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New technology for recovering residual metals from nonmetallic fractions of waste printed circuit boards

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ABSTRACT

Recycling of waste printed circuit boards is important for environmental protection and sustainable resource utilization. Corona electrostatic separation has been widely used to recycle metals from waste printed circuit boards, but it has poor separation efficiency for finer sized fractions. In this study, a new process of vibrated gas-solid fluidized bed was used to recycle residual metals from nonmetallic fractions, which were treated using the corona electrostatic separation technology. The effects of three main parameters, i.e., vibration frequency, superficial air flow velocity, and fluidizing time on gravity segregation, were investigated using a vibrating gas-solid fluidized bed. Each size fraction had its own optimum parameters. Corresponding to their optimal segregation performance, the products from each experiment were analyzed using an X-ray fluorescence (XRF) and a scanning electron microscope (SEM) equipped with an energy dispersive spectrometer (EDS). From the results, it can be seen that the metal recoveries of −1 + 0.5 mm, −0.5 + 0.25 mm, and −0.25 mm size fractions were 86.39%, 82.22% and 76.63%, respectively. After separation, each metal content in the −1 + 0.5 or −0.5 + 0.25 mm size fraction reduced to 1% or less, while the Fe and Cu contents are up to 2.57% and 1.50%, respectively, in the −0.25 mm size fraction. Images of the nonmetallic fractions with a size of −0.25 mm indicated that a considerable amount of clavate glass fibers existed in these nonmetallic fractions, which may explain why fine particles had the poorest segregation performance.

1. Introduction

Waste printed circuit boards (WPCBs) has exhibited rapid growth over the recent years, along with large amount of waste electrical and electronic equipment (WEEE) because of the rapid development of advanced technologies and improvement in the standard of livings. The proper recycling of WPCBs is an important part of WEEE treatment. WPCBs are normally composed of metallic and nonmetallic fractions (NMFs). The former mainly comprises Fe, Cu, Sn, Pb, and Al, and even precious metals, such as Au and Ag, while the main components of the latter are epoxy resin, glass fibers, ceramics and other plastics (Ghosh et al., 2015; Silvas et al., 2015). Recycling of WPCBs is of high economic value because of their metal content. In addition, chemically rich, halogenated flame retardants present in WPCBs pose potential risks to the environment and living things (McDonald, 2002; Ren et al., 2014). Therefore, the proper disposal of WPCBs is required for environmental protection.

Recovery of metals from WPCBs has attracted increased attention due to their high economic value; therefore, many recycling processes apply chemical/metallurgical and physical methods for proper metal recovery (Yoo et al., 2009; Kaya, 2016). Pyrolysis (Li et al., 2010; Hall and Williams, 2007), roasting or pyrometallurgy (Hao et al., 2014), and hydrometallurgy (Behnamfard et al., 2013; Petter et al., 2014) are the main chemical methods that have been extensively studied. However, chemical methods face serious problems, such as high chemical reagent consumption, secondary pollution, and long treatment time, as far as their industrial application is concerned. Since WPCBs are composed of various materials, physical-mechanical methods based on physical properties of materials, such as component disassembly (Zeng et al., 2013; Yang et al., 2009), corona electrostatic separation (Li et al., 2007a; Das et al., 2009), gravity classification (Eswaraiah et al., 2008; Habib et al., 2013), triboelectric separation (Zhang et al.,

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2017a) and shape separation (Gungor and Gupta, 1998), have been widely used to recover metals from WPCBs. The continuous operation of physical-mechanical methods provides the precondition for their industrial application.

The industrial application of corona electrostatic separation based on some significant differences in the density and electrical conductivity of the nonmetallic and metallic particles has achieved successful commercial results (Botsh and Kohnlechner, 1997). Liberation between metallic and nonmetallic fractions is a basic of physical-mechanical separation methods. Therefore, crushing is an essential process. The crushed fraction is treated with a corona electrostatic separator to separate the metallic and nonmetallic particles. However, the low separation efficiency of the corona electrostatic separation process for fine particles results in the detection of valuable metals in NMFs (Li et al., 2007b).

To recover residual metals from NMFs, a process of vibrated gas-solid fluidized bed (VGFB) was used in this study. The normal gas-solid fluidized bed separation uses air as the medium to achieve "float-sink" of mixtures based on their own density. However, the ordinary gas-fluidized bed has a poor adaptability in terms of the separation of fine mixtures. For fine particles, VGFB based on a traditional gas-fluidized bed was used in this work. In VGFB, the vibration increases the separation efficiency of fine particles by overcoming inter-particle forces and reducing particle agglomeration. As a dry physical-mechanical method, VGFB has provided efficient separation of particles for coal preparation (Yang et al., 2015). In WPCBs, an obvious density difference between nonmetallic and metallic fractions exists, which increases the feasibility of the VGFB separation (Eswaraiah et al., 2008).

In this study, NMFs were sampled from a typical WPCBs recycling line in Anhui province, China. A previous study showed that a large amount of metals still remained in NMFs (Zhang et al., 2016). Therefore, the present study mainly focuses on recovering the residual metals from NMFs of WPCBs by VGFB. The operational factors, such as air velocity, vibration frequency, and fluidizing time, which had a significant impact on separation performance, were investigated. In addition, the effect of particle size on VGFB segregation was evaluated. The segregation efficiency of VGFB and products obtained under optimum conditions were analyzed.

2. Material and methods

2.1. Mechanism of separation

For a gas-fluidized bed, both particle size and density have a remarkable effect on the segregation process while the latter plays a dominant role (Rowe and Nienow, 1976). The terminal setting velocity (u), defined by Eq. (1), plays a key role in this segregating process.

$$u = \sqrt{\frac{4}{3}\frac{gd(\rho_s - \rho)}{C_D \rho}} \tag{1}$$

where d is the diameter of particles, ρ_s and ρ are the densities of particles and fluid, respectively, C_D is the drag coefficient, and g is the gravity acceleration. The high-density particles will preferentially overtake low-density particles by falling rapidly through the bubbles and settling faster in turbulent regions.

The residual metals are mainly Mn, Sb, Ti, Pb, Zn, Sn, Mg, Fe, Cu, and Al, all of which have higher density than nonmetals (Zhang et al., 2017b). Under the VGFB operation, bubbles with periodic expansion will appear, which leads to the development of a turbulent region. A segregation process takes place when metallic particles sink preferentially over nonmetallic particles, this process is presented in Fig. 1. After stopping the air flow supply, the segregated bed layer is formed by the difference in densities.

2.2. Sample preparation

The sample, used in this study, was collected from a typical recycling line of WPCBs in Anhui province, China. The process flow is shown in Fig. 2. WPCBs with electronic components were first crushed by a shredder, and then magnetic separation and eddy current separation were used to recycle iron and aluminum, respectively. Based on fine crushing (using a grinder) and vibration sieving, WPCBs particles of −1 mm in size were obtained and a sufficient liberation between metals and nonmetals was achieved. Corona electronic separation was then used to determine the separation of metals and nonmetals. In this study, three size fractions of −1 + 0.5 mm, −0.5 + 0.25 mm and −0.25 mm were obtained after sieving, and the yields of each size fraction are given in Table 1.

The yield of each size fraction shows an even distribution. In each size fraction, the ratios of the upper size to the lower size are not higher than 3:1, which would reduce the influence of particle size difference on the segregation process by decreasing the disturbance among particles that have large size differences (Yang et al., 2013).

2.3. Vibrated gas-solid fluidized bed apparatus

The VGFB separation system, as shown in Fig. 3, is composed of a roots blower, a pressure tank, a rotameter, a vibrating table, a gas-solid fluidized vessel, and a control unit. The airflow from the blower moves through a pressure tank, followed by a rotameter and finally into a gas-solid fluidized vessel. A turbulent region provides voids for segregation. A stable air-pressure is generated by using a pressure tank while air flux is measured through a rotameter. The adjustable vibration energy is introduced into the

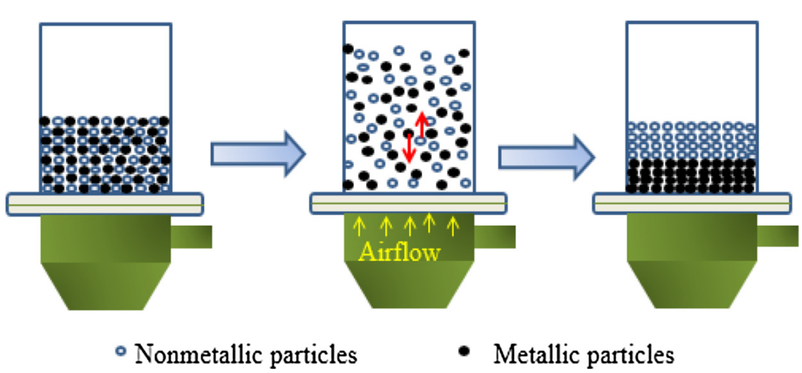

Fig. 1. Segregation process of metallic and nonmetallic particles.

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