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The stripping effect of using high voltage electrical pulses breakage for waste printed circuit boards

Chenlong Duan *, Jun Han, Shen Zhao, Zhonglin Gao, Jinpeng Qiao, Guanghui Yan

Key Laboratory of Coal Processing and Efficient Utilization of Ministry of Education, School of Chemical Engineering and Technology, China University of Mining and Technology, Xuzhou 221116, China

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ABSTRACT

In this study, high voltage electrical pulses were utilized to process waste printed circuit boards to cost effectively liberate metal and nonmetal materials. Relative mass $\omega_i$and particles content $\eta_i$indexes were defined to assess the stripping effect produced by high voltage electrical pulses breakage. For relative mass level in the 0–10% range, in the −6+3 mm fraction, particles content accounted for 84.84% of the total particles, while the mechanical crushing only occupied 8.84%. Voltage and pulse experiments were carried out to investigate the crushing effect of high voltage electrical pulse breakage for printed circuit boards. It was found that when the voltage and pulse number was at 160 kV and 300, the stripping rate of copper was 98.56% and 92.58% in the −25+13 mm fraction respectively. The measured bending strength of the material revealed the selective crushing effect of high voltage electrical pulses in the different material interfaces. A liberation mechanism was elaborated by using the energy band theory, and a process model was utilized to reveal the mode of crushing. Furthermore, the microscopic appearance of the resulting product confirmed that copper underwent high-temperature melting, while the resin was decomposed during the crushing process. Compared to conventional mechanical crushing process, high voltage electrical pulses can better liberate metal-bearing than mechanical comminution technology.

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1. Introduction

The rapid development of electrical and electronic equipment has generated large amounts of e-waste. The annual production of e-waste is estimated to be 40 million tons, and continues to grow at a 4% pace (Rajarao et al., 2014; Wang et al., 2016). Particularly, China would generate 15.5 and 28.4 million tones of e-waste in 2020 and 2030, respectively (Zeng et al., 2016; Duan et al., 2016). Thus, China implemented the Management Regulation on the Recycling of Waste Electrical and Electronic Products On January 1, 2011(Li et al., 2017; Zhang et al., 2012). E-wastes are of significant economic value as they contain various precious metallic species with typical grades one or two orders of magnitude higher than the nominal run of mine. While the e-wastes are becoming increasingly popular as a source of precious metals, they also contain toxic materials such as heavy metals and flame retardants which are detrimental to the environment when not handled properly (Xue et al., 2012; Fu et al., 2011; Duan et al., 2011; Rajagopal et al., 2016). Overall, only 15–20% of the e-wastes are currently recycled, and most of them are either landfilled or incinerated producing serious environmental concerns (Fu et al., 2011; Duan et al., 2011; Rajagopal et al., 2016). Therefore, it is of paramount importance to develop new techniques allowing cost-effective processing of e-wastes.

The conventional methods currently used for the reutilization of waste printed circuit boards (waste-PCBs) involve physical, pyrolytic, and chemical processing technologies (Dang et al., 2005; Li et al., 2007a, 2007b; Qiu and Qiu and Qian, 2009). Pyrolytic and chemical methods require high energy and water consumption, whereas physical processing technologies are currently the most economical and environmentally friendly methods (Duan et al., 2009). However, the crushing process is critical for physical recycling of waste-PCBs. The metals contained in waste-PCBs can be liberated by shear fragmentation, although it is difficult to liberate metal and nonmetal bonding surfaces (Zhao et al., 2012; Zhao et al., 2004). Generally, metals are released in the −1+0 mm fraction, although the following sorting practice is heavily affected by the fines produced (Li et al., 2004). Usually, the suitable size of shaker separator is the −0.1+2 mm fraction, and for particle sizes lower than 0.074 mm, over 70% of the metal content is lost during the sorting process (Zhao et al., 2012). As revealed by electrostatic separation experiments, the fines produced in the −0.074 +0 mm fraction are prone to agglomerate, deteriorating the final

* Corresponding author.
E-mail address: clduan@cumt.edu.cn (C. Duan).

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separation performance (Hou et al., 2010; Li et al., 2007a, 2007b) Flotation treatments also showed that the recovery of metal was sharply reduced upon decreasing the particle size. In particular, when the particle size was lower than 0.074 mm, more than 30% of metallic copper were lost to the tailing (He and Duan, 2017). Traditional mechanical crushing can liberate these materials at the expense of achieving excessive particle size reduction and large amounts of fine particles, which are impossible to recover in the downstream process. Therefore, mechanical crushing is not effective in releasing applicable materials in the coarse size range, thereby affecting the recovery efficiency of these materials.

In recent years, high voltage electrical pulse (HVEP) has been used to disintegrate ores and concretes with the aim to recover valuable materials (Menard et al., 2013; Shi et al., 2013). This technology achieves crushing by generating powerful shock waves with a pressure exceeding 10^3 MPa. HVEP has been used to crush copper sulphides, ilmenite ores, and chromates, being more effective in releasing useful minerals and producing ore less affected by attrition as compared to traditional mechanical crushing(Andres, 2010; Wang et al., 2011). In addition, HVEP is also applied as an emerging technology to extract valuables from the tissue composition of fruits and vegetables. This method destroys cells by softening them to release more bioactive compounds (Galanakis, 2012; Deng et al., 2015). Currently, for the treatment of e-waste, HVEP is a new technology to process waste-PCBs, and there are few studies in this area. (Martino et al., 2016) compared the impact of HVEP and hammer mill on the crushing effect, and studied the crushing effect of HVEP at different energy levels by SEM. (Zhao et al., 2015) mainly focused on the material port fractal of fragmentation of waste-PCBs by HVEP. Based on our researches on the liberation effect of HVEP for waste-PCBs previously (Duan et al., 2015), the stripping effect of HVEP for waste-PCBs was further studied. A characterization method was applied to evaluate the stripping effect of HVEP, and the selective crushing of HVEP in the different material interfaces was proved. Moreover, the mechanism of the HVEP breakage was analyzed theoretically for waste-PCBs.

In this paper, waste-PCBs were broken by HVEP equipment, and the stripping effect of HVEP was investigated by proposing a theoretical formula describing this effect. By adjusting the Voltage and pulse, the metal stripping rate was elucidated. Further, selective crushing via HVEP was proved in different interface materials by testing the mechanical properties of the materials. In addition, the liberation mechanism induced by HVEP was illustrated by using the energy band theory. Scanning electron microscopy (SEM) and electron probe micro-analysis (EPMA) were used to observe the micro-structure and analyze the physical–chemical changes of the materials. Waste-PCBs are mainly made up of glass fiber cloth, epoxy resin, and copper, and these materials have different electrical properties. Thus, HVEP crushing waste-PCBs can better achieve metal-bearing liberation and reduce the generation of fine particles. The HVEP method is worth recommending to handle waste-PCBs.

2. Materials and methods

2.1. Material preparation and characterization

The FR-4 CCL material was obtained from a local PCBs factory. FR-4 CCL is also known to be a basic raw material substrate for PCBs, which is laminated by multilayer glass fiber cloth (GFC) and copper foil. The surface of the CCL was not etched, which is reliable to research on the stripping effect of HVEP. The graphics card was collected in a local computer town and selected to give a bending strength measure. The morphology and element compositions of the graphics card section are shown in Fig. 1. The interior of the graphics board was laminated by a number of GFCs, and there were copper wires between the layers.

2.2. HVEP breakage equipment and processing

The HVEP equipment used to dispose PCBs (SELFFRAG) mainly consisted of a high voltage power supply, a high-voltage pulse generator, and a reaction tank. A schematic diagram of the HVEP equipment is shown in Fig. 2. The control panel is used to adjust the experimental parameters of the device. The main parameters of the equipment are summarized in Table 1.

The HVEP equipment starts with the generator being charged by the power supply, and the stored energy is subsequently released by the pulse generator in a very short time (Chemer and Marmo, 2003). The HVEP crushing solid insulation material conditions is inside breaking of the material. However, to achieve internal breakdown conditions, the inside electric field strength of the material must reach the breakdown conditions, while the external electric field strength has to be below the external material breakdown conditions (Bluhm et al., 2000). To achieve these conditions, the object can be located in a liquid having a higher breakdown field strength. The strength of water to withstand voltage increases rapidly by reducing the voltage rise time. In particular, when the voltage rise time was below 500 ns, the breakdown voltage of water was higher than that of a rock (Bluhm et al., 2000). In addition, water also has a high dielectric constant, which can reduce its internal electric field strength. Furthermore, the HVEP crushing in water can also decrease the generation of dust, thereby mitigating environmental pollution and harm for human health. The HVEP can selectively break the composite material. PCBs are mainly composed of copper foil, resin, and glass fiber. Because of the different electrical properties between metal and nonmetal, the energy of HVEP mainly operated on the Copper Foil–GFC interface, thereby easily liberating these two components as shown in Fig. 3 (Duan et al., 2015). In addition, significant concentrations of metal can be achieved over a narrow size range during the crushing process.

All the FR-4 CCL was cut into 50×50 mm pieces. 200 g of FR-4 CCL were used in batches, and twelve repeated experiments were performed at each factor level. In order to prevent particle overgrinding during the crushing process, a 1 mm sieve was added to the bottom of the crushing chamber such that particles below 1 mm in size passed through the sieve into the aggregating box during the crushing process. Since the crushing was carried out in water, the crushed product was filter-dried, subsequently classified using a standard sieve, and the yield of each fraction finally calculated. With the aim to verify the selective crushing at the interface of different materials, every graphic card electronic component was removed by hand before HVEP breakage, the bending strength of the graphics card measured by the dynamometer, and the experiment conducted in strict accordance with standard flexural strength test methods. Repeated tests were performed on each sample to ensure test accuracy, and the bending strength of material was subsequently calculated according to the formula.

2.3. Evaluation of the stripping effect

The conventional method used for calculating mineral release is based on the percentage of monomer particles with regard to the total number of particles. However, since the structure of PCBs is different to that of typical minerals, the release of PCBs can be considered in along and perpendicular to the board directions. Thus, a new characterization method must be applied to reflect the stripping effect of the HVEP crushing. The mass of particles for each size fraction was weighted and ranked them according to their mass. The relative mass of each particle in this size fraction ω_i was calculated as Eq. (1).

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