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Improvement of jig efficiency by shape separation, and a novel method to estimate the separation efficiency of metal wires in crushed electronic wastes using bending behavior and "entanglement factor"

Theerayut Phengsaart[a,*], Mayumi Ito[b], Naoki Hamaya[a], Carlito Baltazar Tabelin[b], Naoki Hiroyoshi[b]

[a] Division of Sustainable Resources Engineering, Graduate School of Engineering, Hokkaido University, Kita 13, Nishi 8, Kita-ku, Sapporo 060-8628, Japan
[b] Division of Sustainable Resources Engineering, Faculty of Engineering, Hokkaido University, Kita 13, Nishi 8, Kita-ku, Sapporo 060-8628, Japan

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ABSTRACT

Jig separation, one of the oldest and most widely used methods in mineral processing that separates particles based on density differences, was applied to recover valuable materials from residues of an actual recycling plant treating small home appliances. In this study, a modified TACUB jig called RETAC jig (R&E, Co., Ltd., Japan) was used to separate plastics and metals including copper (Cu) wires from real recycling plant residues. The results showed that the decrease in separation efficiency was largely because of Cu wire entanglement that trapped and prevented particle motion in the separation chamber. Jig separation of model samples and evaluation of bending behavior and "entanglement factor" of Cu wires were carried out to investigate this phenomenon. The results showed that higher Cu wire content and longer Cu wires (i.e., a higher entanglement factor) had lower separation efficiencies.

To limit the effects of wire entanglement, two methods of shape separation were investigated. These shape separation techniques increased the recovery of Cu wires in the Cu concentrate from 64% (without shape separation) to 97% (with shape separation using probability of passage) and 95% (with shape separation using induced entanglement). In addition, estimation of jig separation efficiency using the entanglement factor is proposed.

1. Introduction

In recent years, rapid development in science and technology as well as the growing appetite of consumers for various kinds of electronic devices as lifestyle products have caused a surge in demands for natural resources (e.g., metals) and the generation of wastes, which poses serious problems to the future of our modern society. Among the many types of wastes, generation of waste electrical and electronic equipment (WEEE) is one of the fastest growing worldwide. Every year, 20–50 million tons of WEEE are generated and is estimated to increase annually at a rate of around 3–5% (three time faster than other forms of municipal solid wastes (MSW)), which could be attributed to the reduction of average lifetimes of many electronic products (Huang et al., 2009; Tesfayea et al., 2017; Tuncuk et al., 2012). Because of this, recycling of WEEE that contain various valuable materials using techniques like physical separation (e.g., gravity separation and flotation) and hydrometallurgy have become important industries in many developing and developed countries (Havlik et al., 2014; Lambert et al., 2015; Mäkinen et al., 2015; Tesfayea et al., 2017; Tuncuk et al., 2012).

Recycling laws in Japan for "large" home appliances like air conditioners, televisions, refrigerators, and washing machines were enacted in 1998 and were recently extended to "small" home appliances such as personal computers, mobile phones, digital cameras and clocks, game consoles, music players, and hair dryers (Ministry of the Environment of Japan, 2014). Because the process flow for the recycling of large home appliances was already established, recycling plants simply applied this process to small home appliances. Although large pieces of metals could be recovered by magnetic and eddy current separation techniques, those with finer sizes could not be recovered and end up in the final plastic residues. This means that additional treatment is needed for the final plastic residues because they still contain substantial amounts of valuable metals especially copper (Cu).

The jig, a gravity concentrator, separates different kinds of materials by density differences, so plastics with low densities could be separated

* Corresponding author.
E-mail address: theerayut.phengsaart@gmail.com (T. Phengsaart).

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from metals with higher densities. Jigs typically operate under wet conditions and are widely used in mineral processing especially for coal cleaning due to their simple operation, low cost, and higher efficiency compared with dry-type separation techniques (Boylu et al., 2015). The TACUB (Takakuwa air chamber under bed) jig, commercially marketed as the BATAC jig, is one of the most commonly used jigs in coal cleaning. Its series of multiple air chambers, usually composed of two cells under the separation chamber extending to its full width, give a more uniform distribution of water pressure resulting in better separation. Pressurized air is injected into the air chambers adjacent to the separation chamber, causing water to pulsate and induce stratification (Ito et al., 2010; Tsunekawa et al., 2005; Wills and Napier-Munn, 2006).

Numerous studies have been done on the jig separation of coal especially on the stratification behavior of particles, a relatively complex process with many interrelated parameters. Some of these parameters are inherently controllable (i.e., manipulated variables) that could be optimized in a given pulsation cycle (e.g., strokes, bed thickness, and water level). However, some uncontrollable factors (i.e., disturbance variables) also play crucial roles in jig separation like feed grade, specific gravity (SG) of particles, size distribution, and particle shape (Ahmed, 2011; Cierpisz et al., 2016; Kawatra and Caraon, 2013).

In recent years, jig separation has become an integral part of many recycling plants for plastic-plastic separation. For example, most plastics found in WEEE could be used as fuel in electric power generation plants except for those containing chloride (Cl^-), which have adverse effects on boilers, so they are generally removed (Kikuchi et al., 2008; Kuwayama et al., 2011). Polyvinyl chloride (PVC), one of the most common plastics containing Cl^-, has higher density than other common plastics like polypropylene (PP), polystyrene (PS), and acrylonitrile butadiene styrene (ABS). PP, which is lighter than water, could be recovered easily by sink-float separation using water while the heavier PVC could be separated from PS and ABS by jig separation (Hori et al., 2009a; Kuwayama et al., 2011; Tsunekawa et al., 2012).

In this study, the RETAC jig (R&E, Co., Ltd., Japan), a modified BATAC jig especially designed for plastic-plastic separation, was applied to separate plastics and metals from several plastic-dominated residues of recycling plants that process discarded small home appliances. The RETAC jig is a promising type of jig because of its high efficiency as a result of precision control of the wave form during jig separation (Hori et al., 2009b; Tsunekawa et al., 2005).

Preliminary experiments to treat real plastic-dominated residues using the RETAC jig showed very low separation efficiency because of Cu wire entanglement during jig separation that likely limited the upward motion of plastic particles in the separation chamber. To elucidate the factors and mechanisms involved in this entanglement phenomenon, jig separation of model samples was conducted under various conditions. To improve the jig separation efficiency when plastics and wires are both present in samples, two methods of shape separation for Cu wire removal were evaluated as a pre-treatment step. Moreover, the bending behavior of Cu wires and its role in the entanglement phenomenon was elucidated. Finally, a new parameter, the entanglement factor, is introduced to estimate the jig separation efficiency of plastic-dominated residues from WEEE recycling plants.

2. Materials and methods

2.1. Samples

The plastic-dominated residues used in this study were obtained from a recycling facility in Japan. Fig. 1 shows the treatment flowchart for end-of-life small home appliances utilized by this company. Discarded small home appliances are first crushed and are then treated by low-intensity magnetic separation to separate magnetic (steel) and non-magnetic materials. The non-magnetic fraction is sieved using an 8-mm aperture screen to separate the fine fraction containing plastics, glass,

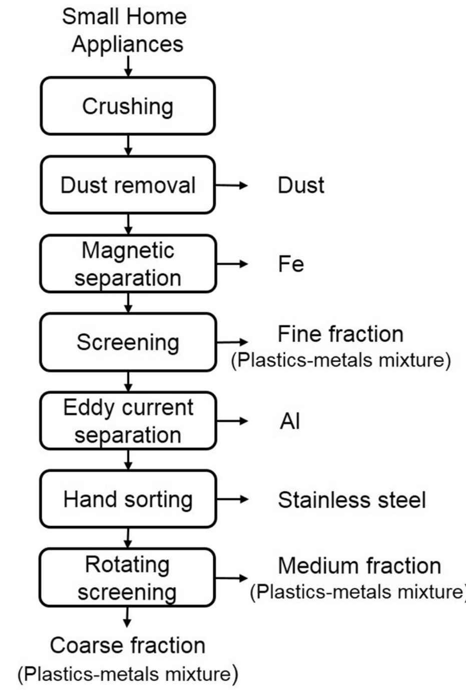

Fig. 1. The treatment flowchart for discarded small home appliances of a recycling plant in Japan.

wood, paper, and various metals like Cu, aluminum (Al), and iron (Fe). Materials retained on the screen are treated by an eddy current separator to recover Al and the resulting product is hand sorted to recover stainless steel. The remaining materials are classified by a rotating screen (16-mm aperture size) into medium and coarse fractions, which are mostly composed of plastics, glasses, wood, paper, and various metals.

Samples from the coarse, medium, and fine fractions of the final residue were used in this study. Before jig separation, floating materials were removed by sink-float separation in water and the sink products were sieved through a 1-mm aperture screen. Materials retained on the screen were fed to the RETAC jig. This size fraction was selected because it is within the lower operational limit of a BATAC jig (around 0.5 mm) and separation of particles with sizes less than this value is difficult using this technique (Gupta and Yan, 2006).

For the characterization of samples, size distribution was analyzed by sieving while the SG distribution was measured by sink-float analysis using water and zinc chloride ($ZnCl_2$, Wako Pure Chemical Industries Ltd., Japan) (SG of 1.0, 1.2, 1.4, and 1.8). The different components of the products were separated by hand picking into three fractions: Cu wires, other metals (e.g., Al and Fe), and other materials (e.g., plastics, glasses, wood, and paper). The fractions grouped as "other metals " were analyzed by an X-ray fluorescence (XRF) spectrometer (Rigaku EDXL300, Rigaku Corporation, Japan). An ashing furnace (Ishizuka Denki Seisakusho, Japan) was used to determine the combustible components in the "other materials fractions", which are composed primarily of plastics. The ashing method involves slow heating to 815 °C for 90 min, which was followed by burning of the samples at this temperature for 2 h. For the metal analysis of "other materials fractions", the samples were ground at low temperature with liquid nitrogen and dissolved in a microwave-assisted digester (Ethos Advanced Microwave Labstation, Milestone Inc., USA) using aqua regia, a 1:3 mixture of concentrated nitric acid (HNO_3) and hydrochloric acid (HCl) (Wako Pure Chemical Industries, Ltd., Japan). The leachates were then analyzed by inductively coupled plasma atomic emission spectroscopy (ICP-AES, ICPE-9820, Shimadzu Corporation, Japan) (margin of error = ± 2%).