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Current status and future perspective of waste printed circuit boards recycling

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Abstract

For waste electrical and electronic equipment (WEEE), large quantities of waste printed circuit boards (PCBs) are released into environment. In light of their characteristics including complex structures, high metals content and potential hazards, waste PCBs are regarded as the most difficult parts of WEEE to be recycled. Therefore in recent ten years, the issue has attracted much attention from researchers and enterprises. This article reviews the latest processes of waste PCBs developed from laboratories to pilot engineering applications, and presents the most suitable available technology for waste PCBs, typically categorized as manually dismantling and automatic approaches in developing and developed countries, respectively. Towards achieving the better sustainability and recyclability for waste PCBs, nonmetal powder and precious metals should be developed for a deep recovery following mechanical treatment. Additionally, a significant shift is emerging from dismantling for recycling of printed wiring boards, to disassembling for remanufacturing of electronic components, which will indicate that a new paradigm of reclaiming waste PCBs is shaping.

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Keywords: printed circuit boards (PCBs); waste electrical and electronic equipment (WEEE); recycling; best available technology; trends

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1. Introduction

Printed circuit boards (PCBs) are used to mechanically support and electrically connect electronic components using conductive pathways, tracks or signal traces etched from copper sheets laminated onto a non-conductive substrate, employed in the manufacturing of business machines and computers, as well as communication, control, and home entertainment equipment. PCBs are essential parts of almost all electric and electronic equipment, and its rapid development has revolutionized the electronics industry. A large quantity of obsolescent electronic products has rapidly led to considerable waste generation, even in the developing countries [1-2]. Therefore, numerous waste PCBs were released into environment without proper treatment or disposal. On the other hand, PCBs production is dramatically increasing in the near future based on the global gross, shown in Fig.1.

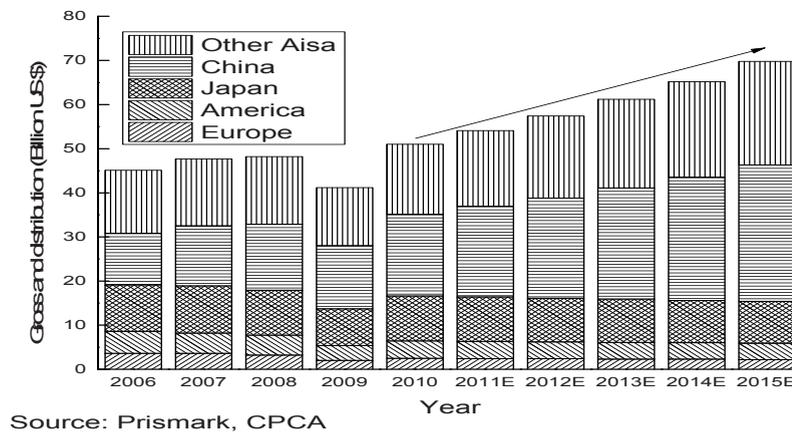


Fig.1 PCBs increasing based on the global gross

Since a conductive circuit generally consists of copper, although aluminum, nickel, chrome, and other metals are sometimes used, and PCBs are the platform upon which microelectronic components such as semiconductor chips and capacitors are mounted. Therefore, PCBs usually contain epoxy resin, fiberglass, copper, nickel, iron, aluminum and a certain amount of precious metals such as gold and silver; those materials and metals along with electronic parts, are attached to the board by a solder containing lead and tin [3]. Many research works have revealed that the composition of metals, ceramic and plastics could reach 40%, 30% and 30%, respectively [4-5]. Meanwhile, the concentrations of precious metals such as gold and palladium in waste PCBs are richer than in natural ores, which makes their recycling important from both economic and environmental perspectives [6].

Waste PCBs have been paid much more attention from researchers and enterprises, not only due to their rich resource content, but also due to their potential risk for environment and human health with informal recycling. While some articles ever reviewed the waste PCB recycling [7-8], this article in a new orientation will review the latest recycling of waste PCBs, present the best available technology in developing and developed countries, and depict the trend and development toward sustainability of PCBs.

2. Latest recycling processes of Waste PCBs

2.1 Mechanical recycling process of PCBs

Many recycling processes of waste PCBs have been tested in a laboratory scale. For instance, the pyrolysis process was employed to obtain high pure metals [9-12]. Uncertainty and potential pollution have declined the process to expand into a field scale. A more popular recycling process of waste PCBs found worldwide, is mechanical recycling owing to a fact that valuable metals in PCBs are elementary substance. The mechanical recycling process for waste PCBs has been applied in one hundred field plants in China.

The PCB mechanical recycling can be broadly divided into two major steps shown in Fig.2. The first step is the dismantling and/or separation of different components and materials, generally using mechanical or metallurgical processing to upgrade the desirable material content. Shredding, electrostatic separation, supercritical extraction, and pyrolysis are the main technologies employed in this step. The second step is the further separation or screening and processing of metal streams; this is probably the most important step from economic and environmental viewpoints. Many methods are available to extract metals from post-processing PCBs. These technologies are very different in terms of economic feasibility, recovery efficiency, and environmental impact.

The most attractive research on dismantling process is the use of robots. Unfortunately, full (semi) application of automation dismantling for recycling of PCBs is full of frustration. In the practice of recycling of PCBs, selective dismantling is an indispensable process since: (1) the reuse of components has first priority, (2) dismantling the hazardous components is essential, and (3) it is also common to dismantle highly valuable components and highly graded materials such as battery in order to simplify the subsequent recovery of materials.

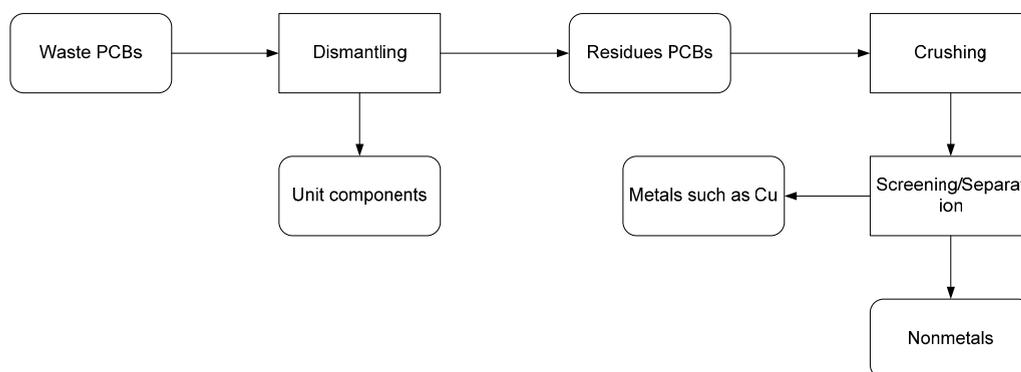


Fig.2 Mechanical processes for the recycling of waste PCBs

Most recycling plants utilize manual dismantling. For instance, a typical dismantling process is operated at Ragn-Sells Elektronikåtervinning AB in Sweden [13]. A variety of tools is involved in the dismantling process for removing hazardous components and recovery of reusable or valuable components and materials. The purpose of crushing is to strip metals from the base plates of waste PCBs. Crushing technology is intimately related to not only energy consumption of crushing equipment, but also further selective efficiency. Waste PCBs are comprised of reinforced resin and metal parts such as wires and joints. They have a high hardness and tenacity. Comminution of waste PCBs and high effective liberation of the metal composition from non-metals is the prerequisite of the following sequence separation for better recovery of waste PCBs. More often, two-step crushing is necessary for proper screening, as illustrated by Fig.2. Screening has not only been utilized to prepare a uniformly sized feed to certain mechanical process, but also to upgrade metals contents. Screening is necessary because the particle size and shape properties of metals are different from that of plastics and ceramics. The primary

method of screening in metals recovery uses the rotating screen, or trammel, a unit which is widely used in both automobile scrap and municipal solid waste processing.

Magnetic separators, in particular low-intensity drum separators are widely used for the recovery of ferromagnetic metals from non-ferrous metals and other non-magnetic wastes. Over the past decade, there have been many advances in the design and operation of high-intensity magnetic separators, mainly as a result of the introduction of rare earth alloy permanent magnets capable of providing very high field strengths and gradients. Electric conductivity-based separation separates materials of different electric conductivity (or resistivity). There are three typical electric conductivity-based separation techniques: (1) eddy current separation, (2) corona electro static separation, and (3) triboelectric separation. Corona electrostatic separation is an important technique feasible for fine particles with the size range of 0.6–1.2mm. In the corona electrostatic separation, electrode system, rotor speed, moisture content, and particle size have the greatest effect in determining the separation results [14-15].

2.2 Primitive open-soldering methods used in less developed countries

In China, immature technologies are the main obstacle to the recycling of waste PCB assemblies. During the manual dismantling process in informal dismantling and recycling sites, e-recyclers use chisels, hammers and cutting torches to open solder connections and separate various types of metals and components. PCB assemblies, which are more complicated and difficult to process, are simply cooked on a coal-heated plate and melted (on the iron plate or flat wok) in order to resell the chips and other recovered components to acid strippers for further processing. A pungent smell permeates the workshops, accompanied by black fumes rising from the cooked scraps [16-17]. It is true that such kind of manual dismantling process mentioned in China was used for more than 10 years ago, but it has been prohibited according to Chinese law recently. Actually, the aforementioned process is still adopted a simple improvement by using electric heating plate, which is semi-enclosed, temperature-controllable, and comprised exhausted gases collector.

The fact, which the PCBs assembly is one of the fastest growing sources of waste in many developing countries, has attracted attention on the need to recycle, recover and reuse materials that have been consigned to informal dismantling sites. In India or Nigeria, the above mentioned methods have been widely used as well. The major common point of these disassembling technologies is the recovery of the solder remaining on the board by subjecting it to a temperature greatly higher than the molten point of the solder. In these processes of PCB assembly dismantling, pyrolysis under high temperature heating, during which the toxic products from resins and adhesives are decomposed, is a common occurrence [18].

2.3 Intelligent and automatic approaches and their application

A flexible automated cell for PCBs assemblies dismantling has been proposed and described in several publications [19]. First, the PCBs assemblies are fixed on frames and fed into a dismantling cell. Next, a recognition system with an image-processing “Vision System” identifies reusable parts and toxic components on the PCBs assemblies, by comparing the shape and labels of the parts with a database containing information from manufacturers and information from the reuse market. The dismantling cell removes reusable and hazardous components from various PCBs assemblies and produces PCBs assemblies which are less environmentally hazardous, and electronic components suitable for reuse.

Legarth et al. reported another automated method for disassembling PCBs assemblies as follows [20]. The first step in the selective dismantling is to identify and obtain information about the PCBs assembly via 3-dimensional pictures. Picture processing algorithms give statements about components of interest and extract data on how to disassemble them, such as co-ordinates and rotation angles. Only sockets and solder joints are separated. Application of small amounts of force and heat such as hot air and a vacuum gripper may be used. Surface-mounted Device components, hot liquid and a parallel-jaw gripper are

employed to disassemble Through-hole Device components. The task of the simultaneous dismantling module is to evacuate the entire printed circuit board.

Another automatic disassembly system has been developed by the NEC Corporation [21]. The system comprises two heating units and two removal units. The first removal unit is equipped with impacting propellers and PCBs assembly reversing arms. The second removal unit is equipped with shearing propellers. The PCBs assemblies are fixed to a holder in either vertical or horizontal configuration. There is no identification module in this system, however, before the disassembly process, the forces required to remove components are calculated according to the connection type and direction configuration. Actually, due to the complexity and high cost of equipment, such automated methods can rarely be practiced, particularly in China.

2.4 Semi-automatic approaches and their application

Compared to automated approaches, a semi-automated method is flexible. A more practical technology, known as a semi-automated approach, has been developed for the recycling of PCB assembly. The electronic components on the PCB assemblies are removed by a combination of heating them to above the melting point of solder and applying such external forces as impact, shearing and vibration. The recycling ratio of useful materials recovered from a test PCB assembly using this method was 65%, as compared to 23% with a traditional method of refining useful metals from PCB assemblies.

In order to control set temperature and heating rate during the dismantling process, an updated semi-automated PCB assembly dismantling cell has been developed and commercialized by Chinese researchers, which is commercially applied. It includes the following subsystems or units: sequential heating units, apart-removal unit, a PCB assembly transport system, a solder-removal unit, and a component-collection unit. This system controls the PCB assembly's heating rate effectively by matching the temperatures of the six heating units and the velocity of the PCB assembly's progress through the dismantling cell. The heating technology, which could be called semi-automatic approaches, has been successfully used in e-waste recycling company in China as well. Case of Beijing, the equipment, which comprises heating system (electric resistant tube, exposed to air) at a temperature of 250°C, exhausted gas controlling stall, and a conveyor belt to collect bare board, has been used, and the capacity is 800 kg per day [22].

3. Future trends toward sustainable waste PCBs recycling

3.1 From simple recycling to deep recovery

More attention was paid to copper recycling from waste PCBs in the past. Currently, some focuses are emerging, for instance, of a changing from easy recycling to deep recovery. Precious metals should be recovered in an environmentally sound manner based on the past experience and lessons of hydrometallurgy and pyrometallurgy. On the other hand, more than 70% wt of nonmetallic material generated from mechanical treatment of waste PCBs should be recovered, if not easily disposed such as incineration. Actually, many products made with nonmetallic material have been developed with the support filler, to reduce the cost and enhance the performance [23-25]. It means that superior performance fillers play a key role in high-tech material areas. However, the products generally cannot be sold well, which mainly are subject to two sides: one is the lack of high environmental performance and technical performance, the other is little recognition by market. Therefore, new product and smooth market will be developed in the future, toward the nonmetallic material utilization.

3.2 From dismantling to disassembling

Dismantled PCBs assemblies have a significant environmental impact because they contain heavy metals and halogen-containing flame retardant, such as lead (soldering tin), mercury (switches, round cell batteries), cadmium (pins), brominates and mixed plastics that can seep into the environment if not properly managed. Cell batteries may ignite or leak potentially hazardous organic vapors if exposed to excessive heat or fire. Explosion may result if a capacitor is subjected to high currents and heating. Thus, in this process, round cell batteries and capacitors that are large or contain polychlorinated biphenyl should be manually removed and separately disposed of in an appropriate way. Circuit boards can then be sent to a facility for further dismantling (for reuse or reclamation from ICs which contained precious substances or soldering tin) and copper recovery (from bare board) works. Hg switches are being phased out. The main sources of Hg and Cd are accumulators on PCB assembly [26].

While the melting of soldering tin could lead to the separation and recycling of electronic components, in addition to the melting of soldering tin, the mechanical strength of the pin which is packaged to the through hole is another key factor in separating the components. The strength required to disassemble electronic components depends on the number of pins, their arrangement, and mass. For THD packaging, the strength needed to successfully disassemble components is dependent on factors like liquid adhesion of the solder tin, mass/gravity of components (in favor), and bending resistance of the pin inserted in the through-hole. The resistant strength against dismantling is influenced by the adhesion force of the liquid solder tin (if heated) and the mechanics of the bend of the pin. When heating soldering tin, the strength induced by the superimposed layer consisting of compounds having certain Copper/Tin ratios is transferred into adhesion strength located in welding sites. So disassembling of waste PCBs is possible to remanufacture the electronic components.

Typically, past researches have focused on printed wiring board treatment via dismantling of PCBs. The purpose of dismantling is to remove the electronic components, which can decline the following processes for printed wiring boards. These processes can often lead to damage the electronic components. Therefore in the future, a significant shift should be from dismantling for recycling of printed wiring boards, to disassembling for remanufacturing of electronic components, which will indicate that a full recycling covering all the aspects of waste PCBs is shaping.

3.3 A new fate paradigm of waste PCBs in consumer electronics

Based on the previous analysis, a new fate paradigm of waste PCBs is drew towards sustainable industry of consumer electronics, illustrated in Fig.3. When consumer electronics approach the end of life, some products can be reused for consumption again, some products or waste PCBs can be disassembled for remanufacturing, some can be dismantled for following recycling, some can be recovered for raw material, and others should be disposed.

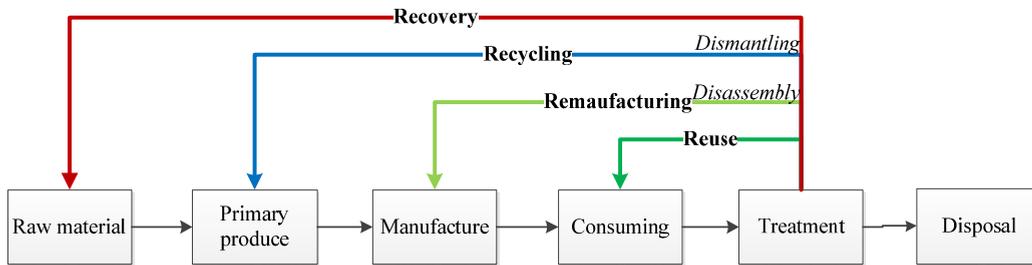


Fig.3 A new fate paradigm of waste PCBs in consumer electronics

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