Hydrostatic Support-Free Fabrication of Three-Dimensional Soft Structures

Dong Sung (Danny) Kim^{1*} and Bruce L. Tai¹

¹*Texas A&M University, College Station, USA*

**dannyplus@tamu.edu, btai@tamu.edu*

Abstract

This paper presents a support-free fabrication method for three-dimensional soft structures by creating a hydrostatic condition. The hydrostatic force inside the polymer resin can, theoretically, keep a soft structure in position and shape. The key technology behind this method is the low one-photon polymerization (LOPP), which can initiate polymerization at the focusing spot under the resin surface, as opposed to the surface one-photon polymerization in stereolithography (SLA). To prove the concept of LOPP, an optics setup for a wide beam gradient along with a low-absorption wavelength was built for this study. An ultraviolet (UV) curable silicone was adopted as the soft material. The experiments consisted of a qualitative observation for LOPP phenomenon and a quantitative study on the cured geometry and volume under various UV exposure conditions. Results have demonstrated the “in-liquid” polymerization using LOPP and also unveiled the challenges of geometrical resolution and accuracy as a function of UV beam gradient, intensity, and exposure time. Further investigation is required for better control over this method.

Keywords: Soft structure; Additive manufacturing; Low one-photon absorption

1 Introduction

Additive manufacturing (also known as 3D printing) technologies have been advanced in the past decade to be capable of fabricating a wide variety of materials into the 3D configuration, such as plaster powders, thermal plastics, photopolymers, to metals and other advanced materials. Applications have also been broadened from simply display, toys, to functional uses. However, additive manufacturing cannot completely replace the conventional molding technique due to the requirements of surface finish, tolerances, or the constraint from the material property itself. One challenging example is printing ultra-soft, jelly like materials, particularly those can hardly support their body weights, such as silicone and gellan gum [1]. Soft material is useful in making

* Corresponding author

synthetic tissues for biomedical research, training, device testing, or medical treatment in the human body[2, 3]. Yet, depending on the solidification method, printing such soft materials could require a substantial amount of support structure to ensure the part integrity. Using support structures is common in 3D printing, but it requires a post processing to remove the support material. Some, or all, of the post-processing procedures are not suitable for soft and fragile materials. For example, fused deposition modeling (FDM) employs a soluble support material to build the overhang structures. The support structure will be dissolved in an agitated base solution. In stereolithography (SLA), the support structure is printed simultaneously with the part in the liquid resin and trimmed manually after printing. Commercial UV-based products, such as Connex machines (Stratasys, Edina, MN), use water-soluble wax as the support material and needs to be cleaned with high-pressure water blasting system. Furthermore, fully removing the support structure inside the deep cavity, internal void, or channels are technically difficult and time-consuming. To address these issues, this paper is presenting a novel, support-free, soft material fabrication method in additive manufacturing.

The key concept of the support-free fabrication is to create a hydrostatic condition for the solidified material and to eliminate the conventional layer-by-layer manner. The hydrostatic condition enables for the structures to maintain their positions and shapes without any support structures. This is a direct translation from powder-bed printing technologies such as selective laser sintering (SLS). SLS generally does not build any support structure since the part is immersed in the powder bed and directly sintered with the supports from surrounding loose powders. The non-layering technique is inspired from the 3D stereo drawing pen [4], so that the overhang structure can be fabricated as a continuous piece at a time. Together, the technique is named Hydrostatic Support-Free Fabrication (HSFF).

Creating a hydrostatic condition is challenging. SLA and digital light processing (DLP) technologies both utilize UV light to cure the part in a resin bath. However, they do not necessarily create a hydrostatic environment for several reasons. First of all, the curing process is layer-by-layer from the surface or from the bottom, meaning that the part is not completely immersed in the middle of the bath. Second, both technologies require continuous movement of the printing base to form a 3D geometry. The disturbance to liquid will not allow a soft body to stay in the shape. Lastly, the cured portion may have a significantly different (heavier) density that can only be partially supported by the uncured resin. To achieve the hydrostatic condition during the process, UV light must cure the part from the middle of the liquid bath. However, a single wavelength UV light (i.e., one-photon polymerization (OPP)) would result in curing along the entire beam path. Two-photon polymerization (TPP) could be one of the alternatives. TPP is a non-linear process to realize the curing process only at the focal point[5]. But, this technique requires complex configurations and high-cost optical devices such as ultrashort pulse lasers. All of these make TPP less practical in the additive manufacturing market. Instead, a similar TPP may be achieved using low one-photon polymerization (LOPP).

Low one-photon polymerization effect is proposed in [6], which utilizes low absorption of photoresists and wide beam gradient with high numerical aperture (N.A.). The photoresists have specific absorption rate depending on wavelengths. In general, one-photon polymerization process uses the wavelength that the photoresists have a high absorption rate. In contrast, low one-photon polymerization uses the wavelength that the photoresists have relatively very low absorption rate [7]. Using low absorption rate of the photoresists prevents the polymerization along with the beam path, thus to realize the focal curing effect of TPP. However, a successful LOPP requires precise control over UV wavelength, intensity, exposure time, and known polymerization properties. To verify the concept and feasibility of HSFF, this study uses a non-commercialized UV curable silicone material from Dow Corning (Midland, MI) that has a low absorption rate at 365 nm wavelength and a comparable density before and after curing to study this technology.

The paper is organized as follows. Section 2 presents the overall experimental setup including the silicone material and the testbed. Section 3 explains the experimental methods and results of the LOPP support-free 3D fabrication. This is followed by Section 4, discussion based on the results and

comments on the future advancement of this technology. The conclusion will be presented at the end of this paper.

2 Experimental Setup

The material selection and testbed development are introduced in this section. It is important that the material and optics setup can achieve LOPP and the hydrostatic condition.

2.1 UV Curable Silicone

In order to achieve LOPP, the UV wavelength must be within a low absorption region. The silicone materials used in this study is a non-commercialized product provided by Dow Corning. The UV curable silicone contains two parts. One is the silicon resin, and the other is the photo-initiator, activated by a certain range of UV wavelength. The initiator plays a major role in the polymerization. The absorption spectrum of the photo initiator was measured using a spectrophotometer (U-4100, Hitachi, Tokyo, Japan) and presented in Figure 1. As can be seen, the absorption begins around 400 nm wavelength down to 300 nm and below. The wavelength of 365 nm is adopted in this study as it has a low absorption coefficient 0.051, but not extremely low. A longer wavelength toward 400 nm can lead to lower absorption but also requires a significant amount of time to cure the silicone.

Figure 1 Absorption spectrum of the material plotted on a logarithmic scale.

To realize the hydrostatic support-free fabrication, the silicone resin must have a minimum difference in density before and after polymerization (i.e., cured and uncured silicone). This is because a large difference can cause the motion of the cured part as a result of gravity against buoyancy force. The physical properties were not disclosed by the silicone supplier, but the measured densities of liquid and solid phases were found both around 0.95 g/ml. The other important physical property is viscosity. A viscous liquid material provides resistance against the motion inside the liquid. Along with the similar density, high viscosity can further improve the stability of the cured part.

2.2 Testbed Development

The overall experimental setup is shown in Figure 2(a). The setup consists of a UV lamp system (OmniCure S2000, Excelitas Technologies Corp., Waltham, MA), the optical lens array, and the 3-

axis reconfigurable motion stage (Moog Animatics, Milpitas, CA). The whole setup is covered by amber plates to block the UV wavelength from the environment.

The lamp system has a wide beam spectrum from 250 nm to 650 nm. A bandpass filter can be added to provide a sole wavelength of 365 nm from the lamp system. The lens array is composed of the aspheric lenses (Edmund Optics Inc., Barrington, NJ), the bandpass filter (Edmund Optics Inc., Barrington, NJ), and iris diaphragms (Edmund Optics Inc., Barrington, NJ) as shown in Figure 2 (b). The aspheric lenses are used for collimating and focusing the beam with the magnification 1/5 that produces the focal spot with 1mm diameter. In addition, to realize wide beam gradient, the aspheric lens with the numerical aperture (N.A) =1 is used as the final lens. The iris diaphragms are used to align the beam. The beam intensity is controlled by the electrical shutter of the lamp system that changes the iris opening from 1 % to 100 %. Note that the actual output light intensity is not linearly proportional to the iris opening. For example, 70% opening does not necessarily mean a 70% intensity of the fully opened iris. Therefore, the actual energy dose (intensity multiplies exposure time) needs to be calibrated with the irradiance values measured by a radiometer. Using the dual light guide, the beam from the system can be connected simultaneously with the lens array and the radiometer (R2000, Excelitas Technologies Corp., Waltham, MA). A wide beam gradient is one important factor to realize LOPP. However, lenses with high numerical aperture (NA) have a short focal length. In this testbed, the final lens (The second aspheric lens in Figure 2(b)) has the back focal length (BFL) of 6.9 mm

The light box (with UV wavelength blocked) is used to observe the fabrication process. The X, Y, Z-axis motion stages enable three dimensional motions for the fabrication purpose. The entire system is built by 8020 aluminum frames and linear sliders that have a resolution of 2.5 μm and can be numerically controlled using G-codes. Small acrylic boxes (with the external dimensions of 25.4 mm $\times$ 25.4 mm $\times$ 16.4 mm and 25.4 mm $\times$ 25.4 mm $\times$ 6.3 mm as shown in Figure 2 (c)) are used as a silicone resin container. Given the current optics setup with BFL = 6.9 mm, the acrylic box needs to be placed close to the last aspheric lens to ensure the focal point inside the liquid for hydrostatic printing. The lab jack is for coarse adjustment of sample height.

Figure 2 Experimental testbed: (a) the overall setup, (b) schematic diagram of the lens array, and (c) acrylic boxes as a silicone resin container.

3 Experimental Design and Results

The experimental study consists of two parts: qualitative observation and quantitative measurement. The qualitative observation is designed to create different cured volumes under different intensities and exposure times, based on trial-and-error, for proof of LOPP concept. The quantitative portion is to find the effects of light intensity and exposure time on creating LOPP. The details are presented in this section.

3.1 Observation

This part of the experiment was to demonstrate the concept of the hydrostatic support-free fabrication by LOPP. Figure 3 shows the schematics of OPP and LOPP. As mentioned in Introduction, OPP occurs along the entire beam path due to quick absorption of UV light regardless the gradient light intensity. In contrast, LOPP takes place from the focal point. With the low UV absorption, the curing time is dominated by the light intensity along the gradient beam path. Therefore, the curing can be controlled with a proper exposure time.

Figure 3 Schematic diagram of one-photon polymerization (OPP) and low one-photon polymerization (LOPP).

To prove LOPP in this experiment, an H-shape structure was aimed for observation as shown in Figure 4. The cured part was completely transparent and cannot be seen within the silicone resin. Thus, the remaining liquid must be drained in order to observe the occurrence of polymerization. The fabrication of this structure was from the left to the right. The long left pillar was built by a high intensity and long exposure time to create OPP effect and then switched to a shorter exposure and lower intensity to create an LOPP bridge. Two iris opening powers, 100% and 70%, were used for different intensities. The feed rate of the light source, controlled by the motion stage, was used to determine the exposure time in the unit of second per millimeter. Finally, another long exposure was used to create the right pillar of the H-shape. Although the LOPP-created bridge could exist alone under the hydrostatic condition, it cannot be observed after the liquid resin was drained. Therefore, the long pillars of the H-shape were needed to secure the structure inside the acrylic box for the purpose of observation.

Figure 4 Printing of H-shape structure for proof of LOPP concept

Figure 5 shows the results of printed H-shape structures. Under the fabrication conditions with 100% opening power and exposure time of 60s/mm, the entire structure was generated only by OPP due to high intensity and long exposure time, shown in Figure 5 (a) where the bridge portion was not seen. By reducing the exposure time to 30s/mm, the structure was still made with OPP. However, because of a shorter exposure time, the bridge portion had a thinner thickness as shown in Figure 5 (b). Since the top of the structure is lined up with the liquid surface, it means that a short exposure time is likely to result in a limited penetration depth, instead of being LOPP. By reducing the beam intensity to 70% opening and maintaining the short exposure time at 30 s/mm, there was no bridge portion between the pillars. With an increased exposure time to 55 s/mm at 70% opening power, the bridge structure then was formed again, as shown in Figure 5 (c). The bridge portion might contain both OPP and LOPP effects. The bridge portion with a gap from the liquid surface could be considered LOPP. The extra solid area on the middle part is possibly produced by OPP.

At this point, it was difficult to distinguish LOPP and OPP effects mainly due to the limitation of the limited working distance of the final lens (i.e., BFL = 6.9 mm.) With the geometrical constraints from the lens frame and acrylic box, the focal point was approximately 3 to 4 mm below the liquid surface. Given a possible low resolution of the LOPP effect (i.e., the pillar size of Figure 2(b)) with the current optics setup, the cured region might propagate to the liquid surface, resulting in a vague boundary between LOPP and OPP effects. A more quantitative comparison was then carried out in the next section.

Figure 5 Observation results: (a) the structure under the fabrication conditions with 100% opening power and exposure time 60s/mm, (b) with 100% opening power and exposure time of 30s/mm, and (c) with 70% opening power and exposure time of 55s/mm.

3.2 Parametric study

This experiment was designed to quantitatively measure the LOPP effect in the current optics setup. A shallower acrylic container (4.9 mm in depth) was used so the focal point could be lined up near the bottom surface. This way allowed the pillar to grow from the bottom without the OPP-made structures for support as in Sec. 3.1. As shown in Figure 6, OPP would create an entire pillar through the liquid bath. On the other hand, LOPP only makes shorter pillars. By measuring the dimensions of the cured pillars, OPP and LOPP can be verified.

This study was conducted by changing the intensity and exposure time. Two intensities with 100% opening and 70% opening were used. For the 100% opening power, the exposure time was increased every 5s in an ascending order up to 80s. For the 70% opening power, the exposure time was increased every 10 s up to 200 s. One acrylic container was used for 100% and 70% cases individually. For each case, a test was 5 mm apart from each other. The complete samples are shown in Figure 7. The pillar dimensions were measured at the end of the experiment using high-resolution images from top and side followed by measuring the pixel length.

Figure 6 Schematic of OPP and LOPP effects on the structure growth

Figure 7 The cured pillars by 100% opening power (left) and 70% opening power (right)

The results with 100% opening power are shown in Figure 8. The exposure time was increased from 5s to 80s. There was no cured pillar until 50s. At 55s, the pillar was partially cured with a height of 2.2 mm near the focal point. It can be seen that the threshold for LOPP with 100% opening power has a narrow window between 50s and 55s. From the exposure time beyond 60s, a full length pillar was observed through the resin depth, meaning an OPP effect. Except the exposure time of 55s, the pillar height was around 4.5 and 4.7 mm. The 0.3 mm difference from the container depth could be due to the measurement error, the surface tension of the silicone resin, or slight buckling effect on the pillars without the hydrostatic force. In addition to the pillar height, the diameter was also measured to observe the correlation with the exposure time. Note the pillar was not really in a perfect cylindrical shape, so the diameter was measured in an average sense. Figure 8(b) shows a minimum diameter of 0.5 mm at the exposure time 55 s, corresponding to the shorter pillar of 2.6 mm. From 60 s and onwards, the pillar diameter increased to about 1.2 mm; the maximum was 1.5 mm at the 80 s. It can be seen that once the pillar is formed, the dimensions do not change significantly with the exposure time.

(a) (b)
Figure 8 Results of 100% opening power: (a) the pillar height vs. exposure time and (b) the pillar diameter vs. exposure time.

The results of 70% opening power are shown in Figure 9. There were 5s intervals for each point between 5s to 50s and 10s intervals for each point between 50s and 200s. No pillar was cured between the exposure time 5s and 100s. The polymerization was observed at 110s and beyond. The pillars at 110s and 200s collapsed prior to the measurements and thus marked as 0 mm in height. Compared to the 100% opening results, 70% shows more variations. The height varied from 1.3 mm (at 160 s) to 3.3 mm (at 150 s) though most of the pillars stayed around 2.6 mm level. Obviously, there existed a gap of 2.3 mm from the resin surface. This means an LOPP effect that produces the pillars inside the silicone resin. Figure 9(b) shows the measured diameter of the pillars. Unlike 100% case, there was an ascending trend with the increased exposure time. The minimum diameter was 1.3 mm at the exposure time of 120s and the maximum was 2.4 mm at the 200 s. The average of the diameter was 1.7 mm, about 40% larger than those in the 100% opening power case. The low pillar height at 160 s could be due to an incomplete polymerization as a result of the unstable light source or locally lack of photo-initiators.

(a) (b)
Figure 9 Results of 70% opening power: (a) the pillar height vs. exposure time and (b) the pillar diameter vs. exposure time.

4 Discussion

LOPP can successfully cure the material in the middle of the silicone resin but the cured volume and shape are largely dependent on the UV light setup. Traditionally, the cured polymer volume is proportional to the total energy absorption (i.e., dose) under a uniform exposure. Following this hypothesis, Figure 10 calculated the cured volume as a function of UV dose from the experimental results. The values of dose were calculated with actual irradiances measured by the radiometer and exposure times. The irradiance values were 381 mW/cm² for the 100% opening power and 272 mW/cm² for the 70% opening power. The cured volumes were estimated from the pillar height and diameter in the Results section. Interestingly, with 100% opening power, a lower dose is required to achieve the same cured volume as that needed for 70% opening power. This is because of a larger effective beam zone in 100% opening power than the 70% cases. This is also an evidence of the LOPP effect in the 70% opening power.

Figure 10 Dose vs Cured Volume for 100% and 70% opening power.

The cured geometries are quite different between two cases, in spite of a similar cured volume. The pillar is tall and thin in the case of 100% opening power, and short and wide in the case of 70% opening power. This is a result of beam gradient that promotes polymerization in different directions. Figure 11 shows a schematic explanation for this phenomenon. An ideal graded light beam is in a shape of hourglass after passing the final lens of the optics setup. Around the focal point has the highest intensity where the polymerization can easily occur. This region is called effective beam zone. This zone is larger under 100% opening power due to a higher intensity as shown in Figure 11(a). As a result, the pillar tends to grow through the entire resin depth. In contrast, 70% opening power has a smaller (shorter) effective beam zone because of lower intensity, as shown in Figure 11(b). Thus, polymerization occurs only within a limited height.

Figure 11 Schematics of effective beam zone depending on the opening powers (a) 100% opening power, (b) 70% opening power, (c) axial growth and radial growth

As to the diameter difference, 70% opening power seems to cause more radial growth than that of the 100% opening power. This may be caused by material diffusion or beam transformation by cured parts. To understand the growth mechanism, more following studies are needed. Based on the observation in this study, the pillar of 70% case could be thin at the beginning and grow vertically. Because of the limited effective beam zone that inhibits the growth, a continuous UV exposure polymerizes the silicone resin around the cured volume, resulting in a wider pillar. The increasing trend of the diameter in Figure 9(b) is an evidence of this phenomenon. Although the traverse growth is not observed in 100% power opening, it is believed that the pillar will eventually grow as the exposure time increases. The last measurement point at 80 s of Figure 8(b) shows an increasing trend of the pillar diameter.

5 Conclusions

A hydrostatic fabrication was demonstrated in this paper through LOPP effect. LOPP was achieved using a low absorption wavelength (365 nm in this study) and a gradient light beam via the optics setup. It was found that both light intensity and exposure time could significantly affect the fabrication quality. A higher intensity leads to immediate polymerization along the beam path, called OPP, which is not desired in this application. Low intensity can effectively confine the polymerization within the effective beam zone, which essentially determines the resolution of the fabrication process. The current setup may achieve only 1 to 2 mm resolution based on the pillar dimensions. A better resolution can be achieved with a smaller focal size, longer wavelength (lower absorption), or a largely graded light beam.

In addition, it was found that the cured volume under LOPP is proportional to the exposure time to the UV light. Based on the experiments, the polymerization was hypothesized to grow in both axial and radial directions with respect to the light beam. The radial growth becomes more substantial when the cured height has reached the limit of the effect beam zone. With further improvement of the testbed and the experimental design, the polymerization mechanism by LOPP will be further investigated in the future work.

The proposed hydrostatic fabrication, if successful, could be an alternative to SLA for photopolymers. The advantages including direct three dimensional polymerization instead of a layer-by-layer approach, and elimination of support structures. The limitations are the selection of proper wavelength and optical system, and the possible lower resolution than SLA.

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