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Performance investigation of thermally enhanced polymer composite materials for microelectronics cooling

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ABSTRACT

Driven by the low density, corrosion resistance, manufacturability, and low raw material and manufacturing costs of polymer composite materials, significant attention is being devoted to the innovation, characterization, and implementation of such materials. In this study the thermal and mechanical properties of a broad range of commercially available, injection moldable, thermally enhanced polymer composite materials are reviewed to help identify candidate materials that could replace conventional metal alloys in microelectronics cooling heat sink and heat exchanger applications. The material property characterization data reviewed consists of vendor data generated in accordance with applicable characterization standards. From twenty seven commercially-available polymeric composite materials, two promising groups of materials, namely polyphenylene sulfide (PPS) and polyimide 66 (PA66), are identified.

A preliminary investigation of exchanger heat transfer rate is undertaken using computational fluid dynamics (CFD) to identify the envelope of thermally enhanced composite material thermal conductivities required for effective heat transfer in gas–liquid heat exchanger applications. The thermal performance of a thermally enhanced PPS, parallel plate cross-flow air–water heat exchanger prototype is shown numerically and experimentally to be comparable to that of a conventional aluminum exchanger having the same geometry, demonstrating the potential feasibility of replacing conventional metallic heat exchangers with thermally enhanced polymeric composite heat exchangers in microelectronic air–liquid cooling applications.

1. Introduction

The development, characterization, and implementation of polymer composite materials for the thermal management of electronic equipment has recently began to attract attention [1–4]. The enhanced thermal conductivity, low density, low cost, ease of manufacture and corrosion resistance of polymer composites make these materials attractive for the replacement of conventional heat sink and heat exchanger materials [5,6]. Polymer manufacturing is generally less expensive and energy-intensive than metal manufacturing [7]. Polymer low density also enables the manufacture of light structures that can facilitate assembly and transportation. Relative to standard polymers, composites have higher impact and yield strengths, higher temperature limits, and higher thermal conductivities [6]. The thermal and mechanical properties of the polymers are enhanced through the addition of fillers such as carbon fibers into the polymer matrix. The inclusion of up to 70% (volume%) carbon fibers, typically 100–300 μm long, 10 μm in diameter, having a thermal conductivity of up to 700 W/m K, can increase polymer effective thermal conductivity from 0.5–30 W/m K [8]. Thermally enhanced polymer composites can enable innovative designs that may not be manufactured with metals, owing to the moldability and thus geometric flexibility of polymer composites. Polymer composites are particularly suited to air cooling applications characterized by a low Biot number (i.e., high convective thermal resistance relative to the internal conductive resistance). However, their properties depend upon the injection molding process parameters and can be highly anisotropic. Thus, the carbon fibers ideally require to be oriented in the primary direction of conduction heat transfer. Although thermal conductivity is of importance, many other material properties need to be carefully considered for the selection of a polymer composite for a given application.

The objectives of this study are to help identify commercially-available candidate polymeric composite materials having properties suitable for heat exchanger applications for the thermal management of microelectronics. To identify an envelope of feasible thermal conductivity values, the thermal performance limits of polymer composites are first discussed. A review of commercially-available polymer composite material properties is

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then presented to identify candidate material groups. Although this study is an important step towards the identification of suitable polymer composite materials for use in electronic cooling applications, and a range of vendor products is reviewed, the material property information presented in this article is not exhaustive. A preliminary investigation of exchanger heat transfer rate is undertaken using computational fluid dynamics (CFD) to identify the envelope of required thermally enhanced composite material thermal conductivities for effective heat transfer in a typical air–water cross-flow parallel plate heat exchanger applicable to microelectronics thermal management. The predictions are used to select a commercially-available thermally enhanced composite polymer material for prototyping and further experimental characterization. Heat exchanger performance is compared with that of both a standard polymer material (i.e., low density polyethylene (LDPE)) and aluminum.

2. Application of polymer composites to electronics cooling

Recent investigations of the thermal performance of polymer composites for heat transfer applications include Bahadur and Bar-Cohen [5], Luckow et al. [9], Cevallos et al. [6,10], and Hall et al. [11]. Potential applications of polymer composites include solar water heaters, heat recovery systems, seawater heat exchangers used in desalination and oil and gas processing, and compact, millimeter-scale heat exchangers.

Cevallos et al. [6] reviewed 40 years of polymer heat exchanger history, research, and potential applications of this technology. In particular, compact heat exchangers with millimeter-sized passages were identified as promising applications enabled by the moldability and geometric flexibility of polymer composites.

Luckow et al. [9] assessed by modeling the thermal performance of polymer composites having thermal conductivities from 5 to 40 W/m K in a prototype parallel-plate counterflow gas–liquid heat exchanger. The heat exchanger module had fins of 10 mm height and 1 mm thickness, and was operated at 1 m/s liquid velocity and gas flow rates of 0.008 m^3/s to 0.12 m^3/s. For heat exchanger material thermal conductivities of approximately 5 W/m K and above, the heat transfer was found to be relatively insensitive to further increases in thermal conductivity, especially above 20 W/m K, due to the gas-side convective thermal resistance dominating.

Thermal anisotropy is a potential limitation of polymer composites relative to metallic materials. Bahadur and Bar-Cohen [5] experimentally characterized the anisotropic thermal conductivity of a commercially available polyphenylene sulfide (PPS) carbon fiber composite material, and presented a validated model to describe the thermal conductivity of such polymer composites. The authors quantified the influence of the fiber material, volume content and orientation on the composite thermal conductivity. For example, for a 70% volume content of carbon fiber, 10 μm in diameter, the reported axial thermal conductivity (i.e., parallel to the fibers) was found to be 15 W/m K, whereas the radial thermal conductivity (i.e., normal to fibers) was 4 W/m K. The majority of studies on thermally enhanced polymers for heat transfer applications [e.g., 1,2,12] discuss the anisotropy in thermal conductivity, but few address the anisotropy in mechanical properties (i.e., tensile, compressive and flexural strength, elastic and Youngs' modulus, coefficient of thermal expansion) and its impact of structural integrity. However, Robinson et al. [13] undertook a thermo-mechanical stress analysis of a thermally enhanced polymer composite heat exchanger, and found that the stresses due to pressure loading were more sensitive to heat exchanger geometry, while the stresses due to thermal loading were more sensitive to material mechanical property anisotropy (i.e., transverse and shear modulus, Poisson's ration, coefficient of thermal expansion). Additional studies are required to assess the mechanical behavior of polymer composite materials in electronics cooling applications.

Hall et al. [11] proposed an experimental methodology for determining the influence of injection molding process parameters on fiber orientation in thermally-enhanced polymer composites. The experimental method involved the use of traditional light microscopy on a sample section to measure fiber orientation. This method could be used as a manufacturing process verification, and for understanding fiber behavior when the composite is injected in the mold.

Cevallos et al. [10] analyzed moldability considerations that should be incorporated in the design of polymer heat exchangers.

Collectively, these efforts have demonstrated the value of polymer composites in heat transfer applications, and have highlighted the challenges to overcome their mechanical and thermal performance limitations. Efforts to overcome some of these challenges include Burns and Jachuck [14] and Cheng and Van der Geld [15]. Given potential thermal conductivity (hence conductive resistance) limitations, both studies focused on enhancing gas-side convection using multiphase flow for specific gas–liquid polymeric heat exchanger applications. Gas-side heat transfer coefficients of up to 500 W/m^2-K were reported by Burns and Jachuck [14] for the condensation of water vapor from a gas stream, demonstrating the effectiveness of polyether-etherketone (PEEK) polymer film compact heat exchangers for such an application. Cheng and Van der Geld [15] enhanced the air-side convective heat transfer using a mixed steam–gas stream in an air-water polyvinyldene-fluoride compact cross-flow heat exchanger, which resulted in a four-fold increase in the air-side heat transfer coefficient as compared to single phase air-side heat transfer.

3. Overview of commercially-available polymer composite materials characteristics

The mechanical and thermal properties of a range of commercially available, injection moldable, thermally enhanced polymer composites are reviewed here to guide the selection of candidate materials that could replace conventional metals in heat exchangers applications for microelectronics cooling.

Current commercially-available, thermally enhanced polymer composite materials that can be injection molded, produced by six leading vendors, are compiled in Table 1. For the purpose of non-commercialism, the vendors are anonymously designated throughout this article. The majority of these materials use either polyamide 66 (PA 66) or PPS as their matrix.

Table 1
Commercially-available thermally enhanced polymer composites identified in this study.

Polymer composite (abbreviation)	Vendor (abbreviation)
Polyamide (PA)	Vendor 1 (V1)
Polyamide 6 (PA 6)	Vendor 6 (V6), Vendor 4 (V4)
Polyamide 66 (PA 66)	Vendor 3 (V3), Vendor 2 (V2)
Polyphenylene sulfide (PPS)	Vendor 1 (V1), Vendor 3 (V3), Vendor 2 (V2), Vendor 6 (V6)
Polycarbonate (PC)	Vendor 5 (V5), Vendor 6 (V6)
Polyphthalamide (PPA)	Vendor 3 (V3), Vendor 1 (V1)
Liquid crystal polymer (LCP)	Vendor 1 (V1)
Polyamide 12 (PA 12)	Vendor 6 (V6)
Polybutylene terephthalate (PBT)	Vendor 6 (V6)
Polyaryletheretherketone (PEEK)	Vendor 6 (V6)
Polypropylene (PP)	Vendor 1 (V1)
Polypropylene Homopolymer (PPh)	Vendor 6 (V6)
Polyurethane (PU)	Vendor 6 (V6)