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Material Recovery and Characterization of PCB from Electronic Waste

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Abstract

Printed Circuit Boards are commonly exist in computers, laptops and mobile phones. Since it contains of a variety of metals and semiconductors, it is difficult to recover the materials in PCB. This paper aims to characterize the composition of these materials and a method to properly recycle and recover the materials in them. This paper utilized simple mechanical and chemical procedures to recover PCBs. Collected PCBs were disassembled, pulverized and separated by using density and magnetic separation method. By using the chemical recycling method, 98.82% purity of $CuSO_4$ hydrate and $Al_2(SO_4)_3$ hydrate were recovered from the PCBs. It is found that the milling methods, size of the sample and the density of the separating solution determine the effectiveness of the materials recovered.

Keywords: Material recovery; electronic waste; printed circuit board

1. Introduction

Among other electronics and electrical equipments, mobile phone and computers have the most rapid development in technology. Since the introduction of the first mobile phone by Motorola in 1985, the mobile phone technology has evolved to flip phones in 1989, 2G GSM network in 1991, introduction of SMS in 1992, vibrating phones in 1996, mobile web and first Blackberry mobile in 1999, internal antenna in 2000, camera embedded phones and 3G network in 2001 to the introduction of 4G in 2009. The size and weight of mobile phones also decreases with time, from 794 grams to around 100 grams nowadays [1]. With an estimation of over 4 billion phones worldwide [1] and the advancement of technology, the amount of waste produced from used mobile phones is expected to grow rapidly. Based on a survey conducted in a university in Indonesia on students mobile phone

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consumption, most students only use their mobile phones for one year [2]. This result is in conformity with EPA reports cited in [1] and annual mobile phone collection report by Australian Mobile Telecommunication Association, which reported that Australians upgrade or exchange their mobile phones every 18 to 24 months [3]. This consumption pattern lead to 106 tons of collected mobile phones in Australia during July 2010 to June 2011 [4] or an estimated of 140 million mobile phones world wide [1].

Meanwhile, the development of computer had dated back to 4000 B.C. and had evolved in the early years of 20th century as the development of microchips were established [5]. Modern computing had transformed the world since the late 1940s up until now. At the moment, new technology is rapidly developing to enhance the use of computers. Computers become inseparable to human life [5, 6]. This rapid development, although beneficial to human life, also produce a major problem in terms of electronic waste generation. In 2008, U.S. Environmental Protection Agency reported an estimation of 29.9 million desktops and 12 million laptops were discarded in 2007 [7].

Both of these electronics products have a similarity. Both of them contains printed circuit boards (PCB). PCB is a thin board made of epoxy resin or fiberglass, which is coated with layers of thin copper films. PCB consists of various valuable metals such as Au, Pd, Ag, and Cu. However, it may also contains hazardous materials such Gallium Arsenide, Antimony, Berylliums, Brominated flame retardants and many more [8-15]. Many research have been conducted to recover the precious metals and to remove the harmful elements in PCB [8-16]. However most of these methods require high tech equipments and large investments.

Indonesia, as the fourth largest population in the world, is also having problems in managing its e-waste generation, especially from computers and mobile phones. In Jakarta, it is estimated that there are 10 tons of PCB waste that enters the waste stream every month. These wastes are managed without proper handling by informal sectors. Since these informal sectors cannot invest in high tech equipments and machineries, it is important to provide a more economical, yet environmentally friendly solution to this problem [17]. Therefore, the objective of this paper is to provide a simple material recovery procedure, which can be applicable to informal sectors, and to characterize the composition of materials contained in PCB and memory cards.

This paper is structured as follow. The first section will explain the collection method conducted to gather the samples for the study. It is then followed by describing the recovery methods used in this research. The third section will summarize the findings of the experiment and define the effectiveness of the recovery methods based on the condition of the experiment.

2. Sample Collection

The products, which are discussed in this paper, are used computers and mobile phones. These products were gathered from different sources. From these products, three components were examined, which are PCBs from mobile phones, PCBs from personal computers (PC) and memory cards.

The computers were collected from the inventory of broken components at Universitas Pelita Harapan. The computer and information system department (CISD) at the university provides service and repairs to computers that belong to the university. From time to time there are computers that end up in the recycling facility where they will be auctioned to a third party for recycling. Six computer PCBs and five memory cards were obtained from the facility to be used in this research.

The mobile phones used in this research were gathered from a collection program conducted at Universitas Pelita Harapan. The collection was conducted for one week through a "Donate and Win" program (Fig.1). E-waste recycling is a new concept to most Indonesian. Although a leading mobile phone manufacturer also conducts similar collection program but many have never heard about this program. This program raised many comments on the issue however, from around 900 people exposed to the event, the collection only managed to collect 27 mobile phones from 23 donators.

Fig 1. Mobile phone collection

3. Recovery Method

The method to recover the content of the PCBs and memory cards consists of three steps, namely disassembly, mechanical recycling procedure and chemical recycling procedure. As mentioned previously, the objective of these experiments is to replace the methods used by the informal sectors. Therefore, the methods selection considers the applicability of the method to informal sectors. Methods that require high investment and sophisticated equipment were omitted. [19].

3.1. Disassembly

Eight mobile phones, six computer PCBs and five memory cards were used as the sample in this experiment. Disassembly was conducted to separate the PCBs from other components. Disassembly was conducted manually by using desoldering tool with hot air. This process emitted gaseous substances that might be harmful to health. To ensure the safety of the operator and the environment, this process was conducted under a fume hood by wearing a gas mask

The disassembly process requires approximately 20 minutes for each mobile phone and approximately 70-80 minutes for each computer PCB. Memory cards were not disassembled and were processed as is. After being disassembled, around 20% of the mobile phone PCB weight was lost and approximately 30% from computer PCB ware removed. The weight of the disassembled PCBs from computers, mobile phones and memory card range from 200 to 315 grams, 6 to 16 grams, and 15 to 20 grams, respectively, depending on the size, shape and brand of the product.

Fig 2. Disassembled mobile phone PCBs

3.2. Mechanical recycling

After being disassembled, the samples were processed mechanically. First, the samples were pulverized in a milling machine. Then, pulverized samples are separated by density by using an organic solution. The heavier fraction, which is assumed to consist of metal content, is separated using magnetic separation process. Energy Dispersive X-Ray Spectroscopy (EDX) is used to analyze and characterize the samples in the experiment. Details of the process are explained in the following subsections.

3.2.1. Milling process

There were two types of milling machines used in this experiment, which are ball-milling machine and disc-milling machine. The disassembled samples were first cut into 40 x 10 mm pieces by using JORG cutting machine. To fit into the machine, the cut pieces were cut again by using a cutting scissors to the size of 20 x 10 mm. The cut pieces were fit into the jar and milled. Although both machines perform similar function, there are some differences in the result of the milling process.

The ball-milling machine, shown in Fig 3 (a), have smaller capacity and can only fit around 25 grams of sample. The time required to mill each sample into 100 micron is approximately 120 minutes. Meanwhile, a disc-milling machine (Fig 3 (b)) can fit up to 200 grams of sample and for each sample required only 40 minutes to produce pulverized PCB in 100 micron size. To identify the effect of sample size to the separation processes performed, the sample were divided into four sizes, namely 74 microns (200 mesh), 100 microns (140 mesh), 149 microns (100 mesh) and 200 microns (75 mesh).

Fig 3. (a) Ball-milling machine; (b) Disc-milling machine

Comparing the two milling machines, the ball-milling machine produces more uniform results than the disc-milling machine. Some of the sample processed in the disc-milling machine could not be pulverized uniformly and produced some residue with the size of larger than 74 microns. This residue caused differences in the type of materials identified in the EDX analysis. Samples which were pulverized by using ball-milling machine were identified to consist of element C, O, Al, Si, Ca, Fe and Cu. Meanwhile, those, which are pulverized in a disc-milling machine, did not contain Ca and Fe because most of the samples which contain those elements were in the residue.

3.2.2. Density separation

The samples that have been pulverized were then separated by using density separation method. This procedure aimed to separate the metals from the nonmetals by using an organic solution Tetrabromoethane (TBE). Tetrabromoethane (TBE) is chosen for its high density, 2.967 g/ml. In this experiment, TBE is mixed with acetone to lower its density and consequently, lowering its viscosity. The lower viscosity causes faster material separation and more efficient filtration. According to Veir et al. [18], TBE should be mixed with acetone with volume proportion of 1: 0.27. However, when tested with 100 microns sample, the sample was not separated efficiently. Most of the samples were still floating. The density of TBE and acetone mixture was then lowered until it reached the ratio of 1:0.6. At this ratio, the density of the solution was 2.01 g/ml.

The samples were separated into light and heavy fraction. The light fraction is defined as all the samples that float on the test tube while the heavy fraction is the samples that sink into the test tube. The light and heavy fraction were extracted from the test tube, filtered and then dried. The dried samples were then analyzed using Energy Dispersive X-Ray Spectroscopy (EDX) to characterize the composition of the PCB samples.

Table 1 and Table 2 show the result of EDX for computer PCB, mobile phone PCB and memory card for light fraction and heavy fraction, respectively. The results show that density separation was not efficient for computer PCB. Al was found more in the light fraction than in the heavy fraction because its density is lower than the solution. This also occurred in mobile phone PCB samples. However, since Si element is more dominant in memory card sample than in other samples, this phenomenon did not occur in memory card samples.

The effectiveness of density separation process was also influenced by the particle size of the samples. In computer and mobile phone PCB samples, Cu is more effectively separated at size 149 microns. On the other hand, Si is more effectively separated in samples with particle size 74 microns for all of the samples. This result confirmed the relationship of particle size and the effectiveness of the density separation process.

Table 1. Composition of light fraction

Product	PC		Memory Card		Mobile phone	
Particle size (μm)	74	149	74	149	74	149
C	4.76 %	3.83 %	5.29 %	4.95 %	5.93 %	4.96 %
O	27.15 %	28.24 %	34.81 %	36.84 %	28.07 %	25.26 %
Al	45.8 %	44.29 %	31.93 %	27.73 %	46.28 %	50.51 %
Si	11.94 %	13.48 %	23.74 %	26.04 %	8.24 %	7.76 %
S	0.26 %	0.27 %	0.23 %	0.19 %	0.21 %	0.31 %
Cu	5.79 %	4.48 %	1.55 %	2.16 %	7.53 %	6.89 %
Sn	4.31 %	5.40 %	2.46 %	2.09 %	3.74 %	4.31 %
Total	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%

Table 2. Composition of heavy fraction

Product	PC		Memory Card		Mobile phone	
Particle size (mm)	74	149	74	149	74	149
C	3.57 %	4.10 %	3.40 %	3.58 %	5.21 %	2.74 %
O	29.88 %	30.45 %	40.32 %	34.27 %	28.9 %	16.15 %
Al	40.73 %	39.04 %	22.51 %	29.11 %	43.18 %	40.85 %
Si	15.32 %	13.86 %	28.74 %	24.65 %	11.16 %	6.60 %
S	0.3 %	0.28 %	0.16 %	0.20 %	0.26 %	0.30 %
Cu	4.31 %	7.39 %	1.36 %	3.83 %	6.93 %	29.39 %
Sn	5.91 %	4.88 %	3.52 %	4.37 %	4.37 %	3.99 %
Total	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%

3.2.3. Magnetic separation

The magnetic separation was conducted manually by using neodymium magnet by placing the samples in a Petri Dish. This method only applicable to samples which were pulverized using the ball-milling machine. The problem in magnetic separation was agglomeration of the particles. This agglomeration caused the magnet to also pull the nonmetal materials which agglomerate with the ferrous materials. About 37% of the sample were able to be separated in this process.

3.3. Chemical recycling

The chemical recycling method is conducted by dissolving 10 grams of heavy fraction sample of 149 μm mobile phone PCB in a mixture of 25 ml H_2O, 25 ml of concentrated H_2SO_4, and 10 ml of concentrated HNO_3. The solution was then heated on a heating plate. After all the gaseous substance have evaporated, the heater was turned off and the solution was kept still for 5 minutes until there was no more vapor and a bright green solution was produced.

The process was continued to cementation process. In cementation process, ions are reduced to zero valence at solid metallic interface. This process is usually used to refine leach solutions. In this process, the solution produced previously is dissolve in 150 ml H_2O and 5 ml HCl. Four aluminum coins were added to this solution to let the cementation process occur. The aluminum coin will exchange ion with copper and the solution will be opaque. After the solution was kept for 24 hours, the copper will sink to the bottom of the beaker glass. It was then filtered and dried in under a fume hood for another 24 hours. The dried copper could be seen in Fig 4.

The copper produced from the previous procedure was then further treated to produce copper hydrate crystals. The copper powder (3.40 g) was dissolved in a solution, consists of 6.8 ml of concentrated H_2SO_4, 6.8 ml of concentrated HNO_3 and 34 ml H_2O. The mixture was heated at 150°C and a brownish yellow smoke was emitted. The mixture was then filtered, leaving a bright blue solution. The solution was then reheated until it was saturated and the volume of the solution was about half. The saturated solution was quenched into cold-water bath. This process forced the transformation of liquid solution to a pure solid crystalline phase, producing $CuSO_4.5H_2O$ shown in Fig 5.

Fig 4. Dried copper

Fig 5. $CuSO_4.5H_2O$ crystals produced

To check the composition of the $CuSO_4.5H_2O$ produced from the experiment, the crystals were tested using Atomic Absorption Spectroscopy (AAS). The analysis shows 98.82% purity of the crystals (Table3).

Table 3. AAS result for $CuSO_4.5H_2O$ composition

Elements	Concentration (%)
Fe	0.048
Ca	0.0028
Mg	0.0016
Pb	0.0014
Al	0.0153
Ag	0.00006
Plastics (Silica etc)	0.40
Total Impurities	**0.469**
H_2SO_4	**0.25**
H_2O	**0.46**
Total	1.18
Purity of $CuSO_4$. $5H_2O$	**98.82**

Similar procedure was conducted to samples of computer PCB (74 and 149 μm) and memory card. However, the result was different to mobile phone PCB. The color of the crystals produced from computer PCB was whitish green, as shown in Fig 6. The crystal was identified as $Al_2(SO_4)_3.5H_2O$.

Fig 6. $Al_2(SO_4)_3$. 5 H_2O produced from computer PCB

4. Summary

Based on the experimentation result, it can be concluded that ball-milling machine is preferable than disc-milling machine due to its uniform pulverization although the time requires to ball-mill is longer than disc-mill. The size of particles determines the effectiveness of density separation procedure. The preferable particle size for density separation is 149 microns.

The materials from mobile phone, computer and memory card were recovered by using mechanical and chemical processing procedures. The copper contained in mobile phone PCB were extracted and producing copper sulfate hydrate ($CuSO_4$.5 H_2O) with 98.82% purity. This substance can be sold with a market price of Rp. 28,000/kg or around US$3/kg. Although the result is not as promising as gold extraction from PCB, with simple procedures and low investment, this is an alternative that should be considered.

Meanwhile, since the Aluminum content in computer PCB is higher than in mobile phones, aluminum sulfate hydrate ($Al_2(SO_4)_3.5H_2O$) were extracted from computer PCB.

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