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Selective Laser Sintering of Phase Change Materials for Thermal Energy Storage Applications

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Abstract

With a global concern about energy and carbon dioxide emissions, renewable energies have attracted extensive attentions. One of the crucial aspects is waste heat recovery and thermal energy storage. Phase change materials have unique merits in latent heat thermal energy storage, due to its capability of providing a high-energy density storage by solidifying/melting at a constant temperature. The increased global demand for phase-change-materials-enabled energy storage systems exposed limitations of established manufacturing methods in terms of processing speed, material waste, and flexibility. In this research, a phase change composite was developed by mixing paraffin wax with a thermal conductive expanded graphite. Using a layer-by-layer laser sintering method, these two materials combined at a micro-scale, forming a phase change composite that possesses good thermal conductivity, superior latent heat, and good mechanical strength. This work investigated the key parameters for successful production of paraffin wax/expanded graphite composite using laser sintering technique. In particular, the paraffin wax is melted and then impregnated into the inter-particle pores of expanded graphite through capillaries. It serves as a binder that bonding the expanded graphite molecules together as into a solid form-stable object in the laser sintering process. To validate the developed sintering process, both single-layer and multi-layer samples with various geometries have been fabricated and tested. Results showed good structural integrity and functionality of the printed parts. The produced thermal conductivity was in the range of 1.4 – 1.9 W/m.K for single-layer and 0.75 – 0.80 W/m.K for multi-layer, and the latent heat of fabricated samples is in the range of 161 – 166 kJ/kg for both single-layer and multi-layer structures. These experimental results verified that the developed laser sintering process could be used as an effective nontraditional manufacturing technique for fabricating phase change materials for thermal energy storage applications

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1. Introduction

Phase change materials (PCM) have become game changers in modern thermal energy application. Due to the phenomenon of state change in phase, thermal energy can be stored and extracted in the form of latent heat. Liquid-to-gas phase change provides huge amount of the latent heat (1). However, the major drawback of such phase change is the respective phase volumes required to contain the gaseous phase. Therefore, solid-liquid phase change has been considered a better approach and investigated in many literatures.

The key benefit of solid-liquid phase change materials is due to the high latent heat to sensible heat ratio, where the thermal energy can be stored without significantly increasing the PCM temperature beyond its melting point. This advantage allows a uniform thermal heat absorption or extraction throughout the system.

For thermal energy storage applications that need to store the thermal energy at a fast rate, the thermal conductivity is a major property that needs to be taken into account. Other properties include mechanical strength and form stability – the ability to contain liquid phase PCM within the structure without leakage – must also be considered. Nevertheless, most phase change materials have poor thermal conductivities comparing to metallic materials such as copper or aluminum. Paraffin wax, for instance, has a thermal conductivity of 0.21 W/m.K comparing to 385 W/m.K and 205 W/m.K for copper and aluminum respectively (2). Therefore, many researchers have investigated methods of combining phase change materials with various thermal conductive materials. Sari et al. (3) (4) have studied different combination of paraffin wax, as a phase change material, with expanded graphite and high density polyethylene (HDPE) in order to enhance, mainly, the thermal conductivity of such composites. Fang et al. (5) considered a paraffin – boron nitride (BN) nanomaterial composites due to the former's superior thermal conductivity that, theoretically, can range between 1700-2000 W/m.K (6).

In this research, paraffin wax was selected as PCM due to its superior stability during phase change, relatively high latent heat capacity, wide range of melting temperatures, and its low cost and commercial availability. On the other hand, expanded graphite was selected as the form stable matrix due its superior properties such as light weight, relatively high thermal conductivity and its commercial availability.

As a composite, paraffin wax and expanded graphite have shown promising overall properties at a scaled-up level, especially, in lithium ion batteries business (7) (8) (9). In fact, PCM/expanded graphite phase change composite is commercially available (10) with thermal conductivity range between 5 - 25 W/m.K - depending on the PCM-to-expanded graphite weight ratio and the fabrication method, fair to good mechanical strength, and excellent form stability. The thermal conductivity could be 10 times the one that PCM offers alone (11).

In addition, the effects of fabrication process on thermal conductivity of the produced phase change composite is significant. Mills et al. (7) discussed in details the method of producing PCM/expanded graphite composite. Simply, the fabrication process begins by compacting expanded graphite flakes into a mold under controlled pressure and time. The produced expanded graphite matrix was then predrilled, allowing for maximum PCM fusion, and finally, impregnated into a hot bath of PCM material that is in the liquid phase at atmospheric or near atmospheric pressure (7). Despite of its capability in fabricating the desired PCM/expanded graphite composite, the process parameters such as pressure, compacting duration, and fusion temperature, etc., affect the product properties greatly. Furthermore, this fabrication technique requires a considerable amount of time and leaves a huge amount of waste material due to the predrilling process, as well as, the final machining. Additionally, this technique is limited to simple geometries such as cylinder and cube (8).

In contrary, 3D-printing techniques offer unique benefits in free form fabrication with near zero material waste. Among various 3D printing techniques, selective laser sintering (SLS) offers many advantages when considering carbon-based materials such as graphite. Bourell et al. (12) and Leu et al. (13) used indirect SLS technique to fabricate bipolar plates using natural graphite powder as the matrix, and the phenolic powder as a binder with the addition of carbon fiber or carbon black. The phenolic powder volume ratio has to be held at 30 -35% in order to bind the graphite powder. After the laser sintering, post processing was required by heating the parts in an oven gradually to dissolve the unwanted phenolic powder, and to enhance mechanical properties (12) (13). To the best of