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Proceeding Paper

Study of Metal Recovery from Printed Circuit Boards by Physical-Mechanical Treatment Processes †

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Abstract: The acceleration of the global production and consumption of electronic devices and the concerns related to waste electrical and electronic equipment (WEEE) motivated this research. Printed circuit boards (PCB) can be found in almost all types of electronic devices, and their composition contains heavy metals that can cause environmental impacts due to improper disposal. However, on the other hand, there are elements with added value, such as copper, gold, silver, iron, aluminum and other critical raw materials, such as tantalum, that can be recovered. Metal recovery can conserve natural resources since it prevents new minerals from being extracted, being a great contribution to the circular economy. In this research, the PCB element composition was initially determined through the scanning electron microscope analysis. Then, the PCB was shredded in a cutting mill and classified in grain size classes by sieving. Afterwards, magnetic separation has been performed together with gravity and electrostatic separation of the non-magnetic fraction. In gravity separation, the metal recovery was satisfactory for the particle size −0.6 + 0.3 mm and for the particle size −1.18 + 0.6 mm. In electrostatic separation, the efficiencies obtained were higher for the smaller particle size (−0.3 mm).

Keywords: printed circuit board (PCB); physical-mechanical separation; metal recovery

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1. Introduction

Mobiles, computers, and tablets have become indispensable in everyday life, and this has happened very quickly and intensely. Companies create more and more innovative products, with better performances than the previous ones, and many of them are not made to last. This turnover of electronic products transforms into waste the castoff materials producing a rapid increase in their disposal. The consequence of environmental impact connected to the toxicity of some elements can not only cause risk to human health but also problems on the quality of several ecosystems [1].

According to The Global E-waste Monitor (2020), the global production of electronic waste grew by 9.2 Mt since 2014, reaching 53.6 Mt in 2019, with an average of 7.3 kg per person. The worldwide e-waste is projected to rise to 74.7 Mt by 2030. Although this growing amount is a challenge for any waste management system, WEEE offers a secondary source of raw materials that are readily available for recycling. The proper disposal of electronic waste after its useful life combined with the recovery of materials generates a great contribution to the circular economy. It closes the loop, removing the waste from its disposal sites, taking into the processing again and reincorporating it into the production cycle. In this way, the primary resources of metals and energy can be saved for the next generation [2]. For example, there can be found a hundred times more gold in a ton of smartphones than in a ton of gold ore [3].

EEE has a complex and heterogenic composition. It can contain not only organic components but also significant concentrations of precious metals (gold, silver, copper), critical raw materials (cobalt, palladium, indium, germanium, tantalum) and noncritical (aluminum and iron). Printed circuit boards (PCBs) are inserted in electronic waste and are essential elements of most electronic equipment, found in computers, cell phones, TVs, etc. These boards are typically composed of resin and fiberglass with thin layers of copper to which electronic components connect. PCBs may vary with the type of equipment, but in general, they have the same components [4]. This heterogeneous composition of the PCB makes recycling processes difficult. However, in compensation, the presence of common and precious metals makes it an interesting source of secondary raw material [5].

Based on this, the objective of this research is to study alternatives for the recovery of metals from printed circuit boards, focusing on the physical-mechanical treatment recycling process, to obtain a concentrate product. The process performed consisted in characterizing the PCB, disassembling and comminuting the board, classifying the products into different particle size classes. Following this, the magnetic, gravity and electrostatic separation were performed to extract the metals (with respective evaluation).

2. Experimental

2.1. Materials

The PCB used in this research, containing all components, were kindly supplied by OSAI spa. It is a PCB of a server, has an area of about 1840 cm^2, a thickness of about 2.6 mm, and its total weight is 1.8 kg.

PCB typically consists of more than 20 different types of metals, divided into base metals such as copper, iron, nickel and tin; precious metals such as gold and silver and heavy metals such as lead and zinc and CRM, such as tantalum [6]. The board without the electronic components connected is also known as Printed Wiring Board (PWB) and is constituted by sheet layers of non-conductive substrate between sheet layers of copper (Figure 1). On the surfaces, conductive tracks are printed or deposited. While the board behaves as a dielectric, the tracks have the function of electrically connecting the various components of a circuit. The electronic components, depending on their function, can be made up of different materials [4,7].

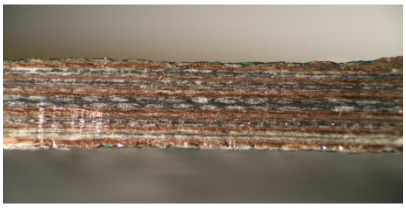


Figure 1. Macroscope cross section image of PWB.

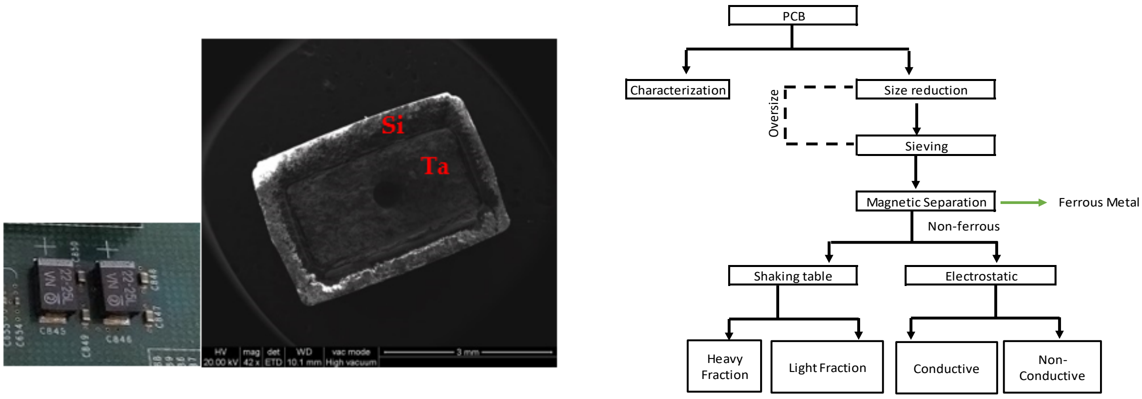
A review analysis of the values in mass percentage of some metals, obtained experimentally by several authors, was conducted. The metal content varies from 19% to 40% by weight and averages 34%. The main metals found in PCBs are copper, aluminum, tin, and iron, with a content of nearly 12–27%, 2–7%, 1–4%, 0.2–8%, respectively [5,8–21]. This variation can be explained by the different board types analyzed, the characterization methods and the change in the composition of PCBs over the years [4].

Until 2006, solders containing lead were permitted, but after the RoHS directive, the Pb was not allowed, thus the use of Pb in solder decreased. The new solders are mainly composed of Sn, Ag and Cu. Other precious metals such as gold and palladium are also found in PCBs. Iron and nickel are commonly found in electronic components of the board. For epoxy resin, some metal oxides (Al2O3, CaO, MgO) are applied as fillers [4]. Critical raw materials, such as tantalum, is widely used in capacitor due to its higher capacitance value per volume [7].

2.2. Methods

The methodology applied involves the identification of the PCB constituent composition, followed by their physical processing, which started with the dismantling of the board, after a comminution and granulometric classification; subsequently, the classified material was subjected to magnetic separation, electrostatic separation, and gravity separation. The PWB of this research is composed of two thicker outer layers and eight thinner inner layers in copper, interspersed with glass-reinforced plastic (GRP).

The PCB has about 27 aluminum capacitors, 98 tantalum capacitors, 25 large ceramic capacitors; 13 inductors and heatsinks; 8 transistors; 19 integrated circuits and 5 different types of PCB connectors. All the electronic components composition analysis was conducted by the SEM with EDS, a technique that allows the identification of elements present. A presence of a significant number of metallic elements has been detected: Sn, Pb, Au, Cu, Ni, Pd, Ag, Al, Fe, Ta, Ba, Mn. Figure 2a shows an example of a capacitor in which was identified tantalum and silicon.



(**a**) (**b**)

Figure 2. Tantalum capacitor in the PCB and also analysed with SEM (**a**); Process flowsheet applied in this study (**b**).

The process flowsheet of this work is represented in Figure 2b. In the dismantling phase, the removal of the largest volume components was performed. The elements removed (the liquid electrolytic capacitors and the central process unit) were not conducted forward to the subsequent steps. The remainder of the board was finally cut in pieces of about 2.5 × 4.0 cm, in order to provide adequate feed for the shredder RETSCH SM100 used for comminution. The granulometric classification was accomplished by sieving the milled products in the following sieve series: 1.18 mm; 0.6 mm, 0.3 mm.

Magnetic separation uses the magnetic susceptibility of some metals to separate them from others. This characteristic determines how the material behaves in the presence of a magnetic field, if attracted or repelled, classified it into three categories: (i) ferromagnetic, materials that have high magnetization; (ii) paramagnetic, those that weakly magnetize; and (iii) diamagnetic, are the materials that have negative magnetic susceptibility, which causes repulsion to the field [22]. The magnetic separation was performed manually by means of a CoAlNi magnet at a distance of 1 cm in all classes fraction. In the case of printed circuit boards, through this type of separation, it is possible to obtain a magnetic fraction rich in iron and nickel and a non-magnetic fraction, which contains the rest of the materials.

The separation by gravity or density is based on the gravitational forces of a particle moving through a fluid (water or air) [6]. In the present work, the application of the wet shaking table WEDAG 1933 is studied for the recovery of the metals fraction present in the PCB scraps. This methodology works well on a restricted particle size class and with a considerable difference in density among the particles. Shaking tables have low investment and low operating costs. In mineral processing, it is considered one of the most environmentally friendly methods, since it is not necessary for chemical or heating processes [23]. The products resulting from the separation are concentrated, mixed and tailing. After the passage, the products collected in the different fractions were placed to dry in an oven at 40 °C.

Electrostatic separation has been executed by means of a Corona electrostatic separator. The Dings Coronatron separator is applied to separate particles with a difference in conductivities [23]. Since PCB consists of conducting metal layers and non-conducting substrate, corona electrostatic separation is the most used due to its great efficient, environmentally friendly and economical process [6]. Two passages with a voltage of 20 kV and a rotation speed of 30 Hz were performed.

In order to ascertain the metal existing in the classified fractions and after the physical enrichment processes studied, samples were collected for qualitative (visual) analysis using optical macroscope WILD was carried out. The visual evaluation is performed by classifying the grains into different groups: copper, metallic excluding copper, fiber glasses, green plastics, and black plastics. In the end, the percentage of each product is calculated in the total.

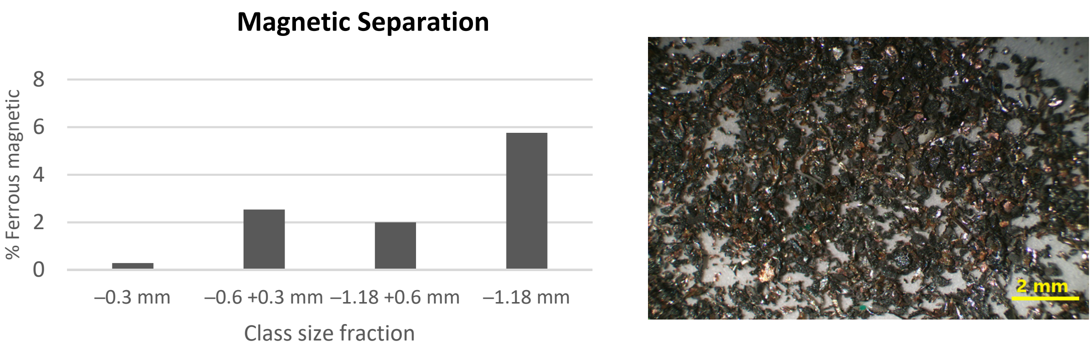
3. Results and Discussion

3.1. Granulometric Separation

After the cutting mill, a significant release of fine particles was observed. It can be observed that around 84% of the particles are smaller than 1.18 mm, and about 21% of the sample has a particle size less than 0.3 mm.

3.2. Magnetic Separation

The class with the smallest size −0.3 mm was the one that presented the lowest value of separated ferromagnetic elements, 0.3%; this may be associated with its low presence. The greater amount of ferromagnetic material is observed in Figure 3a for the +1.8 mm fraction, and this may be due to the element being used in larger components, such as supports, and remains in the larger fractions due to its mechanical properties, making it more difficult to grind than polymeric materials or ceramic, which have brittle properties.



(**a**) (**b**)

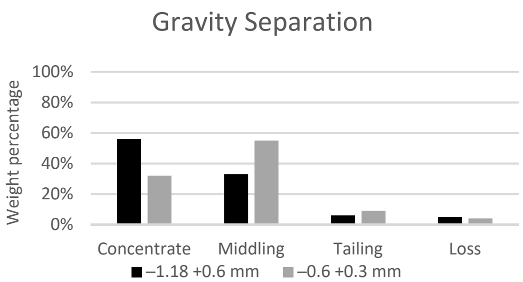
Figure 3. Quantity in % of ferromagnetic metals separated by the different class size (**a**); The magnetic separation results for the particle size class −0.3 mm (**b**).

It was observed that some metals, such as copper, are found in both the magnetic and non-magnetic fractions; since it is a metal with a high amount in the WEEE PCB, it ends up being dragged along with the iron and nickel particles (Figure 3b). Furthermore, it is also the result of the agglomeration of particles, attracting non-magnetic elements by the magnetic fraction [24]. All the ferrous metal products obtained from magnetic separation is considered recovered product. Although the amount of magnetic material present in printed circuit boards is small, it is interesting to separate it before performing electrostatic separation, since the magnetic force influences the particles, resulting in poor separation of copper.

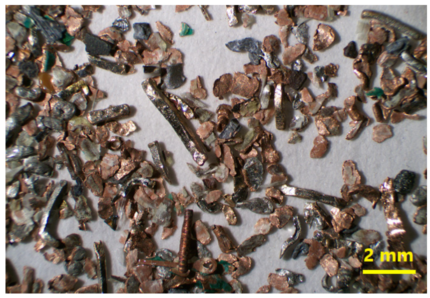
3.3. Gravity Separation

The two size fractions −1.18 + 0.6 and −0.6 + 0.3 mm of non-ferrous material were conducted successfully to the wet shaking table separation. The grain size class −0.3 mm, despite being within the operating size, was not subjected to this treatment due to the difficult collection of products after separation. Regarding the +1.18 mm class size, despite a possible efficient separation, it was not subjected because the volume of material was too low to perform the process.

The sample conducted to the gravity separation was equal to 170.7 g for the class size −0.6 + 0.3 mm and 652.75 g for the class size 1.18 + 0.6 mm. The products obtained were weighed, and the data are shown in Figure 4a. In both cases, the separations were satisfactory, obtaining a concentrate product rich in metallic elements Figure 4b and a poor tailing product, as it was desirable.



(**a**)

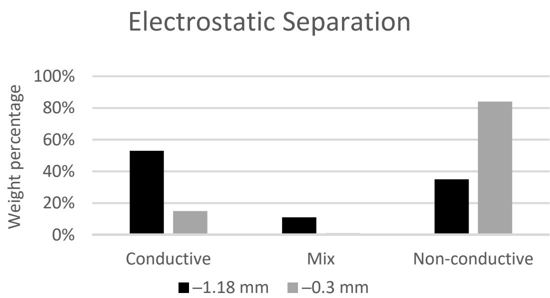


(**b**)

Figure 4. Weight of the products from shaking table as percentage (**a**); The concentrate product for the particle size class −0.6 + 0.3 mm (**b**).

3.4. Electrostatic Separation

According to the Figure 5a, it is possible to observe a reduction in the metallic material for the granulometric class −0.3 mm; this is due to the fact that it consists mainly of fibrous material resulting from the fragility of the laminate and its subjection to shear forces at the moment of comminution.



(**a**)

(**b**)

Figure 5. Weight of the products obtained from electrostatic separation as percentage (**a**); The conductive product for the particle size class −0.3 mm (**b**).

The conductive product obtained for the class size −0.3 mm (Figure 5b), is composed of mostly metallic elements in copper color and some in silver color. The mixed product, despite having a predominance of metallic elements with a copper color, also has polymeric elements. The non-conductive product has an appearance with a predominance of polymeric fragments in greenish color. The conductive product from the class size +1.18 mm is mainly composed of fibers, and resins are attached to the metal elements. The metallic elements found are flakes and filaments, the first being more abundant. It was also observed that they have copper, gold, and silver colors. The mixed product is mainly composed of metallic and non-metallic elements. Moreover, the non-conductive product has an appearance with a predominance of polymeric fragments in black color and fiberglass.

3.5. Metal Recovery Balance

For the evaluation of the metal recovery of the separation process, it was decided to assess the efficiency as a function of the percentage of the copper; since this is a precious metal and highly present in the PCB, making it the main target of separation. The copper particles and the other materials were evaluated by the image fields captured, and the particles belonging to the same particles group were counted. The percentage distribution, in numerical terms, for the different fractions and obtained products was established. The grains were divided into different particles group, copper (Cu), metals excluding copper (Me) and non-metals (NM) materials, for each experiment performed. All the ferrous product obtained from the magnetic separation is considered recovered. In the gravity separation, the recovery of metals is measured by the concentrate product. In contrast, the metallic fraction recovery considered for the electrostatic separation is the products conductive and mixed.

It was observed that a good metal recovery is obtained using the magnetic separation for iron and its alloys; only in the finer fractions a small percentage of non-ferrous materials are dragged and remain attached to the iron grains. The metal recovery in the gravity separation showed good results and with similar percentages in the two granulometric classes, 64% for fraction +0.6–0.3 mm and 67% for a fraction of +1.18–0.6 mm, which shows an efficient technique for this range particle size. A metal loss of 11% and 15% occurs for these fractions, respectively. Electrostatic separation is considered ideal for the finer particle size class, not only because of the difficulty to apply the shaking table, but also due to the fact that the metallic percentage (heavy product) is low. In the granulometric class +1.18 mm, even though the electrostatic separation shows relatively good to the presence of copper, there is a high presence of plastics and glass fiber embedded to copper grains, making a product poor in concentration. It is also possible to conclude that 88% of copper and 78% of other metals could be recovered.

4. Conclusions

It is advantageous to perform pre-processing on the boards as an initial step, removing some components, thereby reducing undesirable materials and minimizing wear on the comminution equipment. The physical-mechanical processing implies conventional processes: dismantling, fragmentation, and separation of the material in different granulometric classes. The comminution step enabled the liberation of the metals embedded in the board. The different mechanical behavior, presented in the distinct elements, provided to the particles resulting from fragmentation, characteristics necessary for their subsequent separation. However, although the characterization of the products was carried out by a qualitative technique, the products in terms of the presence of metallic elements corresponded to efficient results. The application of magnetic separation proved to be efficient, as it enabled the accumulation of iron in the magnetic fractions (85–99%), and it is possible to conclude that the largest amounts of iron are found in the large particle size fraction of the PCB. In the separation by gravity, finest and coarsest classes fractions were excluded due to operational reasons and volumetric availability, respectively. The results show a good metal recovery, about 64% for the class size + 0.6–0.3 mm and 67% for the class size+ 1.18–0.6 mm. The portion of conductive material (Cu) was 55% for the coarsest particle size fraction and 81% for the finest. This indicates the efficiency of the electrostatic separation, mainly concentrating this element, as well as the reduction size providing the liberation of this metal. With this procedure, a metal concentrate has been obtained, which will make it easier to extract the individual elements by metallurgical methods.

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