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Optical properties of 3D printed reflective and transmissive components for use in LED lighting fixture applications

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ABSTRACT

The abundance of commercial LED lighting fixtures in the marketplace has resulted in price erosion, forcing manufacturers to look for ways to lower manufacturing costs. 3D printing holds promise for providing new solutions that not only can increase the value of lighting but can potentially reduce costs. During the past few years, 3D printing has been successfully adopted in industries such as aerospace, automotive, consumer products, and medical for manufacturing components. For the lighting industry to adopt 3D printing for fabricating light fixtures, it has to show that different subcomponents of an LED light fixture, including thermal, electrical, and optical components, can be successfully made. Typically, optical components are either transmissive or reflective type. In both cases, the component's optical properties affect fixture efficiency and beam quality. Therefore, the objective of this study was to understand how short-term and long-term optical properties are affected when using 3D printed optical components. In the case of transmissive optics, several optical elements were printed and aged at higher than ambient temperatures and their corresponding spectral transmissions were measured over time. Similarly, several reflective optical elements were printed and characterized for spectral reflectivity as a function of print parameters, including print layer height, print orientation, and the number of print layers before and after aging the parts at higher ambient temperatures. These results are useful for optical component manufacturers to understand the possibilities of using 3D printing to make high-quality optics for lighting fixture applications and for 3D printing material and printer hardware manufacturers to understand the requirements of optics for the illumination applications.

Keywords: 3D printed, additive manufacturing, optics, reflector, TIR, lens, LED, lighting

1. INTRODUCTION

Solid-state lighting technologies have matured significantly in the past few years and are now used in practically all lighting applications. However, the abundance of commercial light-emitting diode (LED) lighting fixtures has resulted in price erosion, forcing manufacturers to look for ways to lower costs, including manufacturing overseas, exploring new materials, and simplifying product design. 3D printing holds promise for providing solutions to some of these issues and increasing the value of lighting. For example, additive manufacturing technologies can help increase the value of lighting by enabling local manufacturing opportunities to make custom lighting fixtures on demand, at or near construction sites, which could become an integral part of the architectural design and construction process. However, to gain wide adoption, 3D printing technologies and materials need to show that the different components of an LED light fixture (Figure 1) can be successfully made and meet the performance and useful lifetime expectations under realistic conditions.[1]

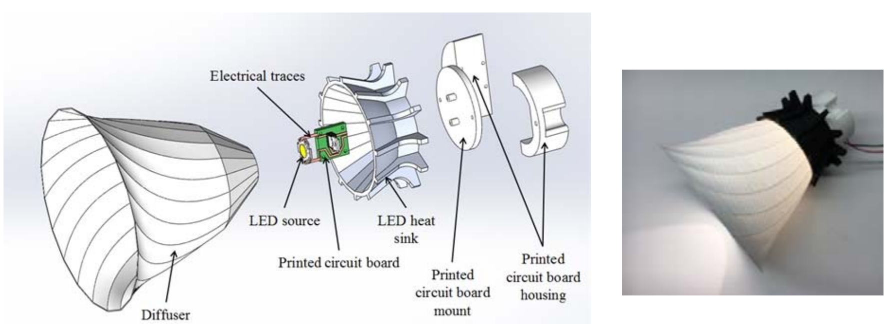

Figure 1. Example of different components, including heat sink, electrical, and optical subassemblies, of an LED lighting fixture (left) and an assembled, functional 3D printed fixture prototype (right). [1]

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Like any other light source, LEDs often require secondary optics to shape the beam to meet design objectives in terms of light distribution. Traditional lighting systems rely on glass, metal, and plastic materials for lenses, reflectors, and diffusers, primarily because of practical reasons, including size and geometry, temperature of operation, environmental conditions, ruggedness, and price. The variety of LEDs in the market offer many more opportunities for optical designs, and now LED lighting systems primarily rely on plastic materials for all three types of optics because of the flexibility that molded plastics offer and because of the typically lower temperature of operation of LED lighting systems compared to incandescent and high-intensity discharge systems. With this in mind, it is expected that 3D-printed optics soon will be available for lighting applications. When they are, the materials and printing methods will have to take into consideration not only the optical and photometric characteristics but also the long-term performance expectations of lighting systems for general applications. In general, lighting systems are design to last several years, and in some cases, decades. For example, municipalities and utilities in the U.S. calculate the life cycle costs and depreciation of roadway lighting fixtures considering that they will have a useful lifetime of 27 years. Similarly, in commercial and industrial applications, it is not uncommon to find lighting fixtures that are expected to last as long as 20 to 30 years. It is true that in many cases spaces are renovated much sooner but in any case, lighting systems in commercial general lighting applications need to be rated for several thousands of hours.

The most common optical components used in LED lighting systems are transmissive (often total internal reflection, TIR, lenses) and reflective (often based on opaque materials with high reflectance such as aluminum and white paints and coatings). In this study, several 3D printable materials with transmissive and reflective properties were investigated for their potential to be used in the fabrication of functional optical components for LED lighting applications.

2. METHODOLOGY

2.1 Experimental design

Four sets of samples were prepared for the study, grouped by the material type used to print them. One of the sets (transmissive) was printed using an optically clear resin designed for stereolithography (SLA), and the other three sets (reflective) were printed using different types of white materials designed for filament fusion fabrication (FFF), including two types of polylactic acid (PLA) and one type of copolyester with no styrene (CoP). For each of the three PLA and CoP materials, nine samples were printed in different thicknesses by varying the extrusion width or the number of extrusions using fused filament fabrication.

After printing and preparation, the optical properties of all samples were measured. Once this step was completed, the samples were exposed continuously to a 50°C ambient temperature over a period of several hundred hours to study the optical degradation over time of each material type. The selected temperature for the long term test is consistent with temperatures observed in LED light fixtures under typical operating conditions; for example, in residential and hospitality applications.[2]

2.2 Transmissive samples fabrication and characterization

A 25-mm diameter and 15-cm long cylindrical rod (Figure 2) was 3D printed using stereolithography. The material chosen was an optically clear resin, a thermoset material, with near colorless optical properties used for applications to mimic the appearance and tactile properties of clear thermoplastic material. This particular material has a glass transitioning temperature (T_g) of 43°C and a coefficient of thermal expansion (CTE) <180 (μm/m)/°C in the range from -40°C to 100°C. The fabrication of the cylindrical rod was outsourced to a third party service bureau. Due to the inherent fabrication limitations of the SLA technology, the cylindrical rod was 3D printed at a 5° horizontal tilt. The rod was then cut into 3-mm and 6-mm thick discs of 25-mm diameter (Figure 2). All flat surfaces of the samples were polished using polishing paper starting at 2400 grit and increasing progressively to 3200, 4000, 6000, 8000, and finally 12000 grit. The transmittance of the polished samples was measured using the experimental setup illustrated in Figure 3. Test samples were placed on one port of an 8-in diameter sphere using a standard holder. A double monochromator was coupled to a second sphere port at 90° with respect to the sample port. A 12 V, 75 W working standard halogen lamp was used as the reference source for the spectral transmittance measurements.

After the initial transmittance characterization the samples were exposed continuously to an ambient temperature of 50±3°C in a laboratory grade oven during the heat treatment phase of the experiment. The disc samples were periodically taken out of the oven and cooled down to ambient room temperature (~23°C) before their transmittance was characterized. Measurements were taken at 112, 231, 308, 421, and 560 hours of exposure to the 50°C environment.

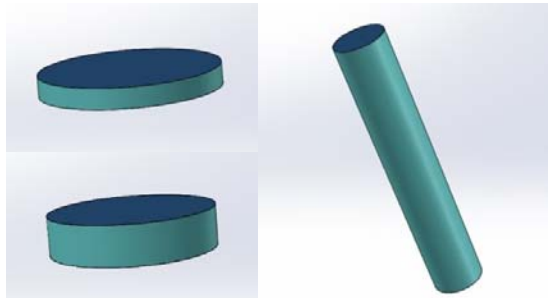

Figure 2. Schematic drawing of the rod and the 3-mm thick (middle) and 6-mm thick (right) samples.

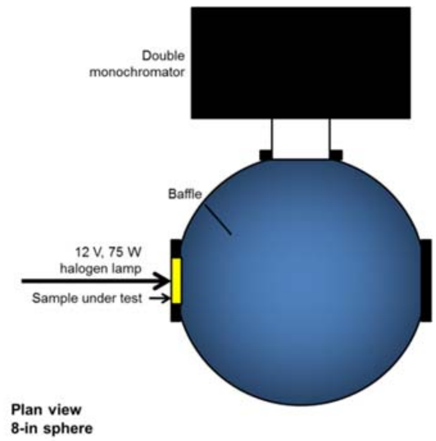

Figure 3. Integrating sphere setup used to measure the spectral transmittance of the clear resin 3D printed samples.

2.3 Reflective samples fabrication and characterization setup

The most common 3D printing technology, fused filament fabrication (FFF), was used to produce the reflective type samples. Figure 4 illustrates the geometry of a 3D printed reflector using FFF. The fabrication starts at the build platform with the layering of thermoplastic material extruded from a heated nozzle. Due to this fabrication process, the reflective properties of the non-smooth surface used to shape the beam of light emitted by the light source depend on both the material geometry and the printing process. A detail of the non-smooth surface can be seen in the inset in Figure 4.

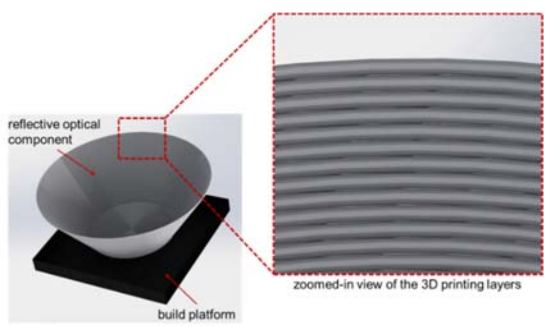

Figure 4. Illustration of the details of a 3D printed reflector using fused-filament fabrication (FFF).

The print process is controlled by the printer parameters used during the fabrication, which include the extrusion layer height, the extrusion width, and the wall width (i.e., multiple extrusions wide wall). Figure 5 shows these parameters. Square samples of 37-mm on side were 3D printed in the vertical orientation with a 0.35 mm nozzle.

Round samples were then punched out using a 1-3/16-inch hole-punch tool. The resulting discs were mounted to the experimental setup illustrated in Figure 6.

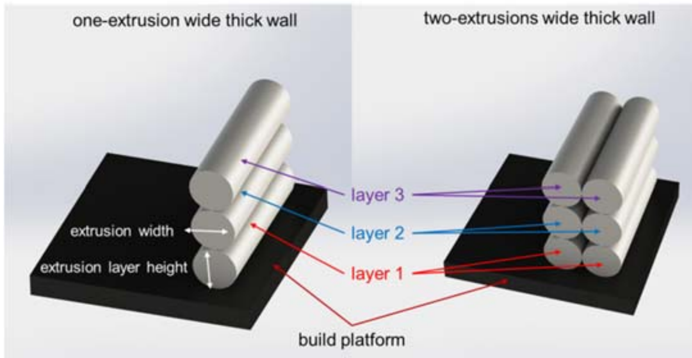

Figure 5. 3D printing parameters used in the fused-filament fabrication of the PLA and CoP reflective samples.

Three different white filament materials were used to 3D print the samples as described above. Two sets of samples using each filament material were 3D printed by changing either the extrusion width (keeping constant the extrusion layer height and the thickness of the wall (Table 1)), or the width of the wall (keeping constant the extrusion layer height and the extrusion width the same (Table 2), resulting in a multiple-extrusions-wide wall).

Table 1. Characteristics of the PLA and CoP samples for constant extrusion layer height and wall thickness.

Sample ID	Extrusion layer height [mm]	Extrusion width [mm]	Number of extrusions to make wall
Sample A	0.2	0.4	1
Sample B		0.6	
Sample C		0.8	
Sample D		1.0	

Table 2. Characteristics of the PLA and CoP samples for constant extrusion layer height and extrusion width.

Sample ID	Extrusion layer height [mm]	Extrusion width [mm]	Number of extrusions to make wall
Sample A	0.2	0.4	1
Sample B			3
Sample C			5
Sample D			7
Sample E			11

The spectral reflectance factor (0°/d) was measured for each of the nine samples in each of the three materials (two PLA, one CoP) using the setup shown in Figure 6.

Generally, for each sample, the procedure included recording a reference measurement using a white standard reflectance (Labsphere Inc., SRT-99-050-EPV), a sample measurement, and two dark measurements (one for the white standard and one for the test sample). A collimated beam of a current-controlled Xenon light source was used for all measurements. For the reference measurement, the white standard reflectance was placed in the port of the sphere diametrically opposite to the reference light source. The test sample was mounted to the sphere port at 90° with respect to the white standard. For the sample measurement, the positions of the test specimen and the white standard were swapped as illustrated in Figure 6. The spectral power distribution of each measurement (including dark readings) was collected and used to determine spectral reflectance and reflectance factor characteristics. Multiple measurements for each sample were conducted, in random order, to understand the repeatability and uncertainty of the measurement setup. The uncertainty of the measurements was estimated to be ± 2%.

After the initial spectral reflectance characterization, the samples were exposed continuously to an ambient temperature of 50±3°C using the same setup as that for the clear resin samples. The white PLA and CoP samples were periodically taken out of the oven and cooled down to ambient room temperature (~23°C) before their transmittance was characterized.

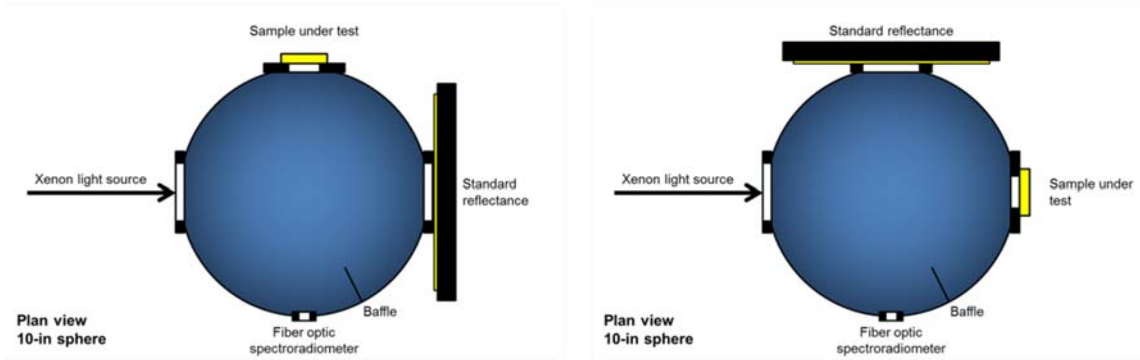

Figure 6. Integrating sphere setup used to measure the reflectance factor and spectral reflectance of the white reflective samples. The corresponding dark readings were taken by removing the sample or the standard reflectance.

3. RESULTS

3.1 Transmissive samples

Figures 7 and 8 show a summary of the optical properties of the clear SLA resin samples before and after exposure to an ambient temperature of 50°C. As can be seen in Figure 7, the relative spectral transmittance of the resin tested is relatively flat across the visible spectrum but has a sharp cutoff starting at approximately 420 nm. When exposed to a high temperature environment (50°C in this case), the region between 380 nm and 500 nm is the most affected with a maximum 10% reduction in transmittance at 415 nm after 560 hours. For lighting purposes, the observed changes in spectral transmittance only translate into a reduction of approximately 2% in average transmissivity. This is because the photopic luminous efficiency function discounts heavily the short and long wavelength regions of the visible spectrum but not the middle of the spectrum (~555 nm). Thus, if these samples were to be used as optical elements in a lighting fixture, the lumen depreciation after 560 hours would be of the order of 2%. However, as can be seen in Figure 8, the appearance of the sample after aging at 50°C is clearly yellowish in comparison to the original condition. This effect could be even more noticeable for phosphor-converted white LEDs. These LEDs typically use a 440-465 nm blue pump to excite a phosphor. The peak of these LEDs corresponds with the region where the sample depreciated the most, likely resulting in a visible change of light color to a yellowish tint. A 441 nm LED sample is illustrated in Figure 7. Note that because this particular material is not perfectly clear, the average transmittance depends on the thickness of the sample. In this case, there seems to be a drop in transmittance of approximately 1.5% per millimeter in thickness (Figure 7).

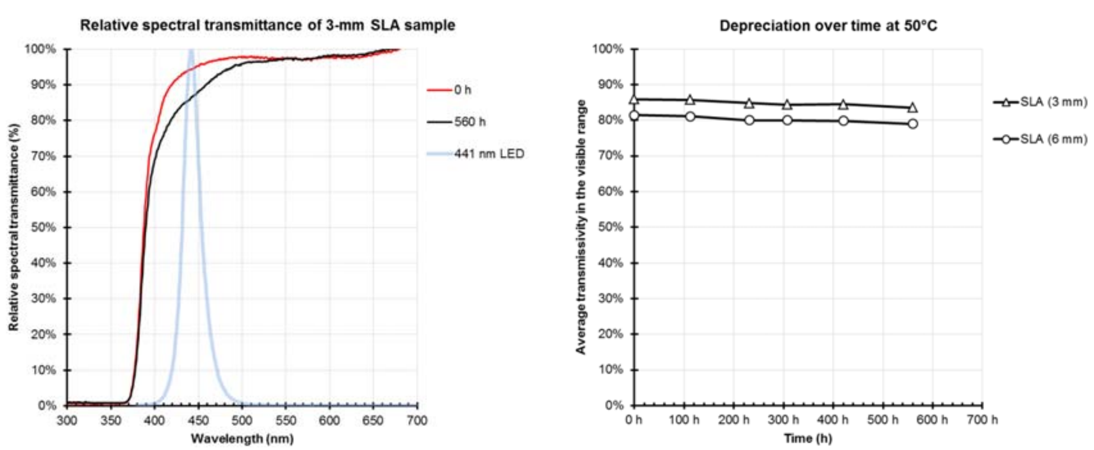

Figure 7. Change in relative spectral transmittance (left) and average transmissivity (right) of the SLA resin samples tested as a function of time when exposed continuously to an ambient temperature of 50°C.

Figure 8. Picture showing the yellowing of the 3-mm sample after 560 hours.

3.2 Reflective samples

Figures 9 to 11 show a summary of the optical properties of the white PLA and CoP samples before and after exposure to an ambient temperature of 50°C. Both PLA and CoP material types have a relatively flat spectral response in the visible range and exhibit a sharp cutoff starting at approximately 400 nm (Figure 9). Of the three materials, the PLA1 samples had the flattest spectral reflectance and the highest overall reflectance factor (~92%). Figure 10 shows, as expected, how the reflectance factor increases with the thickness of the samples up until approximately 2 mm and then remains constant. For practical purposes, this thickness would be the point at which the translucency of the sample is minimal.

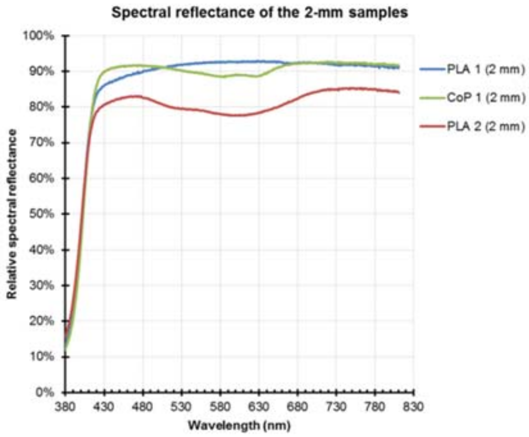

Figure 9. Initial relative spectral reflectance of the 2-mm samples for each of the three white materials tested. All samples as tested before being exposed to a high temperature ambient.

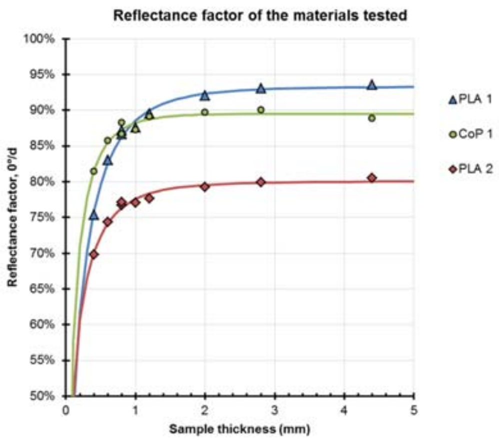

Figure 10. Initial reflectance factor (0°/d) for each of the 27 samples tested (3 materials, 9 samples per material). All samples as tested before being exposed to a high temperature ambient.

Unlike the clear resin tested, none of the white materials (PLA, CoP) showed any measurable or visible degradation after continuous exposure to 50°C for 620 hours (Figure 11).

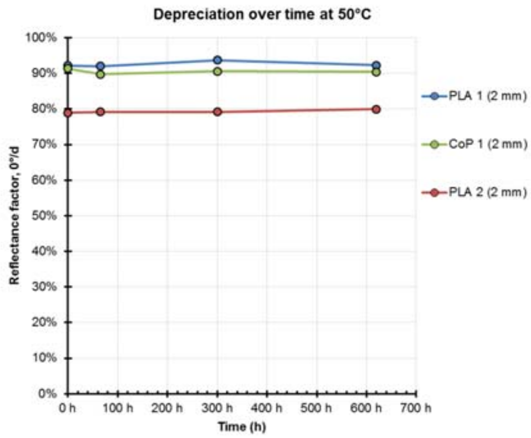

Figure 11. Final reflectance factor (0°/d) of the 2-mm samples for each of the three white materials tested after being continuously exposed to a 50°C temperature ambient for 620 hours.

3.3 Discussion

The PLA and copolyester samples showed reflectance properties suitable for LED lighting applications and did not show measurable degradation when exposed to a 50°C ambient temperature. The transmittance of the SLA clear resin samples was reasonable but showed a systematic reduction in transmittance in the 380 nm to 500 nm region, which coincides with the peak emission of the blue pump LEDs used in white phosphor-converted LEDs.[3] This could result in undesirable changes of light color appearance in a short term, which may not be acceptable in many lighting applications. Polymer-based materials typically degrade due to thermal stress and short wavelength exposure.[4][5] However, in this study the samples were kept in a dark oven during aging at 50°C. Therefore, the transmittance changes observed in this study can be considered due to thermal effects only. Further studies are necessary to estimate the effect of exposing these materials to short wavelengths as well as high temperatures, as they would be under realistic conditions.

4. SUMMARY

The objective of this exploratory study was to characterize the optical properties of materials that could be used to 3D print reflective and transmissive optical elements for LED lighting applications. A summary of findings follows:

Transmissive elements (SLA):

- Transmissivity decreases by approximately 1.5% per mm in thickness
- The SLA resin tested showed a systematic reduction in transmittance in the 400 nm to 500 nm region when exposed to 50°C. This can result in undesirable color shift, especially with phosphor-converted white LEDs as these have a blue pump in the range 440-465 nm to excite the phosphors.

Reflective elements (PLA 1, PLA 2, CoP 1)

- As sample thickness increased, the reflectance factor (0°/d) increased up to approximately 2-mm where it became constant (PLA1 = 80%, PLA2 = 90%, CoP1 = 92%)
- The reflectance factor of all three materials tested remained constant for 560 h when exposed to a 50°C ambient temperature
- Extrusion width and wall thickness have a similar effect on reflectance factor

5. ACKNOWLEDGMENTS

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