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THE COMMINUTION OF PCB AND LED IN ORDER TO IMPROVE METAL RECOVERY

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ABSTRACT

The utilisation of secondary raw materials for resource recovery allows the conservation of primary ores, prevents certain environmental issues by removing potential environmental hazards, and can significantly reduce the carbon-dioxide emission and ecological footprints. E-wastes or waste electrical and electronic equipment (WEEE) are a potential resource for various materials, as several typical critical metals (such as indium, rare earth elements, precious metals, lithium and cobalt) are widely consumed in the production of such products. In case of printed circuit boards, various metal recovery technologies have been investigated throughout the years. However, as LED technology is relatively recent, no significant methods have been proposed for pre-treatment and metal recovery, yet. The aim of the article is to provide literature overview on the comminution methods used in case of PCBs and LEDs before metal recovery.

INTRODUCTION

Due to the continuous scientific and technological development and innovation, and market expansion, the replacement of electrical and electronic equipment is accelerated. Therefore, the generation of e-waste is rapidly increasing, which is confirmed by the joint report of the International Telecommunication Union, United Nations University and International Solid Waste Association [1]. The improper disposal of e-wastes can cause serious environmental issues, due to the toxic substances they contain [2, 3]. Thus, recycling WEEE is a relevant research subject both for waste treatment and for the recovery of valuable and critical metals, such as copper, nickel, tin, gold, palladium, indium, and rare earth elements (REEs) etc. [2, 4, 5]. The critical raw materials for the EU, based on the latest assessment in 2017 can be observed in Figure 1 [6].

In 2016, around 44.7 Mt of e-waste was generated globally and only 8.9 Mt, around 20% of it was documented to be collected and recycled. The European continent, including Russia, had the highest regional collection rate with 35%, followed by the American continent with 17% and Asia with 15% [1]. In Hungary, the rate of e-waste recycling has been rapidly increasing since 2011, reaching over 50% by 2015 [7].

Generally, e-wastes are disassembled – the reusable and toxic components are removed – and mechanical processes are used for pre-treatment to separate metals from non-metals, to improve the valuable material recovery rate and to facilitate the processing [8, 9].

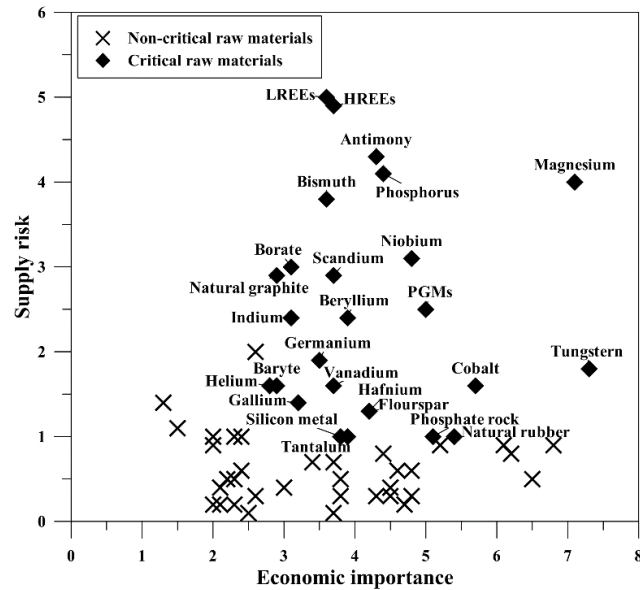


Figure 1.
Critical raw materials for the EU in 2017

The aim of the article is to provide literature overview on the comminution methods used for metal recycling in case of two kinds of e-wastes: printed circuit boards (PCBs) and light emitting diodes (LEDs).

PRINTED CIRCUIT BOARDS

PCBs (Figure 2) are integral parts of any electrical and electronic equipment, like mobile phones, notebooks or colour televisions. Waste PCBs contain many electronic components, such as resistors, relays, capacitors, and integrated circuits, making them one of the most complex, hazardous and valuable parts among e-waste [4, 10, 11]. In case of PCB preparation, it should be decided if the various components should be individually removed and separated to enhance the purity of the product, or all parts should be simultaneously comminuted and processed [12, 13].

A great number of researchers has studied and developed possible methods for metal recovery, typically using various mechanical processes for liberation and the facilitation of the recovery process.

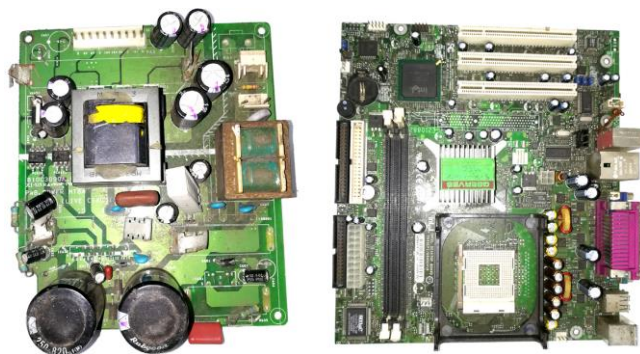


Figure 2.
Representative examples of waste PCBs [14]

Pyrometallurgical methods

Among the pyrometallurgical processes, smelting is the primary method used in case of e-wastes [15]. The main steps are liberation, separation and purification. However, total liberation is not achieved by crushing or grinding but by smelting the wastes in furnaces at high temperatures, as it is done at Umicore. Umicore is the world's largest waste recycling facility, located in Hoboken, Belgium. Here, several pyrometallurgical steps are carried out for total liberation, then hydrometallurgical, and electrochemical processes are used for precious metal recovery (gold, silver, PGMs) [16].

On the other hand, experiments on the use of pyrolysis for metal recovery from PCBs have also been carried out [14, 17-19]. In some cases, no crushing or grinding was performed on the PCBs beside cutting or breaking them to smaller pieces but the examined metals (copper, REEs) could be effectively separated and recovered from the pyrolysis residue [14, 17, 18]. Bidini et al. used a Retsch SM 2000 cutting mill to reduce the size of scrap PCB to be pyrolysed under 30 mm. According to their results, the dissolution efficiency improved, the amount of non-metal residue was reduced, and bromine could also be recovered [19].

Hydrometallurgical methods

In e-waste treatment, hydrometallurgical processes refer to the leaching of metallic components in aqueous solvents, such as strong acid and alkaline, which are then subjected to separation and purification and the concentrated solutions are also treated for precious metal recovery. They are a cleaner and less expensive alternative to pyrometallurgical processes with distinct advantages in separating REEs [2, 10, 14, 20, 21].

Kim et al. focused on gold recovery from mobile phone PCB scrap, which was used either without cutting (average size around 35 mm × 40 mm) or after manually cut to 2-3 mm pieces. It could be observed that gold leaching was hindered as the particle size decreased [22]. After copper separation, Park and Fray could recover silver, gold, palladium from shredded waste PCBs, the precipitates of the input metals were 98 wt.%, 97 wt.% and 93 wt.% respectively [23]. The effect of supercritical water pre-treatment and acid leaching was investigated by Xiu et al., concluding that the Sn, Cd, Cr, Zn, and Mn recovery could be enhanced. The particle size was reduced under 3 mm using a cutting mill [24].

A new ball milling method was tested by Zhang et al. for Cu and precious metal recovery. First, the size of the metallic components of PCBs mixed with multilayer ceramic capacitors was reduced under 0.25 mm with a cutting mill. Then co-milling reagents were added to the mixture and a planetary ball mill was used for further milling. Finally, the recovery efficiency of Cu, Ag and Pd via leaching was examined. According to their results, with the optimised parameters, the proposed process can avoid the use various toxic acids typically used for Cu, Ag and Pd recovery, and consequently, the release of gaseous pollutants can be avoided [25].

Bioleaching

Bioleaching refers to the use of microorganisms for the extraction of metals. Compared to the hydrometallurgical methods, bioleaching is greener as less wastewater and waste gas are produced. It is selective to specific metals; thus, the specific microorganism can be difficult to select and culture [20, 26]. Ni, Cu, Al and Zn was successfully extracted by Ilyas et al. from PCBs crushed with a Rotoplex shredder crusher and an Omniplex hammer crusher, then further ground to 0.08 mm [27]. Liang et al. carried out experiments on crushed and then ground scrap PCBs, using the 100–200 μm fraction. Using mixed cultures, the enhanced extraction of copper, nickel, zinc and lead could be observed [28, 29].

Mechanical separation techniques

The techniques of mechanical separation are based on differences in certain characteristics of the materials, e.g. density, magnetic susceptibility, electric conductivity, the physico-chemical surface variance of the particles etc. [2, 4, 30]. He and Duan examined an efficient and low-cost reverse floatation technique appropriate for Cu, Pb, and Sn recovery. The waste PCBs were first manually cut to 50×50 mm pieces, then crushed below 3 mm in a laboratory-scale impact crusher. Finally, the sample was ground below 0.5 mm in a ball mill. Their results indicated the concentration of metallic components in the larger fractions of the ground product and a decline in recovery efficiency as the size fraction decreased [4]. An eco-friendly process to get enriched rare-metal concentrate was proposed by Kumar et al., including pneumatic separation and froth flotation. The PCBs were manually cut into small pieces and then subjected to scutter crusher to reduce the size below 10 mm. Finally, the size was reduced to a maximum of 1.5 mm with a high-speed hammer mill [31]. According to Cui and Forssberg, after secondary shredding in a laboratory scale hammer mill, the examined PCB scrap showed excellent liberation in the <5 mm fractions. Thus, metals concentrated in these fractions could be efficiently separated, using e.g. Eddy current separation, corona electrostatic separation or jigging [32].

LEDs

LED can be used in LCD screens as backlights, in LED screens, in lighting equipment in homes and industry, in cars and instruments. The possible rare earth elements found in LEDs (Figure 3) include cerium, yttrium, gadolinium and europium among other metallic components, like gallium and aluminium. Moreover, some heavy metal and organic materials can also be found in them, which are hazardous to human beings and the environment. Thus, in 2012, LCD displays with LED background illumination or OLED screens were not yet of any quantitative importance among WEEEs. In LCD displays with LED background illumination, indium is used in the LED semiconductor chip [8, 33, 34, 35].



Figure 3.
A photo of an LED [34]

Swain et al. examined the recovery of gallium from the waste dust generated during the manufacturing of LEDs. The dust was mixed with Na_2CO_3 and milled in a planetary ball mill. The ground samples were then dried, annealed and Ga was successfully recovered via leaching [36]. Zhan et al. adopted pyrolysis and physical disaggregation to concentrate rare metals of waste LEDs which can then be recovered from the pyrolysis residue after crushing, screening, grinding and secondly screening. The technology could be utilised to recover Ga and In from the examined LED waste [37].

In [39] the possibility of the recovery of Ga from end-of -life LEDs was investigated at labour scale combining the mechanical pre-treatment with the following chemical-thermal techniques. By the mechanical preparation, after physical liberation the conductive parts (Cu) were successfully removed. The non-conductive part contained the GaN layer on the surface of the LED chips, the calculated Ga concentration was as high as 516 ppm. It was experimentally proved that the mechano-chemical activation in stirred media mill is an effective tool to obtain the high recovery of Ga in the pregnant solution after chemical leaching using HCl.

The first study on the extraction of Cu, Ni, and Ga from LED waste by bio-hydrometallurgy technology was carried out by Pourhossein and Mousavi in 2018. A mixture of discarded pin-type LEDs was prepared and crushed with an industrial crusher then milled using a Fristch type ball mill. With the help of an iron-oxidizing bacteria, they could recover copper, nickel, and gallium from the $\leq 70 \mu\text{m}$ fraction [38].

SUMMARY

The recycling of PCBs is a more extensively investigated topic due to the novelty of the LED technology. Furthermore, the investigations to date have mainly focused on the recovery of precious metals.

The mechanical activation of PCBs is not necessarily required for certain methods, such as smelting. However, according to the relevant literature, various comminution equipment can be used for the pre-treatment PCBs – i.e. shredders, hammer mills, disc or ball mills –, depending on the subsequent recovery method. In case of LED treatment, there are still no specific methods developed for metal recovery.

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