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Reviewed Paper

3D-printing by patterning and advancing a liquid photo-polymer film

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Abstract

We present an additive manufacturing process, which uses the surface tension of a photo-polymer resin to suspend a film across a wide aperture and curing a pattern on the film. A horizontal film is made by dipping and raising an aperture from a shallow pool of resin and the film is polymerized selectively with a 405 nm laser. After each step of selective curing with a pattern, the build plate is moved backwards to advance the part. This process consumes a much smaller amount of resin as compared to a bottom-up vat photopolymerization machine. This paper presents the proof of concept of the process along with the machine and two parts printed using this process. Furthermore, the paper discusses the effect of process parameters such as pressure on the suspended film, and an extension of the process to a continuous interface polymerization. The process presented has the potential for in-situ additive manufacturing in micro-gravity conditions for space applications.

1. Introduction

The vat photopolymerization process is one of the first additive manufacturing processes developed with a platform moving through a vat of photo-polymer resin solidifying into hardened resin upon exposure to patterned or scanned light of certain wavelengths [1,2]. Such a system is called a Stereolithography Apparatus (SLA), which was developed as a top-down system wherein the part starts building from the top of the vat progressing till the bottom of the vat or the end of print. A top-down machine requires an entire vat equal to the height of the print prefilled with photo-polymer resin. This requires a large quantity of resin before a part is printed regardless of the part dimensions. Thus, this hinders scalability and the cost of resin for making a large part also increases. There have been advances from the initial SLA machines [2-7], two of which were the development of a bottom-up SLA machine and continuous liquid interface polymerization. Both processes used a transparent film onto the vat [3][5]. This transparent film allowed the build to be inverted, starting from the bottom of the vat where the transparent film is placed. Thus, large build volume with a constant volume of vat could be achieved. In [7], a top-down digital-light-processing based process was extended to concurrently embed fibers in spatial paths. A top-down system enables the printer to have manipulation systems over the vat without obstructing the light source. However, the height of the part is limited to the depth of the vat. To overcome these limitations, in this paper, we present prospects for using the surface tension of the photo-polymer resin to suspend a film (like a soap bubble), where polymerization takes place [8]. This enables printing in a top-down manner without a large, prefilled vat. We printed two parts from the suspended polymer-film using a handheld laser (which will be later replaced with a scanning laser). We also discuss the effect of wetting by the film onto a build platform and effect of pressure on the film to manipulate the shape of the film.

2. Process and Method

2.1 Proof of Concept

The machine developed in this work consists of a movable platform that is actuated by a stepper motor and a linear guide, moving the platform up and down. The build-platform consists of a cavity for liquid resin that is used to dip and make a film. The apparatus that holds the liquid photopolymer film consists of a fixed aperture funnel of an opening of 24 mm and a transparent window for the laser irradiation and the entire apparatus is enclosed with a port for applying pressure. Figure 1 illustrates the apparatus for holding the film along with the pressure chamber.

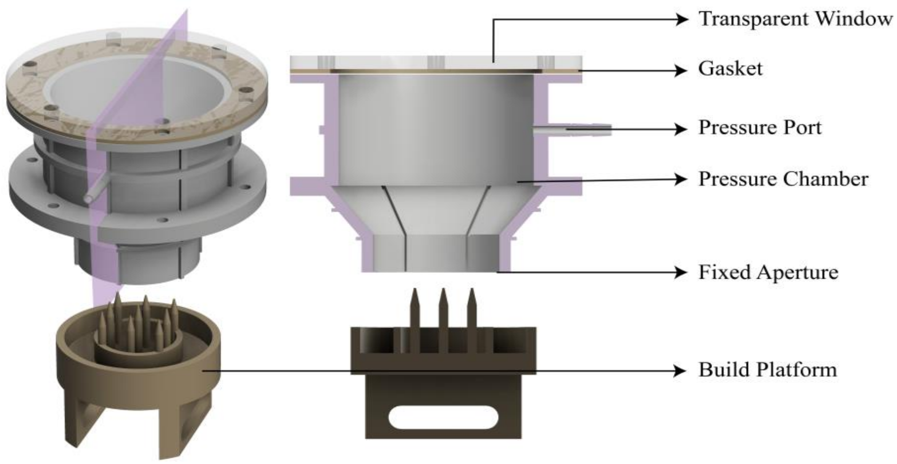

Figure 1. Schematic diagram of the apparatus (fixed-aperture funnel) that holds the liquid film across the aperture

2.2 Material

A 14:3 blend of Tough 1500 photopolymer and BYK-145 polymeric surfactant is used as the resin. BYK-145 surfactant lowers the surface tension of Tough 1500 as well as increases the viscosity of the resin. Although Tough 1500 is a low-surface tension liquid polymer and can sustain a film without a surfactant, a surfactant can be used to increase the longevity of the suspended film.

2.3 Process

Start: The printing process starts with the build platform touching the aperture funnel. The resin filled cavity wets the circumference of the aperture, and then the platform moves down with the liquid polymer forming a catenoid surface with the aperture and the circular cavity. The platform is further lowered till the catenoid thins and forms two separate surfaces. One is on the aperture that will be used to polymerize a layer.

1st layer: The film formed across the circular aperture is then carefully placed over the build platform, which are a set of spikes that touch and help the film to remain flat. The contact area of the spikes and the film is polymerized using a 405 nm laser.

Subsequent layers: After the first layer is printed the aperture is made to dip again to form another film even though the earlier film remains intact. The new film is now placed on top of the previously cured part. This process is repeated as the current scope of the work does not have a refilling mechanism to replenish resin consumed from the film. Figure 2 demonstrates a step-by-step process of forming a part.

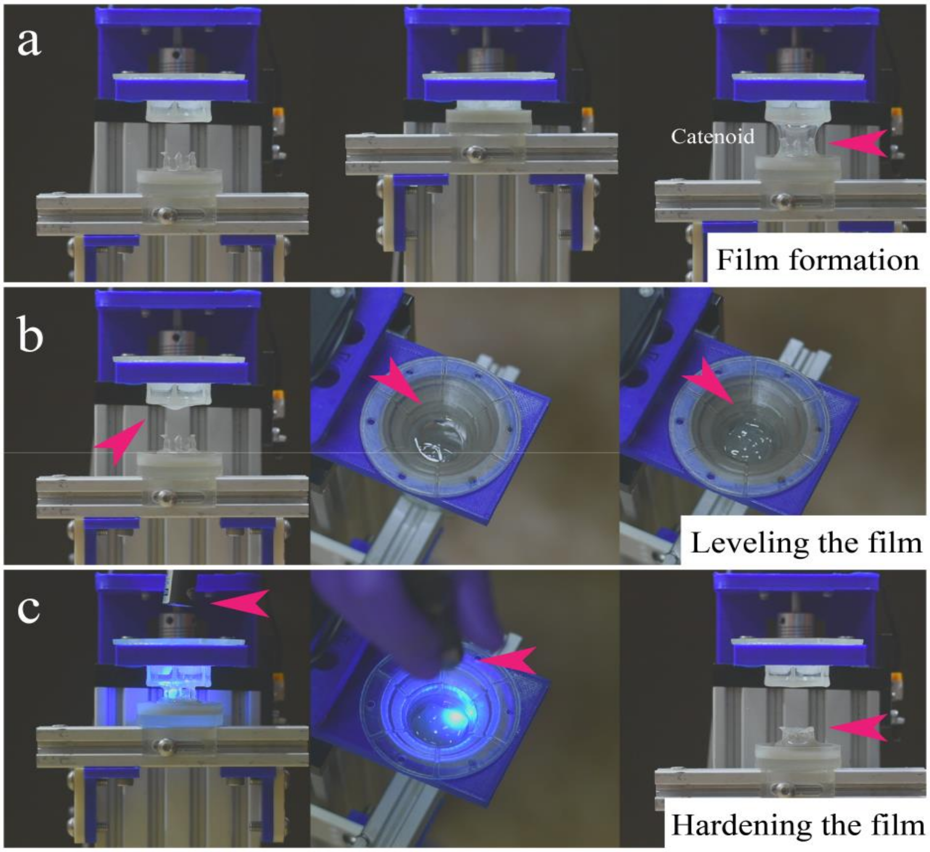

Figure 2. The process is annotated in a step-by-step manner: a. shows the process of the formation of the film, where the pink arrow highlights the catenoid. b. shows the catenoid breaking into a flat film the pink arrow points at the film that is formed. After the film is formed, the film is leveled to the build as shown in b. c. The handheld laser is used to cure the film onto the needles (build platform) the pink arrow highlights the laser and the part formed after curing.

3. Results

Two parts with simple features were printed from the process and the machine. Figure 3a is an annular cylinder and 3b is a hollow rectangular box with one face opened. Selective curing of the film is achieved although a handheld LASER was used to manually scribe patterns over the film. A scanning LASER or a short-throw projector is required to get accurate parts.

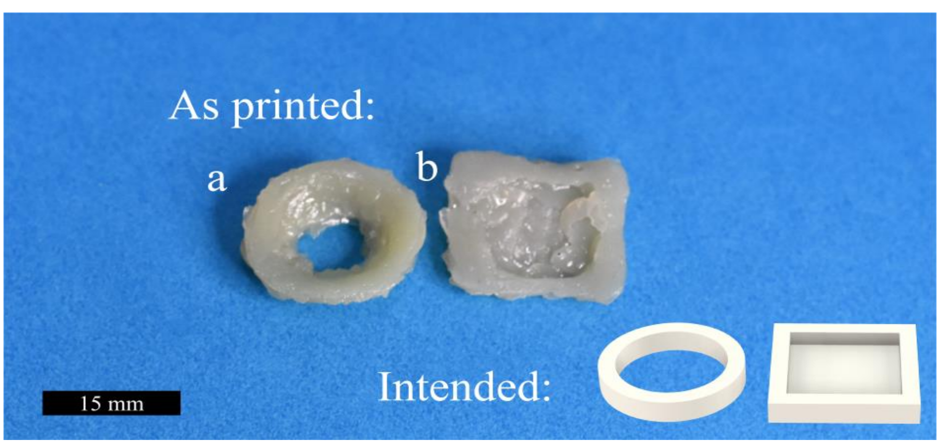

Figure 3. An annular cylinder and a box printed is shown and an illustration of the part is also shown.

4. Discussion

Draining of excess liquid from the film: After the liquid catenoid surface separates into two meta-stable films, the film on the aperture accumulates until gravity forces it into a droplet and a stable film. Here, the gravity forces overcome surface tension and viscous forces in the liquid to form two ensembles, i.e., a film and a droplet. The droplet formed wets the spikes on the build platform and hinders the film to remain flat when it meets the spikes.

Effect of pressure on the film: When the pressure chamber is enclosed and sealed with the transparent window, a positive or negative delta pressure can be applied to briefly change the shape of the film. When the difference in the pressure is zero, the film will form a minimal surface across all boundaries wetted by the liquid. This can be understood from the Young-Laplace's equation for static meniscus given as follows:

$$\Delta P = \gamma \quad \frac{1}{R_1} + \frac{1}{R_2} \quad \text{or } \Delta P = 2\gamma H$$

$$\gamma\left(\frac{1}{R_1} + \frac{1}{R_2} - \frac{1}{\gamma/\Delta P}\right) = 0$$

Here γ denotes the surface tension of the liquid and ΔP denotes the pressure difference between the interfaces formed by the liquid and H is the mean of principal curvatures of the surface. There are two sides of this surface that form in the case of a film with an air-liquid interface. This can be seen in the catenoid in Figure 4 where both these sides are at P_{atm} when the film is formed.

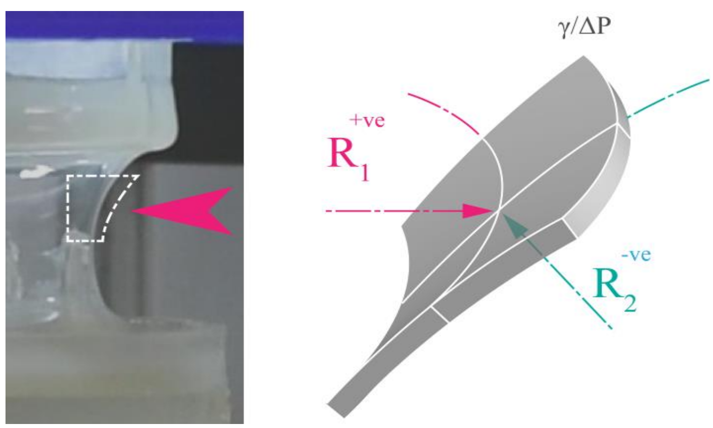

Figure 4. A patch of the minimal surface (catenoid) formed is illustrated, here $H = 0$ as $\Delta P = 0$.

When ΔP is zero, a thin film will have its mean curvature as zero. It is important for the film to be thin, or else a pressure gradient due to the thickness of the film equalizes a factor of the mean curvature. Any non-zero ΔP applied in the chamber after the film is formed will deviate the surface from a minimal surface ($H = 0$). Figure 5 shows the effect of pressure on the liquid film. It can be noted that the wetted boundaries do not change much with pressure applied. A positive pressure gradient would expand the film as $-\frac{1}{\gamma/\Delta P}$ is a negative quantity hence R_1 must increase and vice-versa when a negative pressure gradient is applied. In this process, pressure can be used to modulate the surface of the film while printing parts with large area of exposure or large circumference of wetting.

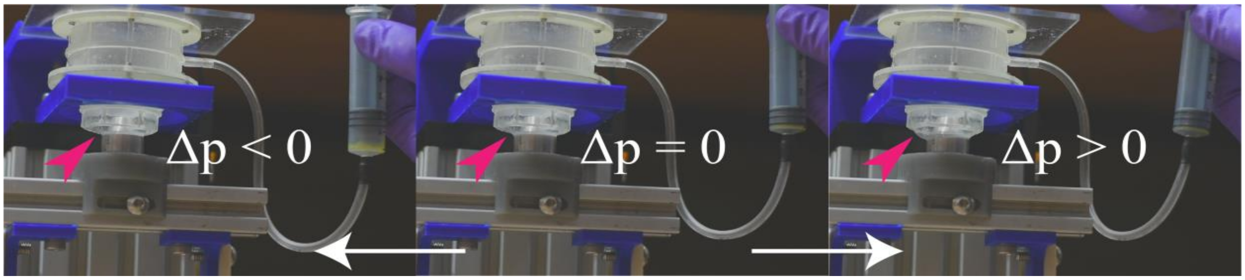

*Figure 5. The effect of pressure on the film can be seen. A positive **ΔP** expands the film although the contact with the build platform does not change.*

Augmentation to Continuous Polymerization: The current scope of the work encapsulates a layer-by-layer process as a handheld laser is used to selectively cure the film. The exposure time could not be reduced below the response time of clicking the button on the laser manually. A fast-scanning laser can cure a portion of the film under the air-liquid interface and prevent the oxygen inhibition layer from curing. This way, a portion of the film below the air-liquid interface is solidified and the film over the cure part remains wet. The cured part now can move down, and a fresh coat of resin can flow through the film. This also requires a mechanism to precisely add resin into the film. We aim to build a device to replenish the resin used from the film. Currently, a fresh coat of resin is brought by dipping the apparatus in resin and raising it up to form a new film.

5. Closure

The proof of concept of using a photopolymer as a liquid film on which polymerization takes place illustrates the potential of augmenting it as an additive manufacturing technique. The minimal use of resin as well as the scalability of the axis and the surface area of the film provide compelling reasons to pursue such a process in-lieu of vat photopolymerization techniques. The issue of draining excess liquid from the film because of gravity forces over the viscous forces is non-existent in micro-gravity like that in outer space. In such conditions a large film as well as a slightly thicker film can be made and used. In the current scope of the work, it cannot be compared with VPP processes in terms of surface quality, strength and geometric limitation of the part created in this process. These are prospects for future work with an improved prototype of the concept.

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