A Review on Printed Circuit Boards Waste Recycling Technologies and Reuse of Recovered Nonmetallic Materials

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Abstract— From the use of renewable resources and environmental protection viewpoints, recycling of waste printed circuit boards (PCBs) receives wide concerns as the amounts of scrap PCBs increases dramatically In recent years there has been increasing concern about the growing volume of end of life electronics and the fact that much of it is consigned to landfill without any attempt being made to recycle the nonmetallic materials it contains. The production of electric and electronic equipment (EEE) is growing rapidly in most developed countries. Waste of electric and electronic equipment (WEEE) is significantly increasing. A large amount of nonmetallic materials in printed circuit board (PCBs) are disposed of by combustion and disposal in landfill as the main method for treating nonmetals in PCBs, but it may cause secondary pollution and resource wasting. Therefore, it is urgent to develop a proper recycling technology for waste PCBs. Several recycling technologies and potential reuses of recovered nonmetallic PCBs were reviewed in this paper. From the review, it can be said that, PCBs recycling process usually includes three process which is pretreatment, physical recycling, and chemical recycling and the recovered nonmetals were used to make models, construction materials and composite boards. The PCB nonmetal products have better mechanical characteristics and durability than traditional materials and fillers. Products derived from PCB waste processing have been brought into industrial production. The study shows that PCB nonmetals can be reused in profitable and environmentally friendly ways.

Keywords— printed circuit board, nonmetallic, recovery, precious metals, recycling technology

Introduction

Waste of Electrical and Electronic Equipment (WEEE) is a diverse and complex in terms of materials and components make up as well as the original equipments manufacturing process. In Malaysia, a cumulative total of 403.59 million units of WEEE have been generated in year 2008 and total of 31.3 million units has been discarded in the same year. Printed Circuit Board (PCB) form about 3% by weight of the total amount of WEEE and it contains nearly 28% metals and almost 70% non metallic materials. Discarded PCBs are also categorized as hazardous waste and it being listed under SW 110/ SW 501 by Department of Environment (DOE). The production of electric and electronic equipment (EEE) is growing rapidly in most developed country such as in China, Cambodia, India, Thailand and also in Malaysia. In Malaysia, the growth of electric and electronic industries has also increased 13% from year 2000 to 2006 [1] in their inventory report that the amount of WEEE will be increase by an average of 14% annually and by the year of 2020, a total of 1.17 billion units or 21.38 millions tons of WEEE will be generated.

Printed circuit board (PCB) is one of the most common components inside EEE at which without it, those electric and electronic instruments cannot function properly[2,3]. Recycling of PCB is an important subject not only from the treatment of waste but also from the recovery of the valuable materials [4,5]. PCB is particularly problematic to recycle because of its heterogeneous mix of organic materials, metals and glass fibers [5,6].

The dust produced due to that process is basically consist of metals and non metallic materials [4, 5, 7]. The problem is generally focused on the non metallic materials since it is being noted by Department of Environment as hazardous and being listed under SW 501/ SW 110. Since it contains chemical hazards [8], hence it needs to be disposed at licensed scheduled waste disposal site which is Kualiti Alam Sdn. Bhd. The problems arise as the cost of disposal of these hazardous residues is so expensive. Kualiti Alam Sdn. Bhd charge RM150 / tonne of PCB together with other charges including cost of packaging, segregation, transportation and others. In stead of that, these residues are capable to give risk to the human health and surrounding environment if it is not being properly managed [8]. Menad et.al.[9], cited that once PCBs are being filled, it will poses significant contamination problems at which the landfills will leach the toxins into the

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groundwater.

Due to that, this research will be conducted in order to cater those problems by reviewing the potential reuse of recovered nonmetallic PCBs for the production of economic valuable products and the recycling technologies involved. This can be achieved by studying the life cycle of PCBs generation as well as its potential reuses. This research is potentially significance since it can help in minimizing the amount of PCBs generated through materials recovering process and at the same time can reduce the negative impacts towards the environment and human health. This research is expected to provide significant proves that the scrap PCBs are highly potential to be reused, recycled and recovered by means of production of non hazardous product that is safe and publicly acceptable.

Compositions of Printed Circuit Boards

Guo et.al [4] had classified that printed circuit board (PCB) form about 3% by weight of the total amount of WEEE. PCBs are electronic circuits created by mounting electronic components on a non conductive board and creating conductive connections between them [10].The creation of circuit patterns is accomplished using both additive and subtractive methods. Lee et.al. [3] and Li et.al. [6] clarified that the typical circuit board is made of epoxy resin, fiberglass and copper. They also cited that usually bromine fire retardant is added to the resin to increase the fire resistance. The conductive circuit is generally consisting of various metals. He et.al. [11] and Veit et.al. [12] had found out that generally PCB scrap contains approximately 40% metals, 30% plastics and 30% ceramics. The typical metal scrap in PCB consists of copper, iron, tin, nickel, lead, zinc, silver, gold and palladium. The copper and other precious metals contained therein make it a potentially recyclable material [3]). In fact, the copper mainly is the most interesting metal and it can be use as a secondary raw material because of its relatively high content compared to the corresponding content in explorable ores. There are three basic varieties of PCBs which are single-sided, double-sided and multi-layered [10, 13]. The spatial and density requirement and the circuitry complexity determine the type of board produced. The choice of manufacturing materials used for PCBs also depends on the application. PCBs contain nearly 28% metals and almost 70% non metallic materials [4, 14]. Non metallic materials of PCBs mainly consist of thermoset resins and reinforcing materials [4, 5, 7] that make it challenging and problematic to be recovered or recycled. Hence, it has zero values and always become end wastes that will be dumped at the disposal site. However, this action will create secondary pollution and cause resource wasting. PCBs are being manufacture through 5 processes. Jacobs Engineering Group (1990) classified that the manufacturing processes involved are cleaning and surface preparation, catalyst application and electroless copper plating, pattern printing and masking, electroplating and etching. After being manufactured, PCBs will be used in most electrical appliances but until certain time, they will meet their end of service life. Rather than being disposed directly, it will be better for non useful PCBs being recycle or recover.

Recycling Technologies of Printed Circuit Board

Recycling process for waste printed circuit board includes three process which is pretreatment, physical recycling, and chemical recycling. PCBs recycling generally start from the pretreatment stage, which include disassembly of the reusable and toxic parts using shredding/separation and then PCBs are treated using physical recycling process. In the end, materials are finally recovered after chemical recycling process that consists of pyrolysis process and gasification process. While, metal fraction can be treated by pyrometallurgical, hydrometallurgical, or biotechnological process [14].Through shredding and separation process, PCB boards are reduced into small sized particles and can be separated by various separation methods such as physical or chemical refining process. In physical recycling process, magnetic separators, low intensity drum separators are widely used for the recovery of ferromagnetic metals from non-ferrous metals and other non magnetic wastes. While, Electric conductivity bases separation such as Eddy current separation [15,16], Corona electrostatic separation [16] are used to separate materials of different electric conductivity such as non ferrous metals from inert materials.[8,18]. This Eddy current separation technology is also used to recover metals, which consists of approximately 28% by weight of a typical PCB scrap [19]. Other than that, Density based separation of particles [8] such as sink-float separation [20] is also used to separate metal from nonmetallic materials in PCB scraps. Hence, it can be said that, physical recycling reported a great potential and a promising recycling method without environmental pollution, lesser investment, operation cost and low energy cost [21]. However, the separation between the metallic and nonmetallic materials in PCB waste has to be enchanced.

Typical chemical recycling process consists of pyrolysis process [9] and gasification process [22]. Pyrolysis actually degrades the organic part of the PCB waste, making the process of separating and recycling the organic, metallic and glass fibre in PCB much easier. One of the main ingredients in PCB scrap, resin is originally produced from crude oil and can be thermally cracked into fuels or petrochemicals. So, it can be seen that, pyrolysis is an economical and environmentally sound resource recovery alternative to treat PCB scraps [23].

Recycling of metallic fractions in PCB can be done through metallurgical recovery. It has been recently reviewed by Cui, 2008 and underlines three approaches which are pyrometallurgy, hydrometallurgy and biometallurgy.

Traditionally, pyrometallurgy technology has been used for recovery of precious metals from WEEE to upgrade the mechanical separation which cannot efficiently recover precious metals. However, pyrometallurgical processing has its own limitation. It results in a limited upgrading of the metal value and hydrometallurgical techniques or electrochemical processing are required for refining.

Hydrometallurgical processes are mainly used for recycling of the metallic ferrous materials in PCB where the extraction of the metal content is profitable [24]. Jianzhi et. al [19] has reported in their studies that different hydrometallurgical processes can be used depending on the substrate material (ceramic, glass, or polymer). They also stated that, for nonmetallic substrates, metals are recovered from substrates by the process of leaching in the resulting solution. While for metallic substrates, electrochemical processing can be used to recover metals. Thus, a pure metal recovered can be sold without any further processing while the remaining nonmetallic substrates still need to be treated thermally prior reusing or dumping in landfills. Hydrometallurgical method is also said to be more exact, more predictable and more easily controlled compared to pyrometallurgical processing.

Biometallurgy has been used for recovery of precious metals and copper from ore for many years [25,26] but biometallurgy used for recycling waste PCBs is still in its infancy. Biometallurgy is one of the most promising technologies in metallurgical processing. Microbes have the ability to bind metal ions present in the external environment at the cell surface or to transport them into the cell for various intracellular functions. This interaction could promote selective or non-selective in recovery of metals. Bioleaching and biosorption are the two main areas of biometallurgy for recovery of metals. Bioleaching has been successfully applied for recovery of precious metals and copper from ores for many years.

However all the processes mentioned above are being done in order to collect the precious metals on that board and reuse it for other purposes. The remaining is the non metallic materials that usually being dumped in landfill. In Malaysia, there is still no suitable process that being use to recover, reuse or recycle this non metallic materials. However, in China, these non metallic materials had been used to produce reproduction of non metallic plate, RNMP [4] and it is proven that the end product capable to generate economic value. RNMP is a kind of composite plate, consisting of non metallic materials of scrap PCBs, bonding agent, reinforcing materials and other additives [4]. In stead of RNMP, non metallic materials also being used as a replacement of wood flour in a production of phenolic moulding compound, PMC [4,27]. PMC is being widely used to manufacture products like saucepan handles and electronic switches. All these products are capable to be commercialized in the market.

Recovered Nonmetallic Materials from Waste PCBs

The recovered nonmetallic material has been used in several ways based on the physical characteristics of the nonmetallic powder. In this paper, a few potential reuses of recovered nonmetallic PCBs have been reviewed.

Many previous applications have used the recovered nonmetallic materials as filler or for concrete and various framing materials. The recovered nonmetallic PCB powder is lighter than cement and sand, has finer granuality which makes the microstructure more reliable, and contains coarse glass fibers which could improve mechanical strength of the materials. Yokoma and Iji [28] have carried out many studying works on recycling glass fiber and resin powder taken from PCBs. In their studies, nonmetals reclaimed from waste PCBs could be as fillers for other products, such as construction materials, decorating agent, adhesives and insulating materials.

Apart from that, Guo and Xu [29], and Guo et al [30] from Shanghai Jiao Tong University have also developed a technique to utilize the nonmetallic PCBs materials in production of Nonmetallic Plate (NMP). In their study, Unsaturated Polyester Resin (UPR) was used as the bonding agent [4] due to its low viscosity, fast cure, excellent chemical resistance, and low cost [31]. In their study, the content of nonmetallic PCBs and filler materials was kept at a constant value of about 60 wt%. The Cu particles and non-metallic PCBs after two-step crushing and electrostatic separating are shown in Fig. 1. The nonmetallic PCBs were added to the raw materials mixture at weight fractions of 0 to 40%. To complete the curing process of UPR, additives were added and tert-butyl perbenzoate (TBPB) was added as the initiators. The glass fibers used were 25mm length [4]. Table 1 shows the raw materials of the NMP used in the study. The production process of NMP is shown in Fig. 2.

The application of nonmetallic PCBs waste does not stop until here. Mou et al [32] used the NMP to produce composite boards. Composite boards are used extensively in many fields including automobiles, furniture, amusement equipment, and decorative materials. The main components used in this composite boards are as listed in Table 2. The most attractive aspect of making composite boards from PCB nonmetallic materials is the potential economic benefit because the recovery not only recycles waste PCBs but also earns a profit. In general it can be said that, products made from composite boards are high value products with large profit margins. A wide variety of products can be made from composite boards for various applications such as trays, kitchen utensils and so on. The most important and useful characteristics of the recovered nonmetallic material is their compatibility with the epoxy resin adhesive used to bind the filler and the fibers, so the nonmetallic PCB has better compatibility with the resin adhesive which suggests better moulding properties and mechanical strength [32]. They used different proportions of nonmetallic PCB in their studies and compared it with the two typical materials used for making composite boards which are talc and silica powder. Their research showed that the outstanding characteristic of the nonmetallic material board is its flexural strength, which was enchanced by more than 50% for the 15% blending ratio when compared with talc. Therefore, they concluded that this charcteristic is good for products that mainly bear bending stresses.

Moreover when compared with talc and silica powder, PCB nonmetals have three main advantages such as, coarser granularity, containing glass fiber and better compatibility with the binding agent used in making composite board. Coarser granularity and glass fiber may enhance the intensity.

Analysis of the mechanical properties conducted by Mou et al [32] indicates that the nonmetallic PCB can best be used to make products which resulted in greater bending stresses because of its excellent flexural strength. The process used to make composite boards from the nonmetallic PCB was also used to make the other construction materials including walls, frames .Steel fiber concrete and glass fiber reinforced plastic (FRP) are two commonly used materials to make construction materials. The main advantages of these products made of PCB nonmetallic are lower in cost and better mehanical strength, especially the flexural strength. Moreover, these processes which make use of PCB nonmetallic materials is a better alternative rather than be sent to landfills.

Nonmetallic PCBs are also used to replace wood flour in the production of wood plastic composites. In analogy, addition of nonmetallic PCB as reinforcing fillers in polypropylene has proven to be an effective way to enhance strength and rigidity with particles size between 0.178-0.104 mm [30]. Modified silane coupling agent, could be successfully added in the composites as a substitute of traditional fillers.

As one of the plastic wastes to a certain extent, the non-metallic PCB can also be used with some effectiveness as a partial replacement of inorganic aggregates in concrete applications to decrease the dead weight of structures. According to Panyakapo and Panyakapo [33], lightweight concrete is extensively used for the construction of interior and exterior walls of buildings for the case where the walls are not designed for lateral loads. In their recent study, they have used thermosetting plastic waste for lightweight concrete. The melamine waste, which is also a kind of thermosets used in PCBs was selected for application in the mixed design of concrete. They found that the ratio of cement, sand, fly ash, and melamine waste equal to 1.0:0.8:0.3:0.9 is an appropriate mix proportion. The results also showed that compressive strength and dry density are 4.14N/mm^2 and 1395 kg/m^3 respectively. It has been proven in their study that, this type of concrete meets most of the requirements for non-loading bearing lightweight concrete according to ASTMC129 Type II standard. Their study indicated that use of waste thermosets of PCB to produce lightweight concrete is a promising method. The nonmetallic PCBs waste is a mixture of waste thermosets, glass fibers and other components, therefore, it can replace the melamine waste to produce lightweight concrete.

Another study by Guo et al [34] also indicated that, the glass fibres and resins powder contained in the non-metallic PCBs can also be used to strengthen the asphalt by composition effect. Adding of the nonmetallic PCBs to asphalt can also reduce the cost of asphalt whose usage amount is very large. This is because, it is more economic since the cost of the nonmetallic PCBs waste can be considered as zero because they are unwanted waste otherwise would be expensive if sent to disposal or treatment.

Conclusions

A successful recycling approach of PCB should take into consideration the separation of the recycled items to compensate for recycling costs. Recycling of PCB in particular, is still a challenging task due to complexity of these materials and possible evolution of toxic substances. This paper describes several PCB recycling technologies and potential methods for reusing recovered nonmetallic from waste PCBs. The nonmetallic PCB can be reused in construction materials, to make models, in composite boards, and in practical products. Although these applications are said better than landfills and incineration, but many improvements are still needed to futher study the potential reuse of this nonmetallic PCB waste into more profitable and practical use. From this review also, it can be seen that using recovered PCB nonmetallic material to make composite boards and related products will be effective solutions for recovering nonmetallic materials of waste PCBs and reduce resource wasting. Developing new techniques for reuse of recovered PCB nonmetals can also help in resolving the environmental pollution associated with the recycling of PCBs and the adopt a more sustainable approach to problems associated with end of life electronics.

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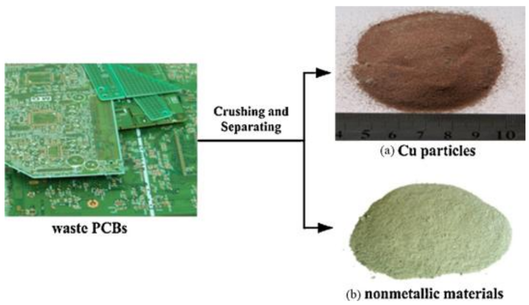

Fig. 1. Metallic fractions (a) and the Nonmetallic fractions (b) of pulverized waste PCBs (Guo et al., 2008)

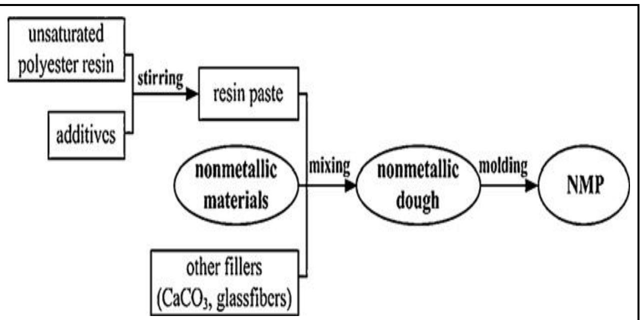

Fig. 2. Flowchart of preparation of the NMP (Guo, 2008)

TABLE 1
Raw Materials of the NMP (Guo, 2008)

Ingredients	Content (wt%)
Nonmetallic fraction	0,10,20,30,40
$CaCO_3$	64,54,44,34.24
Unsaturated Polyester	18
Polystyrene	6
TBPB	0.2
Glass fiber	10
Zinc stearate	1

TABLE 2
Main components in composite boards (Mou et al., 2007)

Ingredients	Ratio (wt %)
Glass fiber cloth	30-45
Epoxy resin	35-40
Fillers	5
PCB nonmetals	15-30

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