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3D-printed heat sinks for thermal management of LED lighting

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ABSTRACT

Today, the aluminum heat sink is one of the most expensive and heaviest components in an LED lighting product. Because manufacturers of LED lighting products face the pressure of having to reduce production costs, exploring ways to reduce manufacturing costs by way of using novel materials and manufacturing processes could be a potential solution. 3D-printed polymer-based composite heat sinks with suitable thermal properties and 3D-printed metal heat sinks could help lighting fixture manufacturers reduce costs. 3D-printed heat sinks have the potential to be customized for increased functionality and visual appeal. This paper presented LED application-specific 3D-printed heat sink thermal performance characterizations. The heat transfer simulations showed that material with effective thermal conductivity values >15 W m^{-1} K^{-1} can potentially satisfy the thermal management requirements of a 50 W halogen equivalent MR-16 type LED integral replacement lamp. An experiment study was also conducted to evaluate the effect of Cu-plating of the PA-12 heat sinks. The Cu-electroplated heat sinks maintained an operating temperature below 105°C at the LED module case location for a thermal load equivalent to a 35 W halogen equivalent MR-16 type LED integral replacement lamp. The 50 µm Cu-electroplating thickness had equivalent performance to a 3D-printing material with an effective thermal conductivity of ~3 W m^{-1} K^{-1}. The 150 µm Cu-electroplating thickness showed similar performance to a material with an effective thermal conductivity of ~6 W m^{-1} K^{-1}.

Keywords: 3D printing, additive manufacturing, LED lighting, thermal conductivity, thermal management, polymer metallization, copper plating, LED junction temperature

1. INTRODUCTION

Light-emitting diode (LED) technology has transformed the lighting industry. In 2018, LED product adoption across all lighting applications reached 30% of all installed bases in the U.S.[1] The transformed number of installed bases is even higher at 50% in indoor lighting applications for small directional lighting products such as MR-16 (multifaceted reflector ~2 inches (~50 mm) maximum dimension on the lighting emitting surface, Figure 1 (a)) lamps.[1] These MR-16 lamps have one of the highest input electrical power to heat sink surface areas[2] due to their compact geometrical requirements (~50×50×25 mm^3 without the lamp base). This leads to a relatively high thermal power to the heat sink surface (i.e., thermal power flux density at the heat sink) compared to other lighting products. MR-16 LED lighting products traditionally used aluminum heat sinks to conduct heat away from the LED and then dissipate the conducted heat to the ambient via convection and radiation. These heat sinks enable the LED's operating temperature to be maintained below a maximum ceiling (typically in the range of 85 to 125°C), for both short- and long-term performance and reliability of these MR-16 lighting products. Today, the aluminum heat sink is one of the most expensive[3] and heaviest components in an LED lighting product.[4],[5] Because manufacturers of LED lighting products face the pressure of reducing production costs, exploring ways to reduce manufacturing costs by using novel materials and manufacturing processes could be a potential solution.[6]

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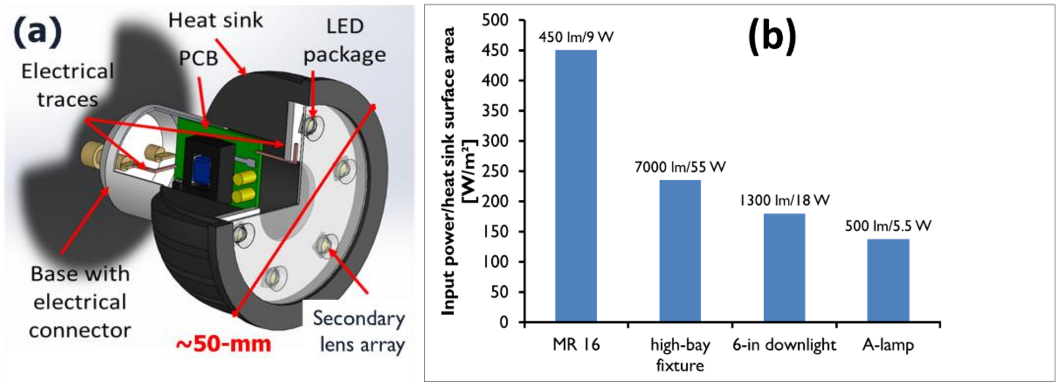
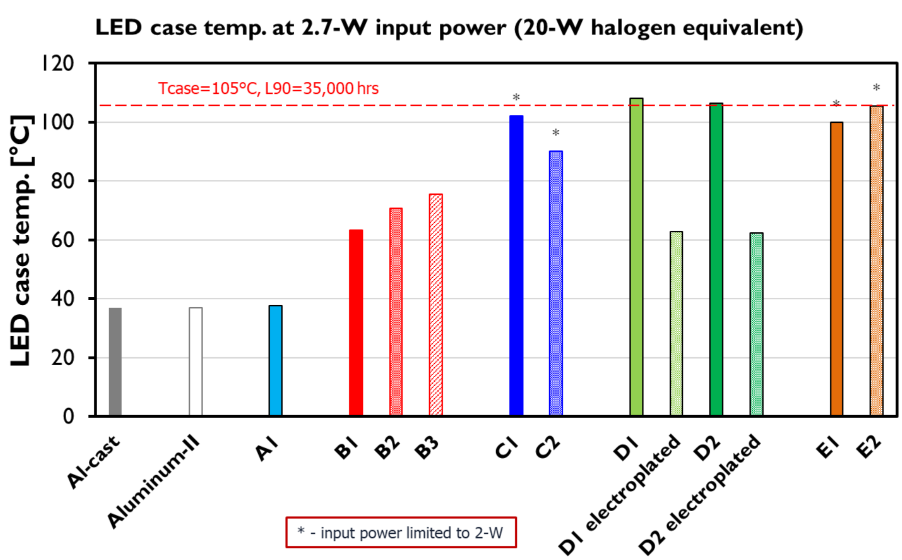


Figure 1. (a) LED-based MR-16 type integral lamp with components and sub-systems and (b) input electrical power to heat sink surface area of LED-based lamps and light fixtures[2]

Published literature on the performance of 3D-printed heat sinks for LED lighting applications shows for heat sinks with low thermal power flux density (e.g.,<150 W/m^2 Figure 1(b)) requirements, those 3D-printed with material having effective thermal conductivities >2 W m^{-1} K^{-1} provide the proper thermal management for maintaining the LED operating temperature below the maximum threshold.[2],[9] For higher thermal power flux densities, which cover most general illumination applications, heat sinks 3D-printed with material having effective thermal conductivities of 10 to 40 W m^{-1} K^{-1} could provide sufficient thermal management.[2],[8] Figure 2 illustrates an exploratory study conducted by Rensselaer's Lighting Research Center with ASSIST (Alliance for Solid-State Illumination Systems and Technologies) 3D Printing for Lighting consortium members.[2] According to Perera and Narendran (2023),[2] heat sinks for LED-type MR-16 lamps were 3D-printed with different heat sink materials, and the LED case temperatures were measured at 20 W halogen equivalent MR-16 total light output.



AM material	Effective in-plane thermal conductivity W m^{-1} K^{-1}
A1	85
B1	4
B2	3
B3	2
C1	~0.4**
C2	~0.5**
D1	0.3
D2	0.3
E1	0.3
E2	0.3

** - in-plane thermal conductivity from material specifications and literature

Figure 2. 20 W halogen equivalent LED-type MR-16 lamp thermal testing results at steady-state operation, from prior study results [2]

Figure 2 indicates as the in-plane thermal conductivity of the 3D-printed heat sink material increases from right to left, the LED case temperature decreases. The LED case temperature reduced from the maximum case temperature of 105°C to <40°C, nearly the same performance achieved by the traditionally fabricated benchmark heat sinks (Figure 2: Al-cast and Aluminum-II). Figure 2 also shows a heat sink 3D-printed with a material with >2 W m^{-1} K^{-1} (Figure 2: B3) that could address the thermal requirements of LED lighting applications such as 20 W halogen equivalent. Figure 2 also shows that electroplating a 3D-printed heat sink improves thermal performance. D1 and D2, 3D-printed heat sinks having an LED case temperature of ~105℃, decreased to ~60℃ with D1 electroplated and D2 electroplated 3D-printed heat sinks. The other tested equivalent halogen MR-16 lamp power levels (electrical, optical, and thermal) are listed in Table 1. The two most commonly used MR-16 lamp wattages, 35 W and 50 W, in indoor lighting applications are also highlighted in Table 1.

Table 1. MR-16 halogen and LED-based lamp electrical, optical, and thermal characteristics [based on a combination of product specification sheets from lamp manufacturers and lamp testing at the LRC]

MR-16 halogen equivalent power [W]	MR-16 nominal light output [lm]	LED based MR-16 nominal input electrical power [W]	LED based MR-16 nominal output optical power [W]	LED based MR-16 thermal power [W]
20	200	2.6	0.9	1.7
35	350	4.5	1.5	3.0
50	500	6.6	1.8	4.8
75	700	9.0	2.3	6.7

Based on the results from these research activities, the current study objectives were to investigate the effects of the thermal performance of three 3D-printed MR-16 heat sinks with designs and 3D-printed components in Nylon polymer PA-12 provided by an ASSIST 3D Printing for Lighting consortium member.

- Conduct a conjugate heat transfer simulation to investigate the effect of material thermal conductivity and heat sink geometry.
- Conduct an experiment study to investigate the effect of post-processing through Cu plating on LED case temperature using 3D-printed heat sinks.

2. METHODOLOGY

2.1 Investigate the effect of material thermal conductivity and heat sink geometry

The ASSIST 3D Printing for Lighting consortium member gave the LRC researchers three material specifications for the heat transfer simulations. Two were PA-12 nylon-based materials (Table 1: Mat. A and Mat. B), and a third, stainless steel metal material (Table 1: Mat. C). Aluminum was used as a benchmark material by the LRC researchers, and the material properties were selected based on the material library in the COMSOL multiphysics commercial software package.

Table 2. Material properties used in the conjugate heat transfer simulations.

Material	Density [kg m^{-3}]	Specific heat at constant pressure [J kg^{-1} K^{-1}]	Thermal conductivity [W m^{-1} K^{-1}]
Mat. A	1010	1185	0.196
Mat. B	1050	2400	0.28
Mat. C	7750	460	17.9
Aluminum	2700	900	207

Three heat sink designs were collaboratively developed by the ASSIST 3D Printing for Lighting consortium member team and LRC researchers (Figure 3). The major dimensions of each heat sink design are listed in Table 3.

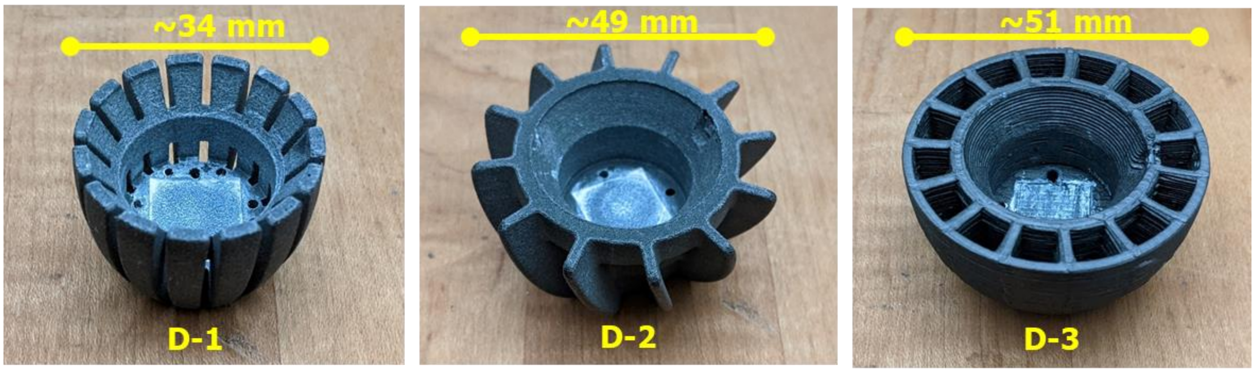


Figure 3. 3D-printed heat sink designs

The conjugate heat transfer simulations were conducted with the COMSOL multiphysics 6.0 commercial software package. For consistency, although half-symmetry could have been employed for designs D-1 and D-3 to reduce computation time and resources due to design D-2 not having a plane of symmetry along the axial direction, all simulations were conducted with the complete design in the thermal simulations.

Table 3. Heat sink design characteristics.

Design	Maximum Outer diameter [mm]	Minimum Outer diameter [mm]	Height [mm]	Surface area [m^2]	Volume [m^3]	f (surface area/volume) [m^{-1}]
D-1	34.3	21.7	25.4	6.06E-03	8.00E-06	7.57E+02
D-2	49.3	34.2	25.4	8.01E-03	1.24E-05	6.48E+02
D-3	50.8	30.9	25.4	1.39E-02	1.73E-05	8.03E+02

All the simulations were conducted with the LED-type MR-16 lamp geometries in the base-up orientations. The LEDs were assumed to be heat sources generating heat based on the specific LED array module characterizations conducted at the LRC following the methodology presented by Chen et al., (2012).[10] An air volume of 200×200×100 mm^3 was used to model the natural convection airflow around the heat sink, with free boundaries defined around the top and the side boundaries and a pressure constraint on the bottom boundary. The LED array module and the LED lens were also modeled.

2.2 Investigate the effect of post-processing through Cu plating

The ASSIST 3D Printing for Lighting consortium member team 3D-printed the three heat sink designs used in the thermal simulations, and another design that uses a gyroid structure was 3D-printed and sent to the LRC researchers. One complete set of the heat sinks (D-1, D-2, D-3, and D-*) was kept as-printed (Figure 4 (a): top row) while the other two sets of heat sinks were Cu-plated at 50 µm (Figure 4 (a): middle row) and 150 µm thickness (Figure 4 (a): bottom row). The researchers used the LED array module characterized and modeled in the previous section for this experiment study. The case temperature of the LED array module was measured using thermocouples at the designated case temperature measurement location (Figure 4 (b)). The LED array module was mounted to the heat sinks using thermal interface material and mechanically fastened to ensure good thermal contact between the back of the LED array module and the heat sink. The photometric testing of these assembled devices were conducted according to IES-LM-79-08.[11]

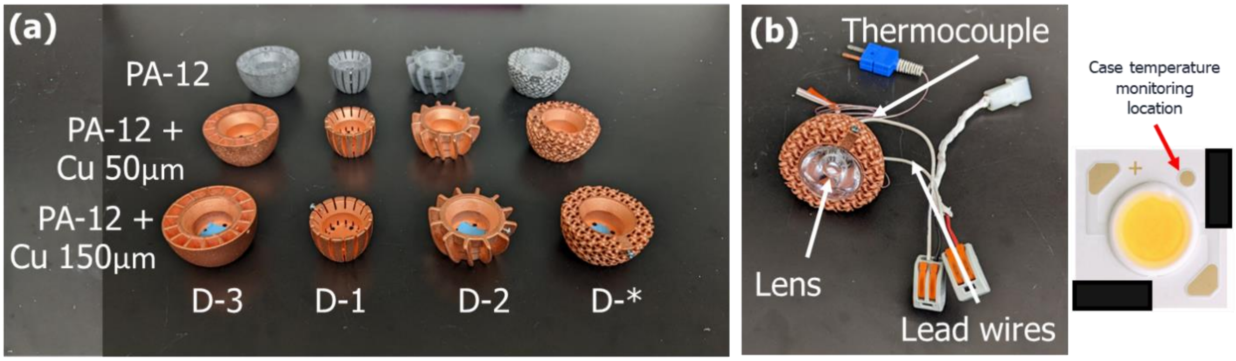


Figure 4. 3D-printed PA-12 heat sinks: (a) one set of four heat sinks was kept as-printed and two sets of four were Cu-plated at 50 and 150 µm thicknesses, and (b) one of the heat sinks prepared for laboratory testing with lens, thermocouples (case temperature monitoring location), and electrical connectors.

3. RESULTS

3.1 Investigate the effect of material thermal conductivity and heat sink geometry

Figure 5 illustrates the conjugate heat transfer simulations conducted with the heat sink designs (D-1, D-2, and D-3) with the four materials (Mat. A, Mat. B, Mat. C, and Aluminum). The simulation results are separated into 20 W, 35 W, and 50 W halogen equivalent applications with respect to the thermal loading. The discontinuous (**---**) line in Figure 5 represents the maximum case temperature of 125℃ based on the specifications from the LED array module manufacturer. The simulation results with case temperatures exceeding 160℃ were not plotted, and these design and material combinations are indicated with *****. Due to the lower thermal conductivity of the material Mat. A and Mat. B (Table 2) as the thermal loading increased, the ability of the heat sink design to maintain an LED case temperature below 125℃ decreased, as illustrated by the increase in the number of * from Figure 5 (left) to Figure 5 (right). The heat sink design D-1 has the smallest surface area among the heat sink designs (Table 3) and the effect of this on the heat sink not having enough surface area to dissipate the heat to the ambient can be seen by the higher LED case temperature.

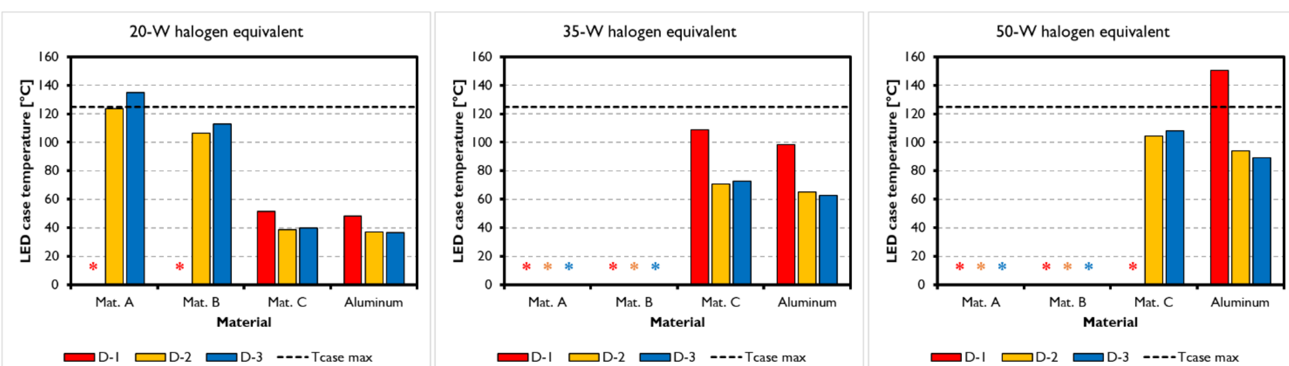


Figure 5. LED case temperature estimates from conjugate heat transfer simulations under: 20 W (left), 35 W (middle), and 50 W (right) halogen equivalent thermal loads

3.2 Investigate the effect of post-processing through Cu plating

Figure 6 shows the experimental results from testing the heat sink designs. The comparison between as-printed (PA-12), Cu-plated at 50 µm (Cu50), and Cu-plated at 150 µm (Cu150) shows that as Cu-plating thickness increases the LED case temperature decreases at any LED input power (Figure 6: D-3). Due to the smaller surface area of the heat sink design D-1 compared to the other designs (Table 3), the measured LED case temperature of heat sink design D-1 was higher. The temperature measurements also saw only minimal changes between D-2, D-3, and D-* heat sink designs. In particular, the heat sink design D-* with the gyroid fin structure had a much larger surface area; the performance was similar to heat sink designs D-2 and D-3 with respect to the LED case temperature. This is due to the increase in surface area (A) obstructing the natural convection around heat sink fins, reducing the average convective coefficient ($h(A,T)$) for the design geometry. ($\dot{q}_{convection} \propto h(A,T) \cdot A$)

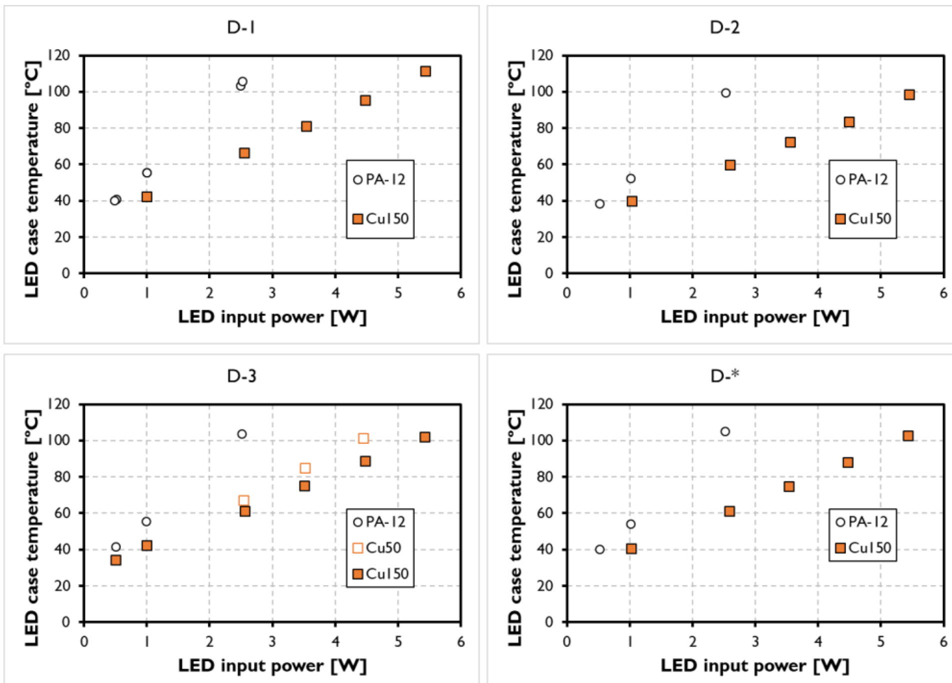


Figure 6. LED case temperature measurements of heat sink designs.

The LED case temperature measurements were used to estimate the effective thermal conductivity provided by the Cu-plating at 50 µm and 150 µm thicknesses. An effective thermal conductivity for each Cu plating thickness was calculated using the measured case temperature values and the simulated conjugate heat transfer model predictions (Figure 7: 20 W halogen and 35 W halogen thermal power curves). The effective thermal conductivity values were estimated by iterating on the effective thermal conductivity values to have the smallest total of the difference squared between the measured LED case temperature and the model-predicted LED case temperature based on the effective thermal conductivity values. The measured LED case temperatures followed the general trend of the simulated results; the deviations from the simulation curve were relatively large (~15℃). These results indicated that the effective thermal conductivity was ~3 W m^{-1} K^{-1} from the 50 µm Cu-electroplating thickness and had equivalent performance to a 3D-printing material with an effective thermal conductivity (Figure 7). The 150 µm Cu-electroplating thickness showed similar performance to a material with an effective thermal conductivity of ~6 W m^{-1} K^{-1} (Figure 7).

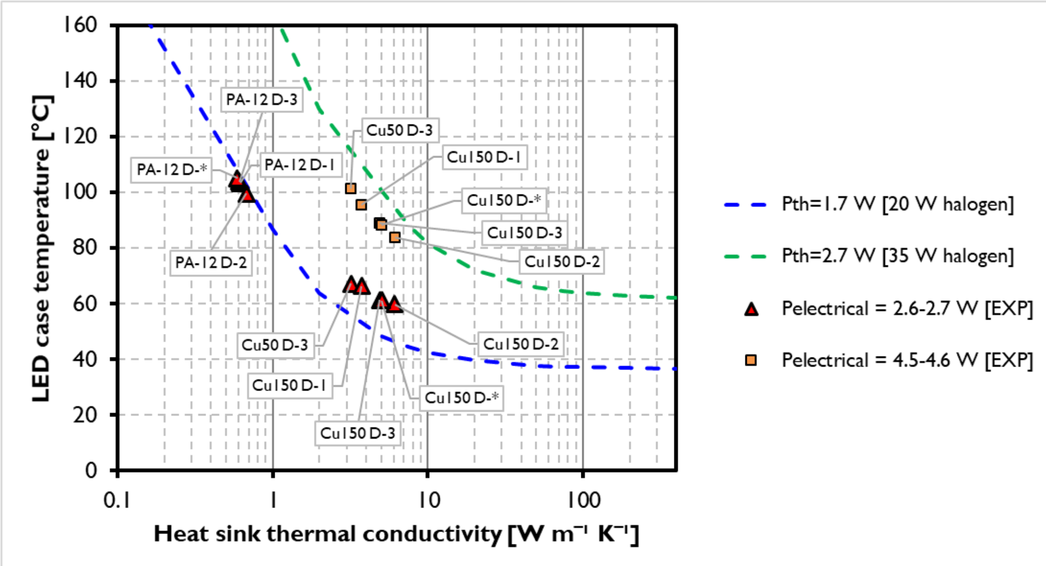


Figure 7. LED case temperature measurements to estimate the effective thermal conductivity.

4. SUMMARY

This paper presented LED application-specific 3D-printed heat sink thermal performance characterizations. Conjugate heat transfer modeling showed that material with effective thermal conductivity values >15 W m^{-1} K^{-1} can potentially satisfy the thermal management requirements of a 50 W halogen equivalent MR-16 type LED integral replacement lamp. Previous laboratory experiments indicated heat sink geometries 3D-printed with PA-12 and electroplated with Cu having improved thermal performance by maintaining an operating temperature at the LED module case location compared to the PA-12 heat sink with no electroplating.

A laboratory experiment was conducted with 3D-printed heat sinks with no electroplating and with electroplating of 50 and 150 µm thicknesses. The Cu-electroplated heat sinks maintained an operating temperature below 105°C at the LED module case location for a thermal load equivalent to a 35 W halogen equivalent MR-16 type LED integral replacement lamp. The 50 µm Cu-electroplating thickness had equivalent performance to a 3D-printing material with an effective thermal conductivity of ~3 W m^{-1} K^{-1}. The 150 µm Cu-electroplating thickness showed similar performance to a material with an effective thermal conductivity of ~6 W m^{-1} K^{-1}.

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