Optical Properties and Lampshade Design Applications of PLA 3D Printing Materials

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The optical properties of PLA 3D printing materials and their influencing factors were considered relative to the manufacture of personalized 3D printing PLA lampshades. Rectangular PLA 3D printing specimens were designed, and their light transmittance and haze were analyzed in terms of color, layer height, and wall thickness using UV spectrophotometer. Using the preferred molding parameters for 3D printing of PLA lampshade, three lampshades were designed and completed *via* 3D printing model fabrication. The results revealed that the milky white specimen had stronger light scattering and better luminous uniformity than the colorless specimen, making it more suitable for the manufacturing of 3D printing lampshades. Among the 3D printing molding parameters, the effect of layer height on the light transmittance and haze of the specimen was not significant. Considering the factors such as time and cost, a 0.3 mm layer height was selected as the preferred molding parameter. The effect of wall thickness on the light transmittance and haze of the specimen was significant. As the wall thickness of the specimen increased, the light transmittance of the specimen decreased, and the haze increased. Considering the factors such as optical performance, time, and cost, a 0.8 mm wall thickness was selected as the preferred molding parameter.

DOI: 10.15376/biores.18.1.1545-1553

Keywords: 3D printing; Polylactic acid; Lampshade

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INTRODUCTION

In modern home decoration, lampshades not only can serve the function of daily lighting, but they also can play an important role in shaping the indoor environment and home style. With the improvement of people's living standards, the concept of personalized customization and green environment protection is being accepted by more people (Yao *et al*. 2020). Materials for lampshades commonly include traditional inorganic optical materials and polymer optical materials. In comparison to the inorganic materials, the polymer optical materials are less heat-resistant, less weather-resistant, lower in refractive index, having a narrower dispersion range is narrower, and having a larger coefficient of thermal expansion. On the other hand, polymer optical materials can have the advantages of environment-friendly character, impact resistance, low density, low cost, easy processing molding, *etc.* In recent years, polymer optical materials have been widely used in the field of optics. Poly(lactic acid) (PLA) can be used in 3D printing of lampshades to apply personalized customization and environment-friendly materials to the design and manufacturing, thereby meeting people's demand for personalized customization and creating environment-friendly home products (Han *et al*. 2022).

Polylactic acid is a new type of bio-based and renewable biodegradable material that can be made from starch extracted from renewable plant resources (*e.g.* corn, cassava, *etc.*). It has good degradability and eventually degrades to carbon dioxide and water without polluting the environment; thus it is recognized as an environment-friendly material (Huang *et al*. 2022). However, studies have shown that PLA depends on abiotic mechanisms for its degradation and that it is quite resistant to biodegradation. It is compostable under relatively high temperature conditions, which are consistent with this abiotic pathway of degradation. PLA is also one of the commonly used consumables for the fused deposition 3D printing process. PLA 3D printing materials have high strength and toughness, low shrinkage, and are not easily susceptible to edge warping and cracking. They can be used to make models of large size. They will not release irritating odor during 3D printing and are safe and environment-friendly (Bai *et al*. 2019).

Light transmittance and haze, as the most important indicators of the optical properties of the material, are also the most important factors to consider when designing a lampshade (Chen *et al*. 2020). In this context, the optical properties of PLA 3D printing materials were experimentally investigated, and the light transmittance and haze of PLA 3D printing specimens were tested and analyzed in terms of color, layer height, and wall thickness. The preferred molding parameters for 3D printing of PLA lampshades were summarized. Finally, the 3D printing design practice of PLA lampshades was carried out, and three lampshades were designed and 3D printing prototype models were manufactured.

EXPERIMENTAL

The rectangular specimen as shown in Fig. 1 was designed by SolidWorks software, with a length of 30 mm and a height of 50 mm. As required by the experimental design, each group of specimens corresponded to different wall thickness dimensions (including 0.8 mm, 1.6 mm, and 2.4 mm).

In the following experiments, the wall thickness dimensions of each group of specimens were described. A Kobra Neo 3D printer (XYZ printing, 0.4 mm nozzle diameter, Anycubic, China) and polylactic acid (PLA) filament (milky white and colorless, 1.75 mm diameter, Anycubic, China) were used for additive manufacturing (AM) by the fused deposition modeling (FDM) method. The extrusion head temperature was set to 210 ℃, the printing speed of the 3D printer was set to 50mm/s, and the other 3D printing parameters were as shown in Table 1 (Che *et al.* 2022).

A U-3900 UV spectrophotometer was used to test the transmittance and haze at the center point of each group of specimens. The haze was tested by integrating sphere, and the reference standard was ISO-14782-2021. Haze, also known as cloudiness, measures the degree to which a transparent or translucent material is unclear or cloudy (Feng *et al*. 2022). Haze arises from cloudy appearance caused by light scattering from the internal or external surface of the material. The haze value is expressed as a percentage of the ratio of the scattered luminous flux of the material to the luminous flux through the material. The greater the haze, the stronger the light scattering of the lampshade, and the better the lighting comfort. For example, the light diffusion plate haze of ceiling lights is usually above 85%.

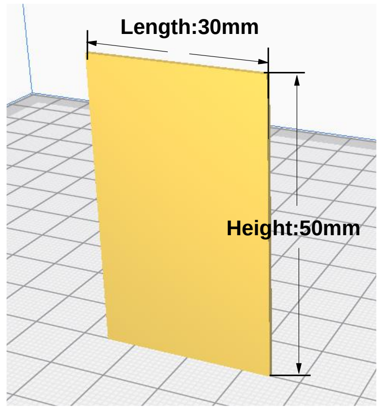

Fig. 1. Rectangular specimen

Table 1. 3D Printing Parameters

Parameters	Settings
Thickness of bottom layer	1.2 mm
Thickness of top layer	1.2 mm
Filling rate	100%
Extrusion volume	100%

RESULTS AND DISCUSSION

Effect of Color on Light Transmittance and Haze

Two groups of specimens were made of milky white and colorless PLA 3D printing filament, and their light transmittance and haze were tested. The 3D printing layer height was set to 0.1 mm, and the wall thickness was set to 0.8 mm. Figures 2 and 3 show the light transmittance and haze test results of milky white and colorless specimens, respectively. The transmittance of colorless specimens in the UV spectral region (λ < 400 nm), visible spectral region (400 to 720 nm), and infrared spectral region (λ > 720 nm) is above 85%, and the transmittance is good. It has higher transmittance in the long-wave UV region (λ of 350 to 400 nm) because long-wave UV has higher frequency and its penetration is stronger. The transmittance of the milky white specimens in the UV spectral region (λ < 400 nm) is below 20%, and the transmittance in the visible spectral region (400 to 720 nm) and infrared spectral region (λ > 720 nm) is between 50% and 65%, all of which are smaller than the transmittance of the colorless specimens, with general light transmittance performance. Since the colorant in the milky white PLA 3D printing filament is titanium dioxide, which has a strong cut-off effect on UV light, a loss of transmission in the long-wave UV region (λ 350 to 400 nm) occurs. As can be seen in Fig. 3, the average haze value of the milky white specimens at 400, 500, 600, and 700 nm is 61.28%, which is greater than the average haze value of the colorless specimens at 400, 500, 600, and 700 nm of 43.91%. This is because the titanium dioxide particles present in the milky white specimens as the dispersed phase in the continuous phase of polylactic acid act to destroy the uniformity of the refractive index in the medium. Thus, when the incident light irradiation in the refractive index of different material partition interface, light scattering occurs, so as to achieve a soft and uniform light output effect (Zhang *et al*. 2021). As a result, the light scattering of the milky white specimens is enhanced, the uniformity of light emission is increased, and the illumination comfort is improved compared to the colorless specimens.

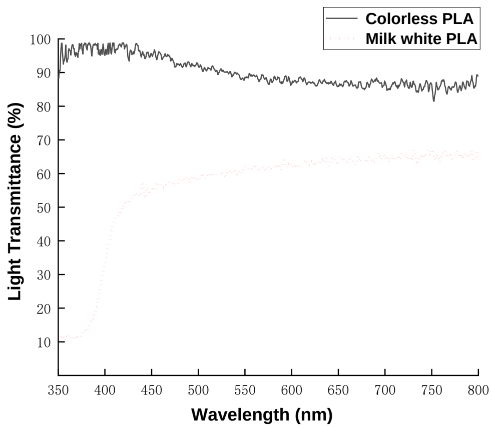

Fig. 2. Effect of color on transmittance

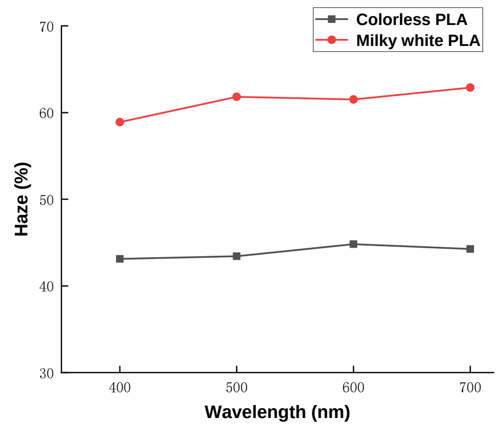

Fig. 3. Effect of color on haze

Effect of Layer Height on Light Transmittance and Haze

The milky white PLA 3D printing filament was selected, and the wall thickness was set to 0.8 mm. Three sets of specimens with three layer height values of 0.3, 0.2, and 0.1 mm were selected and tested for light transmittance and haze tests; the results are shown in Figs. 4 and 5. The transmittance of the three groups of specimens in the UV spectral region (λ < 400 nm) is below 20%, and the transmittance in the visible spectral region (400 to 720 nm) and the infrared spectral region (λ > 720 nm) is between 50% and 65%. Comparing the transmittance curves of the three groups of specimens, the transmittance curves of the three groups of specimens in each spectral region are relatively close to each other, and the transmittance difference is small. The transmittance curves at 500 to 600 nm wavelength were selected for amplification, and it was seen from the amplification curves that the transmittance of the specimen decreased with the decrease of the layer height. This is because as the layer height decreases, the more dense the material buildup between the layers of the specimen, the smaller the surface roughness, and the greater the reflection rate of light. Therefore, at the specimen-air interface, more light is reflected, less light is transmitted, and the transmittance is reduced. As shown in Fig. 5, the average values of haze for 0.3, 0.2, and 0.1 mm layer height specimens were 61.28%, 61.53%, and 61.61%, respectively. Thus, they increased with the decrease of layer height. As the layer height decreases, the density of the specimen increases, the more the polymeric substance and crystalline aggregates inside it are dispersed, and the more the refractive index of light propagating inside the material fluctuates (Yang *et al*. 2022). Therefore the scattering of light increases, the uniformity of light output increases, and the haze increases. In summary, the effect of layer height on the light transmittance and haze of the specimen was not significant. Since the layer height range of desktop FDM 3D printer is usually 0.05 mm to 0.3 mm, within this range, the larger the layer height, the shorter the manufacturing time and the lower the cost. Therefore, considering the factors of time and cost, a 0.3 mm layer height was chosen as the preferred molding parameter.

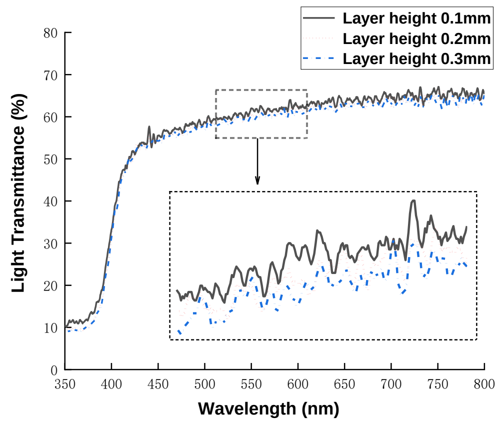

Fig. 4. Effect of layer height on light transmittance

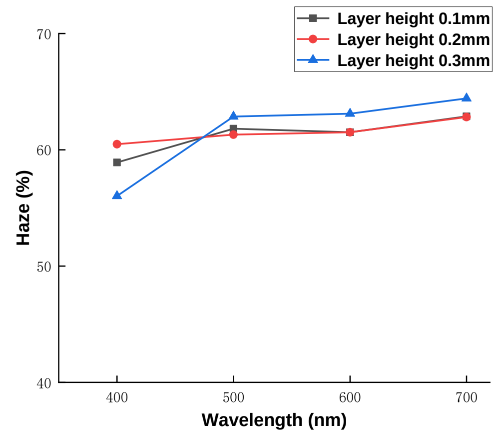

Fig. 5. Effect of layer height on haze

The Effect of Wall Thickness on Light Transmittance and Haze

The milky white PLA 3D printing filament was selected, and the layer height was set to 0.1 mm. Three sets of specimens with three wall thickness values of 0.8, 1.6, and 2.4 mm were selected to test their light transmittance and haze. Figures 6 and 7 show the results of light transmittance and haze tests for specimens with 0.8, 1.6, and 2.4 mm wall thickness, respectively. As can be seen in Figs. 6 and 7, the transmittance values in the visible spectral region (400 to 720 nm) for the 0.8 mm wall thickness specimens ranged from 65% to 73%, with an average haze value of 57.55%. The values of transmittance in the visible spectral region (400 to 720 nm) for the 1.6 mm wall thickness specimens ranged from 50% to 65%, and the average value of haze was 61.28%.

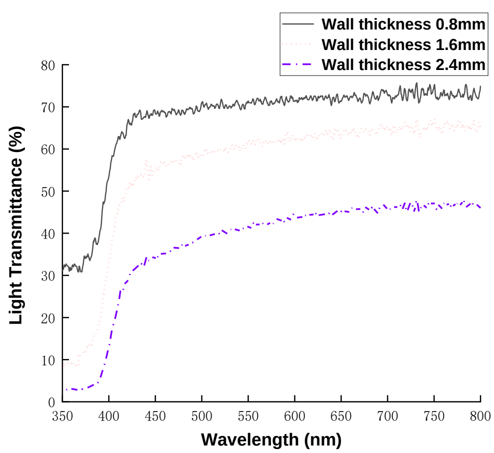

Fig. 6. Effect of wall thickness on light transmittance

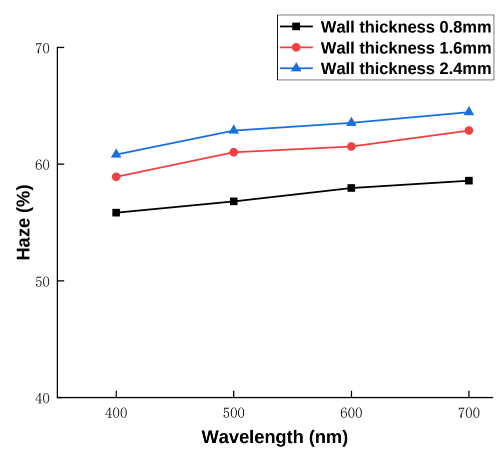

Fig. 7. Effect of wall thickness on haze

The values of transmittance in the visible spectral region (400 to 720 nm) for the 2.4 mm wall thickness specimens ranged from 30% to 45%, and the average value of haze was 62.93%. With the increase of the wall thickness, the light transmittance of the specimen decreases and the haze increases. This is because with the increase of wall thickness, the light penetrating the specimen increases, the specimen absorbs and scatters more light, the light transmittance effect becomes worse, and the light transmittance rate decreases. At the same time, the increase of the wall thickness causes the enhancement of the light scattering of the specimen, the uniformity of the light is also enhanced, and the haze of the specimen increases (Wang *et al*. 2022). In summary, the wall thickness has a significant effect on the light transmittance and haze of the specimen. Considering the optical performance, time and cost, a wall thickness of 0.8 mm was chosen as the preferred molding parameter.

Design Practice

Morphological design

Morphology is the first element to convey product information (Liao and Qin 2018). In the user research activity of “3D printing Lampshade Design”, 60 questionnaires were effectively collected from users aged 15 to 40 years old, including 15 people aged 15 to 25 years old, 15 people aged 26 to 30 years old, 15 people aged 31 to 35 years old, and 15 people aged 35 to 40 years old. Among the 60 questionnaires distributed, young people expressed curiosity and love for 3D printing lampshade design and thought it was full of futuristic sense; a small number of people disliked 3D printing lampshade design and thought it lacked practicality. This interview contains 6 different types of morphological characteristics keywords (gradual, regular, symmetrical, interspersed, flowing, organic), and respondents are required to choose the morphological characteristics keywords that make them feel most comfortable. Among the top 3 morphological features, "symmetrical" was the most frequent, accounting for 28.33%, followed by "regular", accounting for 21.67%, and finally "flowing", accounting for 11.67%.

Fused deposition 3D printing is prone to process problems such as unformability, holes, collapse, and drawing during the molding process of complex surfaces (*e.g.*, twisted surfaces, shaped surfaces, and thin-walled surfaces). Therefore, in the morphological design of lampshades, one should try to avoid the use of complex surfaces. Instead, it is recommended to use more regular geometric shapes and to combine the regular geometric shapes through a variety of morphological evolutions to show morphological characteristics. According to the results of user research, three lampshades were designed in this work for the bedroom environment. The design style was modern avant-garde type, with simple geometric shapes as the basic shape, through rotation, release, distortion, symmetry, array, and other forms of evolution to form a set of regular and fashionable lampshades, reflecting the sense of forward-looking and technology, which may be more suitable with modern bedroom decoration style (Feng *et al*. 2019). The design scheme is shown in Table 2.

Material and color

The lampshade was designed as part of a decorative table lamp for the bedroom, while the other main structures of the decorative table lamp included the lamp base and the LED bulb. The lamp base is made of metal, which is an off-the-shelf product and does not require 3D printing. The lampshade is made of plastic, which is a polylactic acid 3D printing material. In order to fit in with the quiet and warm bedroom atmosphere, the lampshade needs to ensure that the LED bulb has a moderate brightness, while at the same time it needs to achieve a soft light effect (Ding *et al*. 2022).

Table 2. 3D Printing Lampshades Design Scheme

Design Images	Geometric Elements	Evolutionary Approach	Morphological Characteristics
	Triangles, hexagons	Rotation, symmetry, array	Symmetrical
	Quadrilateral, decagonal	Release, symmetry, array	Regular
	Curved surface, triangle	Release, distortion	Flowing

From the above experimental comparison, it can be seen that the milky white specimen has higher haze and better lighting comfort than the colorless specimen. So the milky white was chosen as the color of the 3D printing lampshade.

Fig. 8. PLA 3D printing lampshades display

Slicing processing and 3D printing

Three lampshades were designed, sliced, and 3D printed. The lampshade models modeled by SolidWorks software were exported as STL format files, using Cura software to slice the three lampshades (Li *et al*. 2022). The slicing process needs to set the main 3D printing parameters, including layer height, wall thickness, *etc*.

Based on the above test results on the light transmittance and haze of the PLA 3D printing specimens, the preferred parameter combination for the 3D printing lampshade is 0.3 mm in layer height, 0.8 mm in wall thickness, and the color of the 3D printing filament is selected as milky white. The 3D printing lampshades were produced using this preferred combination of parameters, and the finished lampshades are shown in Fig. 8. The 3D printing lampshades based on PLA materials ensure sufficient light transmittance, but also obtain a matte white, uniform, and soft light output with better optical performance.

CONCLUSIONS

1. The light transmittance of the milky white poly(lactic acid) (PLA) specimens is less than that of corresponding colorless PLA specimens, and the haze is greater than that of the colorless PLA specimens. In contrast, although the light transmittance of the milky white PLA specimens is average, the light scattering is stronger, the light uniformity is better, and the lighting comfort is improved, which makes the material more suitable for the manufacturing of 3D printing lampshades.
2. Among the 3D printing molding parameters, the effect of layer height on light transmittance and haze of the specimen is not significant, and a 0.3 mm layer height was chosen as the preferred molding parameter considering time and cost. The effect of wall thickness on light transmittance and haze of the specimen is significant. With the increase of wall thickness of the specimen, the light transmittance of the specimen decreases and the haze increases. Considering the factors such as optical performance, time and cost, a 0.8 mm wall thickness was selected as the preferred molding parameter.
3. Fused deposition 3D printing is prone to process problems such as unformability, holes, collapse, and drawing during the molding process of complex surfaces (such as twisted surfaces, shaped surfaces, and thin-walled surfaces). Therefore, in the morphological design of lampshades, complex surfaces should be avoided as much as possible, and regular geometric shapes can be used more often, and regular geometric shapes can be combined and presented through a variety of morphological evolution methods to show their morphological characteristics.

REFERENCES CITED

Bai, H., Zhao, M.-X., Wang, H.-X., Han, Y.-L., He, S.-L., and Zhang, Z.-G. (2019). "Analysis and countermeasures of warpage deformation in FDM 3D printing process," *China Plastics Industry* 47(1), 60-63, 68. DOI: 10.3969/j.issn.1005-5770.2019.01.013

Che, X., Ma, J.-F., Hou, H.-Y., Lin, C.-Q., Huang, Y.-H., Wen, H.-W., Li, S.-J., and Guo, J.-W. (2022). "Preparation of polypropylene fluorescent materials and their 3D printing test," *Engineering Plastics Application* 50(1), 133-137, 154. DOI: 10.3969/j.issn.1001-3539.2022.01.023

Chen, J.-M., Li, P., and Zhu, X.-D. (2020). "Research on design methods of lighting products," *Furniture and Interior Decoration* 2020(10), 85-87. DOI: 10.16771/j.cn43-1247/ts.2020.10.016

Ding, T.-T., Yan, X.-X., and Zhao, W.-T. (2022). "Effect of urea–formaldehyde resin–coated colour–change powder microcapsules on performance of waterborne coatings for wood surfaces," *Coatings* 12(9), 1289. DOI: 10.3390/coatings12091289

Feng, X.-H., Yang, Z.-Z., Wang, S.-Q., and Wu, Z.-H. (2022). "The reinforcing effect of lignin-containing cellulose nanofibrils in the methacrylate composites produced by stereolithography," *Polymer Engineering and Science* 2022(9), 2968-2976. DOI: 10.1002/pen.26077

Feng, X.-H., Wu, Z.-H., Sang, R.-J., Wang, F., Zhu, Y.-Y., and Wu, M.-J. (2019). "Surface design of wood-based board to imitate wood texture using 3D printing technology," *Bioresources* 14(4), 8196-8211. DOI: 10.15376/biores.14.4.8196-8211

Han, Y., Yan, X.-X., and Zhao, W.-T. (2022). "Effect of thermochromic and photochromic microcapsules on the surface coating properties for metal substrates," *Coatings* 12(11), 1642. DOI: 10.3390/coatings12111642

Huang, N., Yan, X.-X., and Zhao, W.-T. (2022). "Influence of photochromic microcapsules on properties of waterborne coating on wood and metal substrates," *Coatings* 12(11), 1750. DOI: 10.3390/coatings12121857

Li, W.-B., Yan, X.-X., and Zhao, W.-T. (2022). "Preparation of crystal violet lactone complex and its effect on discoloration of metal surface coating," *Polymers* 14(20), 4443. DOI: 10.3390/polym14204443

Liao, J.-P., and Qin, X.-L. (2018). "Research on the application of 3D printing in cultural and creative product design," *Beauty and the Times* 2018(03), 80-81. DOI: 10.16129/j.cnki.mysds.2018.03.029

Wang, L., Han, Y., and Yan, X.-X. (2022). "Effects of adding methods of fluorane microcapsules and shellac resin microcapsules on the preparation and properties of bifunctional waterborne coatings for basswood," *Polymers* 14(18), 3919. DOI: 10.3390/polym14183919

Yang, Z.-Z., Feng, X.-H., Xu, M., and Rodrigue, D. (2022). "Printability and properties of 3D printed poplar fiber/polylactic acid biocomposites," *Bioresources* 16(2), 2774-2788. DOI: 10.15376/biores.16.2.2774-2788

Yao, M.-J., Tang, X., Zhang, C.-L., and Wang, S. (2020). "Design and application of plastic products based on reverse engineering and FDM technology," *Plastics Science and Technology* 48(12), 45-48. DOI: 10.15925/j.cnki.issn1005-3360.2020.12.011

Zhang, G.-P., Shi, D.-G., Wen, D.-J., Yang, Y.-J., and Feng, R.-R. (2021). "Design of intelligent night lights based on 3D printing technology," *Science and Technology Wind* 2021(27), 9-11. DOI: 10.19392/j.cnki.1671-7341.202127004

Article submitted: November 14, 2022; Peer review completed: December 21, 2022; Revised version received and accepted: December 26, 2022; Published: January 10, 2023.
DOI: 10.15376/biores.18.1.1545-1553