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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

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.

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

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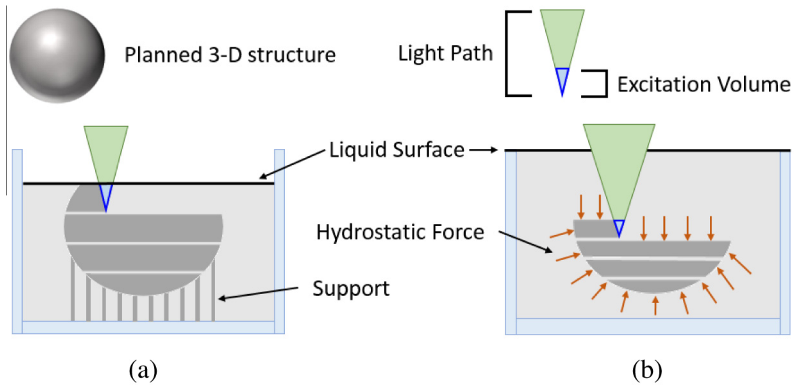

Fig. 1. Schematic comparisons between (a) stereolithography (SLA) and (b) hydrostatic 3D-printing (H3P).

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 and graded light beam. The focusing lens with the highest numerical aperture (N.A. = 1) was selected to maximize the beam gradient.

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.

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 30–180 s at 10 s increment and for 30% intensity was 90–127.5 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

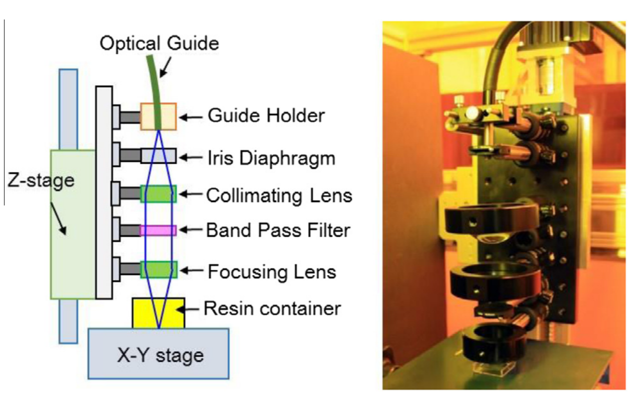

Fig. 2. The experimental setup to create gradient UV light beam.

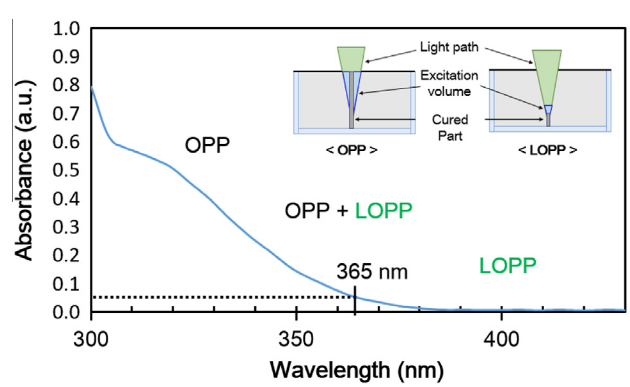

Fig. 3. Measured absorbance spectrum of the UV curable silicone and the effects of OPP and LOPP under different wavelengths in a single-spot curing.