Additive Manufacturing of Optically Translucent Parts

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Abstract

A lithophane is a translucent image created by varying the plate thickness; the image is observed using a back lit light source. Additive manufacturing makes highly complex lithophane fabrication possible. Optical properties of laser sintered polyamide (PA) 12 translucent additive manufactured parts were analyzed and applied to the lithophane fabrication. Several parameters affecting lithophane manufacturing performance are discussed including brightness and contrast versus plate thickness and grayscale level, surface finish quality and manufacturing orientation. Moreover, other thermoplastic semi-crystalline materials were analyzed for LS optically translucent part production. Plates and lithophanes were built using a different AM platform: stereolithography (SL) with Somos® ProtoGen™ O- XT 18420 white resin. Different optical properties and lithophane performance were observed and compared with PA 12 parts.

It was found laser sintered polyamide 12 optical properties varied with light wavelength and reached maximum transmission under green light. When building in the XY plane, thin layer thickness and large maximum plate thickness led to higher contrast and gray scale level. Lithophane quality was largely improved when fabricated in the ZX/ZY plane orientation. Lithophanes made from SL were analyzed but showed lower contrast due to the optical property characteristics of the white resin.

Introduction

Laser sintering (LS) is an additive manufacturing technology that uses a laser to fuse polymer powder into a mass that has a desired three-dimensional shape. The laser heating results in melting and powder local consolidation. Polyamide 12 is a thermoplastic material that is widely used in laser sintering. It has high elongation, good specific strength and melts at a temperature around 180°C [1]. A lithophane is a translucent image created by varying the plate thickness; the image is observed using a back lit light source. It is a design in gray tones [2,3]. It presents a three-dimensional image that completely different from two dimensional engravings and daguerreotypes that are 'flat' [2-4].

The optical properties of the material are essential for lithophane application as this is critical to define the brightness and contrast. The fraction of incident light transmitted by an optical material depends on losses due to absorption and back reflection [5]. The transmittance largely varies with wavelength and materials, which is the ratio of the light transmitted versus the incident light intensity according to the Beer- Lambert law:

$$T = (1-R)^2 e^{-\alpha x} \quad (1)$$

where T is the fraction of light transmitted, R is the fraction of light reflected, α is the absorption coefficient which depends on the absorber chemical composition and the light wavelength, and x is the path length (i.e., plate thickness for lithophanes). The total light transmitted then may be written by applying the Taylor's series expansion:

$$T = \frac{(1-R)^2 e^{-\alpha x}}{1-R^2 e^{-2\alpha x}} \quad (2)$$

For a given absorption coefficient and refractive index, transmittance can be solved using this modified Beer-Lambert Law.

A grayscale digital image is an image in which the grayscale levelof each pixel has a single value, which means it carries only intensity information [6]. Brightness is a visual feature which may be described as the average grayscale level of an image. Since the range of grayscales is 0-255, the image will tend to wash out if large numbers of pixels are changed to become either 255 (white washout) or 0 (black washout). Contrast is an indication of the change in luminescence of an image relative to its surroundings.

The software utility, Bmp2Cnc, was used to convert the grayscale jpg/bmp digital photo to a three-dimensional CAD file. It is based on a relation that linearly translates each pixel grayscale level to a respective height. It reads the file in bitmap format, generally 8 bits. Z-axis depth is changeable based on the manufacturing requirements.

ISO/ASTM 52921: 2013 (E) [7] establishes the standard coordinate systems and test methodologies for additive manufacturing processes. The part initial build orientation is described by listing which axis is parallel to the longest overall dimension of the bounding box first, followed by the axis which is parallel to the second longest overall dimension of the bounding box second, followed by the axis which is parallel to the third longest overall dimension of the bounding box.

Two LS building orientations were used in this research: a 'flat' build in the XY plane, and a 'standing' build on edge in the ZX/ZY plane. 'Standing' manufacturing orientation results in better surface quality and enlarged contrast but requires more time and material consumption. 'Flat' building leads to lower contrast due to the layer limitation but is accomplished with less time and material.

In this paper, work has been done to analysis the optical properties of laser sintered polyamide 12 [8], and the manufacturing issues related to lithophane performance [9,10] are overviewed and discussed.

Optical Properties

The optical properties of optically translucent laser sintered polyamide 12 were analyzed by conducting monochromatic light transmission experiments on laser sintered polyamide 12 blank plates. Blank plates were manufactured on a DTM® 2500 SinterStation, with dimensions 50.8 mm by 50.8 mm and with thicknesses of 0.38, 0.64, 0.83, 0.92, 1.30, 2.33, 4.74 mm, corresponding roughly to 4, 6, 8, 9, 13, 23 and 48 layers of powder during laser sintering with 0.102 mm per layer thickness (system error 5% on z-direction is included). A Unico 1200 110V/50Hz S-1201 spectrophotometer was applied to investigate the light transmittances. Measurement is made from 400 nm to 800 nm in 20 nm increments.

The effect of the wavelength on laser sintered polyamide 12 transmittance is shown in Fig. 1. Transmittance first increased linearly from 400 nm to the peak of 540 nm (25- 87%) and dropped to the lowest at 580 nm, then remained almost constant from 600 nm to 800 nm. At a constant wavelength, transmittance decreased monotonically with increasing plate thickness. It is proposed that the pi-pi* transition is responsible for the transmittance increment from 400-540 nm, while the n-pi* transition explains the transmittance decreasing from 540- 580 nm [8].

The influence of plate thickness on laser sintered polyamide 12 transmittance is shown in Fig. 2. The transmittance of PA 12 plates with a common soft white bulb is presented as well. The white light effect was also calculated based on the theory that white light is a combination of all lights and there is no clear boundary between one color to another [11]. The calculation results match well with the soft white bulb experimental results. All plots show that transmittance decreases with increasing plate thickness. Green light performs the best, showing the largest sensitivity to thickness from 85% to 20% with increasing plate thickness; the soft white bulb transmitted 20% less light compared to the green light, followed by blue, red and yellow light. The transmittance results are verified in Fig. 3 which shows large visual differences on the actual lithophanes.

To conclude, transmittance of laser sintered polyamide 12 decreases with increasing plate thickness. Second, transmittance reaches the highest levels under monochromatic green light. It reaches the lowest levels under yellow light.

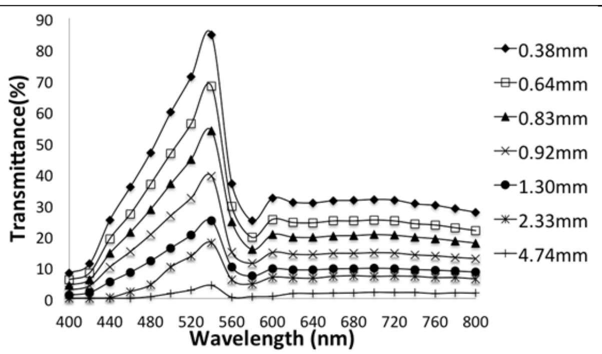

Figure 1: Effect of spectrophotometer wavelength on transmittance of laser sintered polyamide 12 plates with different thicknesses.

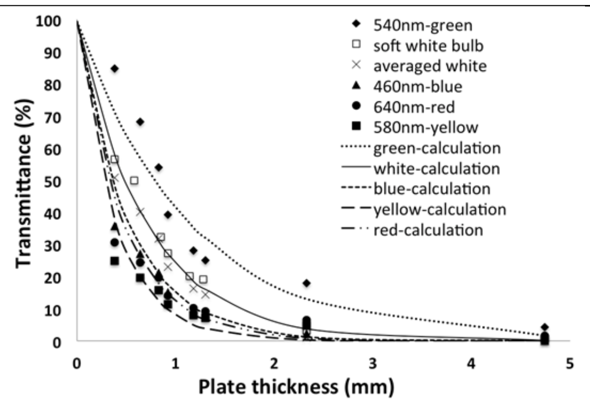

Figure 2: Effect of laser sintered polyamide 12 plate thickness on transmittance under different monochromatic lights and white light. Also included is a calculated dependence for white light based averaging red, green, and blue measurements. All calculated curves are based on Equation 6 with absorption coefficients obtained from the experimental measurements.

Fig 3: Gray-scale processed laser sintered polyamide 12 3.81mm thickness lithophanes under different monochromatic light: green (left), yellow (center). On the right is the initial digital image used to create the lithophanes.

Parameters Affecting AM Lithophane Performance

- *Layer and Plate Thickness Effect*

To analyze the layer thickness and maximum plate thickness effects on laser sintered polyamide 12 lithophane performance, lithophane STL files were generated using a reproduction of Raphael's painting, Agnolo Doni. The lithophanes were built on a SinterStation HiQ using different layer thickness, either 0.076 mm (15 W laser power) or 0.102 mm (24 W laser power) and different maximum plate thickness (1,3 and 5 mm). Lithophane images were captured using a SONY DSC- W55 camera. A Picker 240050 X-ray view/ light box was used in this research, which produced non-adjustable visually uniform white light over the view area.

Fig.4 shows the lithophanes built in the XY plane with maximum plate thicknesses of 1, 3 and 5 mm, which corresponds to 10, 30, and 50 layers, respectively. The top group shows higher contrast compared to the bottom group.Boundaries and features on the face, tie and hands were lucid. With a constant maximum plate thickness, thinner layer thickness results in more grayscale levels on the lithophane since there are more distinct layers in the part.

Moreover, large maximum plate thickness leads to improved contrast and quality since the grayscale levels were enriched. However, if the lithophanes become too thick, problems arise with the viewer-facing surface topography becoming too distracting. Figure 5 illustrates this for four lithophanes, with maximum plate thicknesses of 3, 5, 7, and 9 mm with a front lit white light source and black background. The topography for the lithophanes built with 7 and 9 mm plate thickness become distracting, and the light transmission is very low. There is then a limit on the maximum thickness of the lithophane based on several considerations [10]: for laser sintered polyamide 12 lithophane fabrication, the optimal maximum plate thickness ranged between 3.8 mm and 5 mm.

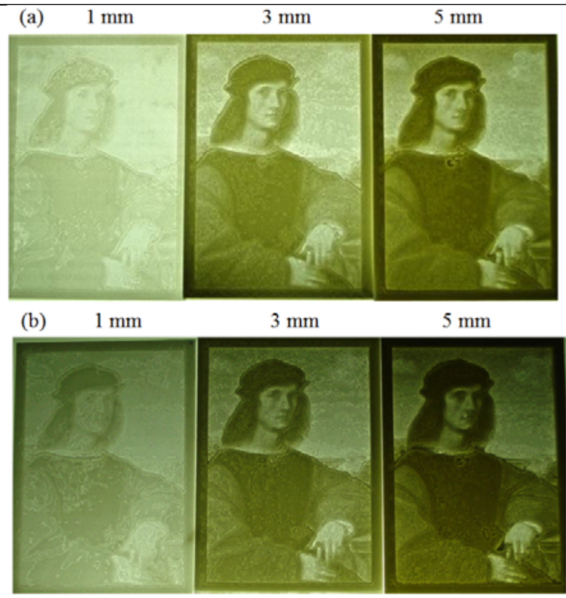

Figure 4: Polyamide 12 lithophanes laser sintered with (a) 0.076 mm layer thickness; (b) 0.102 mm of layer thickness. Maximum plate thickness of each pair was 1, 3 and 5 mm from left to the right. The light source was a white light box.

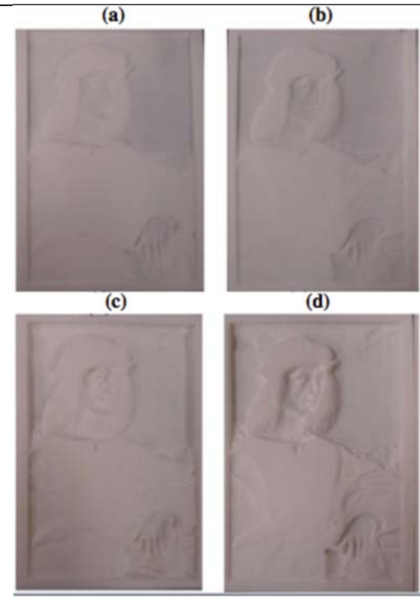

Figure 5(right): Lithophanes presented with a front lit white light source fabricated in the XY plane with the maximum plate thicknesses of (a) 3 mm and (b) 5 mm; fabricated in the ZX plane with the maximum plate thicknesses of (c) 7 mm and (d) 9 mm. All lithophanes were fabricated with a layer thickness of 0.102 mm.

Manufacturing Orientation

To analysis the manufacturing orientation effect on the lithophane surface quality, lithophanes generated from the reproduction of Raphael's painting, Agnolo Doni, were first manufactured in the XY plane and then in the YZ plane and the ZX plane, with maximum plate thickness of 3.8 mm. Fig.6 shows better contrast and finer surface quality on lithophanes built on the ZX an YZ planes compared to the one built on the XY plane. The background and figure jackets on the first two were more identifiable. Lithophanes built in the ZX plane and XY plane were examined using stereomicroscopy with 2.5 X magnification on the portrait tie and right middle cloud area shown in Fig.7. The lithophane built in the ZX plane presents a much smoother surface and less contouring than the one built in the XY plane. Individual layers were observed on the lithophane built in the XY plane, with 38 layers in total. The layers appear like stairs, and each layer defines a quantized grayscale level. The grayscale level of the lithophanes built in the ZX plane was defined by the laser beam motion, so a more continuous level variation was produced.

Figure 6: Polyamide 12 lithophanes laser sintered with 0.102 mm of layer thickness built in the ZX, YZ, and XY planes from left to the right. The size of lithophanes was 127 mm by 76 mm, with maximum plate thickness equal to 3.8 mm. Lithophane photos were captured using white light box illumination.

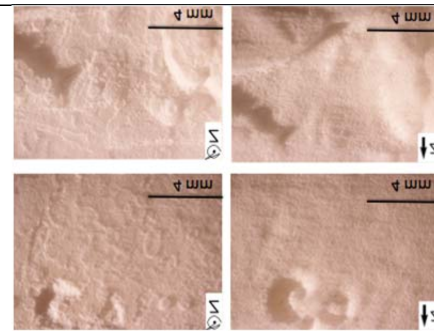

Figure 7: Stereomicroscopy photos of the lithophanes built in the XY orientation (left) and ZX planes (right). The focuses are on the portrait tie (top sequence) and cloud on the middle right of the image (bottom sequence).

It is reasonable to achieve different feature resolutions depending on the manufacturing orientations. Small features in the ZY plane were built using continuous laser beam line scan, while the ones built in the XZ plane had a discontinuous/short line scan on the irregular surface figures. Small features were more achievable with long scan lines, since it was continuous. Long line scanning on rectangular features also led to greater precision on positioning. Thus, small features (diameter or width of 0.13 mm, for example) could be produced for the ZY orientation. It is concluded that for LS lithophane generation, manufacturing "on edge" in, for example, the ZX or YZ plane results in better surface quality on the lithophane faces, especially for the thin parts, but the thinnest feature size is 0.57 mm due to the laser beam diameter limitation. Manufacturing in the XY plane, the thinnest part is roughly one layer, but parts with only one layer thickness are extremely friable.

Surface Finish Quality

To analyze the effect of surface finish on lithophane performance, five blank plates were built with dimensions, 50.8 by 50.8 by 12.7 mm. The polishing experiment was conducted at Harvest Technologies, Belton, Texas. Blanks were first infiltrated with cyanoacrylate to obtain a brittle surface to polish, since the polymer tended otherwise to deform and create strands or scratches when sanded. As the cyanoacrylate soaked into any surface porosity of the part, a change in part transmittance was foreseeable.

An initial experiment was designed to analyze the cyanoacrylate effect on the laser sintered PA 12 transmittance. A portion of a flat specimen was infiltrated on one surface, and a second piece was infiltrated on both surfaces. To investigate the polishing effect, a third piece was infiltrated and polished on one side, while a fourth piece was infiltrated and polished on both sides. A fifth piece was neither infiltrated nor polished as a baseline specimen. The optical transmittance change of all four post-processed plates and the non post-processed plate was measured using the spectrophotometer with varying monochromatic wavelengths. Thickness was measured, and its effect on transmittance was examined. The polishing effect was also measured visually by viewing the polished plates using the white light box. Photos were taken with the polished surface facing and away from the light source.

Fig. 8 shows the surface roughness results for the non-post-processed (original), cyanoacrylate infiltrated, and polished surfaces. The surface roughness decreased to a minimum after polishing. However, the transmittance variations for five blanks at the same wavelength were less than 5%. The non-post-processed plate had a rougher surface finish compared to both face polished plates. Small dimples were present on the non-post-processed plate. The post processes (infiltration, infiltration then polish) only dealt with the plate surface with no significant effect observed on the laser sintered polyamide 12 optical properties. It is unlikely to have a smooth surface finish for the laser sintered polyamide 12 lithophane because polishing is difficult to achieve on curved surfaces.

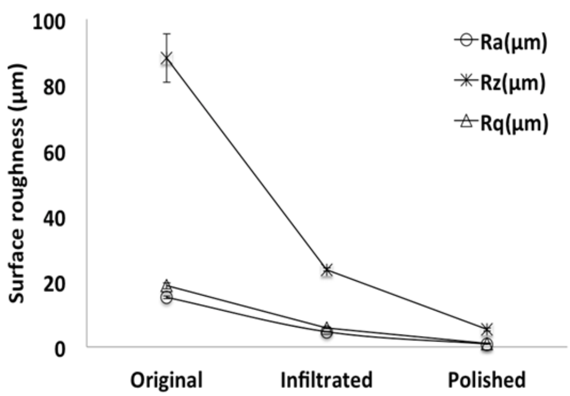

Figure 8: Surface roughness comparison among the non post-processed, cyanoacrylate infiltrated, and polished surfaces. Error bars representing standard deviation of 5% are shown. The surface roughness is quantified by the vertical deviations of a real surface from its ideal form. R_a is the average of the absolute vertical deviations, R_q is the root mean squared value of the vertical deviations, and R_z is the sum of the highest and lowest vertical deviations within a sample length.

Improvement of Lithophane Quality

The definition of a 'good' lithophane surface quality may be proposed based on the above experiments and observations, which are summarized as:

1. Light transmittance should be high (> 70%) at the thin areas and low (< 15%) at the thick sections.

2. The number of grayscale levels should be large, which leads to more continuously varied thickness.

3. The lithophane maximum plate thickness should fall within a range, below which would be too few grayscale levels, and beyond which the lithophane topography would be distracting.

4. The resolution of the lithophane should be relatively high.

In summary, it is proposed that high quality is associated with the lithophane appearance features (brightness, contrast and resolution) under the backlit light source condition that are identical to the original digital image.

Based on the definition, the material selection criteria for producing a 'good' lithophane was carried out, from which the optimal material was found to have an absorption coefficient of 0.5/mm [10]. A group of laser sinterable candidate materials was selected. The primary criteria included the polymer powder type (semi-crystalline or crystalline, thermoplastic) and melting point (160-200°C). The candidate polymers included EBA, EVOH, PA, PCL, PE, PP and PVDF. Polyamide 12 best fits the selection criteria for lithophane laser sintering, followed by EBA, EEA, and PVDF. It is proposed that nanocomposites might lead to improved properties by adding optical translucent nanoparticles into the base thermoplastic matrix [10].

<u>Stereolithography (SL)</u>

Stereolithography (SL) was performed as a comparison to the LS manufacturing method. Blank plates and lithophanes were built at Harvest Technologies, Inc. DSM Somos® ProtoGen™O-XT18420 was used in this study. It is a white, liquid, epoxy resin photopolymer. The effect of the light wavelength on SLA Somos® 18420 white resin transmittance is shown in Figure 10, which has a very different transmittance trend. Comparing the plates made with LS and SL, the LS plate (0.38 mm thick) had higher light transmission than the SL plate (0.34 mm thick) from 460 to 800 nm light wavelength. The 4.71 mm LS blank had consistantly lower transmittance than the 5.11 mm SL blank for all visible light wavelengths. These light transmission differences were shown on the lithophane performances as well.

Two lithophanes were built in the XY and ZY planes at room temperature. All parts were immersed in 99% ethanol for 3 hours after build completion; support structures were then removed manually. Images in Fig. 11a and 11b show lithophanes built in the XY and YZ planes using SL, with a maximum plate thickness of 5 mm with layer thickness of 0.102 mm. The image on the far right is a comparison lithophane built in the YZ plane using LS. Lithophanes built with SL show clear detail and no contours on the background, due to the smaller laser beam diameter (0.2 mm) compared to that for LS (0.5 mm). Smaller laser beam diameter leads to more precise scan positioning and thus better lithophane appearance. The lithophane boundaries, figure jacket and hair were darker on the laser sintered lithophane due to the light transmission differences reported in Fig. 10.

Figure 12 shows magnified images of lithophanes made using SL built flat and vertically, compared to a vertical LS plate. The vertically built SL plate has more support structures to remove than the SL plate built flat, especially for the SL YZ sample. Also the surface qualities of the lithophane made using SL and LS appeared different, due to the differences of the raw material state (Somos® 18420 is liquid and PA 12 is solid).

Since the surface qualities were similar, it is optimal to build the lithophane in the XY plane than the ZY plane. The lithophane made with SL using DSM Somos®ProtoGen™O-XT18420 white epoxy resin showed good and similar resolution when built in the XY or YZ plane. Violet light (wavelength 400 nm) transmitted best among all visible lights. However, the lithophane contrast was lower than that of the LS lithophane due to low light transmission in the resin.

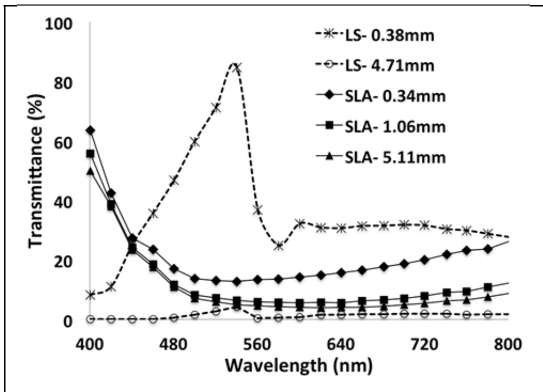

Figure 10: Effect of spectrophotometer wavelength on transmittance of SL resin plates with three different thicknesses. The

Figure 11: SL lithophanes built (a) in the XY plane; (b) built in the ZY plane; and (c) LS lithophane built in the ZY plane. The maximum plate thickness for each was 5 mm. Lithophane

transmittances of laser sintered 0.38 mm and 4.71 mm thick polyamide 12 plates (dashed lines) are shown for comparison.	photos were captured using a white light box.

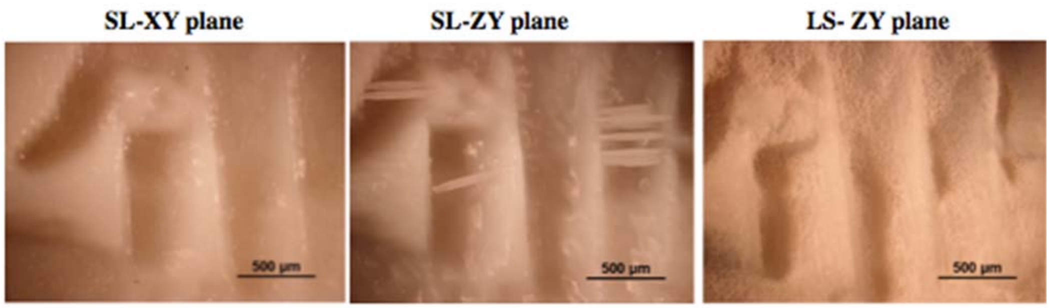

Figure 12: Stereo-micrographs of the lithophane made using SL and LS focusing on portrait hands.

Summary and Conclusions

The objective of this paper is to overview the optical properties, manufacturing issues, and AM manufacturing method relative to laser sintered polyamide 12 lithophane production. First, the optical properties of laser sintered polyamide 12 were analyzed: the light transmission decreases with increasing plate thickness; also, the transmittance reaches the highest levels under monochromatic green light, which was verified by observing lithophane performance under different monochromatic LED lights.

Second, the manufacturing issues for improving the laser sintered polyamide optically translucent part performance were investigated: thinner layers and relatively thicker plates result in finer lithophane performance. However, if the plate becomes too thick, it leads to poor light transmission, and the topography would be observed with front lit light. Sintering a relatively thick lithophane (<5 mm) in the ZX/ZY plane significantly increases the contrast and resolution compared to sintering in the XY plane. The thinnest feature thickness possible in the SinterStation HiQ is in the XY plane 0.13 mm with 0.102 mm layer thickness, and it is 0.57 mm when manufacturing in the ZX/ZY plane with the laser diameter of 0.50 mm.

The surface finish has no effect on the lithophane quality, since the polishing effect may only be applied on the polished flat surface. Laser sinterable material selection criteria were carried out, from which the optimal material was found to have an absorption coefficient of 0.5/mm. PA 12 was the best semi-crystalline material after comparison with a list of other semicrystalline and crystalline candidate materials. The use of nanocomposites for optimal lithophane performance and more precise manufacturing processing may improve lithophane quality.

Stereolithography was analyzed using Somos® 18420 white resin. Transmittance reached the highest levels for violet light. Improved resolution and inferior contrast were observed compared to laser sintered lithophanes.

Overall, this work investigated the optical properties and manufacturing orientation effect on laser sintered polyamide 12 optically translucent parts, and provided solutions for photographic reproduced lithophane surface quality improvement. The work is the first discussion on the factors that affect the fabricated part dimension accuracy, as well as the initial description of the manufacturing orientation effects on surface quality for lithophane production to guide do-it-yourselfers and end users of 3D printers in reproducing their own images. It introduces lithophane additive manufacturing to a wide audience, and provides a durable, high quality, long-lasting photographic record. The study provides analysis of laser sintered lithophane production and serves as a basis for future commercialization art and end-user parts.

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