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Proper disposal treatment for printed circuit board waste: the developoment of pyrolysis based recycling technology

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Abstract—**Disposal treatments of printed circuit board (PCB) waste recently seem to be improper since they all produce a secondary pollutions such as acidification of the soil and heavy metal leached into ground water from landfill and toxicant gasses generates from incineration and material combustion. At present the disposal treatment processes for nonmetallic fraction from PCB waste that have been separated after precious metal separation process are only combustion, landfill and material reused. The most important point is that this nonmetallic fraction from PCB waste can be recovered. Hence, this is a challenge to expose a further separation of materials and materials recovery. From the environmental friendly viewpoint, the only solution to reduce PCB waste problem sustainably is to address the waste material with a proper material recycling technology. The purpose of this study is to determine the suitability of using pyrolysis based recycling as well as to demonstrate its development to be able to process with NMF from PCB. Moreover, the aim is to point out that pyrolysis method can be used as PCB waste disposal treatment and show that now it is an sustainable alternative disposal option for the PCB waste material.**

Keywords—PCB waste, printed circuit board waste, recycling treatment, PCB waste disposal, pyrolysis based recycling, pyrolysis of PCB,

I. Introduction

The rapid uptake of the information and communication technology (ICT) and the increasing demand for consumer electrical and electronic equipment (EEE) have led to a significant expansion of how to dispose environmental friendly in their product end of life. Printed circuit board is an essential and basic part in EEE. It is a complex mixed of materials with diversity and causing a difficulty of how to separate material from each other's. Basic materials consisted in PCB can be classified into two categories which are metallic and nonmetallic. Basically, metallic materials of PCB such as silver, gold, copper and are usually separated and recycled because they always have higher value and can be recovered to like new materials. Whereas, the NMF from PCB waste is usually left over and sent for conventional disposal treatment which creating secondary pollution except material reuse as filler which not a sustainable way of waste disposal in the long run.

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NMF of PCB waste is extreamly difficult to separate and dispose because it consists of variety of material with a complex mixed and diversity. Thermoset plastic, ceramic and glass reinforced fiber are three basic elements in NMF and often containning additive chemical substrates such as brominated flame retardant or BFR. By incineration, it can generate toxicant gases during heating process such as polybrominated dibenzo dioxins (PBDD), dibenzofurans (Fs), dioxins and etc. chemical substrates such as brominated flame retardant or BFR. By incineration, it can generate toxicant gases during heating process such as polybrominated dibenzo dioxins (PBDD), dibenzofurans (Fs), dioxins and etc.

All three basic materials of NMF can be confirmed as recyclable material if they can be separated from each other. From the technical perspective, it is very difficult to separate each of the material from NMF of PCB. However, with the differential of thermal properties of each material would assist and enabling the material separation for NMF.

II. Status of PCB waste problem

A. *E-waste*

At present, electronic waste (E-waste) is one of the fastest growing solid waste streams globally. In European Union was reported that the growing rate for E-waste is 3-5% per annum on average and that is about three times faster than other individual waste streams. One area that has been much concern about is the lack of sustainable in production, use and disposal of electrical and electronic equipment (EEE), which generate E-waste and cause the problems. The electronic industries provides the devices that have become so essential to modern way of life whilst the product life is so short along with the time that new design or technology has launched into the market. With the products increasingly having short life cycles, including hazardous material and generate waste during manufacture and at end of life, this now become a waste problem. United nation estimate that collectively the world generated 20-50 million tones of e-waste every year. A broad range of goods is classified as electrical and electronic equipment, including large and small household appliances, information and technology equipment including computers, computer games, cellular phone and telecommunication equipment, portable electronic devices and etc. as shown in following Table I and classification of material found in e-waste are ferrous 38%, Non-ferrous 28%, Plastic 19%, Glass 4%, Wood 1% and other about 10%.

TABLE I. MAJOR CATEGORIES OF ELECTRICAL AND ELECTRONIC EQUIPMENT

Equipment	*Units (Million)*	*Weight (X1000 tones)*	*% of total*
Househole appliances (Large)	10	392	43
Househole appliances (Small)	15	30	3
IT equipments	22	357	39
Telecommunications	7	8	1
Radio, TV, Audio	12	72	8
Lamps	77	12	1
Monitors and controls	8	8	1
Toys	8	8	1
Electrical and electronic tools	6	28	3
Total	165	915	100

(Information adapted from Babu et al., (2007)

B. *PCB waste*

From the perspective of its material composition, printed circuit boards are particularly problematic to recycle be cause the heterogeneous mix of organic material, metal and glass fiber. PCB waste is complex as far as its materials are concerned and it is therefore to identify and quantify potentially reusable material in order to achieve a better understanding of the complexity of PCB waste and to be able to develop an effective and environmentally friendly material recycling system. Platform of PCB are usually thermoset mainly brominated epoxy resin, this material containing high amount of glass reinforced fiber in order to reduce cost and aim to improve its strength. These thermoset plastics are organic compound naturally and can be recover by thermo conversion process of material. Moreover, the hazardous substance content of PCBs can generate high processing costs, depending on the elimination or techniques require in each case. This is the reason why there is a wide range of studies that focus on the hazardous element elimination of PCB material and concern as it is a very hard to be disposed. The substances can be added into plastic material of PCB such as pigments, flame retardants, stabilizers and plasticizers. PCB platforms are usually thermoset composites, which mainly brominated epoxy resin while containing high amount of glass reinforcement; in TV and home electronic equipment PCBs are often made with paper laminated phenolic resins. Lately Bio based composites have been proposed as substitute of traditional resin used in PCBs. Typical PCB has the following approximate material composition, which are glass reinforced polymer 70% and metal such as Copper 16%, Solder 4%, Iron, ferrite 3%, Nickel 2%, Silver 0.05%, Gold 0.03%, Palladium 0.01% and other (bismuth, antimony, tantalum etc.) < 0.01%.

C. *Incorrect disposal activity*

The most serious environmental impacts related to PCB waste are tied to the incorrect disposal activities performed in those developing countries. Open frame burning of PCB to separate metallic material, landfill and incineration to get rid of PCB waste can cause environmental problems such as toxicant gasses can be generated, solidification of the soil and heavy metal leaching into ground water and not sustainable at all. PCB wastes lately present a growing disposal problem owing to the substances included that may cause a serious damage to the environment and have adverse effects on human health. Therefore, The management of this waste must be done properly.The significant issues with landfills and combustion of PCB waste as aforementioned data and while PCB boards comprise of 3% by weight of waste electronic and electrical equipment (WEEE), this mean vast amount of PCB waste need to be process with a proper recycling plan. Landfilling, incineration or reused the material as a filler are not sustainable solution for the problem and they seemed to be lack of material utilisation.

III. Development of the pyrolysis based recycling for PCB waste

Nearly all of the current recycling technologies available for WEEE and PCB recycling include a sorting, separating and disassemble stage. The reuse components have first priority; remove the hazardous and danger component s before reprocessing is an essential as well as separate highly valuable component. Electronic components have to be dismantled from PCB assembly as the most important step in their recycling chain, to help conservation of resources, reuse of components and elimination of hazardous materials from the environment.

A. *Pyrolysis of material as fuel oil*

Pyrolysis is the thermo conversion process for the organic compound, during the pyrolysis process the organic part of the material can be decomposed to low molecular weight product gasses and can be condensed into a liquid form which can be further used as fuel or feed stock. Whilst inorganic part of PCB such as glass reinforced fiber, metal contents and ceramics retain unmodified and can be further processed for material recycle. There are several types of pyrolysis such as vacuum pyrolysis TGA based pyrolysis, atmospheric controlled pyrolysis and a range of different reactors such as vacuum, screw kiln, rotary kiln, fixed-bed (batch) and fluidized-bed. They all use the same method by following the principle with non-participating of oxygen whilst heating material inside the reactor. Nevertheless from the past research the pyrolysis of material usually use operating temperature in the range of 380 °C-600 °C depending on material decomposition temperature. Vacuum pyrolysis seems to have the more advantage among other types of pyrolysis techniques because the short residence time of gases of the converted organic compound in the reactor and the steam oil left from condenser unit can be used as return fuel to circulate the system so that means the reduction of input energy for the process. Moreover, Pyrolysis oil has a wide variation of chemical and physical properties, because of variation in application of usage and processing conditions. Pyrolysis oil is difficult to produce and upgrade to achieve the best and optimal yield and quality, and different researchers had different level of success according to the variation in processing such as operating conditions, materials, parameter control and etc. In spite of these differences, parameters setting and control may be considered as the main effects to success of making the pyrolysis oil from organic material with best yield and optimum quality

B. *Pyrolysis of PCB waste*

Pyrolysis designates a thermal decomposition of NMF separated from PCB waste in absence of any gasification or reaction agents like oxygen, carbon dioxide or steam. At temperatures beyond 240-550 °C, long-chain or cross-linked hydrocarbon molecules are converted into pyrolysis products gas, oil (condensable, liquids) and char (pyrolysis coke, solid residue). However the operating temperature is depending on the type of material to be process with pyrolysis system. These products can be used as source for raw materials in chemicals industry or for generation of energy. Obviously, pyrolysis is a starting and accompanying process of any thermally driven chemical conversion method, as are combustion, gasification and hydrogenation. Nevertheless, it is also a process in its own right for production of liquids and char. Pyrolysis is still under development, and such processes have been developed intensively over recent years with respect to conversion of solid fuels like coal or biomass, as well as of waste materials.

Unlikely, PCB waste is not same as other plastic waste material. It contains brominated flame retardants (BFR) and other additive to improve their product property. In this case, it need to be concerned if the BFR content and other product additive would affect on the quallity of the pyrolysis output product gases and oil or not and how it affect to the environment.

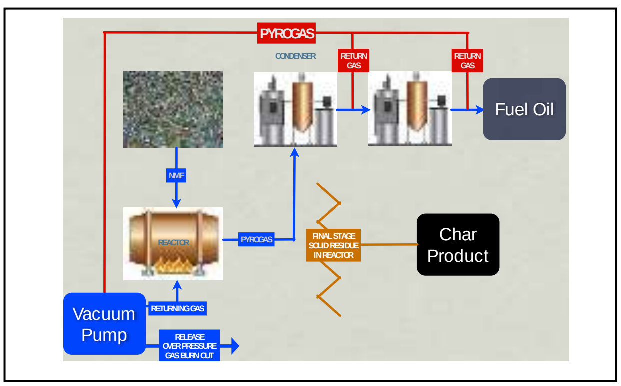

Figure I. Vacuum pyrolysis system draft model

A good design of experiment (DOE) should be based on standard scientific protocols in order to be able to generate a reliable statistical data in parallel with a minimization of any variation within the experiment. The DOE for this research takes account of defining objective of the experiment, selecting the dependent and independent variables, selecting equipment and instrumentation, and determining a number of data points needed for each type of measurements. Table II. Shows the selected variables, which consist of independent variables, and control variables.

- **Temperature** is a key factor for polymer reaction. Only process temperature that can ensure the polymer decomposition. On the other hand, the temperature could not be too high to avoid the polymer burnt out.
- **Pressure** is another factor that need to be considered because under high pressure the solubility is increased which would improve the efficiency of the system.
- **Time**: to save energy and reduce cost short time is desired. The experiment is expected to carry out to find the suitable processing time.
- **Catalyst:** to achieve the highest yield of the process the peocess may need catalyst or chemical media additive inorder to enhance the chemical reaction.

TABLE II. SELECTED EXPERIMENTAL VARIABLE

Selected experimental variable	
Type of variable	***Selected variable***
Independent variables (Factors studied)	Catalyst applied, Temperature, Time and Pressure
Dependent variables (Respond variable Y)	Liquid yield (Fuel oil)
Comtrol variable	Input material (NMF), Particle size, Batch size, Pyro-gas treatment, Reactor temperature

To clarify the parameters, Input factors (Independent variables) and response (dependent variable) are defined. The values of response variable are assumed to depend on the values of the input factors.

Respond variable Y= Liquid yield from pyro gas condensing unit, kg

Factor A = Processing time in condenser

Factor B = Pressure in condenser

Factor C = Temperature used in condenser

Factor D Catalyst used to blend with NMF (BFR reduction)

Control group as present in Table III. These control variables will not be changed throughout the test in experiment because the effect of these variables being changed is not the interesting subject for this particular experiment. The control variables have to be kept constant so as to minimize their effects on the result as presented in Table III.

TABLE III. ASSIGNING VALUE TO CONTROL VARIABLE

Control variable	***Assign values***
Input material (NMF)	125µ- 177µ <1% of metal content
Batch size	1kg/cycle
Pyro gas treatment	Gas condensate
Reactor temperature	380-500 °C

Choosing and sampling groups are very important since there are more than one condition in the experiment. Four factors are considered as main effects that influence on the result output liquid fuel. Temperature, time, pressure and type of catalyst are set into 4 levels of interest. It is interesting to test the process behavior to get the optimal condition of this pyrolysis system. The experiment is designed to conduct with the four levels of each factor as followed. Temperature is set to be 300 °C,200 °C, 100 °C and room temperature at 30 °C respectively with 20 °C differences on each condenser. Pressure is assigned to be 10 Pa, 20 Pa, 30 Pa and 40 Pa. and Time are set to be 30 mins, 60 mins, 90 mins and 120 mins processing time. Catalyst and chemical additive use in this experiment is desire to enhance the hydrocarbon reaction and formation such as Iron (Fe), Calcium (Ca), Calcium carbonate ($CaCO_3$) and Carbon (C).

Measuring and analysis tools are undertaken by tool as listed in Table IV.

TABLE IV. LIST OF MEEASUREMNT AND ANALYSIS TOOLS

Measuring and analysis tools	***Parameters***
Themogravimetric analysis	Proximate operating temperature
Bomb calorimeter	Heating value of raw material and output
Themogravimetric analysis	Initiate pyrolysis behavior
Gas chromatography	Pyro gas analysis
Inductive couple plasma	Heavy metal content in liquid output

IV. Results and discussion

As the most potential approach for PCB recycling, the pyrolysis techniques still need a high level of skill and equipment. Meanwhile, those primitive treatments for the overabundant amount of PCB waste generated per year are not sustainable. From past research indicated that the pyrolysis process is able to recover organic part of PCB into flammable liquid and gases thus these could be potential approach for PCB recycling. However the flame retardant in PCB may affect on the quality of the output, this aspect need to be further investigated. The current treatments for non-metallic material form PCB are absolutely improper, causing the second pollution and resource wasting. The results of this case study indicated that pyrolysis is seemed to be a challenge for proper recycling treatment for non-metallic material from PCB waste.

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