

Evaluation of Mass Loss in Different Stages of Printed Circuit Boards Recycling Employed in Temperature Controllers

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The aim of this work was to evaluate mass loss in each stage of the recycling process for metal recovery from PCBs of controllers and temperature indicators of cold chambers. The stages of process consists of grinding, particle size classification, magnetic and electrostatic separation. It was analyzed 13 kg of PCBs. These PCBs were crushed and ground. The ground material were subjected to magnetic and electrostatic separator. The losses in the comminution stages were 12.69 % and are lower than those found in other related works that used mixtures of different types of PCBs, whereas in this work only one model plates were analyzed. 27.2 % absolute mass loss we reached out after particle size separation with Tyler Series with 1 mm sieve presents the higher mass losses in the whole process and this fraction was not processed as it results in PCBs powder dust that interferes negatively in the electrostatic separation. Comparing the losses in the stages of shredding of PCBs employed in temperature controllers with other studies involving PCBs from the automotive industry and from computers and cell phones, is remarkable that this type of board presents significantly greater potential to be processed for recovery of its materials.

Keywords: Mass losses, PCBs recycling, comminution, magnetic separator, electrostatic separator, temperature controllers.

1. Introduction

Waste electrical and electronic equipment (WEEE or e-waste) are in an increasing flow of production and disposal worldwide. With the rapid and exponential technological advance coupled with the consumer desire to always have the most advanced product as well as the planned obsolescence; the electronic products have their life shorter and shorter^{1,2}.

In 2016, 44.7 Mt of WEEE was generated worldwide and the projection for 2021 is 52.2 millions of tons, considering an annual increase rate of 3-4 %. The current proportion of this waste generated per inhabitant is 6.1 kg.y⁻¹ with a forecast of reaching 6.8 kg.y⁻¹ until 2021, and that only 20 % of the total being recycled³. The low rate of WEEE recycling is explained by the high cost of the processes. An efficient plant for the extraction and reuse of the valuable materials found in these waste requires high-tech machines, which is a reality only in developed countries. Developing countries, such as Brazil, end up doing partial processing of the waste and exporting these flows^{4,5}.

In PCBs, which are indispensable for the production as well as the operation of electronic devices, the concentration of valuable metals is usually much higher than that obtained through traditional mining. It is important to highlight the importance of research and development in the metal recovery from PCB field, since it tends to be simpler, economical in terms of energy, less pollution and results in purer material than the primary sources. In addition, two problems are solved: obtaining valuable metals from secondary sources and reducing the accumulation of waste⁶⁻⁸.

The most advanced e-waste recycling plants use a combination of physical-mechanical and chemical processes for better recovery of valuable metals. A large and unavoidable amount of dust is produced during PCBs comminution procedures. To avoid a large mass loss dust collection systems are used. This prevents dust from being dispersed into the atmosphere or from encrusting into the equipment⁴. Studies show that the powder generated has distinct concentrations of materials according to particle size, and the highest concentrations of valuable metals are found in the smaller particles⁴.

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In this work, PCBs were analyzed, which represent one of the main components of consumer devices, whose lifetime is constantly decreasing, as well as being a source of both hazardous materials for health and the environment, as well as valuable metals and profitable exploitation^{5,6}. Considering that studies involving smartphones and computers (e.g. desktops and laptops) have been extensively published⁹⁻¹², it is possible to highlight the relevance of searching for other PCB waste that do not receive so much visibility. The PCBs can also have a significant volume of disposal as well as potential for recycling. The analysis of mass losses is justified by the need to perform the most efficient monitoring of the waste recovery process. In this way, one can assess which processing is most advantageous in recovering valuable metals. The aim of this study is to evaluate the mass losses at each stage of processing for the recovery of valuable metals from PCBs used in controllers and temperature indicators of cold chambers. The mechanical comminution, particle size separation, magnetic and electrostatic separation processes were done in 13 kg of PCBs. The mass data were collected before and after each step, so that the mass loss could be defined and analyzed at each stage of processing.

2. Materials and Methods

A 13 kg sample of PCBs was used to analyze losses in mass at different stages of the PCBs recycling process. The PCBs were removed from controllers and temperature indicators of cold chambers, donate by Reverse – Waste Management, located in Novo Hamburgo City, Brazil.

The steps of the process are: components removal, comminution, milling ~2 mm, magnetic separation, particle size separation and electrostatic separation. Figure 1 shows a flowchart illustrating all stages of the process.

The electronic components removed were continuous buzzers, with sounding functionality, and electronic connector terminals, used to integrate the inputs and outputs of these PCBs.

The mechanical milling process was done three times in order to fragment the PCBs and facilitate the separation of the materials present in them. It was used a mill (SEIBT, model TS 2X20/600) with work surface of 650 mm x 440 mm and two three-phase motors of 20 HP, 60 Hz, 4 poles. After this stage, the granulometric reduction process was continued in a knife mill (SEIBT, model MGHS 1.5/85) with a 2 HP motor, speed of 1125 RPM and using an 8 mm sieve. Then all the material was processed again with 4 mm and 2 mm sieves. This was done to gradually decrease the particle size.

The magnetic separation was carried out in a barrel magnetic separator with Ne-Fe-B magnet with a magnetic field of 4000 Gauss (brand METALMAG, model P with 300 mm of barrel diameter and 254 mm of width of the barrel magnetic face) with the angle of magnetic circuit adjustment at 0°.

The particle size separation process was performed with the objective of improving the efficiency of the electrostatic separation. A Tyler Series with 1 mm sieve was used to remove particles smaller than 1 mm. These particles smaller than 1 mm easily disperse, reducing the efficiency of the electrostatic separation process. The particle size between 1 - 2 mm was sent to electrostatic separation.

A corona electrostatic separator – CES – (INBRAS-ERIEZ, model ESP-14/01S) was used with the following operating conditions: α – Ionizing electrode angle 30°; d1 – Distance of ionizing electrode and roll surface 40 mm; θ – Static electrode angle 65°; d2 – Distance of static electrode and the electrode 50 mm; n – Roll speed 50 rpm; W – Feed rate 30 g.min⁻¹; U – High voltage supply 30 kV. The schematic drawing of the electrostatic separator is shown in Figure 2. The CES parameters were based on the study of Hamerski et al. (2019)¹³, where different parameters were evaluated, obtaining these values as being the most efficient condition in the concentration of metals coming from PCBs.

The equipment consists of two electrodes: corona and electrostatic; and a grounded roller. An electromagnetic chute was employed with constant feed rate, generating a thin layer of material that was introduced into the electrostatic field through the spinning roller. One spot was used to collect conductive particles and other two-spots to collect middling and nonconductive by-products.

After the electrostatic separation, a metallic characterization for the conductive and middling fractions was conducted through acid digestion followed by ICP-OES analysis. The samples were digested in 20 ml of aqua regia per gram of solids (1:20) for 2 hours in 60°C, with agitation speed of 400 rpm.

A previous sequence of X-Ray Fluorescence analysis (XRF Thermo Scientific, model Niton XL3t) qualitatively determined the main metallic species presents in the conductive and middling fractions. These main species, plus precious metals (silver and gold), were selected to be quantitatively measured by ICP-OES (Agilent, model 5110).

3. Results and Discussion

In this study, the stages of components removal and particle size separation were considered as losses in mass. However, this does not mean that these materials have been lost. Removal of the components was done to avoid damaging the comminution and to have no valuable metals to recover. This procedure was adopted in related works^{11,14,15,16}.

At the stage of removal of PCB components there was a losses in mass of 7.7 %, the initial mass of 13006 g had a loss of 1004 g. After processing the material three times in the mechanical milling, the reduction was 378 g, which is equivalent to 2.9 % absolute loss of the initial mass of PCB, and a relative loss of 3.2 %. Figure 3 shows all relative losses among the processes.

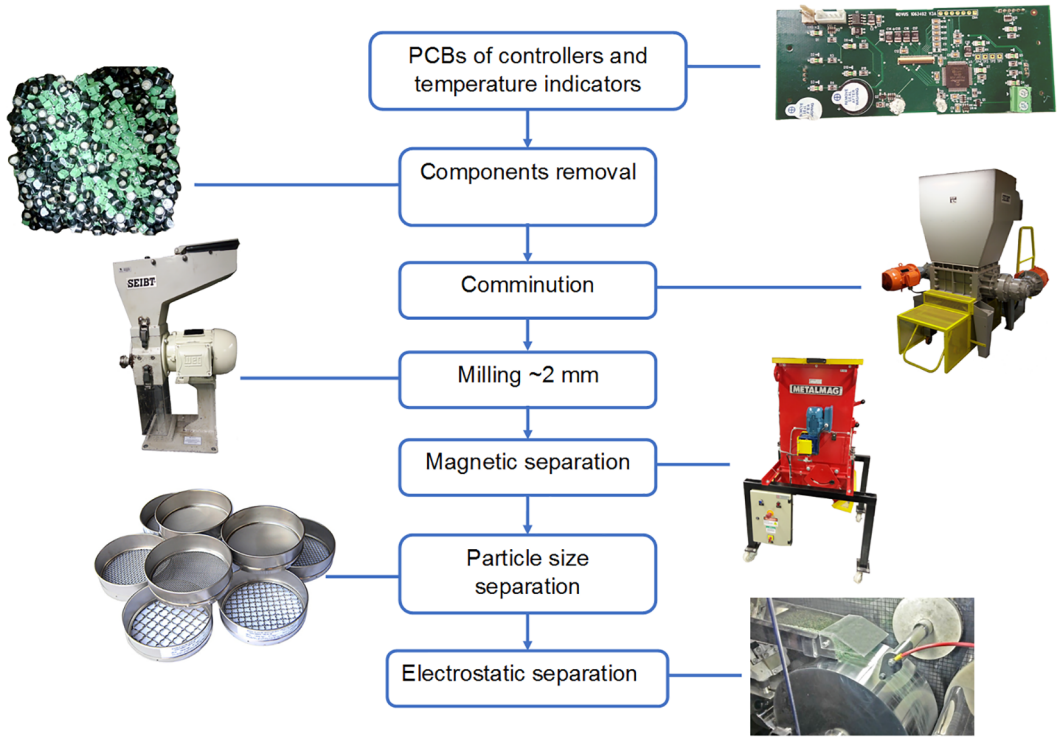


Figure 1. Flowchart of processing steps.
 Author: Eduardo Luis Schneider

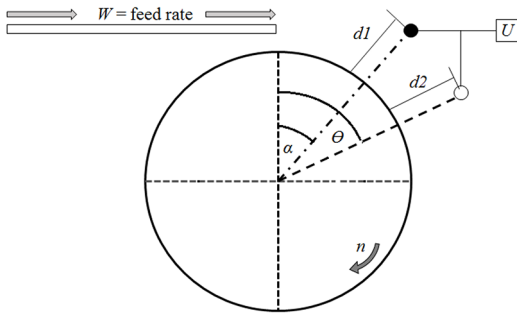


Figure 2. Arrangement of the parameters used in the electrostatic separator. α : ionizing electrode angle; $d1$: distance of ionizing electrode and roll surface; θ : static electrode angle; $d2$: distance of static electrode and the electrode; n : roll speed; W : feed rate; U : high voltage supply.
 Hamerski, et al., 2019.

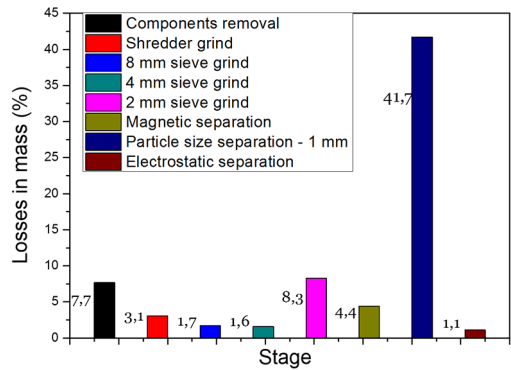


Figure 3. Mass losses of each step.
 Author: Fernando Hamerski.

The grinding step in the knife mill resulted in 204 g of losses for 8 mm sieve and 183 g of losses for 4 mm sieve (1.7 and 1.6 % relative losses, respectively). After further grinding in the knife mill, this time with a 2 mm sieve, there was a reduction of 8.3 % relative loss, corresponding to a loss of 889 g.

The magnetic separation process resulted in the division of the sample into a magnetic and a non-magnetic fraction. The magnetic fraction represented by 385 g of particles

and 1535 g of powder, totaling 17.1 % of PCB amount. The non-magnetic fraction was separated into a portion of powder (341 g) and a portion of particles (8481 g), totaling 8822 g i.e., 78.5 % of initial amount.

Although the efficiency of the processes employed here is not being considered. It is important to compare the amount of obtained material for each fraction (Table 1).

Note that approximately 80 % of the material is fine powder in the magnetic fraction. This large amount of powder after magnetic separation process was also observed in

Table 1. Magnetic fractions

Fraction	Magnetic separation	
	g	%
Magnetic particle	385	3.4
Magnetic powder	1535	13.7
Magnetic fraction	1920	17.1
Non-magnetic particle	8481	75.5
Non-magnetic powder	341	3
Non-magnetic fraction	8822	78.5

another study, with 1600 Gauss of magnetic field, reaching 70.6 %. Hamerski et al. (2018)¹⁷ observed that the amount of magnetic materials is much lower than the other materials (e.g. polymers and ceramics). The loading of fine powder into the magnetic collector can be explained by the susceptibility of the smaller particles to a high magnetic field, in this study, 4000 Gauss.

We reached out 27.2 % for absolute mass loss after particle size separation with Tyler Series with 1 mm sieve presents the higher mass losses in the whole process. This fraction with a particle size smaller than 1 mm was not processed as it results in PCBs powder dust. The PCBs

**Figure 4.** PCB dust accumulation in electrodes.

Author: Fernando Hamerski.

dust interferes negatively in the electrostatic separation, as shown in Figure 4.

The last stage of the study, the electrostatic separation presents least amount of losses with 0.4 % (absolute). The non-magnetic fraction (1-2 mm) submitted to the electrostatic separator, resulting in three fractions: conductive, intermediate and non-conductive. Figure 5 shows magnetic and non-magnetic fractions as well as conductive and non-conductive fractions.

The data of the quantities of each fraction obtained after the electrostatic separator are in Table 2.

Of the amount that was submitted to the electrostatic separator, 14.8 % constitute the conductive fraction. The middling fraction were 7.7 %, corresponding to 380.4 g. The middling fraction is a mixture of conductive and non-conductive material. Conductive material were not varied by the electric field. At the same time, non-conductive material discharges so rapidly and thus disengage from the grounded roller, falling off into the middling material collector.

Conductive fraction represents the most valuable fraction of all processes. The fraction generally contains greater economic value, once high concentration of copper and other metals are expected. Even the aim is of this work is to evaluate the mass losses, it is opportune to evaluate the metals composition of the conductive and middling fractions, given that studies for PCBs of cold chambers are rare.

The elements Cu, Sn, Pb, Zn and Al are the main species found by the XRF analysis in the conductive and middling fractions, and were measured together with Au and Ag in the ICP-OES. The Table 3 demonstrate the metals characterization for the PCBs of cold chambers, comparing with PCBs of other electronic scraps.

The conductive fraction concentrates substantial amounts of Cu and Sn, respectively 35.54 % and 18.39 % of the total. Indeed, the quantity of Cu may be enhanced considering the middling fraction, which presented 26.20 % of copper concentration. Ag and Au, as precious metals, are present in the PCBs of cold chambers, with similar concentration values to other PCBs (e.g. computers and mobile phones)¹⁸.

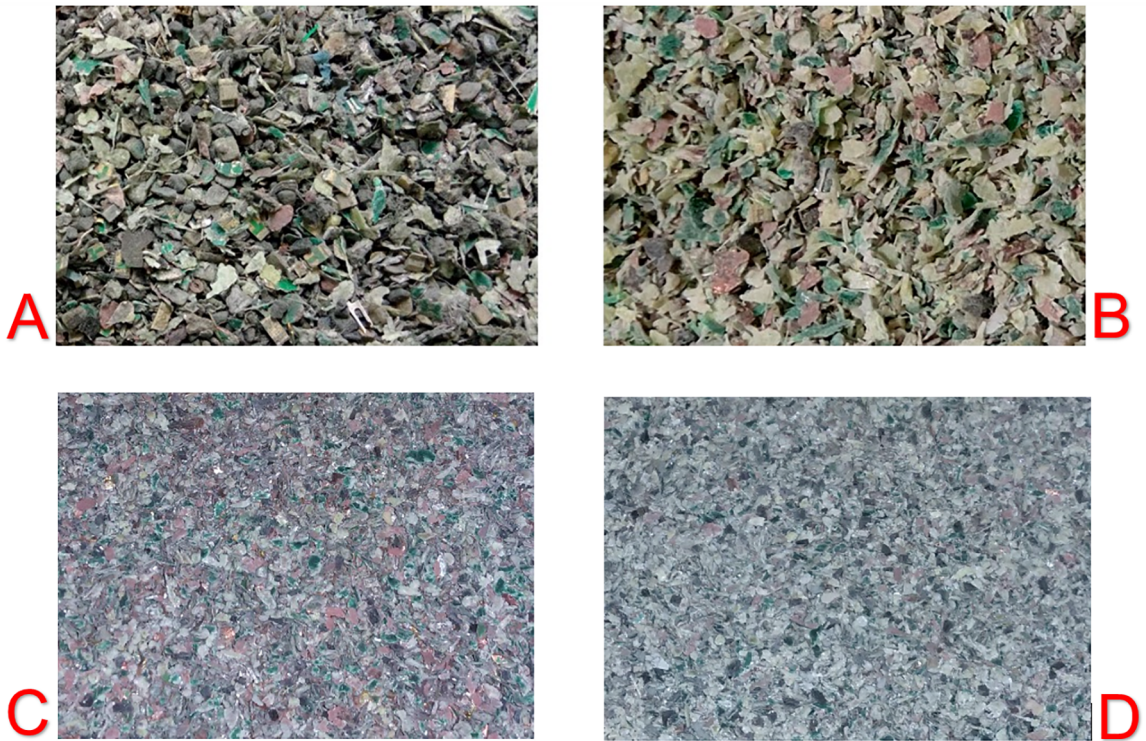


Figure 5. PCB fractions after magnetic and electrostatic separator. A: magnetic; B: non-magnetic; C: conductive; D: non-conductive. Author: Eduardo Luis Schneider.

Table 2. Electrostatic separation fractions.

Fraction	Electrostatic separation	
	g	%
Conductive	734.1	14.8
Middling	380.4	7.7
Non-conductive	3778	76.4

Table 3. Metal characterization for the conductive and middling fractions of different PCBs

%	Yamane et al. (2011) ⁹		Yamane et al. (2011) ⁹		Guo et al. (2011) ¹⁷		Veit et al. (2006) ¹⁸	
	Cold Chambers		Computers		Mobile Phones		Computers	Mixed
	Conductive	Middling	Conductive	Middling	Conductive	Middling	Conductive	Conductive
Cu	35.54	26.20	11.17	0.58	24.32	4.09	56.29	53.04
Sn	18.39	1.84	5.39	0.16	2.72	0.12	7.62	20.22
Pb	2.11	0.32	3.29	0.09	1.39	0.08	8.24	6.42
Zn	1.44	0.00	2.64	0.14	5.75	0.02	7.16	-
Al	0.91	0.94	2.41	0.15	0.20	0.01	1.04	0.59
Ag	0.13	0.07	0.05	0.00	0.16	0.01	-	-
Au	0.07	0.05	0.05	0.00	0.00	0.00	-	-

While the conductive and middling fractions correspond to 14.8 % and 7.7 %, the non-conductive fraction reached 76.4 % of total amount of non-magnetic fraction. It makes sense that the largest amount of material submitted to the electrostatic separator is non-conductive, since the materials present in greater quantities in PCBs are precisely, non-conductive materials, i.e., polymers and ceramics^{18,19}.

The analysis of mass losses is not much discussed in the current literature; therefore, data for comparison of results are scarce, being limited to a few studies that cite losses data in the comminution process^{9,20}. A study²⁰ involving automotive PCBs industry reported a 20 % loss in mechanical processing. Another study evaluating computer and mobile phones PCBs⁹ describes a 27 % of losses.

The analysis of losses in mass in the current study results in 12.7 %. This difference is directly related to the equipment used during the processing of the PCBs. There are different types of mills, with isolated or no collection compartments, continuous sampling or not.

Notes that the results presented only consider the stages of shredding (2.9 % absolute), crushing with 8 mm sieve (1.6 % absolute), crushing with 4 mm sieve (1.4 % absolute) and grinding with 2 mm sieve (6.8 % absolute). The three studies made the removal of components, so that, similarly, they also did not account for this step in the mass losses.

Thus, energy consumption in all steps should be considered in parallel for a real analysis of efficiency to be made.

4. Conclusions

This paper evaluated the mass losses at each stage of processing for valuable metal recovery from PCB used in controllers and temperature indicators of cold chambers. We analyzed 13 kg of PCBs in the comminution and particle size separation, magnetic and electrostatic separation processes. The results show that it is possible to conclude that the step that proportionally registered the largest mass losses was the particle size process with 1 mm sieve (Tyler Series). However, this fraction with lower particle size can be reused, i.e., to develop light aggregates, in partial replacement by volume, to the sand, in cement-based matrices.

Comparing the losses in the stages of shredding of PCBs, in the present study (12.69 %) with other studies involving PCBs from the automotive industry (20 %) and from computers (29 %) and cell phones (25 %), it is concluded that this type of board presents significantly greater potential to be processed for recovery of its materials.

Additionally, the metals characterization of the conductive and middling fraction of the electrostatic separator demonstrated that PCBs of cold chambers have a great potential for copper and tin recovery, as these elements reached high concentrations. The precious metals silver and gold presented similar values of concentration to other PCBs (from computers and mobile phones), also signifying a potential for recovery and further studies.

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