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Locally reinforced polymer-based composites for efficient heat dissipation of local heat source

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ABSTRACT

Local heat source in electronic device is likely to produce hot spot which can degrade the reliability and performance of the device. Various materials have been attempted to enhance the heat dissipation of local heat source. Many theoretical studies have demonstrated that the heterogeneous composite materials with fillers concentrated at the preferential paths of heat flux are effective in cooling the local heat source. However, this unique control of microstructure and property for polymer-based composites has less been achieved in practice due to the technical difficulties in controlling the fillers positions. In this paper, a locally reinforced heterogeneous composite with conductive particles concentrated at the preferential path of heat flux was fabricated to cool the local heat source. The local reinforcement was achieved by using magnetically responsive particles as reinforcing elements and a specific magnetic field to organize the elements into the predefined structure. To evaluate the thermal performance of the proposed material, we performed the comparative thermal tests. The results show that compared to the homogeneous composites, the present composites with local reinforcement can significantly enhance the heat dissipation of local heat source. When heat flux is 5840 W m^{-2}, the locally reinforced composites with a fillers volume fraction of 5% reduced the average and maximum temperature of heater 7.7 °C and 8.7 °C, respectively.

1. Introduction

Over the past few decades, the revolution in electronics has resulted in the packaging of multiple functional units on the same chip [1,2]. These units create a non-uniform distribution of heat source throughout the chip. The local heat source with high power is likely to produce hot spots. These hot spots can lead to excessive stresses on the chip, which degrade the reliability and performance of electronic devices [1–4]. Thermal management of local heat source is a big challenge. Various materials [5–7] have been attempted to enhance the heat dissipation. Thermally conductive polymer-based composites, fabricated by incorporation of highly conductive fillers, are potential for the thermal management materials [8–11]. However, applying the conventional composites that possess uniform thermal properties for the local heat source cooling is still insufficient and not cost-effective [12].

Many theoretical studies [13–17] have demonstrated that the heterogeneous composite materials with fillers concentrated at the preferential paths of heat flux are effective in cooling the local heat source. For instance, some topology designs [13–15] have been applied to the composite material which is loaded with local heat source, to minimize the heat source temperature. These designs are accomplished by locating the fillers in matrix with optimal distribution using the optimization algorithm. The designed results show that concentrating the fillers at the position with large temperature gradient is most efficient to decrease the heat source temperature. In addition, the percolation theory [16,17] can further illustrate the benefit of fillers local concentration. Percolation happens when the high conductivity particles form at least one continuous chain in composites from heat source to sink. At that time, there is a sudden increase in thermal performance [17]. Fig. 1(a) schematically shows a homogenous composite with low fillers loading assembled with local heat sources. Percolation hardly takes place in this composite since all particles are well separated. While, as seen in Fig. 1(b), concentrating the fillers makes it more probable to form the continuous chains resulting in a local reinforcement at the region with local heat source.

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Nomenclature

D	diameter of platelet, μm
d_1	width of body 1, mm
f	filler volume fraction, %
h_c	heat transfer coefficient in simulation, W m^{-2} K^{-1}
k	thermal conductivity of composite, W m^{-1} K^{-1}
k_1	thermal conductivity of body 1, W m^{-1} K^{-1}
L	geometrical factor
l	width of composite, mm
q_0	heat flux of heater in simulation, W m^{-2}
q_1, q_2 and q_3	heat flux through body 1, 2 and 3, W m^{-2}
R_b	thermal boundary resistance at the filler–matrix interface, m^2 W K^{-1}
T_{ave}	average temperature of heat source, °C
T_{max}	maximum temperature of heat source, °C
T_0	temperature of heat source in simulation, °C
T_1	temperature of upper surface of heat sink in simulation, °C
t	thickness of platelet, nm
t_1	thickness of composite layer, mm

Greek symbols

α	inverse of filler aspect ratio
ΔT	temperature difference between the heat source and the upper surface of heat sink, °C
ΔT_{ave}	reduction of average temperature, °C
ΔT_{max}	reduction of maximum temperature, °C

Subscripts

11	in-plane direction
33	through-plane direction
m	matrix
p	particles

The theoretical studies above well illustrate the benefit of fillers local concentration. However, this unique control of microstructure and property for polymer-based composites has less been achieved in practice due to the technical difficulties in controlling the fillers positions. Squeezing [18–20] is a process which can make fillers entrapped and compacted in matrix. The heterogeneity of composites occurs when the rate of matrix flow through the fillers is greater than that of composites deformation [19,20]. However, this method is limited to the thin films and demands highly accurate control of the squeeze rate [19,20]. Electric field [21] is another approach to achieve the unique microstructure, in which the localization of fillers is induced by electric field concentration. But this approach requires ultrahigh DC electric field (1 kV) [21] and multiple processing steps. Recently, an attractive strategy is proposed to control the distribution of fillers in matrix [22,23]. The approach relies on coating the non-magnetic reinforcing particles with superparamagnetic nanoparticles. These coated particles exhibit an ultrahigh magnetic response (UHMR) [23] which enables remote control over their distribution under low external magnetic fields in low-viscosity suspending fluids. Such fluids can be then consolidated to fix the magnetically-imposed distribution and thus produce the composites with deliberately tuned properties. With this strategy, the former investigations [23,24] have shown the possibility in fabricating the polymeric substrate with locally tuned mechanical properties. A careful review of literature indicates that this strategy has not been applied for tailoring the composites thermal properties. In addition, although the reports [20,21] have fabricated the composite with deliberately controlled microstructure, experiments have not been conducted to evaluate its thermal performance.

In this research, we report that the polymer-based composites applied for heat dissipation from local heat source can be reinforced by concentrating the thermally conducting fillers at the preferential paths of heat flux. The locally reinforced composite is fabricated by using the magnetically responsive thermally conducting particles as reinforcing elements and a specific magnetic field to control the elements distribution. Then, a thermal testing system is built to evaluate the composites thermal performance. Finally, we conduct a simulation on the constructed composite to thoroughly investigate its thermal property.

2. Experiments

2.1. Synthesis of locally reinforced polymer-based composites

Polymer-based composite is composed of polymer matrix and reinforcing particles. In this report, we employed the silicone gel (OE-6550, Dow Corning), with a viscosity of 4 Pa s and a relatively low thermal conductivity (0.16 W m^{-1} K^{-1}) [25], as the soft matrix. Hexagonal boron nitride (hBN) platelets (AC-6041, Momentive), with an average diameter of 5 μm and a much high in-plane thermal conductivity (600 W m^{-1} K^{-1}) [26,27], were chosen as the reinforcing elements. To gain magnetic control of the reinforcements, the platelets were coated with 2 wt% superparamagnetic iron oxide nanoparticles via a previously reported procedure [26,27]. hBN platelets (4 g) were first stirred in deionized water (200 ml) at pH = 7. Then, EMG-605 ferrofluid (Ferrotec, U.S.A) (400 μL) diluted with deionized water (5 ml) was added dropwise to the suspension under vigorous stirring. The pH of suspension was held at 7 to keep a negative charge on the surface of hBN platelets. The EMG-605 ferrofluid is an aqueous suspension containing iron oxide nanoparticles coated with a cationic surfactant, which enables electrostatic adsorption of the positively charged magnetic nanoparticles onto the platelets surface. The suspension

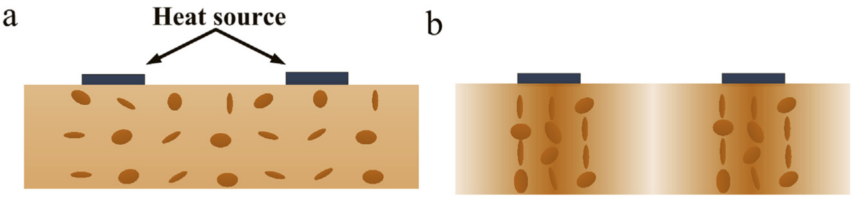

Fig. 1. Schematic of (a) homogenous composite and (b) heterogeneous composite with local reinforcement.