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ABSTRACT

Low energy use and reduced maintenance have made the LED, a solid-state light (SSL) source, the preferred technology for many lighting applications. With the explosion of products in the marketplace and subsequent price erosion, manufacturers are looking for lower cost materials and manufacturing methods. 3-D printing, also known as additive manufacturing, could be a potential solution. Recently, manufacturers in the automotive, aerospace, and medical industries have embraced 3-D printing for manufacturing parts and systems. This could pave the way for the lighting industry to produce lower cost, custom lighting systems that are 3-D printed on-site to achieve on-time and on-demand manufacturing. One unique aspect of LED fixture manufacturing is that it requires thermo-mechanical, electrical, and optical components. The goal of our investigation was to understand if current 3-D printing technologies and materials can be used to manufacture functional thermo-mechanical, electrical, and optical components for SSL fixtures. We printed heat sink components and electrical traces using an FFF-type 3-D printer with different filaments. The results showed that the printed heat sinks achieved higher thermal conductivity values compared to components made with plastic materials. For electrical traces, graphene-infused PLA showed low resistivity but it is much higher than bulk copper resistivity. For optics, SLA-printed optical components showed that print resolution, print orientation, and post-processing affect light transmission and light scatter properties. Overall, 3-D printing offers an opportunity for mass customization of SSL fixtures and changing architectural lighting practice, but several challenges in terms of process and materials still have to be overcome.

Keywords: 3-D printing, additive manufacturing, LED, lighting, solid-state lighting

1. INTRODUCTION

3-D printing, also known as additive manufacturing (AM), constructs three-dimensional objects layer by layer by receiving instructions from a computer-aided design (CAD).[1] There are many AM processes, including:

- Vat photopolymerization
- Material jetting
- Material extrusion
- Powder bed fusion
- Binder jetting
- Sheet lamination
- Direct energy deposition

Of the above processes, the two most popular include material extrusion and vat photopolymerization. In the material extrusion process, a thermoplastic filament is heated and extruded through a nozzle that moves in the x-y plane to complete a layer. The final object is formed once all layers are fabricated.[1] Fused filament fabrication (FFF) or fused deposition modeling (FDM) is the manufacturing technology used in the material extrusion process. In the vat photopolymerization process, commonly referred to as stereolithography (SLA), three-dimensional objects are made by photopolymerizing a fluid medium. Each layer of photopolymer resin is cured with a UV laser directed by a mirror.[1] After each layer is photo-cured, another layer of uncured photopolymer resin is applied onto the previously polymerized layer until the whole object is formed.

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During the past several years, manufacturers in the automotive, aerospace, and medical industries have embraced 3-D printing for manufacturing parts and systems for their applications. According to a recent Forbes magazine article, the goal for using 3-D printing technology is to accelerate product development, offer custom products, and increase production flexibility.[2] The revolution in 3-D printing could pave the way for the solid-state lighting (SSL) industry to step into the 3-D printing era for mass customization and changes to architectural lighting practices by producing lower cost, custom lighting systems that can be printed on-site to achieve on-time and on-demand manufacturing.

The light-emitting diode (LED), a SSL source, has become the preferred technology for many lighting applications today. The main benefits of LED technology include low energy use and reduced maintenance. In addition, SSL offers many other benefits to the built environment where lighting fixtures can be customized to increase visual appeal and functionalities. The benefits of 3-D printing SSL lighting fixtures include custom fixtures, improved visual appeal and functions, rapid prototyping and faster new product introductions, and reduced fixture cost. 3-D printing opens up opportunities for architects and lighting professionals to manufacture custom lighting fixtures on-site to cater to the needs of the space.

A typical 3-D printing process workflow is shown in Figure 1.

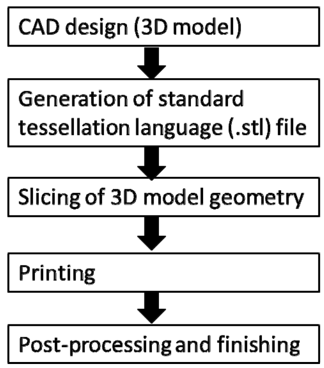

Figure 1. 3-D printing process workflow.

One unique aspect of LED fixture manufacturing is that it requires thermo-mechanical, electrical, and optical components. Past investigations have demonstrated successful 3-D printing of lighting fixture enclosures that look visually appealing. Others have explored the use of AM for creating functional mechanical, electrical, and optical components. The goal of our investigation was to understand if current 3-D printing technologies and materials can be used to manufacture functional components for SSL fixtures and to identify the challenges that need attention so that the above-mentioned benefits can be achieved. The study presented in this manuscript details the investigations and the outcomes.

2. EXPERIMENTS AND RESULTS

2.1 Evaluation of 3-D printed heat sink performance

Today, manufacturers in the SSL industry are faced with the challenge of lowering product costs. Metal heat sinks are commonly used in LED systems to keep LED junction temperatures low for optimum performance and long service life. However, the drawbacks of such heat sinks include heavy, expensive and over-designed thermal properties. Manufacturers are looking for lower cost materials and manufacturing methods to reduce the cost of LED lighting products. Therefore, 3-D printed custom polymer heat sinks with tailored thermal properties can be a way to meet manufacturers' needs. Past literature describes studies that have investigated the use of 3-D printing processes such as powder bed fusion and vat photopolymerization for creating thermal management solutions.[3,4] However, there are no studies investigating thermal management solutions using FFF technology. Therefore, we investigated if custom polymer heat sinks of suitable thermal properties can be printed using the FFF technology using a 3-D printer and filaments available in the market today.[5]

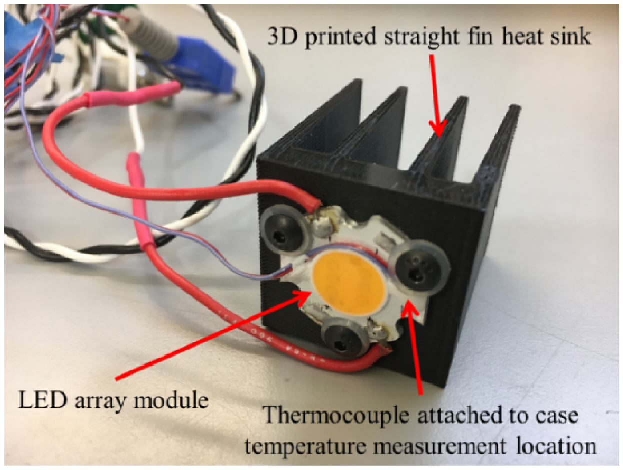

Figure 2. 3-D printed straight fin heat sink with LED array module mounted.

Filaments with metal particles are commercially available for FFF technology in fabricating parts that require a metallic appearance. Past literature show that the inclusion of filler material improves the thermal performance of polymer composites.[6] In our study, we investigated the thermal conductivity of 3-D printed components with varying fabrication orientation and metal infill percentage.[5] Then we used the filament materials and fabricated straight fin heat sink components. A commercial LED array was mounted onto these 3-D printed heat sinks and the corresponding case temperatures were measured. Figure 2 shows one of the 3-D printed straight fin heat sinks with an LED array module mounted and with a thermocouple attached to the case temperature measurement location. To compare the performance of the 3-D printed heat sinks, an aluminum heat sink of the same geometry was also tested.[5]

The results showed higher thermal conductivity values for components printed using filaments with metal filler materials compared to components fabricated using filament materials without filler materials.[5] Similar results were observed in an earlier study with another polymer host material.[7] The results also showed that thermal conductivity values depend very much on the print orientation, as seen in previous studies.[8] The composite filaments printed with carbon graphite, graphene, and carbon black showed much higher thermal conductivity. The infill percentage testing showed an increase in thermal conductivity values with increase in infill percentage.[5] The use of a higher thermal conductive material resulted in a lower LED case temperature, which corresponds to a lower junction temperature.[5] Figure 3 illustrates the estimated junction temperature based on the measured LED case temperature for the 3-D printed straight fin heat sinks fabricated. The LED junction temperature estimate for the extruded aluminum heat sink of the same geometric dimensions is also provided as a benchmark for comparison. However, the achieved thermal conductivity values may not be sufficient to meet the thermal management needs of higher power LEDs with smaller footprint heat sinks.

The filament materials commercially available do not possess the thermal properties to challenge the existing extruded or machined heat sinks. Perera *et al*., in 2017, outlines the required thermal conductivity for a filament material to provide comparable thermal performance for LED lighting applications.[5]

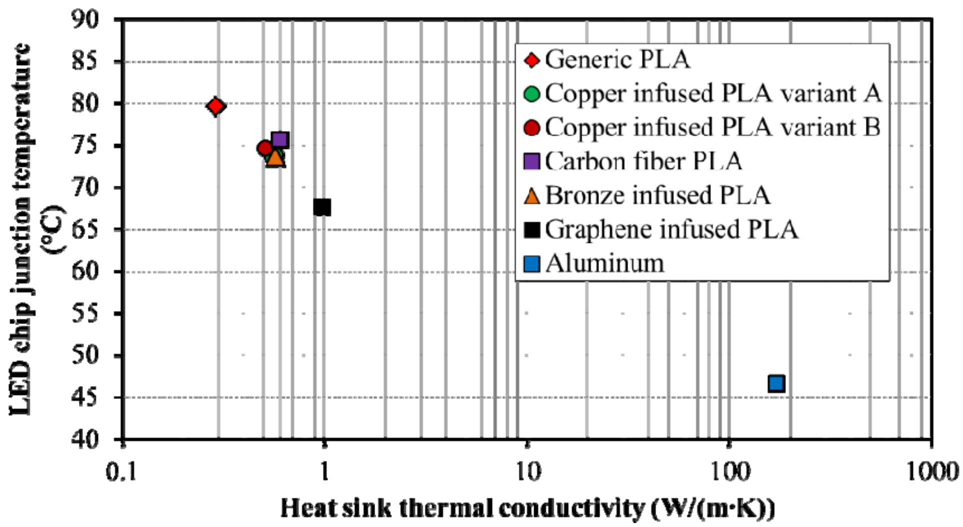

Figure 3. 3-D printed heat sink performance compared with that of an extruded aluminum heat sink from Perera *et al*.[5]

2.2 Evaluation of 3-D printed electrical trace performance

In LED lighting systems, electrical traces are often used to conduct electrical current between different electrical and electronic components. Thotagamuwa *et al*., in 2017 studied whether electrical traces can be printed with suitable electric and geometric properties.[9]

Electrical traces of similar length, width, and different thicknesses and build orientations were printed and tested for electrical resistivity using three different materials (graphene-infused PLA, carbon nanotube-based PLA, and conductive carbon black-based PLA).[9] The electrical resistances of the trace samples were measured (Table 1). In-plane build orientation showed the lowest resistivity (70−80% lower compared to cross-plane) for all three materials. Graphene-infused PLA showed the lowest resistivity (6.1×10^{-3} Ω·m) of all three materials, but it is much higher than bulk copper resistivity (1.7×10^{-8} Ω·m) commonly used in printed circuit board (PCB) applications.

Table 1. Measured 3-D printed electrical trace resistivity values from Thotagamuwa *et al*.[9]

Material	**Electrical resistivity (Ω·m)**		
	In-plane	**45deg-plane**	**Cross-plane**
Graphene-infused PLA	6.10E-03	1.49E-02	2.12E-02
Carbon nanotube-based PLA	1.11E-02	4.34E-02	5.59E-02
Conductive carbon black-based PLA	9.67E-02	3.15E-01	3.70E-01

The use of nanoparticle-based silver inks and liquid metal conductive inks could provide a solution to achieve resistivity comparable to copper. However, these materials cannot be processed using unmodified FFF-type 3-D printers and requires additional liquid or ink extruder components as suggested in literature.[10] Such solutions may still pose a challenge to 3-D printing of non-planer traces. Therefore, future improvements are required to make 3-D printing technologies a viable option for making functional electrical connections in SSL fixtures.

2.3 Evaluation of 3-D printed optical component performance

Vat photopolymerization is one of the most common processes used in the fabrication of optical components.[11] The potential benefits of 3-D printed optical components include ease of creating complex geometric designs and speed of manufacturing. In 2017, Mou *et al*. investigated the optical properties of SLA-printed optical components.[12] In this study, how print resolution affected light transmission and light scatter was analyzed. In addition, the optical setup was rearranged to study the same optical properties as a function of print orientation. The results clearly showed that for light transmission improvement and light scatter reduction, post-processing, print orientation, and print resolution are all important factors to be considered.[12] From this study it was inferred that a print resolution better than 50 μm can produce adequate optical performance for lighting applications, as illustrated by Figure 4. However, the longevity of such 3-D printed optical components is not known and requires further investigation.

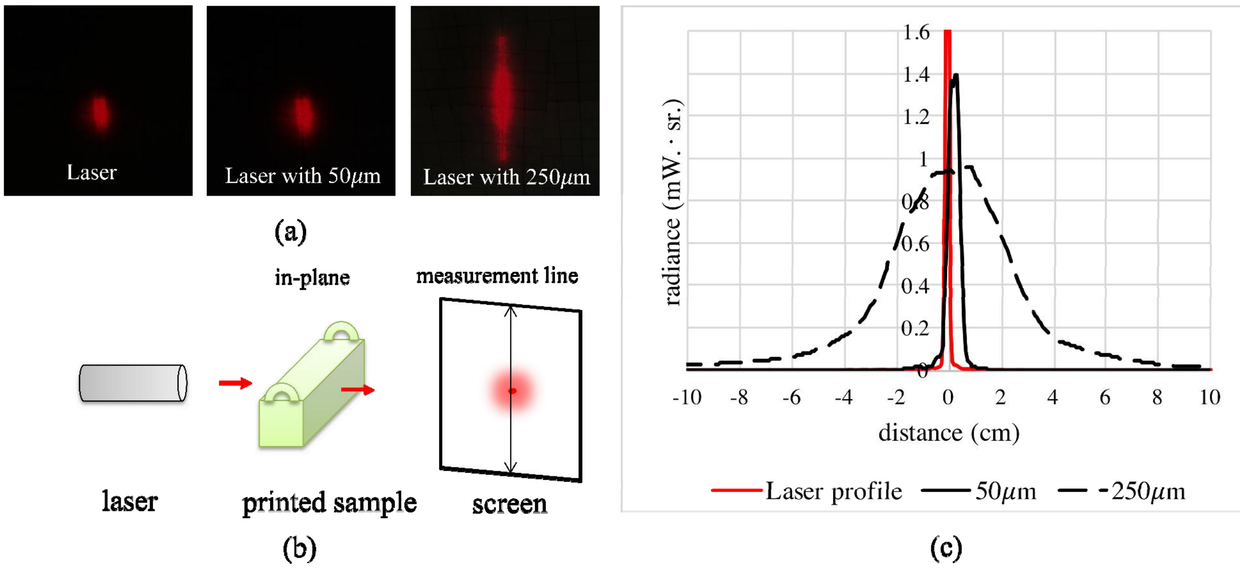

Figure 4. Optical measurement results from Mou *et al.*[12]: (a) Captured image of a bare laser beam (left),50μm print resolution sample (middle), and 250μm print resolution sample (right) at in-plane, vertical measurement condition; (b) Light scattering setup at in-plane measurement condition; (c) Light scattering profile of a bare laser beam (red curve), 50μm print resolution sample (black curve), and 250μm print resolution sample (black dashed curve) at in-plane, vertical measurement condition.

3. SUMMARY

3-D printing has the potential to change current architectural practice, where lighting is an afterthought in built environments, and to improve appearances with custom fixtures manufactured on-site. 3-D printing also has the potential to reduce production costs and reduce time from design to application of products. On-demand, on-site fabrication has the potential to reduce or even eliminate the need for physical inventory and inventory management, which is a considerable burden on a lighting fixture manufacturer.

In order to successfully explore these opportunities, there are challenges that have to be overcome with the presently available 3-D printing technologies and existing 3-D printing materials, such as photopolymer resins, filaments, inks, etc. In addition to this, the present 3-D printing technologies need an integrated approach to combine different parts and fabricate a product with multiple materials and functionalities. At present, these functional components need to be fabricated separately in 3-D printers with different technologies and assembled or integrated separately, where the potential benefits of 3-D printing are not fully realized. Also, faster fabrication and integration are required to meet the needs of the applications.

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