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Direct transformation of waste printed circuit boards to nano-structured powders through mechanical alloying

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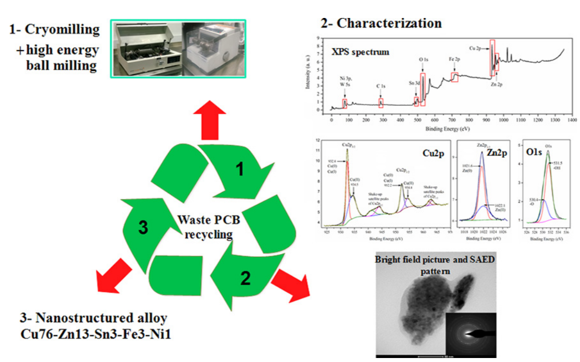
HIGHLIGHTS

- Waste printed circuit boards directly transformed to entirely homogenous nano-structured powder with grain size of 40 nm.
- XPS analyses showed the minimum formation of oxides.
- UV-Vis surface analysis confirmed the surface homogeneity.
- The powder applied as conducting agent in nanofluids.

GRAPHICAL ABSTRACT



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ABSTRACT

Identifying a solution to directly transform waste printed circuit boards (PCBs) to useful alloys will save energy, conserve our valuable resources, and contribute to preservation of our environment. In this study a solid state mechanical alloying was used to directly convert waste PCBs to a homogenous nanostructured alloy (Cu79-Zn13-Fe3-Sn3-Ni1). Electron microscopy analysis showed 10 h milling time after a short period of cryomilling was enough to obtain a homogenous alloy and SAED ring pattern confirmed the nano-structure, although just a portion of particles size of the power was in nano-scale (<100 nm). Lattice parameter, strain and grain size were calculated using XRD analysis. The grain size was 40 nm with a strain of 0.73%. High resolution XPS analysis confirmed minor surface oxidation of produced alloy. The UV–Vis analysis showed a broad peak between 350 and 650 nm indicating the chemical homogeneity of the surface. Also the calculation of input energy confirmed the formation of a nano-structured material during mechanical alloying. Finally, a promising application was investigated as nanofluid after dispersion of the synthesised powder in DI water followed by characterization of pH and conductivity variation. The conductivity of the sample was about 10 times higher than DI water. These results, for the first time, introduce a concept for directly transform waste PCBs to metallic alloys without using any heat or solutions.

1. Introduction

Modern lifestyle and people's tendency to use electronic devices in a short period of time and high consumer demand has contributed greatly

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to the increasing amount of electronic waste (e-waste). It has been reported 43.8 million tons of e-waste was produced in 2015 which is anticipated to reach to 49.8 million tons in 2018 [1]. Besides, the United Nations Environment Program (UNEP) evaluated that each year around 45 million tons of e-waste is generated worldwide which is growing annually. The increasing volume of this waste stream has forced governments to impose restricted regulations on e-waste disposal [2,3].

Waste printed circuit boards (PCBs) are regarded as a requisite part of almost all the e-waste [4]. Owing to the presence of valuable metals such as Cu, Zn, Sn, Fe, Ni and Al in high concentration as well as toxic components, plastics and ceramics in the waste PCBs structure, incorrect disposal of them not only threats the environment but also leads to the loss of valuable substances [5]. In addition, a significant amount of energy will be saved if these metals are recycled instead of being extracted from their virgin ore; i.e., the saving of 95% for Al, 90% for Ni, 85% for Cu, 60% for steel and 75% for Zn and [6]. Shokri et al. [2,5] directly transform waste PCBs into a Cu-Sn nanoparticles through selective thermal transformation. The technology of direct transforming of e-waste into valuable materials or synthesising of new materials is beneficial economically and environmentally.

Considering aforementioned facts, there have been some recycling methods such as mechanical dismantling, physical and mechanical pretreatments, pyrometallurgical and hydrometallurgical processes [7].

One of non-equilibrium materials processing techniques is mechanical alloying (MA) or mechanical milling (MM) in which the final structure of powder depends on milling conditions. However, the final product is expected to be homogenous. It has been found that, solid solutions with more than one element are more easy to form and are more stable compared to intermetallic components attributing to their large entropies of mixing reaction (ΔH_{mix}) which results in disinclination of atoms for diffusion [8]. In this method, due to frequent high energy impact which is imposed by heavy weights of balls, particles become flattened, fractured and again stick toughener or re-weld; thus, all the reactions take place in solid state, having the potential of synthesising supersaturated solid solutions. The properties of the final product depend on milling energy/intensity, ball to powder ratio, the rotation speed of mill, milling time and the type of initial materials [9].

Previous studies have demonstrated effect of MA parameters on synthesise nanostructured materials [10,11]. Olvera et al. [10] utilized MA method to produce MoZn solid solution with crystalline size of 36.2 nm using Mo and Zn powders with ratio of 1:1. Their results demonstrated increasing in lattice strain from 0.085% to 0.276% with increasing milling time. Rabeei et al. [11] produced Cu-20 wt% Fe nanostructured materials with crystallite size of 30 nm using MA process. Their results revealed by increasing milling time, lattice parameter rises and crystal size decreases with the resulting alloy of this work having lattice parameter of 0.3628 nm. The growth of lattice parameter is due to positive deviation of Vegard's law. Popov et al. [12] used nanodiamonds and Ti powders as starting materials in order to generate 22–23 nm titanium carbide nanoparticles by MA technique. Safaei et al. [13] studied the production of nanostructured Fe-30%wt% Mn alloy with crystalline size of 6 nm to study the impact of ball to powder mass ratio and milling time. Results indicated that during reaction, the lattice parameter increased from 0.28167 nm to 0.35776 nm and an increase in milling energy as well as milling time led to better solid solubility. Sesma et al. [14] milled Cu, Zn, and Al flakes with purity of 99.99% as initial materials in order to synthesis Cu-Zn-Al alloy with mixture of α and β phases. Varalakshmi et al. [8] milled Cu, Ni, Co, Zn, Al, Ti powders with purity of 99.7% in planetary ball mill to synthesis BCC solid solution CuNiCoZnAlTi alloy with lattice parameter of 0.290 nm. Sheibani et al. [15] using MA and Cu/Cr powders, produced Cu-7 wt% Cr solid solution alloy in presence of toluene as a control agent in process. Results indicated that the reduction in crystalline size occurred during milling process. In another research, an equiatomic CoCrFeNiCuAl alloy with crystalline size of 5 nm was blended by means of MA route. According to the results obtained from characterization step, the synthesis powder had high lattice strain of 1.32% and showed tremendous homogeneity [16]. The MA method was also used to produce Al–Fe–Ti–Cr–Zn–Cu single phase solid solutions with crystalline size of <10 nm and BCC structure. Based on the same route the similar nanostructured Cu–Ni–Co–Zn–Al–Ti and Ni–Fe–Cr–Co–Mn–W nanostructured alloy was synthesised. Results showed that the prepared alloys had outstanding homogeneity [17]. 10 and 40 nm Fe-Co nanostructured alloys were synthesis by MA or mechanochemical alloying (MCA) with ball milling and hydrogen reduction at 600 °C, respectively [18]. Pabi et al. [19] employed mechanical alloying as well as elemental blends of Cu and Zn with purity of 99.9% and 99.5%, respectively to synthesise α, β and γ phases in the Cu-Zn system with final crystalline size of 15–80 nm. These summaries of pervious study indicate that the MA might be a worthy alternative to produce a homogenous alloy from the metal source (Cu, Zn, Sn, Ni, Fe and Al) present in PCBs.

The synthesised nano-powders using MA can be potentially used as conductive and stable materials in nanofluids. A dilute suspension of conductive nano-particles in liquid called nanofluid [20] exhibit high stability inside the liquid and possess a higher conductivity compared to liquid. This type of fluid can be considered as an alternative media with high capacity of transferring heat industrial heat exchanger.

In this research, for the first time, using waste PCBs as a source of initial alloying powders to synthesis Cu-Zn-Sn-Fe-Ni alloy which is commonly used in range of applications where hardness, toughness and resistance to stress-corrosion is essential such as marine services [21, 22] or where the heat transfer and conductivity plays a vital roles such as nanofluids or additive manufacturing. After two steps of ordinary millings (ring milling) followed by a classification, a combination of Cu, Zn, Fe, Sn and Ni powder without any non-metallic constituent was selected for MA to produce nanostructured solid solution alloy as an advanced material. To characterize the properties of powders, various characterization methods were utilized including XRD, XPS, FESEM, EDS, TEM, STEM, UV–Vis and optical microscopy. Finally, as a potential application nanofluid were prepared and characterized using pH and conductivity measurements.

2. Materials and method

(a) Process

In this research multilayer waste PCBs (motherboard and modem board) collected from Reverse e-waste Company in Australia were used. Fig. 1 shows the whole mechanical process of the separation of the metallic and non-metallic components and producing nanostructure powder from waste PCBs. Prior to cutting, some hazardous and metallic pieces and non-metallic parts of the PCBs such as steel CPU case, capacitors and some large plastic parts were detached from the boards. These parts are readily recyclable using less effort as they are easily separable and are rich in metals or plastics.

For the mechanical milling, three types of milling machine were used; knife mill (Fritsch, Pulverisette 15, with +2 mm mesh) in stage #2, ring mill (Rocklabs, PP) with a stainless steel container in stage #3 and 5 and cryogenic mill (Mixer Mill – Retsch) with a stainless steel container in stage #7. Cryomilling was applied to shorten the process. Sieving machine (Retch, AS200 basic) equipped with different screens was used for the classification of waste PCB samples. The samples were classified into different meshes in stages #4 and #6 (Fig. 1). After stages #6 of sieving the particles bigger than 450 μm was used for MA process. In next step, for MA, a high energy ball mill (SPEX Mixer/Miller 8000D) at room temperature was used [23] with a tungsten carbide (WC) vial (5.7 cm × 6.35 cm, 55 mL) and 2 stainless steel balls (d = 11.2 mm), the clamp movement of 5.9 cm back-and-forth and 2.5 cm side-to-side and clamp speed of 875 cycles/min. The milling process was interrupted in order to avoid the temperature rise, i.e. each step was 30 min milling, 30 min' rest time and the total milling time was accumulated milling