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Long-term performance of 3D-printed optics when exposed to thermal and optical radiation

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ABSTRACT

Vat photopolymerization and multi-jet modeling 3D printers using clear polymer resins have shown promise for making optically clear lenses for LED lighting systems. These clear resins are usually polymethyl methacrylate, acrylonitrile butadiene styrene, and polycarbonate-like photopolymers. One of the main requirements for such lenses in LED lighting systems is stable performance, i.e., maintaining transmitted light and chromaticity for an extended period (over 25,000 hours). A long-term aging study was designed and conducted to understand light transmittance properties as a function of time. The 3D-printed lens samples were exposed to elevated ambient temperature (~45 and 60°C) and short-wavelength optical irradiance (~0.20 and 0.4 W/cm^2) with peak wavelength radiation ~450 nm and FWHM ~25 nm. Test samples were 3D-printed using three clear transparent resins and using vat photopolymerization and multi-jet modeling processes. The lens samples were removed from the aging setup at regular intervals and the transmittance was measured at room temperature. The measured time to 90% lumen maintenance (L_{90}) and 70% lumen maintenance (L_{70}) were affected more by optical irradiance change from 0.20 W/cm^2 and 0.4 W/cm^2 than ambient temperature change from 45°C and 60°C. The vat photopolymerization 3D-printed test samples used for the study showed higher relative transmittance degradation than the multi-jet modeling test samples used in the study for both irradiances and ambient temperatures.

Keywords: 3D printing, additive manufacturing, secondary optics, LED lighting, photopolymer, long-term characterization, short-wavelength optical radiation, thermal degradation

1. INTRODUCTION

3D printing has the potential to address manufacturing limitations by relaxing some constraints related to conventional manufacturing.[1]-[3] 3D printing has been successfully adopted to make custom parts used in the medical, aerospace, automotive, and consumer product industries. The United States Department of Energy (USDOE) has identified the customization of optical components, one of several critical components of a typical LED lamp or an LED luminaire, as one of the opportunities where 3D printing can potentially increase U.S. presence in the LED supply chain.[4] Over the past few years, investigators have started to explore the 3D printing of custom optical components for use in light-emitting diode (LED) lighting system applications with funding from USDOE. One of the main requirements for lenses in LED lighting systems is stable optical performance, i.e., maintaining transmitted light and chromaticity for an extended period (over 25,000 hours). Past literature has reported stereolithography and multi-jet modeling 3D printing technologies using clear resins, which are usually polymethyl methacrylate, acrylonitrile butadiene styrene, and polycarbonate-like photopolymers, as options for manufacturing refractive optical components.[2],[5]-[7]

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Published literature on the long-term performance of 3D-printed optical components is scarce. Past research of a 3D-printed transparent material in an aging study under elevated ambient temperature of 50°C reported a 2% decrease in transmittance through the sample in 560 hours of aging time.[6] Privitera et al. (2019) reported this decrease in transmittance mainly in the wavelength range from 380-550 nm. [9] At the time of writing this paper, the authors were unaware of any published papers on long-term performance of 3D-printed optical components under LED lighting system application conditions, including elevated ambient temperature and optical radiation. Therefore, the goal of this study was to investigate the long-term performance of 3D-printed photopolymer resins when exposed to elevated ambient temperature and short-wavelength optical radiation.

To assess the steady-state operating temperature and the optical irradiance experienced by the optical components of LED lighting systems, two LED-based MR-16 replacement lamps (Figure 1 (a)) and a high-bay light fixture were examined. The measured lens temperatures were 54°C and 67°C (Figure 1 (b)) for the 35-W and the 50-W halogen replacement LED MR-16 lamps, respectively, in open-air. Figure 1 (b) shows the locations where the thermal sensors were attached. The measured optical irradiance ranged from 0.2 W/cm^2 to 0.5 W/cm^2 at the lens surface close to the LED packages. Likewise in high-bay fixtures, the lens irradiance was estimated to reach 0.8 W/cm^2.

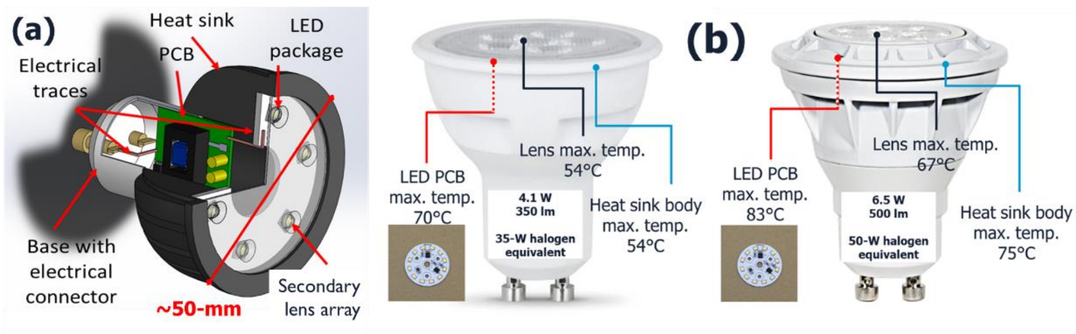

Figure 1. (a) LED-based MR-16 type integral lamp with components and sub-systems and (b) temperature results of the 35-W and 50-W halogen equivalent LED-based MR-16 type integral lamp testing

2. METHODOLOGY

The following test conditions were selected based on past research [8]:

- Two ambient temperatures, 45 and 60°C (±3°C)
- Two average irradiances (within a 19 mm diameter circular aperture), 0.2 and 0.4 W/cm^2

Disc-shaped test samples, 25 mm diameter and 1.5 mm height, were 3D-printed in three photopolymer resin materials. These photopolymer resins were selected based on past literature in which the materials were used for 3D printing components for optical characterizations.[5]-[7] Samples were printed on two stereolithography (SLA-A and SLA-B) machines using two photopolymer resins and one photopolymer resin using a multi-jet modeling (MJM) machine. The SLA-A samples were 3D-printed in-house at 25 µm layer height. These printed samples were washed, cleaned, and fully cured. Then the support structures were removed and the samples were polished using 300-grit sandpaper. The SLA-B samples were 3D-printed by a third-party vendor at 50 µm layer height. The vendor was asked to remove the support structures and polish using 300-grit sandpaper. The vendor applied a clear coat at the end. The MJM samples were printed in-house at a layer height of ~15 µm. These printed samples were cleaned and the supports were removed.

2.1 Characterization experiment setup

The setup used in this study was similar to the setup used in Privitera et al.'s study in 2019[9] for characterizing the 3D-printed test samples (see Figure 2). The characterization experiment setup was used to measure each test sample's inline total transmittance. Initially, the total flux passing through each test sample was captured and measured in a 2 pi steradians solid angle (hemisphere).

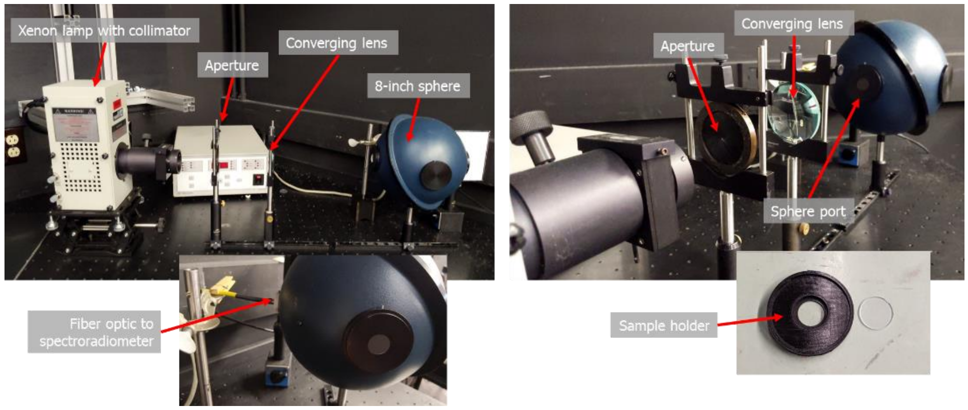

Figure 2. Characterization experiment setup including a Xenon-lamp, integrating sphere, and spectroradiometer.

2.2 Long-term experiment setup

The setup was similar to the long-term irradiance and elevated ambient temperature experiment setup that Appaiah et al. used (2015).[8] The setup shown in Figure 3 (left) was used for irradiating the samples. The test samples were placed on top of an LED module with a reflector. The normalized spectral output power of the LED module is shown in the middle plot. The spatial irradiance distribution on the test samples is shown in the right figure. The LED array module had a peak wavelength of ~456 nm and a full width at half maximum (FWHM) of ~26 nm. The average irradiance was ~0.2 W/cm^2 at 350 mA and ~0.4 /cm^2 at 700 mA at the aperture of the masking plate (diameter ~19 mm).

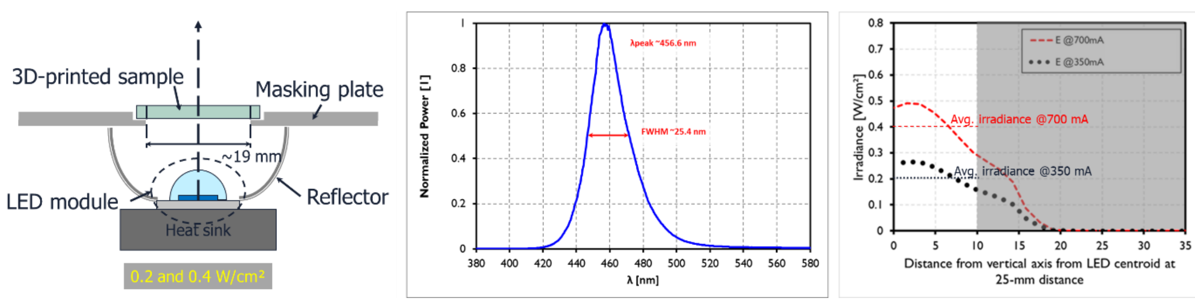

Figure 3. Schematic diagram of the irradiance LED setup (left), LED normalized spectral output (middle), and the irradiance spatial distribution (right)

Figure 4 illustrates the LED module, the reflector assembly, the sample holder integrated with the heating elements, and thermal controllers for both the heating element to maintain the ambient temperature around the test samples at the desired temperature and the thermoelectric cooler for maintaining the LED module case temperature at 30°C.

The test samples were subjected to the following conditions in the aging tests:

- Condition ❶: 0.2 W/cm^2 avg. irradiance and ambient temp. 45°C (low irradiance and low temp.)
- Condition ❷: 0.2 W/cm^2 avg. irradiance and ambient temp. 60°C (low irradiance and high temp.)
- Condition ❸: 0.4 W/cm^2 avg. irradiance and ambient temp. 45°C (high irradiance and low temp.)
- Condition ❹: 0.4 W/cm^2 avg. irradiance and ambient temp. 60°C (high irradiance and high temp.)

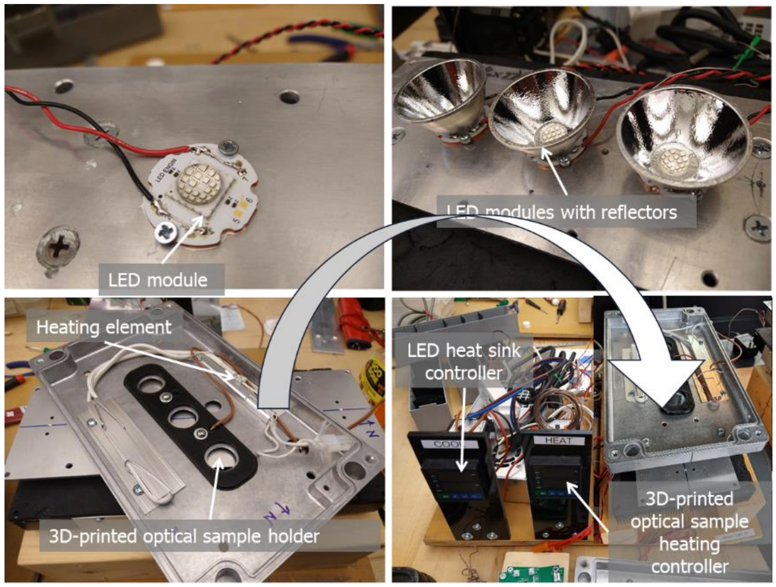

Figure 4. Long-term irradiance and elevated ambient temperature experiment setup

2.3 Characterization and calculation

Initial characterization of all test samples was conducted at time t=0 hrs. Then the test samples were placed on the long-term aging experiment setup. After t_1 hours, all the test samples were characterized for total inline transmittance using the characterization setup. Then, the test samples were placed back in the aging setup. The process was repeated until the transmittance decreased to 40% compared to the sample's normalized transmittance at t=0 hrs. Each time, the measured light levels of all test samples were normalized to the reference acrylic sample (1/16 inch; ~1.6 mm thick, machined from a sheet manufactured using bulk polymerization in a mold).

3. RESULTS

Figure 5 illustrates the relative transmittance change over the aging time of SLA-A test samples under the four test conditions described earlier. The 90% (indicated by the dashed line −−−) and 70% (indicated by the continuous line —) transmittance maintenance relative to its initial value is illustrated on the relative transmittance vs. time charts.

Based on past literature,[8] the authors modeled an equation (Eq. 3.1) of the trend for the 3D-printed samples based on the relative transmittance vs. aging time data collected for 3D-printed sample data that decreased below 90% of transmittance. The parameters (a, b) and (c, d) specify fitted curves of the form indicated in Eq. 3.1 where $\%T$ is the relative transmittance and t is the aging time in hours.

$$\%T = -a \cdot e^{b \cdot t} + c \cdot e^{-d \cdot t} \qquad \text{Eq. 3.1}$$

The fitted curves with the parameters were used to calculate the L_{90} and L_{70}, i.e., the amount of time for the "lumen maintenance" of an LED-based device or, in this case, relative transmittance through the 3D-printed sample to reach 90% and 70% of its initial value. Similarly, L90 and L70 values were calculated for the 3D-printed SLA-B and MJM test samples under the four test conditions provided the relative transmittance had decreased below at least 90% of the transmittance compared to its initial value.

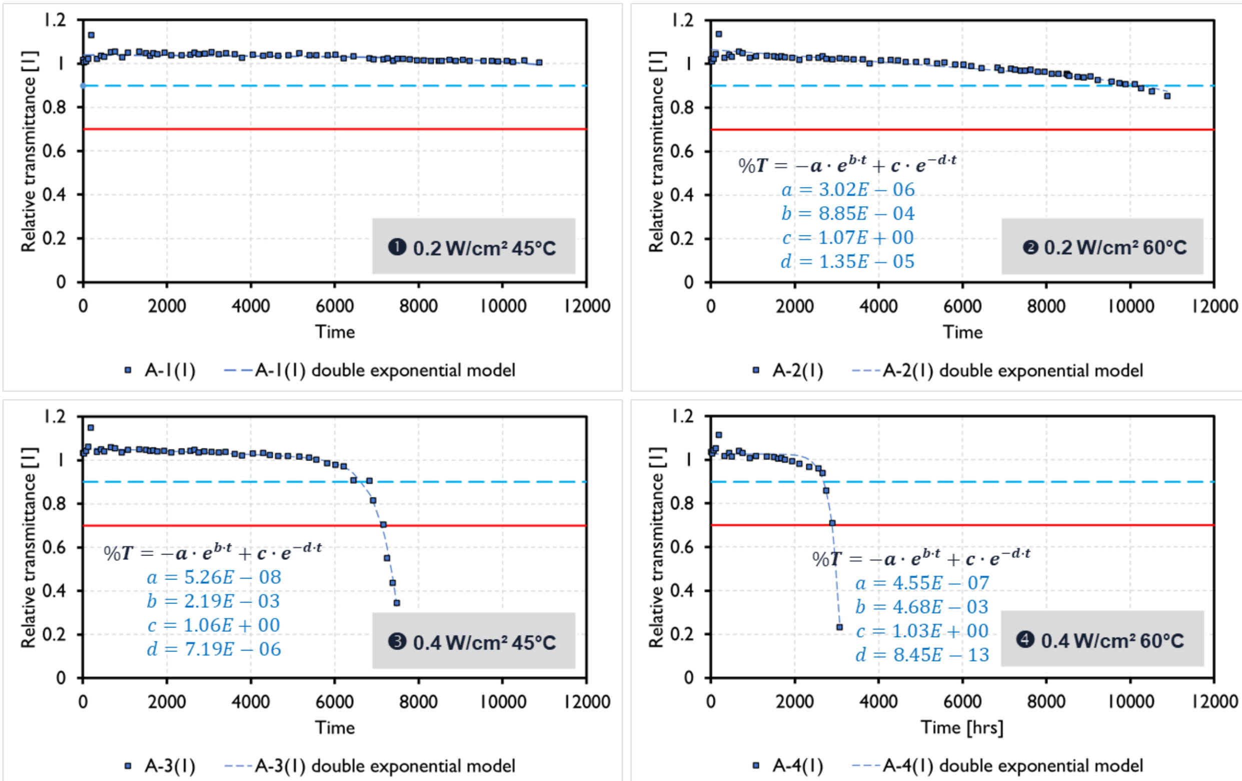

Figure 5. SLA-A 3D-printed test samples relative transmittance vs. aging time under different conditions tested

Figure 6 (left) shows these calculated L_{90} and L_{70} values for the 3D-printed test samples under the different experiment conditions. The MJM-1 through MJM-3 test samples had not decreased below 90% of relative transmittance over the 10,000-hour aging time. Similarly, SLA-A-1 and SLA-A-2 test samples had not decreased below 90% of relative transmittance in that time. SLA-B test sample L_{90} and L_{70} values indicate the relative transmittance degradation rate increasing with conditions numbered ❶→❷→❸→❹. The trend appears to be the same with SLA-A test samples with condition ❸ having a lower relative transmittance degradation rate compared to condition ❹, evident by the L_{70} and L_{90} values of condition ❸ being higher than condition ❹.

Figure 6 (right) illustrates the relative transmittance before aging, at time t=0 hrs, of the test samples compared to the acrylic reference. The relative transmittance with no polishing/post-processing was 89% for the MJM test samples. SLA-A test samples polished with 300-grit sandpaper showed a relative transmittance of 91%, while SLA-B test samples polished with 300-grit sandpaper and clear coating showed a relative transmittance of 97%.

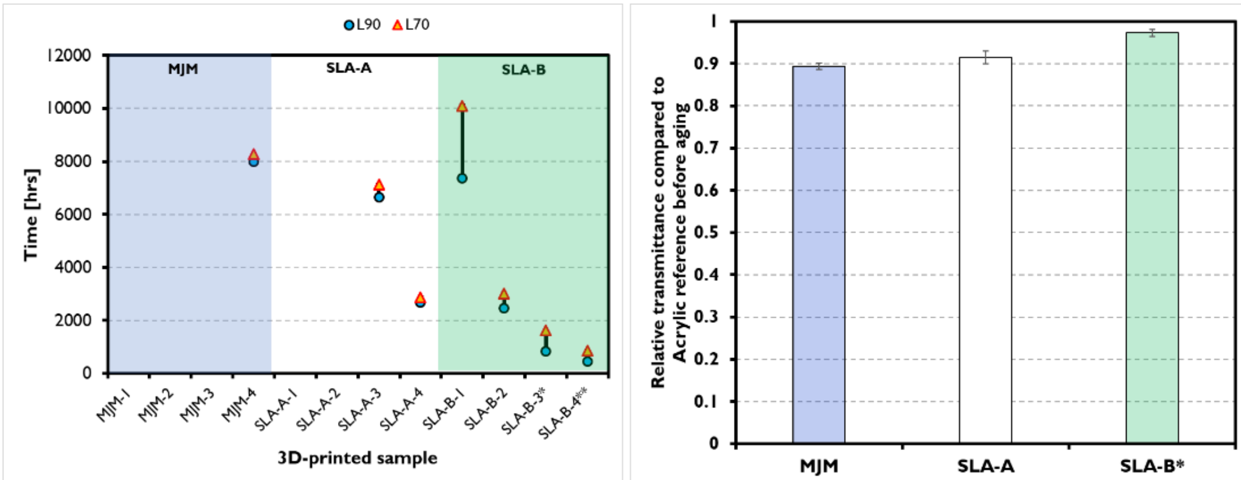

Figure 6. Calculated L_{70} and L_{90} for 3D-printed test samples under the four experiment conditions (left) and relative transmittance compared to the acrylic reference before aging of the 3D-printed test samples (right)

4. SUMMARY

This paper presents the results of a study to characterize the long-term transmittance of LED application-specific, 3D-printed optical components under short-wavelength optical radiation and elevated ambient temperature. Under the irradiance and ambient temperature ranges tested, the L_{70} and L_{90} values were affected by optical irradiance, causing higher relative transmittance degradation compared to ambient temperature. The high optical irradiance of experiment conditions (e.g., condition ❸ at 0.4 W/cm^2 and 45°C) seems to degrade the 3D-printed optical samples more than high ambient temperature experiment conditions (condition ❷ at 0.2 W/cm^2 and 60°C). All 3D-printed test samples degraded below L_{70} in under 8000 hours when subjected to high irradiance and high temperature (condition ❹ at 0.4 W/cm^2 and 60°C).

In selecting machine and material combinations, short- and long-term optical performance should be considered for lighting applications. The experiment showed that the SLA-B machine and material combination with post-processing had the highest inline hemispherical transmittance in the short-term and the lowest L_{70} and L_{90} values in the long-term characterization. The SLA 3D-printed test samples showed lower L_{70} and L_{90} values than the MJM samples, indicating higher relative transmittance degradation of the two tested materials.

The characterization experiment setup and the characterizing procedure were robust in collecting data over 10,000 hours. Using the acrylic reference for normalizing the characterization data through the data collection time proved an excellent procedural addition. The aging experiment setup maintained the irradiance and ambient temperature for over 10,000 hours. Incorporating the thermoelectric cooling units in the aging setup ensured the LED array module case temperatures were maintained at ~30°C, and periodic checks on the constant irradiance levels proved essential for ensuring constant irradiance levels throughout the aging study.

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