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Milling and separation of the multi-component printed circuit board materials and the analysis of elutriation based on a single particle model

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Abstract

Electronic waste, in the form of printed circuit boards (PCBs) or printed wiring boards (PWBs), represents a significant and growing fraction of the waste generated in many communities. It is necessary to identify schemes to manage and dispose this waste in an environmentally safe manner. The present work, examines the use of mechanical means to separate the metallic and non-metallic components present in PCBs. The unique characteristics of PCB construction pose challenges to the mechanical means of separation. In view of these unique characteristics of PCBs, an empirical approach is suggested to evaluate the effectiveness of the mechanical separation process. Two milling operations were used to obtain the feed for the separation using elutriation. Compositions of different size fractions from the milling operations are presented. Experimental data from the separation process is presented and the extent of use of mechanical means that results in optimum separation is identified. The separation efficiency is analyzed in terms of composition, particle size and operating condition of the elutriation flow rate. A probabilistic analysis based on single particle settling velocity shows that separation results with uniform particle size fraction can be described effectively. However, the probabilistic analysis captures only the qualitative features with mixed particle sizes and components.

Keywords: Elutriation; Separation; Settling velocity; Printed circuit boards; Recycling

1. Introduction

Amount of waste generated from products based on the electronic industry, particularly end-of-life waste, is increasing worldwide. Cost effective and environmentally sound methods are necessary to manage these waste [1–5]. Printed circuit boards (PCBs) or printed wiring boards (PWBs) account for approximately 30% of the total electronic scrap generated. Non-metals such as epoxy, glass fibers and other additives, constitute about 70% of the PCBs by weight, while metals such as copper, tin, lead, iron and nickel [6] constitute the remaining 30%. In the metal fraction, copper constitutes approximately 17%, solder is approximately 4%, iron and ferrite are 3%, and nickel is 2% by weight [1,3,6]. Precious metals such as gold, silver and platinum are also present in small quantities. Recycling of PCBs has been difficult due to their multi-component and multi-layered construction. Therefore, various operations leading to efficient and economic liberation and separation of different components from PCBs are being investigated [6–13]. Though energy intensive, mechanical processes are being studied because they can result in good material recovery [6–11]. They also do not require extensive use of solvents and reagents. Chemical processing methods have also been investigated with reagents such as aquaregia [12], tetrabromoethane [1] etc. However, the main disadvantage of chemical processes is the generation of additional hazardous wastes. Among the mechanical processes, size reduction is one of the most critical operations [13]. The hammer mill is one of the most common size reduction techniques studied in PCB recycling. After size reduction, methods to separate the various components have been suggested based on size, density and electrical

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properties or magnetic properties [10]. Elutriation is a simple separation technique based on size and density, and has not been reported for applications in PCB recycling process.

The present work deals with mechanical processing of printed circuit boards to separate metals and non-metals. The objective of this work is to characterize and optimize the mechanical separation process to determine the separation efficiency. Printed circuit boards were size-reduced using hammer mill and pin mill and, in some cases, subsequent size separation steps were carried out. Component analysis was carried out on the fractions obtained to understand the relative amount of different materials as function of milling operation and size. The size-reduced particles were then sent to an elutriation column to separate metals and non-metals. A novel probabilistic analysis, based on a correlation with particle terminal velocity, has been carried out to analyze the results from the elutriation experiments.

2. Experimental details

PCB scrap samples were collected from the scrap boards of the PC Maintenance Cell, IIT Madras, Chennai, India. The boards were size-reduced and subsequently subjected to mechanical separation by classification. The PCB samples were cut into small pieces (approximately 2×2 cm^2) using a hand cutter. The cut PCB samples were crushed in an impact hammer mill where the samples are broken by the impact of the swinging hammers. In some cases the crushed samples were directly subjected to size analysis by sieving, whereas in other cases further milling was carried out using a pin mill before the samples were analyzed for size by sieving (Secor India Ltd). The milling experiments were conducted at constant feed rate and for different speeds of the pin mill. The pin configurations in the impeller of the pin mill were kept constant.

The products obtained from the hammer mill and hammer mill/pin mill were sent to the elutriation column for separation, with the expectation that the separation will result in a metal lean fraction and a metal rich fraction. The effectiveness of the present approach to achieve this separation is being evaluated here. A schematic diagram of the elutriation column (diameter 7 cm) is shown in the Fig. 1. Air was used as the fluid medium. The feed (product obtained from the mills) was introduced in a batch mode from the top of the column. The separation into different fractions was studied at different air flow rates. Flow rate of air was varied from 20 m^3/h to 200 m^3/h. The top and bottom fraction from elutriation were analyzed for size by sieve analysis, and the fractions obtained after the sieve analysis were further analyzed to determine metal and non-metal content in each size range. Taken together, these experiments were intended to investigate the combined impact of size of particles and their metal/non-metal nature, on the efficiency with which such a mix of particles can be separated into a metal rich and a metal lean fraction using grinding followed by elutriation.

Since separation in the elutriation column is dependent on both the particle density and size, to understand the separation behaviour of the multi-component mixture such as PCB, elutriation was also carried out on different size fractions of both the hammer mill and hammer mill/pin mill products. From these experiments on single particle size feed, the relative amounts of metals and non-metals were estimated. This estimation was possible because almost perfect separation was achieved due to single particle size of the feed. Weight loss due to combustion was used as an estimate for the amount of plastics present in different samples, which forms one part of the non-metal fraction.

3. Analysis of the elutriation

The analysis of elutriation results was carried out using a novel probabilistic model, which was based on literature correlation for single particle terminal velocity. Settling or terminal velocity is defined as the velocity of the fluid at which a particle will remain stationary in a vertical stream of flowing fluid or the velocity a particle will attain at steady state when falling in stationary fluid. Many correlations exist to determine the values of settling velocity ($V_{t\infty}$). For example, the following correlation was proposed by Haider and Levenspiel [14] to describe the terminal velocity:

$$v_{t\infty} = \left(\frac{\rho^2}{g\mu(\rho_s - \rho)}\right)^{-\frac{1}{3}} \left[\left(\frac{18}{d^{*2}}\right) + \left(\frac{0.5909}{d^{*0.5}}\right)\right]^{-1}$$
$$d^* = d_p \left[\frac{g\rho(\rho_s - \rho)}{\mu^2}\right]^{\frac{1}{3}}. \qquad (1)$$

Where ρ and μ are density and viscosity of the fluid, ρ_s and d_p are density and diameter of the particle and g is acceleration due to gravity. In this work, the above equation was used for the calculation of the settling velocities of non-metals (plastics and glass) and metals of different sizes. For any particle, if the settling velocity of the particle is less than the elutriation operating velocity (V_e), then the particle would be expected to be elutriated to the top.

It should be noted that terminal velocity of a particle depends on its size as well as density. The milling product of PCB is a multi-component mixture, with particles of different sizes and densities. For the analysis based on Eq. (1), the mill products

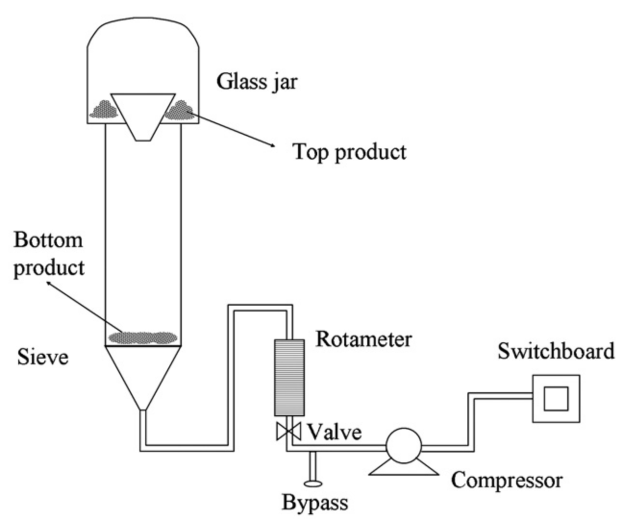

Fig. 1. Setup for elutriation.