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Physical separation route for printed circuit boards

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Abstract: Recently, the consumption of electrical and electronic equipment (EEE) has increased with the advanced technology. A wide range of components made of metals, plastics and other substances are contained in EEE. Electronic waste (e-waste) is easily demounted and separated by manually methods; however, printed circuit board (PCB) which is one the most common components of e-waste need to be recycled with economic and environmental technologies. In this paper, employing physical separation methods to ground waste PCB, an eco-friendly, simple and environmental process for separation of valuable metals was designed and proposed. A heavy fraction with 40.8% Cu, 350 ppm Au and 475 ppm Ag content at recovery of 95.4% Cu, 77.7% Au and 65.1% Ag was obtained from a feed assaying 12% Cu, 130 ppm Au and 200 ppm Ag using shaking table separator. Cu grade was increased from 52.4% to 73.9% with the recovery over 92% by dry magnetic separator and copper alloys were separated from the waste matrix with 98% Cu recovery using electrostatic separator.

Keywords: *physical methods, PCBs, environment, copper, gold, silver*

1. Introduction

The need for EEE has ascended dramatically with the growing and developing of industry. The rapid innovation in technology has resulted in higher performance requirements, availability of cheaper and greater demands in the market shortening the life cycle of the product. E-waste is composed of materials such as metal, glass and plastics and they constitute 90-95% of the total weight of e-waste. E-waste contains a wide range of elements, and 50% of which constitutes iron and steel followed by 21% plastics, 13% nonferrous metals and 16% other constituents like rubber, concrete and ceramics (Lee et al., 2004). The share of PCBs is between 3-5% and generally classified in three groups such as organic, metals, and ceramics (Pilone and Kelsall, 2003). They are used in nearly all electronic equipment, including consumer electronics, military and space applications, medical, calculators, remote control units, and white goods, etc. Glass-reinforced epoxy resin and metallic materials are the main constituent of PCBs. Organic materials are mainly composed of plastics, flame-retardants and paper. PCBs contain high amount of base metals (copper, iron, aluminum and tin), precious metals (gold, silver, and palladium) and rare metals (tantalum, gallium, indium and other rare platinum metals). Ceramic materials in waste PCB are mainly composed of alumina, alkaline earth oxides, silica, mica and barium (Li et al., 2004; Duan et al., 2011).

Waste PCB also contains hazardous metals such as chromium, lead, beryllium, mercury, cadmium, zinc, nickel and brominated flame retardants which are dangerous for the soil, environment, and organisms. Improper recycling techniques can lead serious damages on human, animals and plants. Because of environmental issues and restraints, the conventional waste treatment techniques such as landfilling and incineration are not practiced in most developed countries. By recycling of e-waste in a proper way the valuable materials are recovered and depleted sources could be preserved (Diao et al., 2013).

The content of components in PCBs are different and depends on its area of usage. On average, a PCBs mainly contain approximately 28% metals and 23% plastics. The remaining amount is made up

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of ceramics and glass materials (Zhou and Qiu, 2010). A typical PCBs scrap assays about 5% Fe, 16% Cu, 2% Al and 0.5% Ni, 2000 ppm Ag, 150 ppm Au and other metals (Cui and Zhang, 2008). The precious metal content of PCBs is 10 times higher than a typical rich ore. Thus, PCBs can be considered as a secondary raw material with a high metal content. Lower energy is needed to concentrate and refine the precious metals in the PCBs when compared with the virgin ores (Gup et al., 2008).

Because PCBs have heterogeneous content (organic materials, metals, glass fiber and ceramic) the recycling of precious metals requires sophisticated technologies and a multidisciplinary approach (Goosey and Kellner, 2003). Three major steps which are disassembling/comminution, concentration and refining are generally applied for recycling of PCBs. Firstly, the hazardous and valuable components are separated manually or automatically. After removal of the components, mineral processing operations such as shredding, crushing and grinding are used for liberating metals from undesirable part of PCB. Mechanical and/or metallurgical processes are performed to increase the content of valuable materials and finally the separated valuable fraction is purified using chemical/metallurgical processing for the industrial use. Many investigations were carried out in order to recover metals from waste PCBs (WPCBs) using physical, chemical, or biological methods (Zhang and Forssberg, 1997; Mecucci and Scott, 2005; Veit et al., 2005; Liet al., 2007; Oishi et al., 2007; Eswaraiah et al., 2008).

PCBs are sorted from the EEEs manually and crushed into smaller size fractions in order to ensure proper liberation and then separated into metallic and non-metallic fractions by adopting physical beneficiation techniques. The effective separation depends on shape, size and distribution of the particles, so the liberation degree has an important role in physical processes (Ghosha et al., 2015). In contrast to mineral ores, a particular size fraction for liberation cannot be found in PCBs. The liberation characteristics and the effect of shape and size of PCBs were studied by Zhang and Forssberg (1999) and Li et al. (2010). They concluded that PCB particles have heterogeneous shape and are liberated below 3 mm after crushing/shredding process. A big part of copper wires presents with an elongated shape while plastics and glass particles are either cubic-like or ball-like. The shape difference is advantageous for classification of materials. When the particle size decreases liberation degree of metals from PCBs increases; however, the separation efficiency decreases with fine fraction production.

The liberation degree of PCBs was studied by Sarvar et al. (2015) and they found that the plastic particles are liberated from the metallic fraction at –2.38+1.68 mm size fraction, however complete liberation of ceramics and board pieces from metals were realized at –0.42+0.21 and -0.21 mm, respectively. The wet shaking table was successfully conducted on metal/nonmetal separation for copper/plastic (cable scrap) by Cui and Forssberg (2003). They suggested that at coarser sizes, gravity separation of metals have some significant advantages for subsequent treatment stages when the liberation of particles is achieved. Generally, in gravity separation techniques, the narrow range of fractions increases the separation efficiency (Wills et al., 2006). The size control of feeds before gravity process is needed in order to reduce the negative effect on the size and make the relative motion of the particle specific gravity dependent (Kelly and Spottiswood, 1982).

In physical separation operations, magnetic separators are widely used for the recovery of ferromagnetic metals from non-ferrous metals and other non-magnetic wastes. Electrical conductivity based Eddy current separation and Corona electrostatic separation are used to separate materials of different electrical conductivity such as non-ferrous metals from non-conducting materials. The most widely used processes such as pyrometallurgical and hydrometallurgical generate hazardous gases and effluents which cause atmospheric pollution. The environmentally friendly physical separation route for PCB processing diminishes the negative effects of the hydrometallurgical or pyro metallurgical processes and promises lesser investment, operation and energy cost (Hoffmann, 1992; Menad et al., 1998; Jha et al., 2011).

In the present work, the disassembling and comminution processes followed by physical separation techniques prior to hydrometallurgical or pyro metallurgical process is employed. The main aim of this work is to design a process based on physical separation and obtain a pre-concentrate prior to hydro and pyro metallurgical processes. For this purpose, characterization of crushed PCBs was performed at the first stage and then wet tabling, magnetic and electrostatic separation methods were applied to separate valuable metals from non-metallic fraction.

2. Experimental

2.1 Materials

About 20 kg PCBs from personal computer mainboards were collected and used in experimental studies. Dissembling of components from PCB is the first and the most important step in the recycling process. For that reason, the attachments like cords, frames, capacitors, resistors and wires were selectively removed from the PCBs by manual separation (Fig. 1). Following the manual separation of board parts, various mineral processing techniques such as shredding, crushing and grinding are used to separate metals from cladding materials (resin, fiberglass and plastics). Manually sorted PCBs (Fig. 2a) were cut into small (about 2x2 cm) pieces using a four-bladed rotary cutting shredder supplied from Netplasmak Co. (Fig. 2b). The shredded sample was ground below 2 mm by a ball mill in order to provide effective liberation of metals.

Fig. 1. PCBs of personal computer (a) and mounted parts (b)

Fig. 2. Manually sorted PCB's (a) and shredder (b)

2.2 Characterization studies

The characterization of PCB is performed by mechanical processing, size classification, disc-milling (for pulverization), aqua regia leaching and chemical analysis using atomic absorption spectrometry (AAS). The crushed PCB sample was classified into 6 fractions by manual screening. Each sample fraction was dissolved in aqua regia at about 45°C to assure complete dissolution of metal parts and filtered from insoluble parts (plastic, thermoset resins, etc.). All measurements were done using Varian AA50 AAS apparatus. The technique makes use of the wavelengths of light specifically absorbed by an element. They correspond to the energies needed to promote electrons from one energy level to another, higher, energy level. The weight of fractions and metallic contents are expressed in Table 1.

Table 1. Metal contents of size fractions determined by AAS

Size fraction, mm	Amount, %	Metal grade, %							
		Cu	Fe	Al	Ni	Pb	Au	Ag	Total
+2	17.3	6.36	0.19	10.7	0.02	0.01	0.003	0.003	17.8
-2+1	24.0	10.49	0.26	12.1	0.04	0.02	0.022	0.005	23.2
-1+0.5	13.6	20.92	0.40	12.4	0.10	0.04	0.011	0.008	34.2
-0.5+0.3	10.5	23.53	1.14	4.8	0.21	0.13	0.009	0.038	30.1
-0.3+0.15	10.9	19.73	2.53	2.9	0.37	0.29	0.006	0.040	25.9
-0.15	23.7	5.37	17.98	3.4	0.24	0.30	0.017	0.041	27.5
Total	100.0	12.36	4.80	8.1	0.15	0.13	0.013	0.021	25.8

The screen analysis results in Table 1 show that the particle size distribution of crushing products of PCBs show bimodal distribution. It means that -2+1 and –0.15 mm are the dominant particle size ranges of the crushed products. The results of comminution and classification clearly show that the content of metals and non-metals are diverse at fractions. The chemical analyses in different particle size fractions indicate that the copper content is the highest at -1+0.5; -0.5+0.3, and -0.3+0.1 mm. The results also show that most metals (Fe, Ni, Pb and Ag) are concentrated in the finest fraction by means of the sieving process. In contrast, Al in PCB easily deform and hardly break under the loads, thus Al particles are concentrated in the larger size fractions. It is assumed that gold is interlocked in coarser particles and further grinding is needed to liberate gold particles.

The epoxy glass laminated sheet in PCB consisted of glass fiber cloth and cured epoxy resin, made by bonding and pressing; the internal organizational structure is asymmetric (Duan et al., 2015). The surface morphology of the PCB was analyzed by SEM (Scanning Electron Microscope) and EDS (Energy Dispersive X-ray Spectroscopy) analysis was carried out both locally and regionally to have information about the chemical composition of the products.

2.3 Beneficiation methods

The main objective of physical separation methods is to obtain the nonmetallic materials without any loss of metallic values. This research has focused on the separation and concentration of metals using physical methods such as wet shaking table concentration, magnetic and electrostatic separation (Fig. 3).

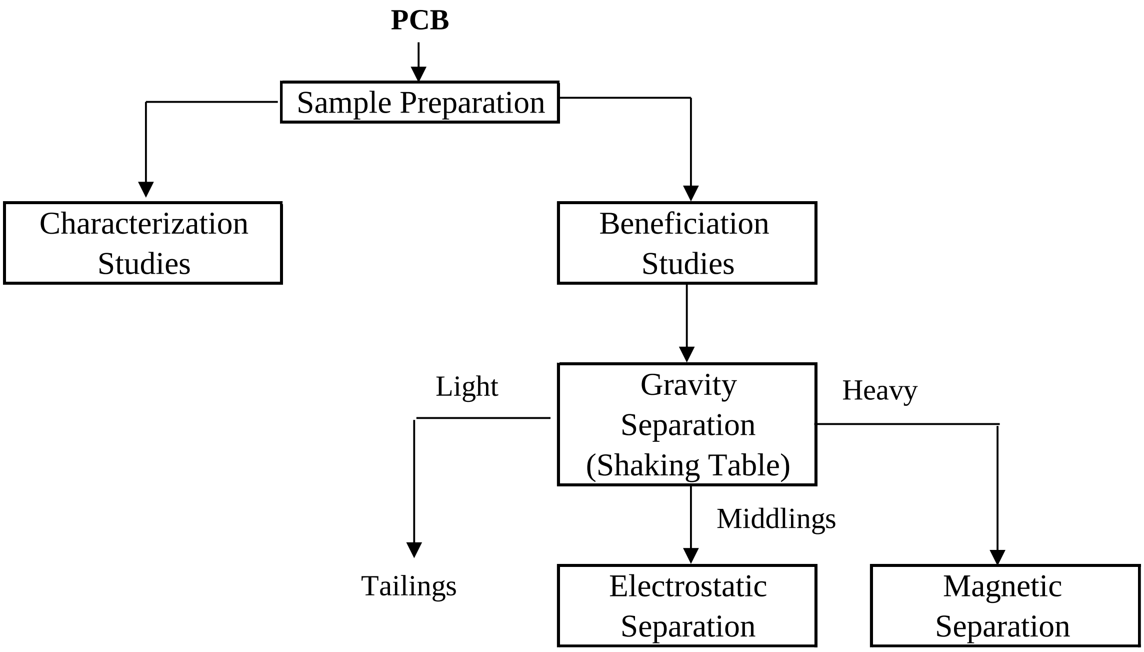

Fig. 3. The general flowsheet of the process

Gravity separation is one of the oldest methods that use specific gravity difference between the minerals for enrichment. Low capital and operating costs increase the attraction of this method. It is accepted as environment friendly process due to the lack of chemicals and extra heating needs. In fluid medium, the particle motion is dependent on the density, size and shape of the particle (Das et al., 2009). In mineral processing, shaking tables are widely used to concentrate particles between 3 and 0.1 mm. The laboratory type Wilfley shaking table used in the experimental studies is made of fiberglass deck with a rectangular shape (800 mm length and 400 mm of width) and inclination is adjustable. The riffles which have 6 mm high on the right side of deck (the feed section) decrease toward the left side (the concentrate section). Two water supplies are placed on the deck as feed water and wash water. Using the two splitters three products namely; concentrate (heavy), middling and tailing (light) are obtained. The shaking table variables are adjusted as water addition of 10 L/min, stroke frequency of 300 #/min, stroke length of 2 mm, lateral angle of 3^o, feed rate of 30 kg/hour.

Magnetic separation of metallic values from non-metallic fraction prior to electrostatic separation was studied by Veit et al. (2005). They concluded that the copper content reached more than 50% at the conductive fraction by removing iron at magnetic separation process. Generally, low intensity drum type magnetic separators are extensively used for beneficiation of minerals with ferromagnetic properties from nonmagnetic metals and other wastes. With the introduction of rare earth alloy permanent magnets high-field strengths and gradients were provided. In mineral processing, dry processes are used ahead of wet processes, however; in the experimental studies, as the first step, a large amount of plastic, ceramic and glass fraction (more than 70% of the feed) was targeted to remove using wet shaking table concentrator. The moisture content of heavy fraction after tabling was easily decreased below 4% using vibrating screen and atmospherically dried in 12 hours. Instead of low intensity dry magnetic separator, the laboratory type high gradient rare earth magnetic separator (REMs) was conducted to gravimetrically separated heavy fraction in order to remove especially ferrous alloyed materials and produce a high-quality copper containing concentrate.

In order to separate metals from non-metallic fraction (plastic, ceramic and glass) the electrostatic separation is widely used in mineral processing technology. It is important and very efficient technique that solid particles are selectively sorted by means of utilizing forces acting on charged or polarized bodies in an electric field. The parameters of electrostatic separator used in experimental studies are given in Table 2.

Table 2. Parameters of electrostatic separation

Size fraction (mm)	High voltage ($x10^4$V)	Cylinder speed (r/min)
-0.3	3.0	40
-1+0.3	3.5	40

3. Results and discussion

3.1. Wet shaking table separation

After comminution process three size fractions (+1, -1+0.3 and -0.3 mm) was prepared using screens and wet shaking table separation was successfully subjected to these groups. Finally, three products (heavy, middling and light) were generated by adjusting two splitters. The obtained products were then dried, weighted and pulverized for identification of metal contents. Finally, the content and recovery were calculated using the obtained data. Because Ni and Pb contents are low, so they are excluded from the assessment. The results of gravity separation of the metallic components from the ground PCBs at different fractions and as combined are given in Tables 3 and 4, respectively. The metal distributions of products are illustrated in Fig. 4.

In wet shaking table beneficiation, the production of a concentrate with high recovery rate, a middling with low amount and rejectable tailings having low grade metal fraction was aimed. By introducing +1 mm PCBs to shaking table, a heavy product was obtained containing about 43% metal (Cu, Au, Ag, Fe and Al) content. A concentrate grade of over 58% total metals was successfully obtain ed at -1+0.3 mm fraction and the total metal content of heavy product dramatically increased to over 95% at finest fraction. The grade of copper at -1+0.3 mm size fraction was found as the highest (49.08%).

Table 3. Metal contents of products in different fractions after tabling

Fraction, mm	Products	Weight, %	Content				
			Cu	Au	Ag	Fe	Al
+1	Concentrate	16.2	21.06	0.022	0.007	0.17	21.86
	Middling	4.4	3.32	0.008	0.002	0.10	3.16
	Tailing	24.0	1.00	0.004	0.001	0.12	5.51
	Total	44.5	8.52	0.011	0.003	0.13	11.23
-1+0.3	Concentrate	9.0	49.08	0.023	0.053	0.82	7.77
	Middling	3.1	1.58	0.005	0.003	0.18	14.66
	Tailing	9.1	0.30	0.003	0.004	0.13	3.97
	Total	21.2	21.13	0.016	0.024	0.43	7.15
-0.3	Concentrate	8.1	42.32	0.047	0.091	52.24	0.56
	Middling	2.3	2.02	0.009	0.033	1.20	2.47
	Tailing	23.8	1.45	0.005	0.024	1.29	3.42
	Total	34.3	11.19	0.015	0.040	13.38	2.68
Total		100.0	12.11	0.013	0.020	4.74	7.43

Table 4. The combined results of tabling

Products	Weight, %	Content, %				
		Cu	Au	Ag	Fe	Al
Concentrate	33.3	33.81	0.028	0.039	13.08	12.85
Middling	9.8	2.46	0.008	0.009	0.39	6.67
Tailing	56.9	1.08	0.004	0.011	0.61	4.39
Total	100.0	12.11	0.013	0.020	4.74	7.43

It can be seen from Table 3 that it is possible to concentrate aluminum at coarse fractions. While the content of Al at +1 mm fraction is 21.86% at finest size fraction it decreases to 0.56%. Conversely mineral particles, the grinding of PCBs with a ball mill gives flat shape products due to ductile and malleable properties of metals. In tabling, the chance of settling of small size Al particles is very poor and they are washed off by the flowing water to the tailing. The large specific gravity difference between the plastic and iron particles makes the gravity operation very suitable for separation of Fe from light materials. The concentrate containing 52.24% Fe was obtained at the finest size fraction. A separation at -0.3 mm lead to a high-grade Ag and Au concentrate which was 3 times higher as compared with that of the feed.

From Table 4 and Fig. 4, it can be easily noticed that a concentrate containing 33.81% Cu grade was produced with 93% recovery and copper lost in tailing is very low. About 75% of Au and 65% of Ag are recovered in concentrate with 281 ppm and 394 ppm content, respectively. As seen in Table 1, Ag particles are accumulated in very fine sizes fraction as compared with Au, thus Ag particles are washed away and lost in tailing product with the flowing water.

Especially resins and glass fibers adhere to the conductive copper foil cohesively and the selectivity decreases mostly at coarsest fraction. For enhanced concentration of metals, it is very critical to liberate the metallic fraction from the PCB pieces. The sections and phases of concentrate sample from +1 mm size fraction were provided with a more qualitative assessment using SEM analysis. EDS analysis confirmed that the particles are mainly composed of Al, Si, Ba, Ca and Cu. Two distinct phases on the particle can be seen in Fig. 5a. While the layer on the left side has a smooth surface, rough surface can be detected at the right side. EDS analysis of section 1 indicated that the particle contains approximately 68.8% Ba. The SEM image of the particle at the rougher surface was magnified

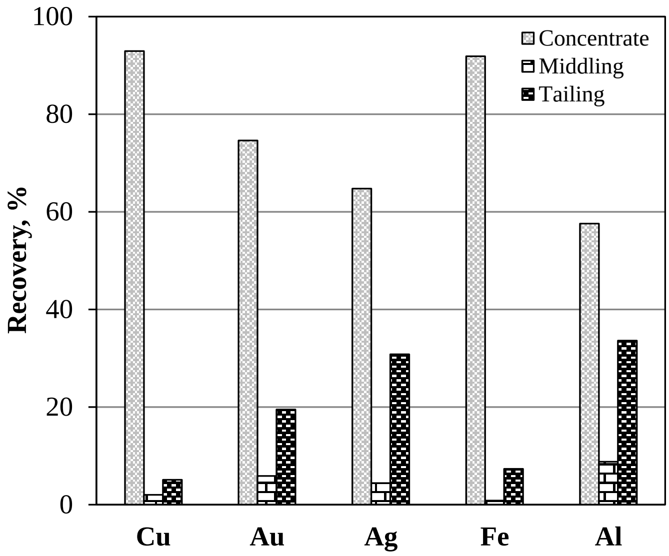

Fig. 4. The distribution of metals after tabling

and illustrated in Fig. 5b. According to the EDS analysis, the rougher layer of particle appears to have 35% Ba and 55% Ca content at section 2 and 63% Cu and 1.3% Ba at section 3. These results have shown that the concentrate from +1 mm fraction contains some unliberated copper foil and needs further comminution process. It was confirmed both from chemical analysis and SEM/EDS studies that enhanced liberation of particles must be provided in order to produce a concentrate with a higher metallic content. For that reason, +1 mm size fraction was re-ground using ball mill and then distributed to other size fractions by screening. The metal content of products after re-grinding is given in Table 5 and obtained products are illustrated in Fig. 6. Metal content of combined products and distributions are given in Table 6 and Fig. 7, respectively.

After re-grinding process the weight of +1 mm fraction was decreased from 44.5% to 13.3%. Thus, the amount of -1+0.3 mm and -0.3 mm fractions were increased to 43.3% and 43.4%, respectively. As shown in Table 5, a concentrate having about 72% metal content was obtained at +1 mm fraction. The excessive grinding of PCB with ball mill caused enlarged Al particles due to malleable properties of this metal and mainly Al increased to metal content along with Cu. More than 77% total metal was concentrated in heavy product at -1+0.3 mm fraction. The highest copper content (73.21%) was achieved at this fraction as same in previous shaking table tests. Koyanaka et al. (1999) reported in their study that glass fibers and epoxy resins pass to brittle fraction more than the metallic materials and enrich in the finer fraction after the impact milling of PCB. As parallel to their findings, with the generation of fine size waste material below 0.3 mm fraction, the concentrate's total metal content decreased from 95% to 90% compared to previous concentration tests.

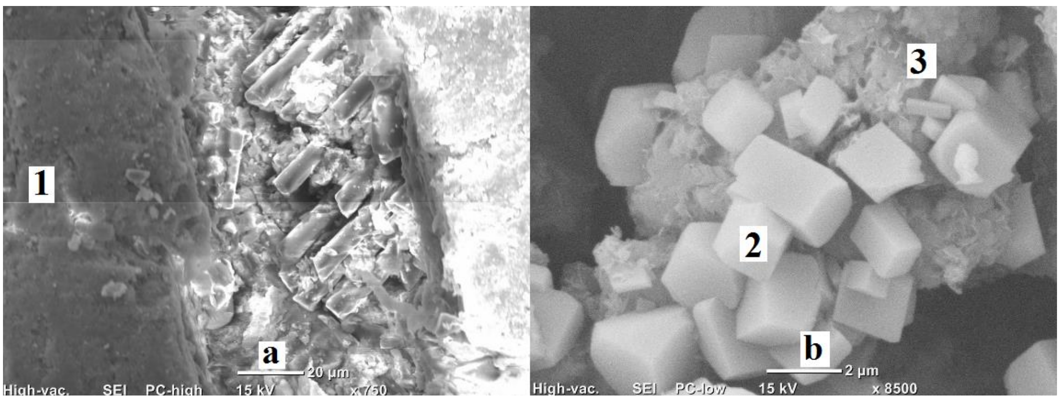

Fig. 5. SEM photos of +1 mm concentrate (EDS analysis of section 1: 25% Al, 6.5% Si and 68.5% Ba; section 2: 10% Al, 35% Ba and 55% Ca; section 3: 33% Al, 63% Cu, 1.7% Ca and 1.3% Ba)

Table 5. Metal contents of products after re-grinding of +1 mm

Fraction, mm	Products	Weight, %	Content				
			Cu	Au	Ag	Fe	Al
+1	Concentrate	2.5	18.09	0.016	0.011	0.60	52.74
	Middling	3.9	0.91	0.006	0.001	0.09	7.36
	Tailing	6.8	0.19	0.002	0.001	0.12	1.80
	Total	13.3	3.81	0.006	0.003	0.20	13.15
-1+0.3	Concentrate	7.7	73.21	0.018	0.056	1.07	3.08
	Middling	9.1	20.03	0.016	0.006	0.33	26.45
	Tailing	26.6	0.39	0.003	0.002	0.25	6.68
	Total	43.3	17.39	0.008	0.012	0.41	10.18
-0.3	Concentrate	8.2	43.38	0.078	0.096	45.46	1.00
	Middling	0.9	14.93	0.022	0.055	7.66	20.75
	Tailing	34.3	1.17	0.005	0.019	2.16	4.22
	Total	43.4	9.42	0.019	0.034	10.45	3.94
Total		100.0	12.13	0.013	0.021	4.74	7.87

Table 6. The combined results of tabling after re-grinding of +1 mm

Products	Weight, %	Content, %				
		Cu	Au	Ag	Fe	Al
Concentrate	18.4	52.32	0.045	0.068	20.79	8.99
Middling	9.9	19.58	0.017	0.009	0.97	25.95
Tailing	71.7	0.77	0.004	0.010	1.14	5.08
Total	100.0	12.13	0.013	0.021	4.74	7.87

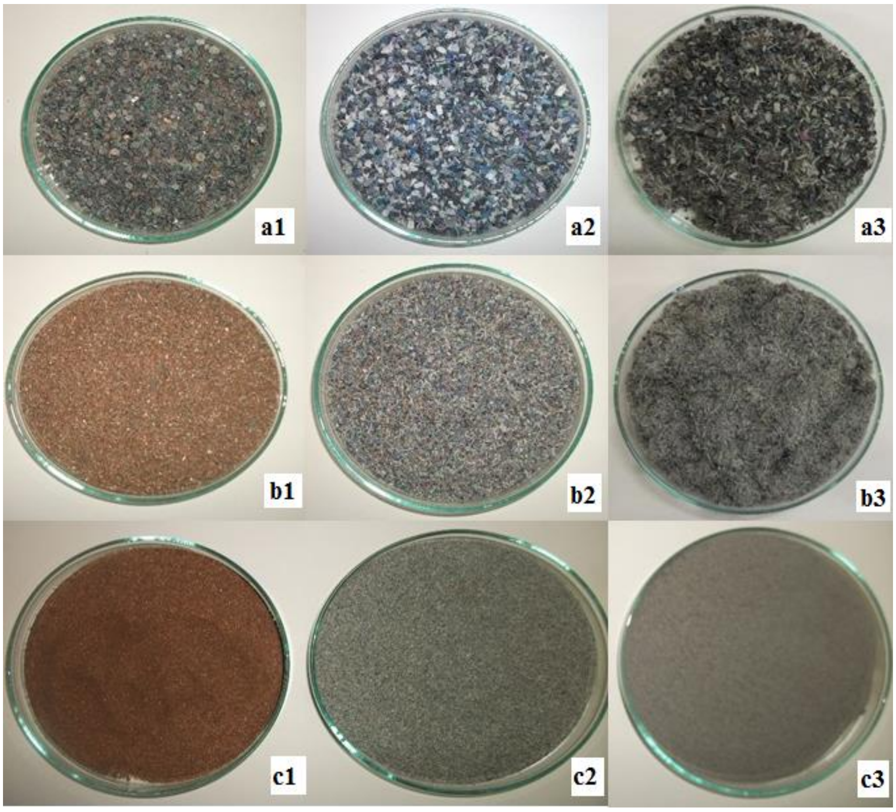

Fig. 6. Photos from shaking table products (1: concentrate; 2: middling; 3: tailing) at different fractions (a: +1 mm; b: -1+0.3 mm; c: -0.3 mm)

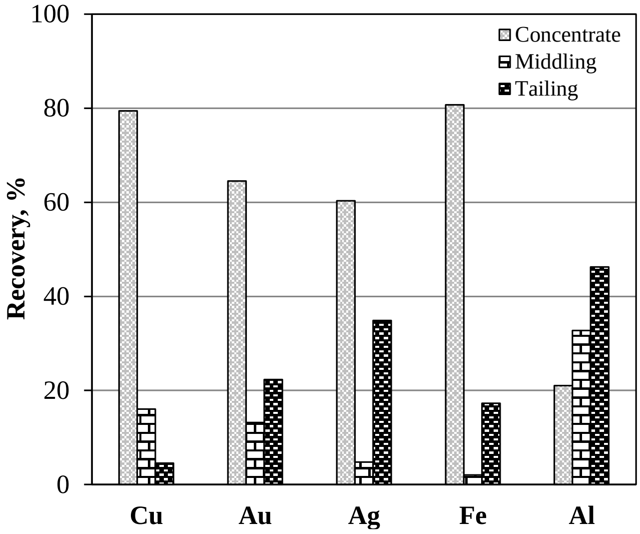

Fig. 7. The distribution of metals in shaking table products with re-grinding

The results in Table 6 clearly show that re-grinding of coarse fraction has a significant effect on production of concentrate with high Cu, Au and Ag content. For instance, a concentrate grade of over 52% Cu with 79.4% Cu recovery could be achieved. It is also possible to obtain a heavy product containing 446 ppm Au and 677 ppm Ag with 64.5% and 60.3% recovery rates respectively. When concentrate and middling products are combined a product with 40.8% Cu, 350 ppm Au and 475 ppm Ag content could be obtained. By decreasing 0.5% to previous tabling test Cu loss in tailing was found as 4.6%, however, an increase in metal loss was observed for both Au and Ag. Further grinding process of coarse material increases liberation degree of particles which is very beneficial for producing high metal content concentrates, however, very fine particles that are ejected from tailing product decrease recovery of Au, Ag and Fe.

3.2 Magnetic separation

Although the amount of ferrous material present in printed circuit boards is low, iron content (45.46%) in heavy fine fraction from shaking table test is found very high. To obtain conductive fractions with higher copper content three heavy fractions from tabling stage were subjected to dry magnetic separator with a magnetic field of 4000 G. The metal content and distribution were determined and presented in Tables 7 and 8.

Table 7. Metal contents of products after dry magnetic separation

Fraction, mm	Products	Weight, %	Content, %		Distribution, %	
			Cu	Fe	Cu	Fe
+1	Magnetic	5.2	5.98	1.32	12.7	84.0
	Middling	4.3	17.23	0.23	30.2	12.1
	Non-magnetic	4.1	34.53	0.08	57.1	4.0
	Total	13.6	18.08	0.60	100.0	100.0
-1+0.3	Magnetic	4.0	43.55	8.25	5.7	72.8
	Middling	3.7	63.09	2.15	7.6	17.4
	Non-magnetic	34.1	78.11	0.13	86.8	9.8
	Total	41.8	73.47	1.09	100.0	100.0
-0.3	Magnetic	18.9	3.40	94.04	3.4	89.1
	Middling	1.9	24.93	64.20	2.5	6.2
	Non-magnetic	23.7	76.11	4.02	94.1	4.8
	Total	44.6	43.01	44.87	100.0	100.0
Total		100.0	52.37	20.53		

Table 8. Metal contents of combined products after dry magnetic separation

Products	Weight, %	Content, %		Distribution, %	
		Cu	Fe	Cu	Fe
Non-magnetic	65.6	73.85	1.65	92.5	5.3
Middling	13.5	20.70	3.03	5.4	2.0
Magnetic	20.9	5.38	91.30	2.1	92.7
Total	100.0	52.37	20.53	100.0	100.0

As expected in magnetic separation, iron was the main element retained in the separator and concentrated in magnetic fraction. At +1 mm fraction, the magnetic separator had an average recovery of approximately 84% Fe in the magnetic product compromising roughly 5.2, percent of the feed weight. By introducing -1+0.3 mm fraction, a heavy product was obtained containing about 8.25% Fe content with 72.8% Fe recovery. At finest fraction, the iron content of magnetic product dramatically increases to over 94%.

As a non-ferrous metal, Cu was concentrated in high grade at non-magnetic fractions. It is clearly from Table 7 that the finest fraction has the higher copper content. Due to high liberation degree of particles at that fraction iron particles were easily driven off from copper particles and Cu content of non-magnetic product increased from 43.01% to 76.11%. Table 8 clearly shows that there is a big difference on copper and iron content between magnetic and non-magnetic fractions. A copper concentrate with 73.85% Cu content and 92.5% recovery was produced.

3.3 High-voltage electrostatic separation

A mixture of copper, silicon and woven glass reinforced resin was effectively separated by Mianqiang et al. (2012). Li et al. (2007b) conducted corona electrostatic separator to recycle PCBs particles between 0.6 and 1.2 mm and they found that corona electrostatic separator is very convenient for this size fraction, however, the productivity decreases with production of fine size fraction. The high voltage tube electrostatic separator used in experimental studies consists of a rotating roll which is connected to the ground, and a high-voltage electrode. The materials are subjected to the rotating roll with a vibrational feeder and conductive metals are separated successfully from non-conductive particles with the help of electrode.

Electrostatic separation is generally applied to PCB samples due to the large difference in electrical conductivity between the metal and the plastics. For that purpose, the misplaced particles (-1+0.3 mm and -0.3 mm middling's) from tabling was subjected to high voltage tube electrostatic separator. Regarding the fact that +1 mm middling from gravity separation contains low copper grade (0.91% Cu) this fraction wasn't concentrated in electrostatic separator and combined with shaking table tailing's. The results from electrostatic separation are given in Table 9.

As it is seen from Table 9, the use of high-intensity separators makes it possible to separate copper alloys from the waste matrix (plastic, ceramic, etc.). The electrostatic separation resulted in high copper recovery. Copper content and recovery reached approximately to 33% and 98% in conductive fractions, respectively. Because Al is conductor and present in higher contents in the feed (26.45%) the majority presence of aluminum was observed in conductive fraction. Mostly liberated and misplaced particles which mainly composed of plastic and ceramic were separated and collected in non-conductor fraction. SEM photos and EDS analysis of non-conducting fraction (section 1: 25% Al, 46% Si, 28% Ba, 1% Mg; section 2: 24% Al, 9% Si, 67% Ca) of individual particles mainly show non-metal fractions (Fig. 8).

Table 9. The results of electrostatic separation test

Products	Weight, %	Cu	
		Content, %	Distribution, %
Conductive	60.4	32.86	98.1
Non-conductive	39.6	0.98	1.9
Total	100.0	20.24	100.0

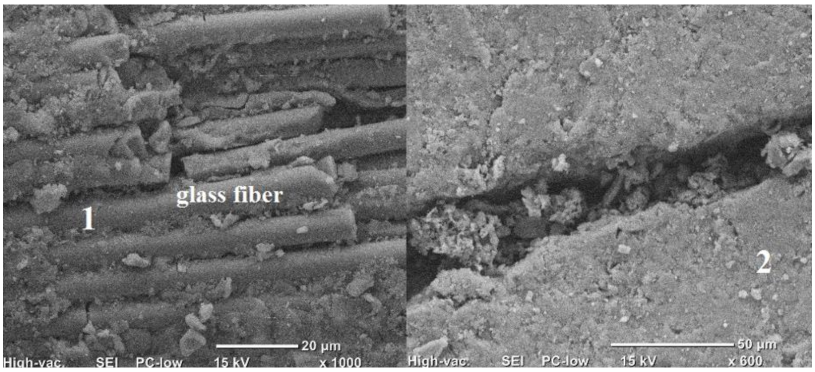

Fig. 8. SEM photos of non-conductor particles

3.4 Proposed flowsheet for Cu recovery

After characterization and beneficiation studies a flowsheet is designed for recovering copper from the ground PCB powder (Fig. 9). Three products (concentrate, middling and tailing) are generated from shaking table separator. The light fraction (tailing) from tabling contains very low grade, rejectable copper with the amount of 71.7% to the feed. It can be seen from Fig. that the loss of metallic copper in primary enrichment stage is only 4.6%. In addition to the high copper recovery, gold and silver are concentrated in heavy product with 78% and 65% recovery rates respectively.

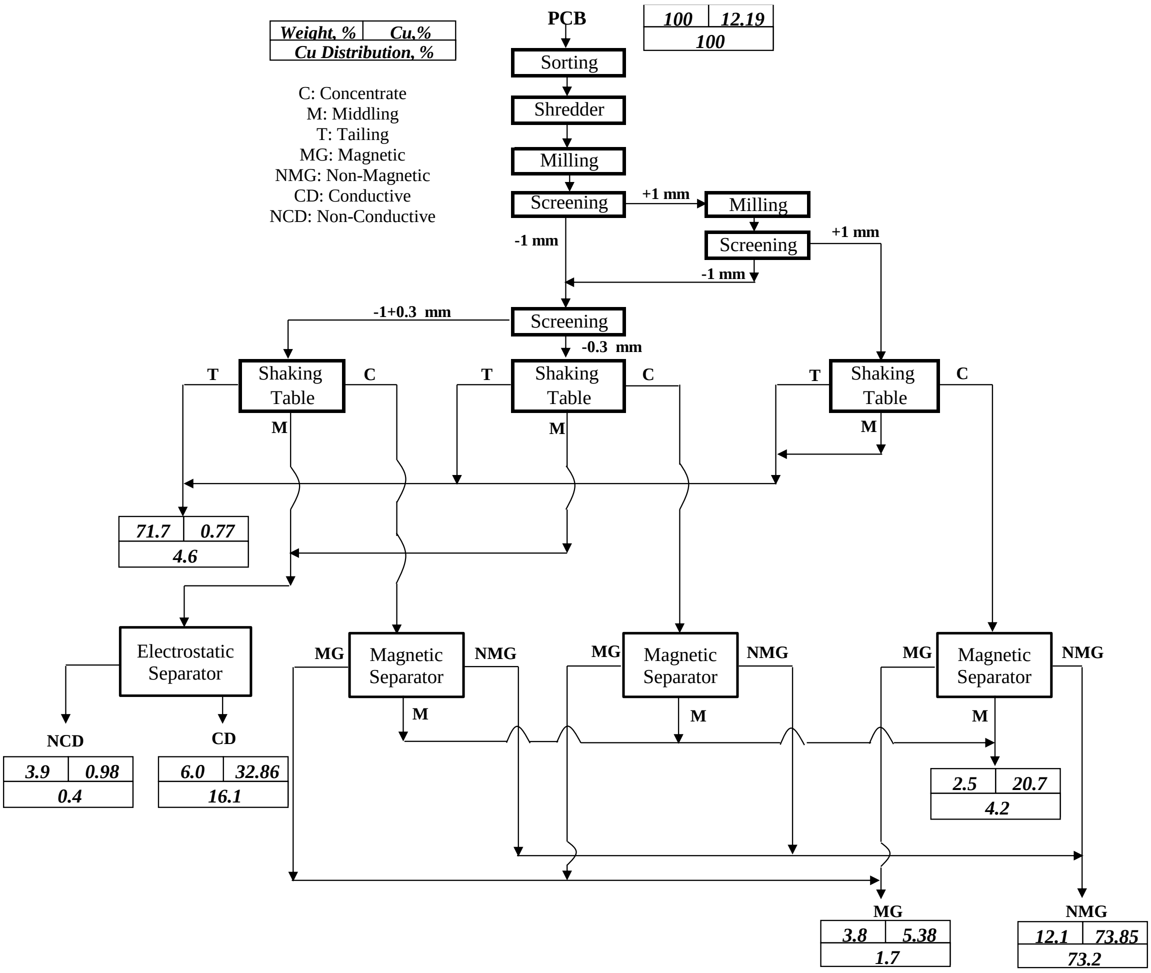

Fig. 9. Proposed flowsheet for recovery of copper from PCB

In order to obtain a metallic concentrate with very low iron content three heavy fractions from tabling stage were subjected to dry magnetic separator. Fe is easily removed and Cu content of non-magnetic product increased dramatically to 73.85%. As a by-product, iron in the magnetic fraction containing 91.3% Fe can be evaluated in steel industry. In electrostatic separation, a concentration with low enrichment but high yield is targeted. Two middling fractions from tabling were evaluated in electrostatic separation and especially, in terms of recovery, great results were obtained. A conductive product was produced with 33% Cu grade and 98% recovery. The liberated and misplaced plastic and ceramic particles were separated and collected in non-conductor fraction. When non-magnetic fraction is combined with conductor fraction a relatively pure metal concentrate with 60% Cu grade and 89% Cu recovery can be obtained.

4. Conclusions

Physical separation methods are found very effective to obtain fractions concentrated on metallic values from PCBs with significantly high content and recovery. A process with the combination of shaking table, magnetic and electrostatic separation is very simple and presents a feasible and environmental friendly technology. In the scope of this study, the first enrichment stage is done using wet method and naturally a drying process is needed. Because a big part of the feed is removed after gravity separation only less than 30% of the feed is beneficiated at subsequent process. In this way, the volume of material in drying process will decrease and extra energy requirement will be very low. According to these findings, the authors believe that physical beneficiation techniques as a prior to metallurgical process present an economic and environmental route for production of metals from PCBs.

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