LIQUID PHASE CONSTRUCTION OF MICROSTRUCTURES

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ABSTRACT

The controlled formation of curved, three-dimensional microstructures can be accomplished through solidification from a liquid phase. As a demonstration, we have placed objects in contact with the interface of a photopolymerizable liquid and air to create various liquid menisci that were subsequently solidified with ultraviolet radiation. Geometric control is achieved through variation of physical and environmental parameters; for example, solidified menisci formed at 25°C were 300μm taller than those formed at 7°C. Comparisons between the polymerized structures and theoretical predictions for liquid menisci indicate that the polymerization process results in repeatable changes in contact angle and meniscus size.

INTRODUCTION

The creation of microscale structures using methods borrowed from the integrated circuit industry has led to the development of Micro Electrical Mechanical Systems (MEMS)**[1, 2]**. These methods are largely limited to the creation of two-dimensional or pseudo three-dimensional (orthogonal) structures**[3, 4]**. Unfortunately, methods to construct non-orthogonal shapes (smooth curves, etc.) at the microscale are limited. Curved microstructures are desirable, as they would have different mechanical responses to loading and different fluid flow patterns around them as compared to orthogonal structures. In this paper, we demonstrate a liquid phase construction process that allows for the rapid construction of smooth three-dimensional microstructure geometries.

Our process is based on the interactions between solids, liquids, and gases that give rise to smooth curves. For example, if a solid is brought into contact with a gas/liquid interface such as air and water, and then moved either into the liquid or pulled away from the liquid surface, the interface will form a smooth, curved shape (Figure 1). The interface between two immiscible liquids of different density will react in a similar way. Both hydrophilic and hydrophobic objects can be positioned at relative heights with respect to the interface, simultaneously forming multiple structures of varying complexity. If the liquid is solidified in this configuration, the result is a solid three-dimensional structure with curved features.

Although the solidification of the liquid will cause the solid objects to adhere to the solid three-dimensional structures, removal of the solid objects is possible through various schemes. For example, the solidification could be partially completed, the object removed, and the solidification completed or the solid object could be constructed from a sacrificial material that would be dissolved after the solidification was complete. Alternatively, the solid object could become part of the completed device. A compliant bottom surface facilitates the final release of the solidified structures as well as allowing the deformed compliant surface to serve as a mold as shown in Figure 1 (far right). Electrical, fluidic, and pneumatic connections could then be established by means of holes created with the various solid objects.

THEORY

Control over the liquid meniscus prior to solidification can be accomplished by using different solid objects and heights, or by varying the interfacial surface tension or density of the liquid. For example, consider the curvature of a one-dimensional gas-liquid interface in contact with a solid (Figure 2). For an arbitrarily curved interface with one principal radius of curvature, R_1, the pressure increase, ΔP, on the concave side of the interface is given by the Young-LaPlace equation, $\Delta P = \gamma(1/R_1 + 1/R_2)$, where γ is the interfacial surface tension and $R_2 = \infty$. The hydrostatic pressure difference between the two fluids is $\Delta P = \Delta\rho g(H_0\text{-}Y)$, where $\Delta\rho=|\rho_1-\rho_2|$ is the density difference between the fluids, g is gravity, H_0 the meniscus height, and Y is the vertical coordinate. Equating these two expressions gives

$$\gamma \frac{d\theta}{dS} = \Delta\rho g(H_0 - Y)$$

at any point, S, on the meniscus. This can be solved analytically for the x and y coordinates of each point on the meniscus:

$$X = \sqrt{\frac{\gamma}{\Delta\rho g}}\left\{\ln\left[\frac{\tan(\beta_0/2)}{\tan(\beta/2)}\right] + 2(\cos\beta_0 + \cos\beta)\right\}$$

$$Y = \sqrt{\frac{\gamma}{\Delta\rho g}}\{2(\sin\beta_0 - \sin\beta)\}$$

where $\beta = \pi/4 - \theta/2$, $\theta_0 \le \theta \le \pi/2$, and $\beta_0 = \pi/4 - \theta_0/2$**[5]**. Thus, the curvature of the meniscus is a function of the interfacial surface tension, the relative weight density of the fluids, and the contact angle, θ_0. In general, surface tension increases faster than density as temperature is lowered, allowing a larger meniscus to be formed at lower temperatures. At a given temperature, careful selection of the density of an immiscible upper fluid, and thus $\Delta\rho$, also allows the size of the meniscus to be modified. Lastly, by varying the height, shape, or surface roughness of the solid, the contact angle can be changed, resulting in a different curvature of the meniscus. The contact angle can also be modified through evaporation of the liquid or prior wetting of the solid object. Three-dimensional shapes produced by this technique have two principal radii of curvature, and the solution must be computed numerically, but the same parameters control the meniscus shape as in the one-dimensional case.

EXPERIMENTAL SETUP

The experimental apparatus is depicted in Figure 3. An xyz manipulator positioned the solid objects with respect to the liquid surface. Norland Optical Adhesive No. 61 (a UV-curable adhesive) was chosen as the liquid to solidify due to its commercial

0-9640024-4-2/hh2002/$20©2002TRF
DOI 10.31438/trf.hh2002.38

availability, low degree of volume shrinkage, and known values of surface tension and density. A compliant surface of polydimethylsiloxane (PDMS) supported by a glass platform held the adhesive. Both the glass and the PDMS are transparent to UV light, allowing the UV lamp to be located below the adhesive. This configuration permitted free motion of the xyz manipulator and unobstructed placement of the solid objects. At a distance of several centimeters, the UV intensity at 365nm from the lamp was approximately 2 mW/cm^2. This produced cure times of several minutes to one hour, depending on the thickness of the adhesive layer. Shorter cure times—on the order of a minute—could be achieved with a more powerful UV lamp.

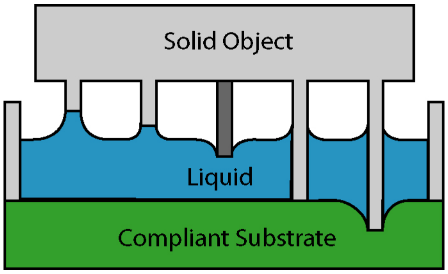


Figure 1. A solid object in contact with a liquid interface forms smooth, curved menisci. *The middle solid object is hydrophobic, while the others are hydrophilic.*

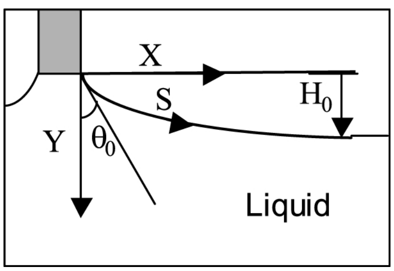


Figure 2. Definition of variables.

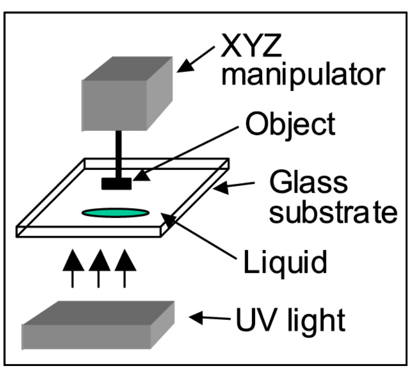


Figure 3. A schematic of the experimental setup.

RESULTS

A variety of curved, three-dimensional microstructures were created at 25°C using this technique (Figure 4). Figure 4a & b shows various "drawn" structures that were created by placing an object in contact with the adhesive and then drawing the object away from the surface and holding it at a constant height during polymerization. Moving the solid objects into the interface creates "molded" structures that assume the shape of the mold, with edges defined by the characteristics of the interface (Figure 4c & d). Finally, moving the solid object through the interface until it deforms the lower compliant surface creates a shape in the compliant surface that acts as a mold to govern the lower surface of the polymerized layer (Figure 4e & f). Deforming the compliant surface has the advantage of producing a structure that perfectly conforms to the deformation in the compliant layer, as the compliant layer is unaffected by the characteristics of the polymerizable liquid. Since the mold is compliant, it can easily be removed (peeled off) from the polymerized structure. For the images shown in Figure 4e and f, a 60µm diameter glass fiber deformed the PDMS surface. Upon removal of the fiber, a 60µm diameter hole was created that allowed fluid to be pumped through the resulting "needle" structures.

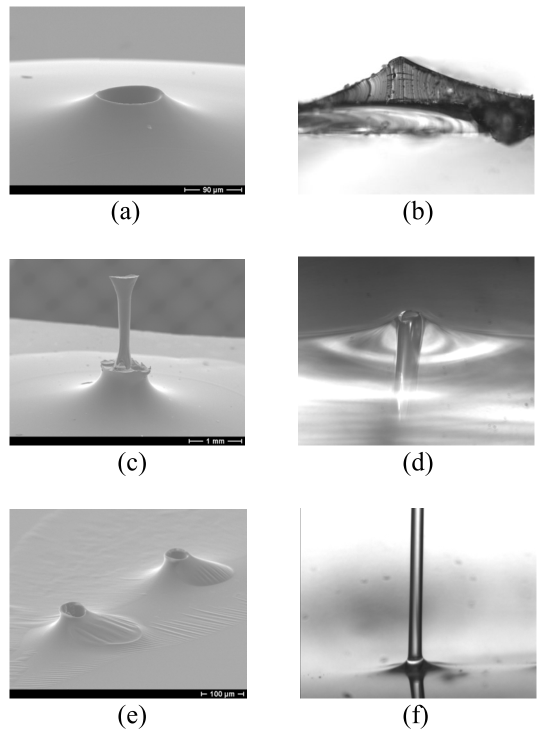
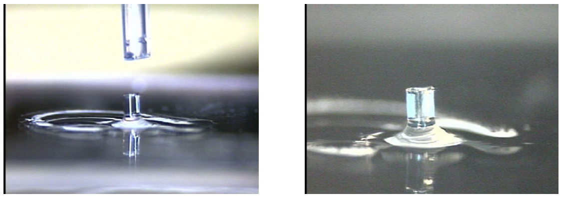


Figure 4. Examples of various polymerized structures. *(a) SEM image of a "volcano" with a cone-shaped interior formed using a drawn glass capillary; (b) Optical image of a "wall" created with a 50µm thick sheet of transparency plastic; (c) SEM image of a "column" created with tubing; (d) An optical image of a "needle" formed by penetrating the entire depth of the fluid with a 60µm diameter glass fiber. Backlighting allows the hole to be seen; (e) SEM image of two "needles" created by deforming a PDMS surface with 60µm diameter glass fibers; (f) Optical image of a "needle" pumping fluid. A reflection of the fluid can be seen in the lower half of the image.*

The fabrication of the devices in Figure 4 was accomplished with several different release schemes. The structures in Figure 4a and b were formed by pulling the solid object away from the solidified structure after polymerization. Teflon was found to be a suitable material for this type of release. As seen in Figure 5, the Teflon object can be pulled away from the polymerized structure without damaging the structure. Another method that we have employed is to coat the solid objects with surfactants for ease of removal after polymerization. This is the release scheme used in forming the structures in Figure 4d and e. Shape memory (or shape changing) solid objects can also facilitate release. For the “column” shown in Figure 4c, tubing that expanded to its original diameter with the application of heat was used to remove the tubing mold from the polymerized structure.



(a) (b)

Figure 5. A release scheme using Teflon. *(a) A Teflon tube and the resulting polymerized structure after release; (b) The polymerized cylindrical structure (diameter=300μm).*

While the structures in Figures 4 and 5 were fabricated at 25°C, we have observed changes in meniscus size and shape in accordance with the theory presented above. Specifically, menisci polymerized at 25°C were 300μm taller than those formed at 7°C. For a constant contact angle, this decrease in temperature should produce a larger meniscus, as surface tension increases faster than density when temperature is lowered. However, the contact angle did not remain constant, and increased to an amount that produced the observed decrease in meniscus size at the lower temperature**[6]**.

CONCLUSION

The combination of various solid objects, photopolymerizable liquids, polymerization conditions, and temperatures allows structures of various sizes and shapes to be created within the limitations of surface tension driven construction. Placing multiple solid objects in contact with the liquid surface prior to polymerization forms complex connected structures. In addition, research on the formation of drops has identified other relevant parameters that influence liquid meniscus formation, providing designers with additional control over geometry**[7]**. Thus, a liquid phase construction technique will enable the formation of diverse, curved, three-dimensional microstructures.

ACKNOWLEDGEMENTS

This work was supported under a grant from DARPA-MTO, BioFLIPS program. We would also like to thank Glenn M. Walker for helpful discussions.

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