Hydrostatic 3D-Printing for Soft Material Structures Using Low One-Photon Polymerization

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Abstract

This paper studies the feasibility of a 3D printing method that enables a hydrostatic condition for support-free fabrication, named hydrostatic 3D printing (H3P). Soft structures are difficult to build in additive manufacturing due to the low stiffness. H3P utilizes low one-photon polymerization (LOPP) to achieve “in-liquid” curing surrounded by the hydrostatic pressure. Single-spot curing and continuous printing were investigated for a UV-curable silicone material under different light intensities and exposure times. Initial results have demonstrated LOPP effects for H3P. The equivalent exposure time in continuous printing was found shorter than a stationary single-spot curing due to a non-linear intensity distribution.

Keywords: additive manufacturing; silicone printing; low one-photon polymerization; two-photon polymerization

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1. Introduction

A variety of materials can be additively manufactured into three-dimensional shapes ranging from plastics, metals, to composites. Depending on the selected additive manufacturing method, support structures are often used to secure the part and enable the layering process, such as in stereolithography (SLA), polyjet printing, and fuse deposition modeling (FDM). The support structures are removed by hand trimming, water-blasting, or solution solvent after printing. One challenge falls in fabricating ultra-soft, jelly-like materials that can easily collapse and deform due to the gravity and low stiffness[1]. A considerable amount of support structure would be needed to ensure the part stability and post-processing for support removal could be detrimental to the soft structure. To overcome the challenge, this paper presents a concept that ultimately eliminates the support structure by utilizing hydrostatic force to stabilize the part during printing, namely hydrostatic 3D printing (H3P). UV-light is used to cure the polymer resin. However, different from SLA that cures a thin layer on the resin surface, H3P is aimed at “in-liquid” polymerization and thus to create a hydrostatic condition automatically. The schematic comparison is shown in Fig. 1.

Figure 1 Schematic comparisons between (a) stereolithography (SLA) and (b) hydrostatic 3D-printing (H3P)

The enabler of the in-liquid polymerization is low one-photon polymerization (LOPP)[2], as opposed to one-photon polymerization (OPP) in SLA. In OPP, an optical beam of high absorbance is used to cure the polymer along the beam path from the surface to a specific depth (Fig. 1(a))[3]. This depth determines the maximum layer thickness. In contrast, LOPP uses very low absorbance rate of photoresists and a great beam gradient with high numerical aperture (N.A.) to realize a smaller excitation volume at the focal point and under the liquid surface[4]. A 3D structure hence can be drawn directly inside of the liquid. LOPP, in fact, is a substitute of two-photo polymerization (TPP)[5]. TPP initiates the curing process only at the focal point by

simultaneous two-photon excitation and typically has nano- or micron-meter resolution[6]. However, TPP requires high-cost ultra-short pulsed lasers, which makes it less practical for 3D printing applications.

The challenge of LOPP is a precise control over wavelength, intensity, and exposure time to produce desired resolution and accuracy. There is no clear definition to distinguish OPP and LOPP. This research letter presents our preliminary works on investigating LOPP for the in-liquid polymerization of a UV curable silicone material. The following Section 2 details the experimentation including testbed design and methods. Section 3 shows the results and discussion, followed by the conclusions in Section 4.

2. Experimental Setup and Methods

The experimental setup consisted of a UV lamp system (OmniCure S2000, Excelitas Technologies Corp., Waltham, MA), an optical lens array, and a 3-axis CNC motion stage (Moog Animatics, Milpitas, CA), covered by amber plates to block the environmental UV light. The optical lens array in this setup was assembled with a light guide, a collimating lens, a band pass filter, iris diaphragms and a focusing lens as shown in Fig. 2 to create a single wavelength, graded light beam. The focusing lens with the highest numerical aperture (N.A. = 1) was selected to maximize the beam gradient.

Figure 2 The experimental setup to create gradient UV light beam

The soft material for the testing was a non-commercial UV curable silicone provided by Dow Corning. The absorbance spectrum was measured using a spectrophotometer (U-4100, Hitachi, Tokyo, Japan), and shown in

Fig. 3. Although there was no clear definition between OPP and LOPP, the wavelength of 365 nm was selected because it had a low absorbance value of 0.051 and was a common band pass filter that can be easily obtained.

Figure 3 Measured absorbance spectrum of the UV curable silicone and the effects of OPP and LOPP under different wavelengths in a single-spot curing.

The experiment method was designed to observe LOPP under a stationary condition (i.e., single-spot curing) and a dynamic condition (i.e., continuous printing). The single-spot curing is illustrated in both Fig. 3, Fig. 4(a) and (b), where a “pillar” forms under the UV light exposure. The container was fully filled with the UV-curable silicone. The focal point was set near the container bottom to allow adhesion to the base rather than floating in the resin after the part was cured. The optically transparent pillars then could be observed after the remaining resin was drained. The design of experiment consisted of two levels of light intensity (100% and 30% based on the system output) and 16 levels of exposure time. The exposure time for 100% intensity was 30 to 180 s at 10 s increment and for 30% intensity was 90 to 127.5 s at 2.5 s increment. Each set of 16 testing points were made in a 4 by 4 array in an individual container. The testing sequence started from left to right in the container, and then moved to the next row. The pillars by LOPP were identified based on the height less than the resin depth, as shown in Fig. 3. An optimal combination of the intensity and exposure time were used for the continuous fabrication.

In the continuous printing, straight volumetric lines were created with several feed rates of the light source. Different feed rates were used because the light beam is typically not uniformly distributed (normal or Gaussian distribution), the exposure time for a unit volume could be different between a stationary exposure and a sweeping-type of dynamic exposure. The baseline feed rate was calculated by the focusing spot diameter (1 mm)

divided by the exposure time selected from the single-spot test.

3. Results and Discussion

Fig. 4(a) and (b) show the results of single-spot tests with 100% and 30% intensities. It was found that 365 nm wavelength can initiate both OPP and LOPP in the selected silicone material. At 100% intensity (Fig. 4(a)), only OPP pillars appeared in the container. A shorter exposure time showed no pillar because the beam absorbance was insufficient to initiate polymerization. As soon as the pillar was formed, it had reached the full height and began to grow radially; thus, it was identified as OPP. These pillars were in a cylindrical shape. On the other hand, 30% intensity created a mixed effect of LOPP and OPP, as shown in Fig. 4(b). At a shorter exposure time, the pillar heights were less than half of the resin depth, indicating the in-liquid polymerization. A longer exposure time led to full-height pillars but they did not grow radially, indicating that the light intensity was too low to expand polymerization. Thus, the pillars were in a conical shape rather than cylinders. In Fig. 4(b), pillars at 95 s and 102.5 s were missing likely due to an unstable LOPP effect or collapse during resin drainage. Another three tests were repeated for 30% intensity and LOPP pillars could appear between 90 and 125 s exposure time.

Figure 4 Results of the tests: (a) single-spot test at 100% intensity with only OPP pillars, (b) single-spot test at 30% intensity with both LOPP and OPP pillars, (c) continuous printing test at 30% intensity and different feed rates (100% presents the baseline) and (d) measured profiles of (c).

In the continuous printing test, the parameters based on the stationary test were 30% light intensity and 125 s exposure time. Given the estimated focusing spot of 1 mm in diameter, the baseline feed rate was 0.5 mm/min. Three scaled feed rates were 0.667 (133%), 0.857 (171%), and 1.200 (240%) mm/min. Fig. 4(c) and (d) show the volumetric lines produced by these feed rates and the surface topography measured by a surface profiler (Model G4, Alicona, Austria). Both the baseline feed rate and 133% speed created a full-height volumetric line, indicating an OPP effect. The 171% feed rate generated a nearly LOPP effect; 240% generated a complete LOPP structure. The height of the volumetric line was mostly less than 2.5 mm compared to the full-height of 4.8 mm. The 240% scale factor is equivalent to a 52 s exposure time, compared to the selected 125 s. This indicates a highly non-linear polymerization across the focusing spot. The moving light beam for continuous printing requires much shorter exposure time to generate LOPP.

4. Conclusions

This research has demonstrated the in-liquid polymerization with LOPP for hydrostatic printing in a stationary single-spot testing and continuous printing. It was found a low-absorbance wavelength can produce both LOPP and OPP effects depending on exposure time and intensity. The intensity must be low enough to produce LOPP structures inside of the resin regardless the exposure time. Therefore, the parameter selection should follow the priorities of wavelength, light intensity, and then exposure time. The current results show that LOPP structures, though feasible, were still of low repeatability with 365 nm wavelength. A longer wavelength with a lower absorbance may be more suitable. Future study will be using 405 nm wavelength for comparison.

The hydrostatic condition was not thoroughly discussed in this study due to the difficulty observing the transparent structure inside the liquid. In general, the ideal polymer for hydrostatic printing should have a nearly identical density before and after curing to achieve zero gravity, and a high viscosity to minimize the motion as a result of density change. If the concept of H3P is successful, the soft material fabrication could be realized without physical support structures.

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