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Research Paper

Preparation and thermal property analysis of Wood's alloy/expanded graphite composite as highly conductive form-stable phase change material for electronic thermal management

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HIGHLIGHTS

- A novel Wood's alloy/expanded graphite form-stable composite PCM was prepared.
- The composite shown high heat storage density and excellent heat transfer ability.
- The form-stabilized behaviors were analyzed experimentally in details.
- The composite had great potential for use in electronic thermal management.

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ABSTRACT

This paper reported a Wood's alloy/expanded graphite (EG) composite phase change material (PCM) with high thermal conductivity and good form-stability. In this composite PCM, Wood's alloy served as heat storage medium and EG acted as both heat transfer promoter and packaging material. The thermal properties of this composite PCM were investigated by means of differential scanning calorimetry (DSC) and transient plane source (TPS) method. The results showed that the phase change temperature of the composite was about 70.5 °C. The sensible and latent heat storage densities as well as thermal conductivity were influenced by the mass percentage of Wood's alloy and the composite's compacting density. The latent heat storage density and thermal conductivity could reach up to 113.1 $J{\cdot}cm^{-3}$ and 65.0 $W{\cdot}m^{-1}{\cdot}K^{-1}$. Appearance observation of the composite revealed that increasing the mass percentage of the alloy and decreasing the compacting density could help to keep the composite form-stable. These findings approved the potential of the Wood's alloy/EG composite for use in thermal management of high power electronic devices.

1. Introduction

It is well known that electronic devices, such as central processing units (CPUs) and light emitting diodes (LEDs), generate heat during their processes of operation. As the input powers of the electronic devices keep growing and the device dimensions keep decreasing in recent years [1,2], the heat generated by the electronic devices is more than ever. The heat accumulated within the electronic devices not only contributes to poor operation performance of the devices but also can lead to overheating, thermo runaway, or even device failure. Therefore, in order to improve the performance of the electronic devices and prevent the devices from thermal damage, efficient and feasible thermal management technologies are necessary.

Using phase change materials (PCMs) for passive cooling is one of those thermal management technologies [3]. Since PCM can absorb and release a large amount of latent heat at nearly constant temperature, this technology can offer a relatively large period of temperature stabilization to the electronic devices especially those whose working time is discontinuous [4]. In the past years, the effectiveness of PCM for thermal management of various types of electronic devices have been confirmed [2,5,6]. Many PCM candidates have been studied to achieve a better temperature control performance in this application field [7,8]. Organic materials such as paraffin waxes and fatty acids are one important category of these materials due to the suitable phase change temperature, high heat storage density and excellent thermal and chemical stability.

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[9–11]. Nevertheless, organic PCMs show comparatively low thermal conductivity (between 0.15 and 0.30 $W \cdot m^{-1} \cdot K^{-1}$ [12,13]), which will severely reduce the heat transfer rate during the phase change process. Besides, liquid PCM leakage often occurs after these materials finish the solid-liquid phase transitions. This may bring an interfacial combination problem to the PCMs with surrounding materials and further may lead to potential damages to the PCM-based thermal management systems [14,15].

To deal with the disadvantageous issues about such PCMs, many researchers attempt to introduce some porous matrixes that can serve as both heat transfer enhancer and packaging material [7,16]. It is expected that the fabrication of a new class of composite PCMs by impregnating the PCMs into those matrixes can allow a great improvement in the thermal conductivity of the PCMs and prevent the leakage of the liquid PCMs at the same time. In the works of Zhang et al. [17,18] and Lachheb et al. [19], expanded graphite (EG) was chosen as the matrix to prepare paraffin/EG form-stable composite PCMs. The property measurement found that the thermal conductivities of these composite materials were 0.36–2.88 times higher than that of paraffin. Yuan et al. [20] and Zhang et al. [21] developed several kinds of fatty acid/EG composites. With the EG mass fraction higher than 5 %, these composites could keep good formability during the solid-liquid change process. Their thermal conductivities were found to be in the range of 1.1–5.2 $W \cdot m^{-1} \cdot K^{-1}$ depending on the EG content.

Even though above efforts have been made, in comparison with traditional heat transfer materials like aluminum and AlN ceramic, the thermal conductivities of the organic composite PCMs are still in a low level and insufficient to satisfy the fast heat storage and release requirements in electronic modules which work with frequent high power input. Recently, the research interests have been drawn on metals and metal alloys with low melting temperature as PCMs [22]. This is due to their well-known great heat transfer performance which can effectively accelerate the speed of heat removal [23,24]. Composite PCMs formed through impregnating metal alloys into porous matrixes are also developed to further enhance their functions. For example, Zhong et al. [25] proposed a 50Bi-27Pb-13Sn-10Cd/graphite foam composite material and its thermal conductivity was determined to be up to 193 $W \cdot m^{-1} \cdot K^{-1}$. A Wood's alloy/compressed expanded natural graphite composite was presented in the later work [26]. The property analysis showed that this composite demonstrated anisotropic characteristics in the thermal conductivity and the value of the conductivity could reach the range of 55–344 $W \cdot m^{-1} \cdot K^{-1}$. These findings indicated a great potential of metal composite PCMs for electronic thermal management uses. By now, the study on the metal composite PCMs is still in the infant stage. Various issues concerning the preparation method, form-stability and thermal energy storage behaviors of this kind of composites under different conditions are not very clear. This makes relevant researches valuable.

The present work aims at searching for a PCM with both high thermal conductivity and good formability for temperature management of high power density electronic devices. Therefore, Wood's alloy (50Bi/25Pb/13Sn/12Cd) which possesses strong heat conductive ability and good compatibility and expanded graphite (EG) which was commonly used as both heat transfer enhancer and packaging material were chosen. By adopting a simply physical mixing method, a Wood's alloy/EG composite PCM was developed in this work. To achieve desirable thermal performance of this composite material, the effects of the mass percentage of the Wood's alloy as well as the compacting density on the properties of this composite PCM including the microstructural features, phase change temperature, sensible and latent heat storage capacity, thermal conductivity and form-stable behaviors were analyzed in details. The results recorded in this work not only confirmed the potential of using the Wood's alloy/EG composite PCM for targeted temperature control application, but also could serve as important parameters for future actual applications of this material.

2. Experimental

2.1. Material and sample preparation

Wood's alloy with compositions of 50Bi/25Pb/13Sn/12Cd (melting point: 73 °C) was purchased from Xinliang Metal Corporation (Dongguan, China). Raw expandable graphite (mesh 50, expandable ratio of 300 $ml \cdot g^{-1}$) was supplied by Qingdao Graphite Co. Ltd., China. The expanded graphite (EG) was obtained through a microwave treatment of the expandable graphite using a domestic microwave oven (Midea Inc., China) with an overall power of 800 W for 10–20 s.

The Wood's alloy/EG composite material was prepared by a three-step method. Firstly, particles of Wood's alloy were heated at 100 °C in an oven until all the metal particles were completely melted. Then, the liquid alloy was physically mixed with certain amount of EG. To ensure a uniform distribution of Wood's alloy into the inner structure of EG, a mechanical stirrer was used and the total mixing time for the metal/EG mixture was about 30 min. Finally, the mixture was cooled to ambient temperature and the composite PCM was obtained. For purpose of fully understand the thermal properties of this composite PCM, a series of samples with different mass percentages of Wood's alloy (70, 80 and 90 wt.%) were prepared.

2.2. Property characterization

The morphology of the Wood's alloy/EG composite material was observed with assistance of a scanning electron microscope (SEM, Quanta FEG 250, FEI Inc., USA). A differential scanning calorimeter (DSC, Q20, TA Instrument Inc., USA) was applied to study the phase change properties of the composite material including the melting temperature and latent heat of fusion. The DSC tests were carried out from 50 to 90 °C at 5 $°C \cdot min^{-1}$ heating rate under N_2 purging of 50 $ml \cdot min^{-1}$. The specific heat capacities of the composite material before and after solid-liquid phase transition were also determined through DSC based on a comparison method. The determination experiments were conducted by introducing sapphire as a reference. A thermal treatment was performed on each testing sample from 25 °C to 70 °C for solid specific heat capacity determination and from 80 to 150 °C for liquid specific heat capacity determination, respectively. The accuracy of the calorimeter in DSC was within ±1% and that of the temperature was within ±0.01 °C. In order to evaluate the form-stabilized performance of the composite material, the composite prepared at powder state was placed in a stainless steel mold and then compressed into block composite samples. After that, these blocks with different Wood's alloy mass percentages and different compacting densities were subjected to 120 °C for 10 h and the appearance of each block was carefully observed to check if the leakage of liquid alloy occurred. The thermal conductivities of the composite samples with various mass ratios of the Wood's alloy and compacting densities were measured by a hot disk thermal constant analyzer (TPS2500, Hot Disk Inc., Sweden) based on a transient plane source (TPS) method. A type 7577 probe, which acted as both the heater and sensor, was chosen considering the thicknesses of the prepared samples and the possible range their thermal conductivities may lie in. The dimensions of the block samples for the tests of form-stabilized performance and thermal conductivity measurement were 40 mm × 40 mm × 5 mm. The uncertainty for these measurements was within ±2%.