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TECHNOLOGY DEVELOPMENT FOR THE SEPARATION OF MULTILAYER COMPOSITES

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Abstract

Waste Printed Circuit Boards (WPCBs) are integral components of virtually all electrical and electronic equipment (EEE), forming the structural backbone of the electronics industry. Classified into single-sided, double-sided, multilayer, rigid, and flexible boards, WPCBs are composed of various electronic components including semiconductors, transistors, and capacitors, which complicates their recycling due to diverse material compositions. Approximately 40% of PCB mass is metallic, 30% plastic, and 30% organic material, with metals predominantly constituted by copper. The recycling process involves multiple stages, including shredding and separation to extract valuable metals and electronic components. Shredding, employing technologies like hammer mills, is critical for effective metal recovery. Advanced methods, such as infrared heater-based automatic removal systems, have been developed for efficient electronic component separation, ensuring minimal environmental impact.

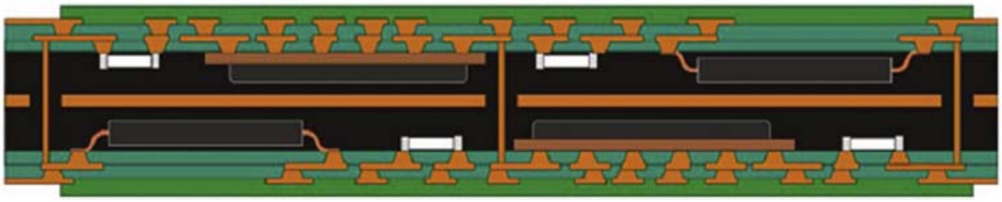
Mechanical and physical processing techniques focus on the extraction of valuable metals like gold, silver, palladium, and copper while recognizing the potential of the non-metallic fraction. Chemical processing using inorganic acids, such as nitric and sulfuric acid, along with oxidative leaching agents, has proven effective for metal recovery. Innovative methods, including the use of aqua regia for gold leaching, have demonstrated high recovery rates. This comprehensive approach to WPCB recycling underscores the importance of integrating mechanical, physical, and chemical processes to achieve sustainable, efficient, and environmentally friendly recycling outcomes.

Keywords: *recycling, WPCB, mechanical treatment, chemical treatment, circular economy.*

General characteristics of WPCB

WPCBs (Waste Printed Circuit Boards) are found in virtually all electrical and electronic equipment (EEE), forming the backbone of the electronics industry. Printed circuit boards can be classified in various ways based on their different characteristics: single-sided, double-sided, multilayer, rigid, and flexible boards [11].

Electronic components form the circuit structure (Picture 1); these are the components that are part of any interconnected electrical or electronic circuit. The electronic components on the board depend on its application, which may include semiconductors (integrated circuit chips), transistors, diodes, capacitors, resistors, connectors, etc. [2]. Various configurations of integrated circuits are possible; changing the encapsulation mode alters their assembly. Different components have different material compositions, which complicates WPCB recycling [2]. Approximately 40% of the PCB mass is composed of metals, 30% plastics, and 30% organic material [4].



Picture 1. EC structure. (source: Marques et al., 2013)

The composition of WPCBs, excluding electronic mounting component materials, is about 28% by mass metal (mostly copper) and 72% by mass non-metallic materials [10]. There is an acceptable degree of imperfection in specific characteristics of printed circuit boards that can be determined based on the intended final use. For this reason, three general classes have been established based on functional reliability and performance:

Class 1: General electronic products such as computers and peripherals.

Class 2: Electronic products intended for servicing, such as mobile phones.

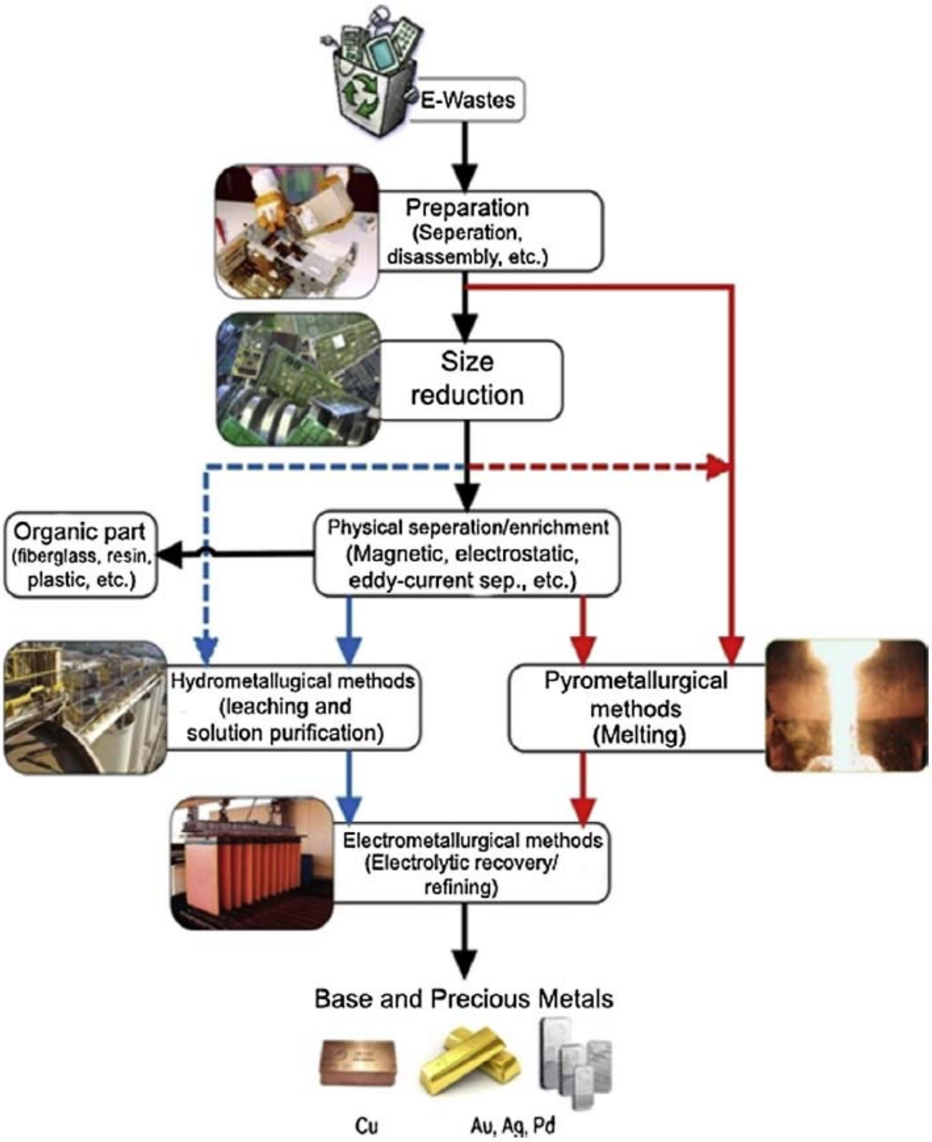
Class 3: High-reliability electronic products, including equipment and products where continuous operation or operation on demand is critical.

Primary WPCB Processing

The recycling process of waste printed circuit boards (WPCBs) involves several stages (Picture 2), including shredding and separation, to extract valuable metals and electronic components (EC) from the baseboards and substrates. These steps are crucial for achieving efficient recycling and environmental sustainability.

Shredding is a critical step in removing metals from the baseboards of PCB waste. The choice of shredding technology impacts both the energy consumption of the equipment and the efficiency of selective metal recovery. WPCBs consist of resin and metal parts, such as copper wires and connectors, which are hard and resistant. A hammer mill, which applies shear force, is suitable for shredding PCB waste. A two-stage shredding method is employed to achieve optimal fragmentation. A high-speed cutting machine is used as a rough crusher, where the rotor and stator cutters generate a cutting action to break down PCB boards into small pieces. Subsequently, a specially designed hammer mill with high-speed hammer heads is used to scrape and mill the materials. This shredding process ensures the removal of metals from the baseboards and reduces wire wrapping around tool tips [9]. The hammer mill screen hole diameter was 1 mm to achieve a high level of metal removal. The parameters of the cutting machine were: circular speed diameter of 1440 rpm and rotor radius of 0.25 m, while the hammer mill crusher parameters were: circular speed diameter of 2000 rpm and rotor radius of 0.2 m [9].

Beyond shredding, the removal of EC from PCB substrates is a vital stage in the recycling process. Traditional methods such as thermal melting and manual separations are used, but they are not suitable for large-scale recycling and cause environmental pollution. To address this, researchers have developed innovative methods. For instance, an automatic removal production line, heated using an infrared heater, achieves a high EC separation efficiency of 94% [12]. In this process, WPCBs are fed into a separation module, and the solders are heated to melting temperature using an infrared heater. Then, rotating steel brush rods are used to remove the EC from the WPCBs. Another method involves using a mill, but its separation efficiency is about 75% [8]. An environmentally friendly and automatic EC separation system has been developed, using electric heating pipes (EHPS) custommade for an EC automatic disassembly machine (ECs-ADM). This system also includes exhaust gas purification equipment, allowing for zero pollutant emissions. It has been shown that heating solders with an infrared heater increases separation efficiency but also produces toxic substances, thus necessitating the use of exhaust gas purification equipment for safety. The use of heat for EC disassembly has been proven to be more effective compared to mechanical methods, while also ensuring safety [15].



Picture 2. E-waste recycling flowchart using various methods (source: Akcil et al., 2015 [1])

Chemical Processing

Nowadays, significant attention is given to efforts to extract valuable metals (gold, silver, palladium, and copper) from waste printed circuit boards (PCBs). Various extraction processes, such as leaching, mechanical processing, and hydrometallurgical methods, have been studied for metal recovery [6]. There are also many review articles focusing on metal recovery and reuse [5]. While the emphasis is on metal recovery, the non-metallic fraction (NMF) constitutes about 70% of the total weight of PCB waste. Recognizing the value-added potential of the NMF, recent separation technologies have begun to consider this significant portion in their designs and operations [3].

Chemical Processing Numerous alternative solvents, including inorganic acids/oxidizing reactive systems, have been extensively studied in the investigation of metal leaching from E-waste. Examining the use of various inorganic acids and oxidants for metal recovery, it was found that nitrate and chloride solutions ensure the highest recovery of copper (Cu) and gold (Au). A pyrolysis stage before leaching is also recommended to enhance metal regeneration [13]. An accelerated leaching of gold from computer circuit boards was observed, using a combination of nitric acid (HNO_3) and hydrochloric acid (HCl) as a leaching solution [14]. Gold leaching in the studies is carried out in three stages. Initially, nitric acid leaching was performed on separate computer chips from PCBs, carefully examining the acid concentration, temperature, fiber density, and leaching time. Later, computer chips and granulated epoxy resins are mechanically crushed and rinsed using optimal parameters. The remaining computer chips obtained after the second leaching stage are processed in the third stage with aqua regia to recover gold and silver [14]. Chemical reactions of gold leaching using Aqua Regia are described in equations (1) - (3):

$$2HNO_3 + 6HCl \rightarrow 2NO + 4H_2O + 3Cl_2 \quad (1)$$

$$2Au + 9HCl + 3HNO_3 \rightarrow 2AuCl_3 + 3NOCl + 6H_2O \quad (2)$$

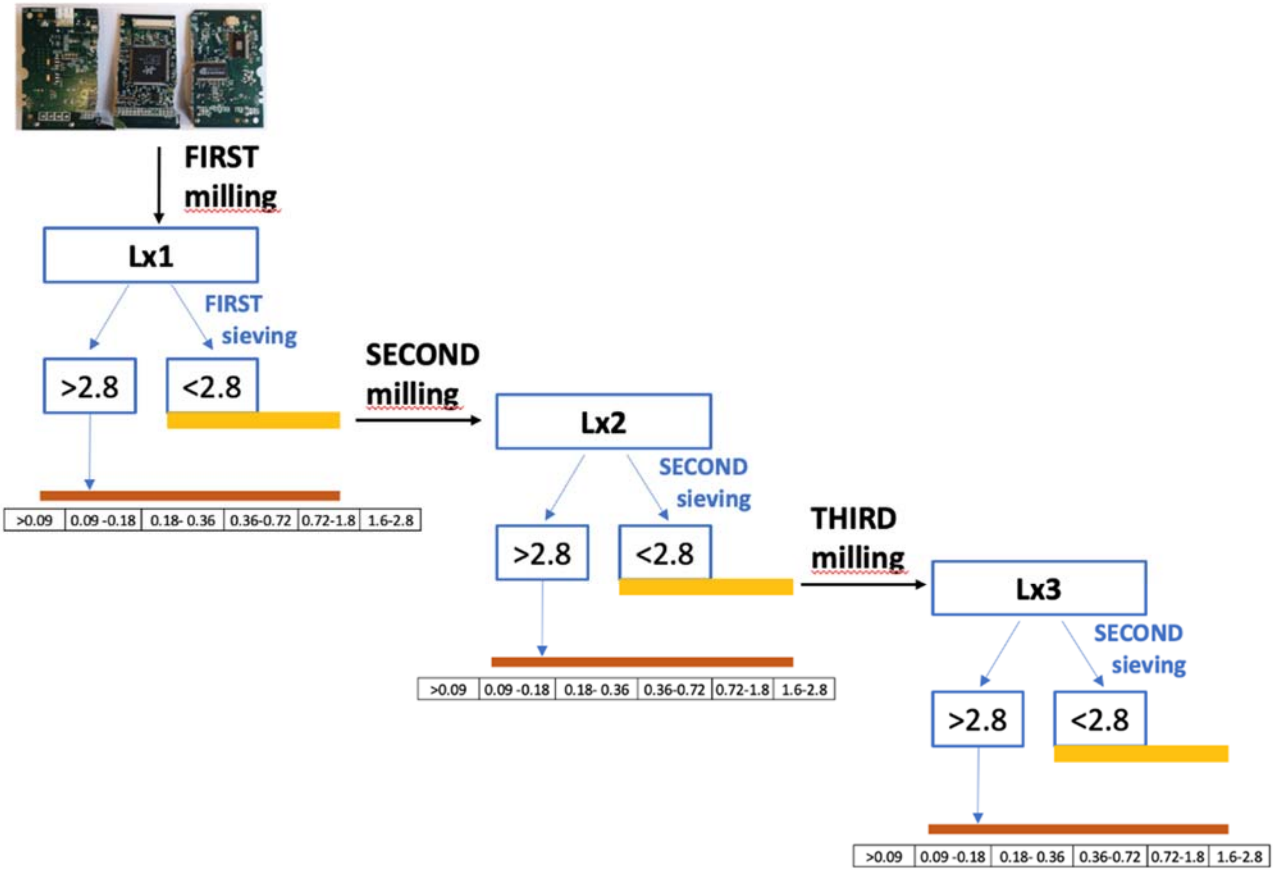
$$3HCl + HNO_3 \rightarrow Cl_2 + NOCl + 2H_2O \quad (3)$$

One of the processes of precious metal recovery from electronic waste containing plastic involves burning E-waste at 400-500 °C for 8-12 hours, followed by washing with hydrochloric acid (HCl) and sulfuric acid (H_2SO_4) at 90 °C to extract the metal. The washing mass is then separated by liquid/solid particle separation and analyzed. The amount of silver in the obtained semi-solid ratios is dissolved in diluted nitric acid (HNO_3) at 60 °C, and the amount of gold and palladium is extracted using HCl and $NaClO_3$, thus the recovery of precious metals reaches 92% [16]. Kinoshita et al. [7] investigated the dissolution of copper (Cu) and nickel (Ni) from waste circuit boards using nitric acid (HNO_3), with regeneration exceeding 90%. They purified the solution by the solvent extraction method. Although nitric acid exhibited oxidative properties that facilitated the recovery of metals soluble in a nitrate medium, such as copper (Cu) and silver (Ag), it is considered an expensive process compared to other acids. On the other hand, sulfuric acid (H_2SO_4) is considered a more economical alternative, especially when used in conjunction with additive reagents such as hydrogen peroxide (H_2O_2), oxygen (O_2), and iron ions (Fe^{3+}). Birloaga et al., (2014) investigated two chemical leaching systems for the recovery of non-precious and precious metals from waste printed circuit boards (WPCB). Sulfuric acid (H_2SO_4) with hydrogen peroxide (H_2O_2) was used for the first group of metals, and thiourea ($CS(NH_2)_2$) with iron ions (Fe^{3+}) in a sulfuric acid medium for the second group. The effect of hydrogen peroxide volume on sulfuric acid concentration and temperature was evaluated in the oxidative leaching process. The selected optimal conditions for copper (Cu) extraction were 2M H_2SO_4 (98% m / t), 5% H_2O_2, 25 °C, 1/10 (S / L) ratio and 200 rpm. Thiourea acid leaching was performed with solid filtrate obtained after three oxidative leaching stages, using 20 g/L $CS(NH_2)_2$, 6 g/L Fe^{3+} and 0.5 M H_2SO_4. The resulting solution contained 40 g/l of zinc (Zn), representing 95% of the metal, with impurities consisting of aluminum (Al) (4%) and small amounts of iron (Fe), nickel (Ni) and tin (Sn). The resulting cement contained mostly copper (Cu), with a purity of about 87%.

Scope of application and implementation:

1. wPCB preparation and separation for size reduction (milling) for different types of wPCBs.
2. wPCB content analysis in different fractions.
3. Optimization of wPCB size for chemical treatment.

4. Chemical processing optimization.



Picture 3. wPCB preparation and size reduction by milling

Conclusions:

Waste printed circuit boards (WPCBs) are an integral part of electronic and electrical equipment, characterized by a diverse range of materials and components. The recycling process of WPCBs involves several critical stages, from shredding to the chemical extraction of valuable metals. The composition of WPCBs poses both challenges and opportunities for recycling efforts. Effective shredding and separation techniques are essential for the efficient recovery of metals and electronic components, with advanced methods such as infrared heating and environmentally friendly disassembly systems enhancing the process.

Chemical processing plays a crucial role in recovering precious metals from WPCBs. Various leaching processes, involving inorganic acids and oxidizing agents, have demonstrated significant efficacy in metal recovery.

The ongoing development and implementation of efficient recycling technologies highlight the potential for significant advancements in the management of electronic waste. By optimizing processes such as size reduction, chemical treatment, and separation, the recycling industry can effectively address the environmental and economic challenges posed by WPCBs. This comprehensive approach not only mitigates the environmental impact of electronic waste but also maximizes the recovery of valuable resources, fostering a more sustainable future for the electronics industry.

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РОЗРОБКА ТЕХНОЛОГІЇ РОЗДІЛЕННЯ БАГАТОШАРОВИХ КОМПОЗИТІВ

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Ключові слова: *переробка, WPCB, механічна обробка, хімічна обробка, економіка замкнених циклів.*

Анотація

Відпрацьовані друковані плати (WPCB) є невід'ємними компонентами практично всього електричного та електронного обладнання (ЕЕО), формуючи структурну основу електронної промисловості. Класифікуються на односторонні, двосторонні, багатошарові, жорсткі та гнучкі плати, друковані плати складаються з різних електронних компонентів, включаючи напівпровідники, транзистори та конденсатори, що ускладнює їхню переробку через різноманітний склад матеріалів. Приблизно 40% маси друкованих плат складають метали, 30% - пластик і 30% - органічні матеріали, причому серед металів переважає мідь. Процес переробки включає кілька етапів, зокрема подрібнення та розділення для вилучення цінних металів та електронних компонентів. Подрібнення із застосуванням таких технологій, як молоткові млини, має вирішальне значення для ефективного вилучення металів. Для ефективного відокремлення електронних компонентів були розроблені передові методи, такі як автоматичні системи видалення на основі інфрачервоного нагрівача, що забезпечують мінімальний вплив на навколишнє середовище.

Механічні та фізичні методи переробки зосереджені на вилученні цінних металів, таких як золото, срібло, паладій і мідь, визнаючи при цьому потенціал неметалевої фракції. Хімічна обробка з використанням неорганічних кислот, таких як азотна та сірчана, разом з окислювальними вилуговувачами довела свою ефективність для вилучення металів. Інноваційні методи, зокрема використання акварелі для вилуговування золота, продемонстрували високі показники вилучення. Такий комплексний підхід до переробки WPCB підкреслює важливість інтеграції механічних, фізичних і хімічних процесів для досягнення стійких, ефективних і екологічно чистих результатів переробки.