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Shredding and liberation characteristics of refrigerators and small appliances

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ABSTRACT

Mechanical disaggregation, or shredding, is an important part of the recycling process. Occurring at the beginning of the processing sequence, it significantly affects the efficiency of downstream processing stages. This study examines the size reduction and liberation characteristics of the single-stage shredding of household appliances to improve the efficiency and quality of the recycling process. Several disposed appliances, including 75 L refrigerators and five major categories of small appliances (vacuum cleaners, videocassette recorders (VCRs), electric rice cookers, fans, and electric heaters), were shredded using a high-speed vertical shredder under varying discharge clearance conditions. The fragments were analyzed according to size, composition, and degree of liberation. It was found that single-stage crushing with the high-speed vertical shredder was sufficient to produce fragments at an appropriate size and with a high degree of liberation. Based on the experimental results, an optimal shredding and separation scheme for the process is proposed.

1. Introduction

In many countries, WEEE (waste of electrical and electronic equipment) management schemes have been established to promote the recycling of all types of electrical goods. WEEE is collected by various means and delivered to treatment plants. The treatment process at these plants generally involves: (1) manually disassembling parts and removing harmful components from appliances; (2) disintegrating them into fine fragments; and (3) recovering marketable secondary raw materials through physical separation. However, there are still several problems in WEEE recycling associated with heterogeneous components, product uncertainty, low recovery and purity of the products, economical value, and environmental pollution. For these reasons, various studies have been conducted to improve the efficiency and economics for recycling various types of WEEE, such as cathode ray tube (CRT) (Tian et al., 2016; Yoshida et al., 2016) and printed circuit boards (PCBs) (Habib et al., 2016; Huang et al., 2009; Wang and Xu, 2015). In addition, the recovery and process problem has been studied. For example, Oguchi et al. (2012) studied various metals' distribution and flow in WEEE by using typical conditions in Japan and also discussed whether pre-separation could helpful for metal recovery from small digital products; however, problems remained regarding amount and the differences between equipment.

Considering these problems, recent studies tend to concentrate more on total processes and value evaluation. For example, an in-depth review study about electronic recycling technology, including the potentiality of risk and economical value (Kaya, 2016), the new idea of "Control-Alt-Delete," for dealing with the electronic waste problem in various regions (Li et al., 2015), the design of an electronic waste (e-waste) recycling process and examination for specific cases (lithium-ion batteries and PCBs) (Li et al., 2016b), the development of an eco-friendly integrated mobile recycling plant (Zeng et al., 2015), a dynamic sustainable supply model to examine the uncertainties of resources from WEEE (Gu et al., 2016), a quantitative measurement model for recyclability that can be a guideline for e-waste management (Zeng and Li, 2016), and WEEE treatment cost evaluation (Li et al., 2016a) have been conducted and suggested. Additionally, the themes of pollution and environment and public health have been dealt with (Cayumil et al., 2016; Wu et al., 2016).

This study focuses on the mechanical disintegration process, which is important unit operation at recycling plants, because this operation takes place at the beginning of the processing sequence and has a big impact on the efficiency of the downstream processing stages. The primary goal of disintegration is to acquire a high

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degree of liberation for the separating processes. This process is one of the main aspects of primary energy consumption in the material processing flow. Thus, there is a definite need to increase energy efficiency by applying adequate stress so that a high degree of liberation can be acquired at the coarsest size without over-disintegration.

This rationale also applies to the processing of natural ores, in which valuable minerals are separated from rocks. Since more than 50% of the total energy consumption in mineral processing is in the comminution process, extensive research has been undertaken in the fields of liberation and comminution characterization, and the modeling of mineral resources (Fandrich et al., 1997; Gay, 2004; King, 1994; King and Schneider, 1998). However, few studies have been conducted on waste (Castro et al., 2005; Chao et al., 2011; Cui and Forssberg, 2007; Zhang and Forssberg, 1999). The primary reason for the lack of research is the difficulty involved in performing the same type of analysis due to the extreme heterogeneity of waste materials. For instance, unlike natural ores, waste products are not a cut and dry system with only wanted and unwanted components, but rather a mixture of numerous materials, such as plastics, metals, ceramics, and many other organic and inorganic components. In turn, shredding produces fragments composed of many materials, and categorizing these fragments in terms of size and composition is not an easy task.

Moreover, these materials exhibit very different mechanical behaviors under stress. Natural ores, mostly being brittle, can easily be broken into pieces under simple compression or impact stress. On the other hand, waste products contain ductile materials that deform plastically before fracturing, which results in shape alteration without breakage, or even in size enlargement, after passing through shredding devices. Therefore, it is not possible for a single machine to efficiently reduce the size of all components. In turn, the shredding of wastes is typically conducted in multiple stages, employing a series of shearing and impacting shredders. The first stage of shredding is often conducted in a low-speed, high-torque shear shredder that shreds the feed material in a range of 150–250 mm. The secondary shredder further reduces particle size, usually using high-speed, low-torque hammer mills. In most of the waste electrical and electronic equipment (WEEE) recycling plants in Korea, shredders and impact mills are combined to create a four-stage shredding process. However, a recent analysis (Kim et al., 2014) revealed that this four-stage process is energy inefficient and potentially redundant as the last stage does not improve the degree of liberation but instead grinds up already liberated material even more. This indicates that increased efficiencies can be achieved through the effective utilization of available technology.

Recently, new types of vertical hammer-style shredders have been developed so that the stages of size reduction can be achieved in a single machine. These devices use intense impact and shear force to treat almost all categories of electronic and electrical wastes, from small devices to large machines, and achieve outstanding selective disaggregation. However, detailed assessments of the effectiveness of these devices for breaking down and liberating home appliance components have not yet been conducted.

The work reported here details investigations on shredding and liberation characteristics of mid-sized refrigerators and five representative categories of small appliances using a high-speed vertical shredder. Tests were conducted at various discharge clearance settings. The resulting products were analyzed in terms of size, composition, and liberation characteristics. The aim of the study is: (1) to examine the effectiveness of breaking down entire refrigerators and small appliances into small pieces in a single pass by using a high-speed vertical shredder; and (2) to find the optimum shredding conditions for different requirements and study the separation characteristics in the subsequent process.

2. Experimental procedure

2.1. Shredding device

Fig. 1 illustrates the high-speed vertical shredder (Kubota KE-100, 75 kW–110 kW) employed in this study. It consists of a chamber containing a rotor assembly with attached hammers of bars and gear-shaped grinders. The high-speed rotating bars located in the top of the rotor perform the primary shredding operation by coarsely crushing the bulky materials. The grinders in the lower section of the rotor shred materials into smaller sizes, carrying out the secondary and tertiary shredding. The required product sizes can be obtained by controlling the outlet clearance, which is done by adjusting the choke rings placed between the shell and the discharge ring. There are several similar models available in the market, such as BMH grinder mills (Danieli Centro Recycling) or V100 – V1000 models (Industrial Shredder).

2.2. Sample

A medium-sized refrigerator (75 L) and five categories of small appliances (vacuum cleaners, videocassette recorders (VCRs), electric rice cookers, fans, and electric heaters) were chosen for this study. For each type, four to nine units were collected from recycling facilities. For refrigerator samples, the compressor, refrigerant gas, internal shelf, PCBs, and packing rubber were manually removed from the units prior to shredding in order to simulate a typical recycling facility's process. In contrast, the samples of the small appliances were tested without any pre-removal of parts. The average dimensions and weights of the appliances are listed in Table 1.

2.3. Shredding and analysis

Fragment sizes are the most important factor for determining the efficiency of separation as well as the degree of liberation. Therefore, the shredding tests were conducted at different settings of the discharge clearance (20–50 mm) to obtain shredded products with different degrees of size reduction. For refrigerators, four units were tested and fed one unit at a time into the shredder. For small appliances, three units were shredded simultaneously.

After completion of shredding, all fragments were collected and analyzed in terms of size and composition. For size analysis, two steps of size fractionation were applied due to the large amount of shredded fragments. First, the shredded fragments were pre-classified into the various size fractions using a large vibrating screen. These size fractions, however, contained fragments with significantly different shapes (acicular, flake, plate, granular, irregular etc.), which would result in a completely different size distribution depending on the method of measurement; thus it was necessary to define the size specially. In this study, as visual examination was used to observe the fragments, the longest dimension was used to define the size. The second step of size fractionation was conducted by measuring each fragment with a ruler and grouping them into <10 mm, 10–20 mm, 20–40 mm, 40–80 mm, 80–160 mm, 160–320 mm, and >320 mm categories.

At the same time, each fragment was examined for composition. The major portion of each fragment was comprised of one type of material, including iron, plastic, urethane, aluminum, copper, PCB, electric wire, sponge, and rubber. Fragments comprised of two or more materials were classified according to material combinations. About 15–30 groups of fragments with two or more materials were identified. The <10 mm fragments were not categorized due to their presence in only a small amount and to the difficulty in visually determining their composition.

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