recovery ratio of PCBs and inhibit excessive breakage of PCBs. Following these experiments, simulations using the discrete element method with a particle-based rigid-body model were conducted to evaluate the comminution performance of the drum-type agitation mill. Experimental and simulation results confirm that the processes of detachment of PCBs from waste appliances and subsequent breakage can be expressed by kinetic equations related to collision energy. It is concluded from these results that the kinetic equations obtained in experiments and simulations can be used to evaluate the recovery process of PCBs from waste appliances.

1. Introduction

Electronic waste (e-waste), which refers to waste electric and electronic equipment, has been one of the fastest growing waste streams owing to rapid advancements in technology. According to various reports (Herat, 2007; Kaya, 2016), global e-waste production exceeds 50 million tons per year and the generated amount of e-waste has been increasing at a rate of 10% per annum. Waste appliances are a major resource of e-waste. Printed circuit boards (PCBs) inserted in waste appliances contain many kinds of electronic components, such as resistors, capacitors, conductors and integrated-circuit chips. Some electronic components contain valuable elements although their compositions vary depending on their use and year of manufacture. Therefore, waste appliances and their PCBs might be useful sources of recoverable material (Fujita et al., 2014; Guo et al., 2009; Huang et al., 2009; Lee et al., 2007; Lixandru et al., 2017).

For the appropriate and effective recycling of e-waste, many technologies for recovering valuable metals from e-waste have been proposed in past decades. As an example, pyrometallurgical (Chiang et al., 2007; Cui and Zhang, 2008) and hydrometallurgical (Huang et al., 2011; Oishi et al., 2007; Silvas et al., 2015; Torres et al., 2018; Yang et al., 2011) processes have been applied to the recovery of copper and precious metals, such as gold, silver and palladium. In addition, physical separation methods have been developed (Guo et al., 2011; Ruan et al., 2017; Zhang et al., 2016). All these methods require comminution as a mechanical pre-treatment process to achieve high-accuracy separation and facilitate the efficient recovery of target metals in subsequent recycling processes.

In common with various types of mineral processing, comminution is the first step in the recycling of waste appliances. Because PCBs containing valuable elements are generally encapsulated by plastic, ceramic or metallic bodies, comminution is conducted not only to reduce the size but also to uncover body components in waste appliances. While comminution can promote liberation, namely the detaching of PCBs from their body components, excessive comminution and/or fine grinding might reduce the efficiency of overall recycling processes. In addition, valuable elements, such as gold and rare-earth elements, are only used in specific parts mounted on PCBs. If these specific parts and the PCBs containing them can be selectively removed or detached from their body components, the target elements and materials can be easily concentrated and their separation employing subsequent separation processes will become more feasible. Therefore, a selective

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comminution system, such as that for the removal or detachment of PCBs from their body components in waste appliances, is strongly desired.

To establish a selective comminution system for the recycling of waste appliances, we have been investigating the applicability of a drum-type agitation mill. Owada et al. (2012) experimentally demonstrated that the drum-type agitation mill can separate PCBs from their body of waste mobile phones in the comminution process. To investigate the behavior of PCBs in the mills and to evaluate the comminution performance of the mills, we previously conducted a numerical simulation and compared results with experimental results (Tahara et al., 2014; Tsunazawa et al., 2016). In our numerical study, we adopted the discrete element method (DEM) (Cundall and Strack, 1979), which has been widely applied to both particle and particulate systems (Sakai et al., 2015; Sun and Sakai, 2015; Tsunazawa et al., 2015), and introduced a particle-based rigid-body model (Tanaka et al., 2007) to the DEM. However, our numerical investigation focused on PCBs detached from waste appliances. Therefore, there is still limited knowledge on the applicability of a drum-type agitation mill to various types of waste appliances.

The objective of the present study was to investigate and evaluate the process of recovering PCBs from waste appliances. To this end, we first performed comminution tests using three different waste appliances: smartphones, a microwave oven and an electric rice cooker. Following these experiments, we conducted DEM simulations using a particle-based rigid-body model under the same conditions as in the experiments to evaluate the comminution performance of the mill. Comparing experimental results with simulation results, we found a correlation between the collision energy and the recovery ratio of PCBs that could be expressed by first-order kinetic equations.

2. Experimental and simulation methods

2.1. Drum-type agitation mill

The present study used drum-type agitation mills of different size. One was a cross-flow shredder (S-1000, Sato Tekko Corporation, Japan) having both a diameter and height of 1.00 m. The other was another cross-flow shredder (S-1250, Sato Tekko Corporation, Japan) having a diameter of 1.25 and height of 1.47 m. Instead of impact impellers, two iron chains were installed at the bottom of these mills.

2.2. Experimental procedure

The present study ground three different waste appliances using drum-type agitation mills. One was a smartphone, considered as a high-value appliance because it contained a relatively large amount of valuable metals and parts. The others were a microwave oven and an electric rice cooker, considered as low-value appliances because they contained smaller quantities of valuable metals and parts than smartphones. Fig. 1 shows examples of these waste appliances while Table 1 lists typical specifications.

In the comminution tests, the rotational speed of two chains was initially set at a fixed speed before inserting the appliances. A given number of appliances were then fed to the mill and comminuted. After comminution, all pieces of appliances were recovered from the mill. The experimental conditions are summarized in Table 2. To evaluate comminution performance, products of smartphones were sieved into six size fractions: ≥64 mm, ≥32 mm, ≥16 mm, ≥8 mm, ≥4 mm and <4 mm. Meanwhile, products of microwave ovens and electric rice cookers were sieved into seven size fractions: ≥128 mm, ≥64 mm, ≥32 mm, ≥16 mm, ≥8 mm, ≥4 mm, and < 4 mm. In each size fraction, PCBs were distinguished from other parts, such as a plastic/metal body and cable, and the particle size distribution was then determined. The recovery ratio of PCBs, which was the weight ratio of recovered PCBs to fed PCBs, was also calculated.

2.3. Numerical simulation

2.3.1. Modeling and conditions

Each appliance and chain ring in the mill were assumed as rigid bodies. These rigid objects were modeled using many fine particles. To calculate the behavior, a particle-based rigid-body model was introduced into the original DEM. With this model, the motion of rigid objects was calculated according to Newton's second law. The contact force acting on rigid objects was calculated as the sum of the contact forces acting on the constituent particles. As is the case with the original DEM, the contact forces acting between a particle and a particle and between a particle and a wall were modeled using the Voigt model, which was composed of linear springs, dashpots and a friction slider.

Fig. 2 shows simulation models of the two cross-flow shredders. The diameter of constituent particles of chain rings was set to 6 mm. Each appliance was modeled by a group of fine constituent particles aligned on a grid. The model conditions are summarized in Table 3. The operation conditions in the simulations were the same as the experimental conditions. The other simulation parameters are listed in Table 4. Although these physical parameters were virtual values, they had little effect on the calculation results. The time step was determined according to the Courant condition and computational load.

2.3.2. Collision energy

The DEM with a particle-based rigid body model could not directly simulate the deformation and breakage of appliances during comminution. To evaluate the breakage of appliances and detachment of PCBs from appliances, the energy of each collision between a constituent particle and another particle or a wall was calculated. Although there are various models of collision energy available (Nakamura et al., 2013; Park and Wassgren, 2003; Soda et al., 2009), the present study calculated the collision energy from the relative velocity of constituent particles at the beginning of collision. This is expressed as

$$E = \frac{1}{2}\frac{m_i m_j}{m_i + m_j} v_r^{\,2}, \tag{1}$$

where m is the mass of a rigid object, subscripts i and j indicate the two collision objects, and velocity v_r is the relative velocity of collision particles at the beginning of the collision.

2.4. Kinetic equations of the detachment of PCBs from appliances

The recovery ratio of PCBs is defined as the proportion of PCBs that detached without breaking to PCBs installed in appliances. For the effective recycling of PCBs, PCBs should ideally detach from appliances without breaking. However, PCB detachment from appliances is generally accompanied by PCB breakage in the comminution process. Both PCB detachment and breakage result from collisions between an appliance and another appliance, inner drum wall, or chains. Such detachment and breakage of PCBs can therefore be related with the collision energy obtained from the DEM with a particle-based rigid-body model. This study assumed that detachment and breakage processes can be expressed by first-order kinetic equations. The detachment ratio of PCBs, D, is

$$D = 100(1 - \exp(-k_D E)), \tag{3}$$