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Disassembly of waste printed circuit board using centrifugal force and air heating

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Abstract: *Waste electrical and electronic equipment (WEEE) is a source of valuable materials through recycling, but has high risks to environment and human health if improperly managed. The most complex part of electronic scrap is the printed circuit board (PCB). Recovery material from PCB scrap may contribute directly to reduce the environmental impacts caused by the extraction of the reserves of natural resources. Several technologies and methods which combines comminution with metallurgical process has been developed for recycling of PCB. This techniques can be improved by previous PCB disassembly. In this work, disassembly of PCB using centrifugal force and air heating were studied.*
PCB were previously removed from power supply or personal computers. Toxic components and plastic parts from PCB were manually removed. After this, PCB's were positioned inside the equipment with solder side in front of the hot air output.
The results demonstrate the feasibility of using this method to separate tin solder, electronics components (EC) and substrate. PCB's from power supply of personal computers (PC) were disassembled by the prototype in a temperature about 203^{o}C and velocity of 900rpm resulting in a recovery of 2.8%wt of solder and 32%wt of EC. Recovered solder was analyzed by an scanning electron microscope with combined energy dispersive X-ray analyzer and its contamination was under 3%.
Recovered solder was analysed quantitatively and compared with grout solder remaining from industrial soldering process which is used as input in the production of new solders. has a characteristic composition similar to the grout solder from industrial soldering process. Contaminants Cu, Si and Fe has minor presence in recovered solder from PCB than in the grout, and Al has no significant difference. This results enable its direct use as input in the production of new solder.
Keywords: *Waste Electric and Electronic Equipment, disassembly, recycling*

1. INTRODUCTION

The IDC (2014) has pointed out a small decay in the global market of computers in 2013 of the order of 10.1%. Although decay, more than 314 millions of computers have been put on the market. Gartner (2014) research indicates 1.8 billion of cellular unities sold all around the world in the same year. The velocity this new electrical and electronic equipment arrives to persons is the same the old ones became residues.

Substitution of technology or even broken electronic makes the linear 'extraction-production-usage-disposal' chain more resource intensive, increases emission to air, weather and soil. Waste of electrical and electronic equipment (WEEE) contains substances that are high-valued and/or highly toxic and for this reason it is a great source of valuable materials at the same time it is a way for hazardous substances to impact environment and human health (Puckett and Smith, 2002; UNEP, 2009).

Besides Printed Circuit Board (PCB) account for only about 6% of the total weight of WEEE, it is responsible for many toxic substances like lead, beryllium, cadmium and arsenic present mainly in old PCB's. Removing pollutants and hazardous components makes discarded PCB a high value waste. Actually, the most promising is the recovery of copper (Bleiwas and Kelly, 2001; Das *et al.*, 2009; Hanafi *et al.*, 2012).

Brazil's Solid Waste National Policy came into force in 2010 and establishes reverse logistic systems for WEEE among others solid residues. After that, same correct destination, as recycling, should be implemented. (Brasil, 2010)

Many technologies and methods that combine shredding or crushing with pyrometallurgical or hydrometallurgical processes have been developed to recycle PCB's. All this techniques can be improved by previous disassembly of PCB.

(Cui and Forssberg, 2003; Xu *et al.*, 2009; Veit *et al.*, 2005)

The goal of this study consisted precisely in apply a method to PCB disassembly, segregating it in solder, electronics components (EC) and substrate by air heating and centrifugal force.

2. BACKGROUND

2.1 Recycling of waste electrical and electronic equipment

There exists many processes and methods, divided in various steps, to recycle WEEE. One step is the disassembly of the WEEE in its constituents, among which is the PCB. Recycling of PCB's can be divided in three steps: disassembly, separation and refine. Due to the challenges found in perform disassembly, this step is kept away in plants that recycle PCB, as stated by Hagelüken (2006b).

Separation involves a comminution process, in which PCB scrap is shredded and/or crushed in a hammer mill for homogenization and particle size reduction (Li *et al.*, 2004, Long *et al.*, 2010; Veit *et al.*, 2005; Hino *et al.*, 2009); crushing can also be performed in a wet crushing equipment, such as hammer mill with water medium, which can help control the fugitive odors and dust emissions, while avoiding excessive temperature in parts of the mill during the process (Duan *et al.*, 2009).

To improve the desirable material content a separation process of metals from non-metals is performed after comminution. Some methods as incineration and acid bathing may release hazardous substances in environment. Physical separation techniques, although being energy intensive, are able to produce streams of metals and non-metals while being comparatively safe and eco-friendly to operate. This techniques includes: screening, shape separation, magnetic separation, electric conductivity-based separation and density-based separation. (Furuuchi and Gotoh, 1992; Koyanaka *et al.*, 1997; Cui and Forssberg, 2003; Veit *et al.*, 2005; Long *et al.*, 2010; Park and Fray, 2009)

Refine step in PCB recycling processes has the goal to separate the target metals from others metals (Yu *et al.*, 2009; Youssef *et al.*, 2012). Two processes are adequate for obtaining high purity metals as output according to Youssef *et al.* (2012): pyrometallurgical and hydrometallurgical processes.

- Pyrometallurgical processing: is the traditional PCB recycling method, with wide industrial utilization in leading global smelter companies. However, investments for smelters require large upfront investments, and facilities are unavoidably large scale (Yu *et al.*, 2009). Furthermore, pyrometallurgy requires major amounts of energy and can form uncontrolled harmful products (Youssef *et al.*, 2012), while achieving only a partial separation of metals. For example, smelters recover precious metals, copper and other metals, but not aluminium or iron, so combination with hydrometallurgical techniques and/or electrochemical processing is therefore necessary (Yu *et al.*, 2009).

- Hydrometallurgical processing: comprises a series of acidic or caustic leaches of solid materials with a range of reagents, and the recovery of metals from these leachates, as described by Yu *et al.* (2009). According to those authors, such processes are easier to operate, when compared to pyrometallurgical processes, and usually require a smaller scale and therefore less investment. However, they may pose a considerable environmental impact due to the toxicity of the reagents used and the large amount of by-products generated, which requires additional investment on waste and water treatment (YYu *et al.*, 2009). On the other hand, such processes can provide controlled environment, good recovery, high selectivity, high purity output, which allows the recovered metal to be sold without any further processing (Li *et al.*, 2004; Youssef *et al.*, 2012). For these reasons, Youssef *et al.* (2012) propose them as the most beneficial processes for separating the target materials.

The reviewed literature presents some other methods for PCB recycling as pyrolysis, biometallurgics, ultrasound on a previously acidified PCB waste sludge and supercritical methanol. But theses processes are performed on laboratory scale (Hall and Williams, 2007; Xie *et al.*, 2009; Xiu and Zhang, 2010, Guo *et al.*, 2010). A recovery process which is realized on industrial scale is the one reported by Hagelüken, and comprises manual separation according to PCB components, comminution by shredding and separation of metals on an integrated metals refinery and smelter.

2.2 Disassembly of printed circuit board

Several works discuss improvement of selective disassembly. Brandstotter *et al.* (2004) shows criteria for automatic disassembly optimization divided in four groups: junction technologies, components, assembly and layout. Feldmann and Scheller (1994) list factors that influence the components adhesion to the substrate: numbers of pins, number of bent pins, bending angles, materials that the pins are made of, relation between hole and pin diameter and friction between the surfaces of the holes and the pins.

Iji and Yokoyama (1997) implemented an automated part removal apparatus that contain two heating units, first one providing removal force in vertical direction and the second one in horizontal direction. A third unit does an abrading process for removal of the remaining solder. There is no information about energy consumption, cost and processing capacity.

Lee *et al.* (2011) developed a prototype which uses four diamond grinders that wear down the solder joints on the backside of PCB's releasing components. Output of the apparatus is EC, substrate and abrasion powder. Copper and solder are mixed with substrate in the abrasion powder, requiring subsequent steps for metal recovery.

Disassembly requires two main aspects: heating and displacement of components, which must be integrated to achieve the goal (Layiding *et al.*, 2005; Feldmann and Scheller, 1994).

For these authors, approaches to heat PCB during disassembly such as laser and infra-red needs to be certified whether these techniques are cost and time efficient and convenient enough for practical application. Laser heating has the disadvantages that is not usable for simultaneous dismantling and is very high energy consumption. Theses authors argument that air heating has the benefits of low cost, cleanness and heating mildness . Tests on disassembly force done by Feldmann and Scheller (1994) demonstrate that for a CI with 8 pins bent for 90^o a force of 16N is enough to remove the component if solder is melted.

Recovery of tin solder from WEEE is more attractive when compared to the natural extraction. The amount of tin in the ore is about 0.01% in weight. Concentration after mill processing and separation reaches 70-77% of tin. Refinery reduces tin oxide to impure metal and so to a high pure metal (99.75% to 99.85%). (Lyman and Gerlach, 1954)

Nevertheless, studies which assess potential impacts of the recycling process are not commons. Rubin *et al.* (2014) conduct a study using life cycle assessment methodology to compare two strategies for recovery of copper from printed circuit board scrap. Bigum *et al.* (2012) concluded that recycling for metal recovery has significant environmental savings as well as in resource consumption.

Accordingly to Lee *et al.* (2011) recovery of all constituents in EC should be explored and not stay limited to major and precious elements.

3. METHODOLOGY

This study was conducted with PCB's removed from obsolete PC's, more specifically from the power supply. PCB's was separated manually from these waste computers and prepared as the starting samples. This PCB's of phenolic cotton paper was one layer (one copper sheet) with THT components. Heterogeneous in structure, PCB's contained a variety of components such as condensers, IC chips, transistors, fuses, resistors, diodes and transformers. Cables, capacitors, heat sinks and some plastics components were manually removed too.

An apparatus for PCB disassembly was designed and manufactured, as shown in fig. 1. This apparatus consist of a centrifuge (triggered by 3 phase motor) heated by 2 common propellers mounted at the top. Inside, a collector made of stainless steel with holes of 0.7mm diameter retain components and permits the melted solder to pass. The external wall of the centrifuge is made of a thermal insulator between two sheet aluminium, in which 3 thermocouples sensors are mounted. A PLC monitors temperature and controls rotating velocity through a frequency inverter.

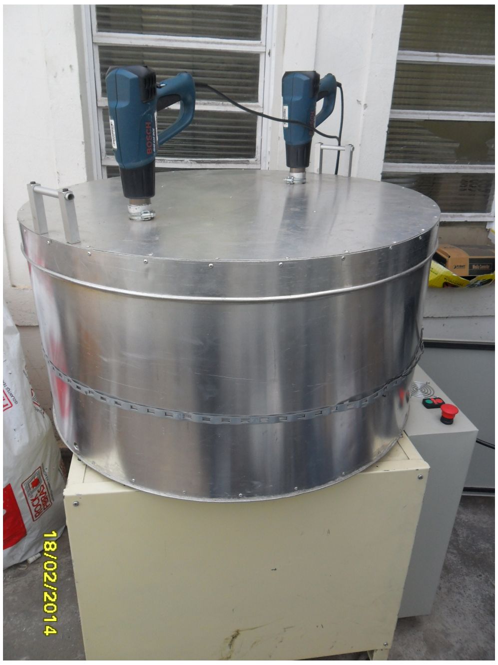


Figure 1: **Prototype for PCB disassembly.**

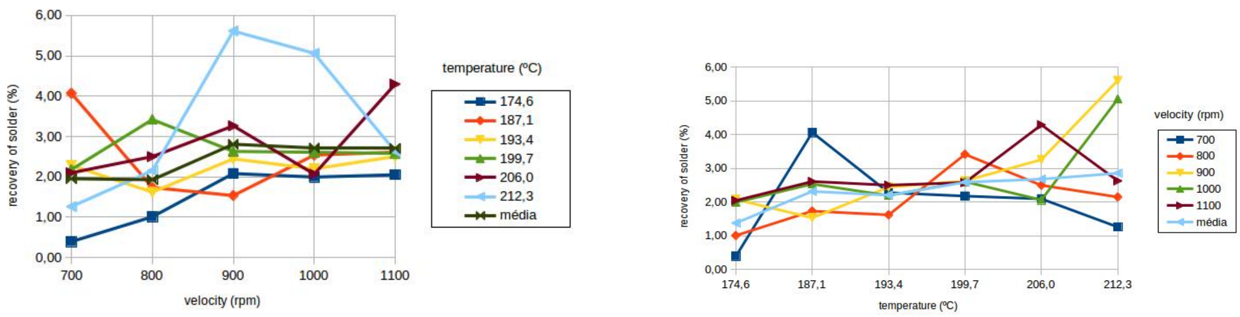
Using the apparatus described above, PCB disassembly was performed with a range temperature varying from solder fusion point (about 183^{o}C) to 220^{o}C and velocity ranging from 700rpm to 1100rpm.

PCB's were weighted before the procedure and the 3 outputs, solder, EC and substrate, after that. Contents of the recovery solder was determined using an scanning electron microscope (SEM) with combined energy dispersive X-ray (EDX) analyser.

4. RESULTS AND DISCUSSION

The chosen PCB contain only metallic and ceramic components. A condition for use of the apparatus, determined in previously tests, is the absence of any plastic part. Due its small fusion temperature (105ºC for polyethylene and 130ºC for polyacetal) , plastics melt before solder and form a grout among EC, solder and prototype.

One of the results of the disassembly of the PCB's was the recovery of solder. Figures 2(a) and 2(b) shows the removal ratio of solder as a function of velocity and of temperature. Another result were the EC removed from PCB.



(a) Recovery of solder as a function of velocity. (b) Recovery of solder as a function of temperature.

Figure 2: **Ratio of recovered material.**

Recovery of solder has a mean ratio between 1.38% and 2.86% with a linear growing as the increase of temperature. The amount of solder increase with velocity until 900rpm and stay constant for upper values.

Recovered solder is shown in fig. 3 and EC removed from PCB is shown in fig. 4. Recovery solder has uniform color and brightness. Prototype was designed aiming material recovering and not reuse of components. So, this approach can be classified as simultaneous and destructive disassembly. However, a visual inspection of the removed EC demonstrates that no physical damage occurred to the components due to disassembly, exception a few ones.

Figure 3: **Recovered solder.**

Figure 4: **Electronic components removed from PCB.**

Processing of the EC from the method proposed can be done independently and considering the characteristics of each component. Reuse of passive components should be investigated more closed. For example, inductors with ferrite core are not stressed at all due to temperature and if a new insulation of resin is applied it can be reused.

The printed board or substrate remains intact with no solder in the holes (1) and with very few EC attached to it. Components which solder wasn't removed (2) or resistors and diodes with bent pins (3) as illustrated in fig. 5, respectively, account for the EC not removed.

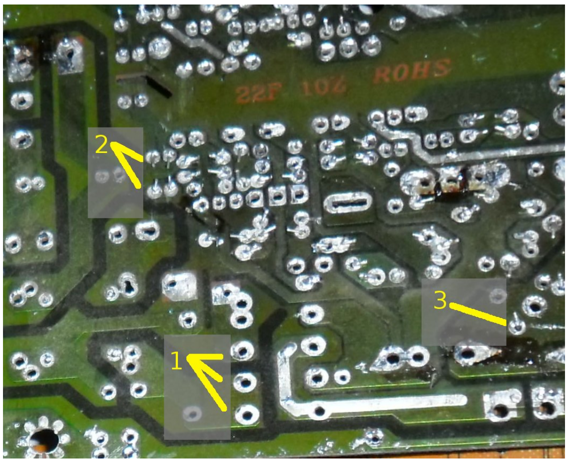


Figure 5: **Detail of processed PCB.**

Recovered solder was analysed by SEM-EDX. Figure 6 shows an image of the sample with magnification of 500x, detector BSD and EHT of 20 kV. It is observed that sample shows 3 majority elements distinguished by color. Light gray is lead, gray is tin and dark gray is silicon.

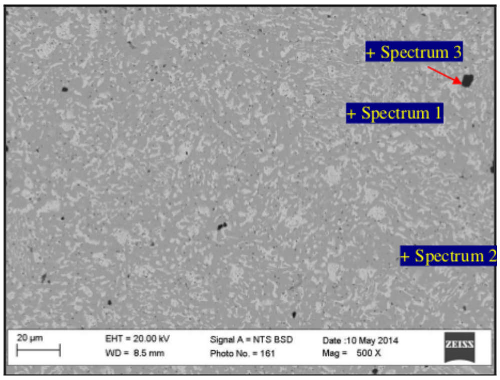
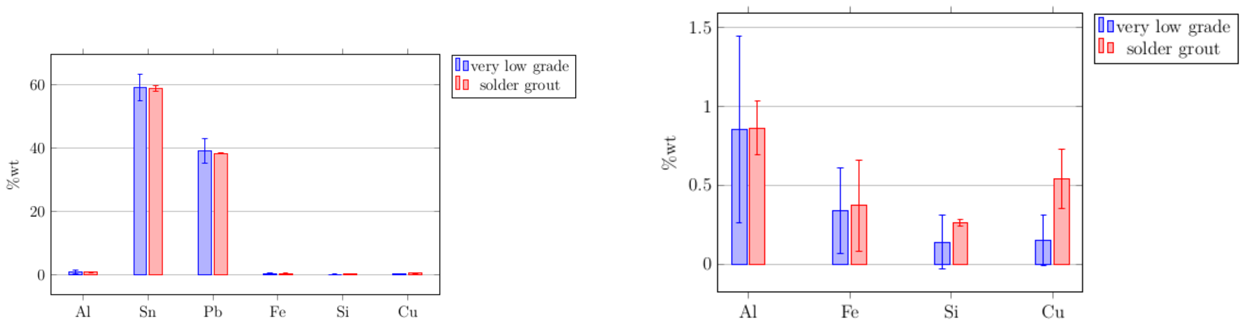


Figure 6: **Image of recovered solder (mag. 500x).**

Recovered solder was analysed quantitatively and compared with grout solder remaining from industrial soldering process which is used as input in the production of new solders. Results are shown on fig. 7(a) and 7(b).



(a) Analysis of recovered solder.

(b) Analysis of contaminants in recovered solder.

Figure 7: **Ratio of recovered material.**

Analysis demonstrates the recovered solder from disassembly has a characteristic composition similar to the grout solder from industrial soldering process. Contaminants Cu, Si and Fe has minor presence in recovered solder from PCB than in the grout, and Al has no significant difference. This results enable its direct use as input in the production of new solder.

The present job do not assess pollutants gases emissions. Authors recognized the importance of data concerning emissions, but the initial step were validate disassembly by the proposed prototype. Presence of smoke was used as parameter to set-up limits of operation. The upper limit of temperature was determined by liberation of smoke and deformation of the PCB's.

5. CONCLUSION

Based on the work presented in this paper, the following conclusions can be deduced. Printed circuit boards have been successfully disassembled. Solder, electronic components and substrate was separated and recovered. PCB disassembly, as proposed, will enable development of new techniques of recycling and/or improvement of that are already in use. Recovered solder can be used as resource in the production of new solder alloys. Recovery of copper from substrate can be optimized due no other metals are attached to it.

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7. RESPONSABILIDADE AUTORAIS

O(s) autor(es) é(são) o(s) único(s) responsável(is) pelo conteúdo deste trabalho.