Proceedings of The Canadian Society for Mechanical Engineering International Congress 2018
CSME International Congress 2018
May 27-30, 2018, Toronto, On, Canada

Composite heat sink LED cooling

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Abstract — Metal coating of 3D printed polymers is an attractive proposition for thermal dissipation of light emitting diodes, due to its high efficiency and markedly lower material costs than conventional aluminum heat sinks. Efficient thermal cooling of light emitting diodes is essential in maintaining electronic and optical performance. The thermal performance of three heat sink designs were experimentally investigated for three applied heat fluxes (0.5-1.5 W cm^{-2}). The results show that metal coating of the polymer heat sinks enables significant heat transfer enhancement of 37% over the uncoated case. The inclusion of an aluminum insert into the base of the composite heat sink design, in tandem with the zinc coating reduced on chip temperatures by 27% over the zinc coated case for the greatest applied heat flux.

Keywords: Light emitting diode; Heat transfer; Metal spray coating; Composite heat sink

I. INTRODUCTION

Light emitting diodes (LEDs) are a fast devloping technology due to their high energy efficiency, long lifecycle, environmental benefits and optical performance [1-5]. LED lighting uses 75% less energy their incandescent or fluorescent counterparts [6]. 70% of the total energy consumed by an LED light is emmitted as heat. Effective thermal dissipation of LED devices is crucial in maintaining luminous performance and extending a LEDs lifespan [6, 9-12]. Numerous authors haven investigated the thermal disipation of LED devices both experimentally [3, 10, 13-15] and numerically [16-21].

Conventional aluminum heat sinks that are used to passively cool LED chips are thermally inefficient. A thermal resistance bottleneck exist at the gas-solid interface (R_2) (Figure 1) which is significantly larger than the thermal resistance from the LED through the aluminium solid (R_1). Metal coating of 3D printed polymers enables the matching of thermal resistances ($R_1 = R_2$) by controlling the thickness of the coated metal, with the polymer substrate acting as a structural component. 3D printing also enables inovative heat sink design, which is not limited by the manufacturing processes of traditional heat sinks.

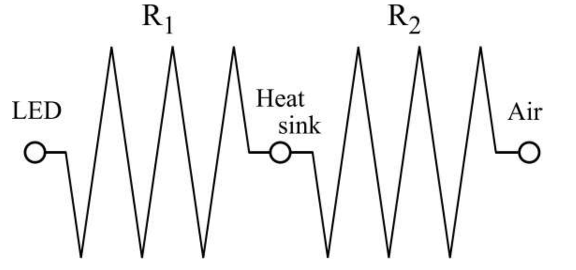

Figure 1. LED cooling thermal resistance diagram.

This research endevours to be the first to experimentally investigate low power LED cooling using composite heat sinks. This was achieved using three heat sink designs tested across three applied heat fluxes (q''_{gen}). This methodology was employed to characterise the thermal dissipation enhancement due to the zinc coating and to demonstrate the technology viability for future adaptation in cooling low power LED devices.

II. EXPERIMENTAL APPARATUS AND DATA REDUCTION

The experimental apparatus consists of three primary components; the composite heat sink, pseudo LED heater pad and the data acquisition system. A schematic of the apparatus is shown in Figure 2.

A. *Composite heat sink*

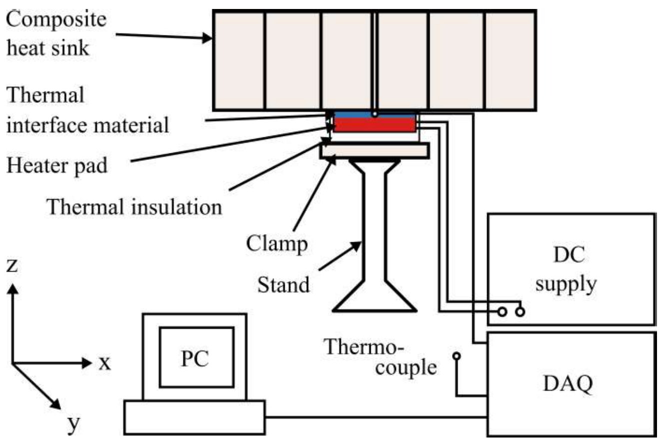

Figure 2. Schematic of the experimental facility.

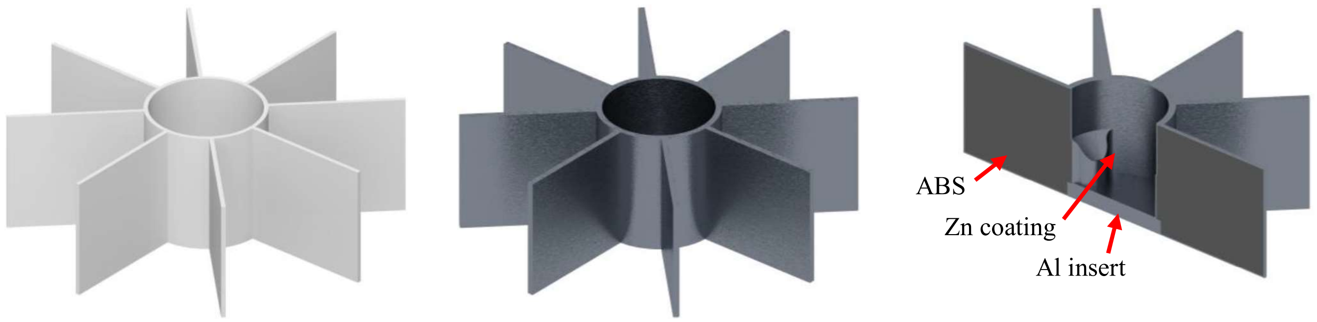

Figure 3. Heat sink design. (a) ABS heat sink, (b) zinc coated heat sink and (c) zinc coated heat sink with aluminum insert.

The three heat sink designs are shown in Figure 3. The design is based on a commercial LED heat sink (Aavid, P/N: NX300159) and they were fabricated using a Stratasys uPrint 3D printer (P/N: 680-50105-D). The heat sinks have a maximum diameter of 132 mm and a height of 42 mm. An eight fins design was implemented to optimize the uniformity of the zinc coating thickness. Each fin measures 41.4 x 42 x 1.5 mm^3 before the zinc coating is applied. The first heat sink (Figure 3a) is an uncoated Acrylonitrile Butadiene Styrene (ABS, k = 0.25 W m^{-1} K^{-1}, ρ = 1040 kg m^{-3}, T P/N: P430) design. The second (Figure 3b) heat sink consists of ABS coated in zinc. The final design is zinc coated ABS with an aluminum insert (5 mm thick, 41.3 mm in diameter) incorporated into the base of the heat sink (Figure 3c).

A Wire-arc spraying system (ValuArc, Sulzer Metro Inc.) was employed in coating the 3D printed heat sink designs with zinc (Sulzer Metro Inc., k = 116 W m^{-1} K^{-1}, ρ = 7140 kg m^{-3}, P/N: 1031592). In wire-arc spraying an electric arc is struck between the tips of two continuously fed wires to melt them. A high velocity air jet strips the molten metal from the wires and create a spray of droplets that impact on the substrate. Zinc was chosen due its high thermal conductivity and its relatively low melting pointing (420°C). This ensured that the polymer heat sinks were not damaged during the coating process. A list of the relevant heat sink properties are outlined in Table 1.

Table 1. Heat sink properties

Heat sink design	**ABS**	**ABS-Zn**	**ABS-Al-Zn**
Initial mass [g]	32.4	32.5	50.3
Coated mass [g]	32.4	117.1	140.9
Average coating thickness [um]	0	268	271

B. Experimental facility

The applied heat flux was generated using a thermal heating pad (Mcmaster-Carr, 25.4 x 25.4 x 5 mm^3, P/N: 35765K14) (See Figure 1). The thermal pad is attached to the base of each heat sink using thermally conductive tape (3M, P/N: 1-5-8810) and is clamped to a fixed pressure of 265 kPa using a torque screwdriver (Mcmaster-Carr, P/N: 5716A21). The thermal pad is insulated from the clamp using 10 mm thick Cryogel z (Aspen aerogel, 25.4 x 25.4 x 5 mm^3, k = 0.014 W m^{-1} K^{-1}) as shown in Figure 1. The heat sink assembly is mounted 150 mm from the ground using a 3D printed stand to ensure unobstructed air flow during testing. A 1.6 mm hole is drilled in the center of the base each heat sink, to facilitate measurement of the heat sink base temperature (T_b) during testing. T-type thermocouples (Omega, P/N: FF-TI-20) are used to measure the base temperature and the ambient surrounding temperature (T_∞). Temperature measurement are acquired using an Omega DAQ (P/N: OMB-DAQ-56).

C. Experimental testing and analysis

Experiments were conducted at atmospheric pressure and room temperature after steady state conditions were reached. The applied heat flux ranged between 0.5-1.5 W cm^{-2} in increments of 0.5 W cm^{-2}. It is assume that all of the generated theral energy is dissipated by the composite heat sink. Temperature data was averaged over a 15 minute period once steady state conditions had been achieved.

D. Experimental uncretainty

The experimental uncertainty for all parameters was implemented using the methodology outlined by Kirkup and Frenkel [22]. A list of the relevant parameter and their associated percentage uncertainty (PU) is outlined in Table 2. All listed values are to a 95% confidence level.

Table 2. Experimental uncertainty

Parameter		**PU [%]**
q''_{gen}	+/-	6
T_b	+/-	2.6
T_∞	+/-	4.4

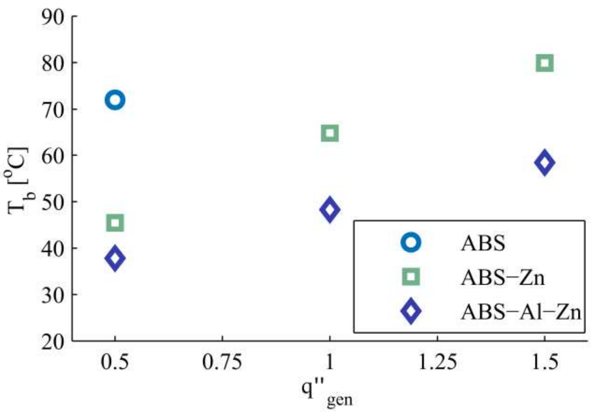

Figure 4. Heat sink base temperature for varied applied heat flux.

III. RESULTS

Figure 4. shows how the base temperature of each heat sink design varies with the applied heat flux. For the lowest $q^{//}_{gen}$ the uncoated ABS heat sink reached a steady state temperature of 72°C. As $q^{//}_{gen}$ is increased to 1 W cm^{-2} the base temperature exceeded the glass trnasition temperature of the ABS (105°C). The zinc coating on the second heat sink (ABS-Zn) reduces the base temperature by 37% over the uncoated case to 45.4°C. As $q^{//}_{gen}$ increases the base temperature increases linearly up to 79.9°C at the maximum applied heat flux.

The final heat sink (ABS-Al-Zn) incorporates an aluminium insert into it base, this enables a much lower thermal resistance path between the circumfrential fins and the thermal pad. The thermal resistance between the inner surface of the inner cylinder and the thermal pad is also significantly decreased by the insert. This results in a greater cooling than the ABS-Zn heat sink. A 48% and 17% decrease in the base temperature is observed over the ABS and ABS-Zn heat sinks respectively, at the lowest applied heat flux. For the largest $q^{//}_{gen}$ a base temperature of 58.4°C was noted, this corresponds to a 27% decrease in comparison with the ABS-Zn heat sink.

IV. CONCLUSIONS

The thermal performance of three low power LED heat sinks have been characterized. Optimum cooling was achieved by the zinc coated ABS heat sink which incorporated an aluminum insert into its base. The zinc coating was shown to significantly increases cooling performance over the uncoated case. Most importantly this research has demonstrated the potential of metal coated polymer heat sinks in cooling low power LED devices. Future work will focus on varying the coating material, numerical simulation to investigate optimum geometry and coating thickness, and direct comparison with an aluminum heat sink of a similar design.

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