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Mechanical and thermal characterizations of non-metallic components recycled from waste printed circuit boards

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In the framework of reuse of non-metal (woven fiberglass layers (WFG) and epoxy resin (ER)) recovered from waste printed circuit boards (WPCBs) as received and maximization of economic and environmental benefits, this research aims to investigate mechanical and thermal properties of recycled woven fiberglass and ER extracted from WPCBs after separation by using chemical (organic solvent) and ultrasonic treatment The experiments were conducted on five samples cut from five different types of waste motherboards according to ASTM D5035 standard. Also, another sample not containing any notches or holes was cut from a blank PCB in order to be used as a reference for strength tests when compared with motherboard samples. Di-methyl formamide (DMF) was used to dissolve ER of all six samples at a low temperature in a simple reactor developed specifically for this purpose (WPCB separator). The new separator was equipped with a high-frequency ultrasonic wave generator used to accelerate the rate of breakage of internal van der Waals' bonds of brominated epoxy resin (BER) by DMF thus reducing the dissolution time and facilitating separation of woven fiberglass layers against metal layers. After that, a rotary decompression evaporator was used to extract ER from DMF/ER solution. Universal testing machine was used to characterize mechanical behavior of recovered woven fiberglass, while thermogravimetric (TG-DTG) and calorimetric analyses (DSC) were used to investigate the thermal behavior of recovered ER. The results showed that the average strength of recovered fiberglass decreased by 48% in comparison with the blank PCB due to the presence of notches and degradation while the reduction in elastic modulus was slight. Also, the recovered ER showed high properties in terms of melting temperature and crystalline degree.

1. Introduction

1.1. Global challenges of electronic waste

Waste electrical and electronic equipment and end of life vehicles are two of the main sources of solid waste (after municipal solid waste), in terms of both volume and growth rate (Rosa and Terzi, 2016). Furthermore, the estimated annually generated volume of electronic waste (e-waste) around the world has been increasing expeditiously, being 65.4 million tons in 2017 compared to 49 million tons in 2012 (Lu and Xu, 2016). This significant rise in the quantities of waste is a result of a rapid growth in electronic industries and decrease of the average lifetime of electronic products. The problem of e-waste receives considerable amount of attention and a number of solutions was proposed from the management side to address it (Li et al., 2015). The waste printed circuit boards (WPCBs), being currently one of the most relevant types of e-waste in terms of recycling potential, represent a relatively small share of e-waste – around 3%. Additionally, according to the analysts and forecasts the global PCB market is growing at a compound annual growth rate of 3.43% (Awasthi et al., 2017).

1.2. WPCB composition

E-waste including PCBs is well-known as an important source of secondary raw materials (Cucchiella et al., 2016). In case of WPCBs, content of non-metal (woven fiberglass and epoxy resin)

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represents 70% of their weight while the rest consists of various metals (Shen., 2006; Cayumil et al., 2016). Therefore, at the beginning of this century, the recycling process of WPCBs was seriously taken into account and an aim to achieve high economic and environmental benefits was pursued by many research papers. Unfortunately, most of these studies were focused on the recovery of precious metals, copper (Cu), as well as on synthesis of nanoparticles, for instance copper-tin nanoparticles from metal components, and neglected the non-metal elements due to the complexity of their recovery and lower economic benefits (Report Linker, 2015; Shokri et al., 2017a). Non-metal recovery is complicated by the fact that non-metal of WPCBs consists of 40% of organic substances (epoxy resin, brominated flame retardants, curing agents, curing accelerators etc.) and 60% inorganic substance (glass fiber made from various oxides, usually SiO_2, CaO and Al_2O_3) (Zhou. and Shang., 2004; Lin and Chiang, 2014). In terms of metal content, the average percentage of Cu in WPCBs fluctuated between 5.10% in 1980 and 12.8% in the mid-1990s and decreased afterwards. The decreases in Ag and Cu amounts could possibly be associated with thinner layers of these metals in newer models of PCBs (Adie et al., 2017).

1.3. Disposing of WPCB non-metal components

Landfilling is considered the main way of the WPCB non-metal components disposal; it is commonly used after the extraction of the valuable copper and other metal components by incineration techniques (Leyens et al., 2000). However, these methods may cause serious problems directly related to environment and human health such as: large areas of land wasted, destruction of the microbial balance of soil, negative effects on the groundwater quality and plant growth by diffusion and infiltration into the soil, harm to the atmospheric environment as a result of volatilization of the lead, arsenic (metals which are used as fillers and colouring agents in WPCBs), and non-metallic materials into the atmosphere (Guo et al., 2009).

1.4. Recycling of non-metallic fraction from WPCBs

Currently, recycling of e-waste became a necessity, not only to address the shortage of mineral resources for electronics industry, but also to decline environmental pollution and human health risk (Zeng et al., 2017). Closed-loop recycling of electronics can be a valuable tool to sustain the future development of the flourishing electronics industry (Zeng and Li, 2016). Furthermore, recycling processes have been developed in order to avoid the above mentioned problems; these processes can be classified into three categories: physical treatment, pyrolysis, and chemical processing (Guanghan et al., 2016; Ning et al., 2017). Physical treatment, including mechanical crushing, sieving, electrostatic separation, etc. refers to disposal of non-metallic components without any chemical reactions (Xie. et al., 2014; Shokri et al., 2017b). Meanwhile, the pyrolysis can be summarized as the decomposition of organic materials of WPCBs into oily hydrocarbon compounds, which can be used as a fuel or chemical feedstock (Zhou et al., 2011). Finally, chemical processing implies using organic or inorganic solvent to cleave the macromolecular reticulate structure of thermosetting epoxy resin in WPCBs (Zhu et al., 2012). Also, a new technology was developed for recovering residual metals from non-metallic fractions of WPCBs using vibrating gas-solid fluidized bed (Zhang et al., 2017). Another promising recycling approach is non-destructive desoldering of WPCBs that is an important stage for recycling of mounted electronic components (Wang et al., 2016). Additionally, some researches try to utilize by-products of PCB manufacturing by applying them for recycling of WPCBs, e.g. usage of spent tin-stripping liquid for leaching of metals from WPCBs (Yang et al., 2017).

Among the previous techniques, organic solvent methods resulted in a high efficiency in terms of recycling rate and separation of the all WPCB elements, including non-metallic ones through breakage of the internal van der Waals' bonds of brominated epoxy resin (BER) and dissolution of BER in an organic solvent thus separation of woven fiberglass layers against metal layers was achieved (Zhu et al., 2013). It is worth mentioning that the metal elements recovered, according to the reported results can be used for several applications, while recovered woven fiberglass layers have limited application since it was recovered in the form of small pieces (15–20 mm^2). Such material can be used as filler after milling in order to improve the mechanical behavior of plastic, wood, and concrete composites. Moreover, the recovered epoxy resin can be applied for the production of composite structural materials in marine, automotive, and various other industries after some additional treatment since according to the publications cured epoxy resin can still be repolymerized and recycled (Jin and Li, 2015; La Rosa et al., 2016; Iji, 1998; Dang et al., 2002). Additionally, recycled polymers from e-waste were already used to produce wood–plastic composites in the interest of resource efficiency and ecological product design (Sommerhuber et al., 2016).

1.5. Mechanical characterization of woven fiberglass

Although, woven fiberglass laminates have a good tensile strength up to 40–200 MPa and reuse of recovered fiberglass in heavy duty applications will lead to a promising results (Siddique et al., 2008; Yang et al., 2015; Zheng et al., 2009; Saiman et al., 2014; Li et al., 2014). Nevertheless, most of the previous separation studies were conducted at a lab scale and maximum size of the separated WPCBs was 40 mm × 40 mm (Verma et al., 2017a), what is the main reason for the limited applicability of the recovered woven fiberglass in composites. Meanwhile, study of the mechanical behavior of the woven fiberglass requires the minimum size of sample 150 (at least) mm × 25 mm (width) according to ASTM D5035 standard (ASTM, 2015). However, melting temperature and crystalline degree of the recovered epoxy resin is still not clear and a few studies examined these parameters, these studies also were focused on only one type of WPCBs and it might be that there is a difference between materials recovered from different types of WPCBs (Verma et al., 2017b). Therefore, this research aims to separate all layers of five WPCB samples having dimensions 170 mm × 35 mm by using a simple separator developed specifically for this purpose. Additionally, the goal is to investigate the mechanical response of the recovered woven fiberglass under directional load, thermal and chemical properties of extracting thermosetting epoxy resin in order to provide a reference for industrial development of recovery and recycling techniques for non-metallic materials of WPCBs.

2. Experimental

2.1. Materials and sample preparation

Di-methyl formamide (DMF) and pure ethanol were supplied by Sigma- 12 Aldrich Corp. Five different WPCB models were collected from a local shop in Lithuania and it was determined that all WPCBs had been taken from discarded desktop computers (produced in between 1998 and 2004) with each model having a distinctive color. In addition, another sample that didn't contain any notches, openings or mounted components was cut from a blank PCB and used as a reference as illustrated in Table 1. All electronic components mounted on the boards, such as resistors, integrated circuits,