ORIGAMI FABRICATION USING SINGLE LAYER PHOTOLITHOGRAPHY AND CAPILLARY FOLDING

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ABSTRACT

Polymer and carbon origami structures are fabricated by first producing patterned sheets with less cross-linked compliant folds and more cross-linked stiff faces through differential UV exposure. The obtained patterned sheets are heated to further raise their compliance by increasing polymer chain mobility. These softened sheets with designated compliant fold regions are then folded to their target polyhedral shape using capillary forces induced by droplets placed on top of them. By cooling the three-dimensional shapes to room temperature and subsequently completing their cross-linking by an additional UV exposure step, the shape of the sheets is locked in the folded position. The obtained polymer origami structures are converted into isometrically shrunk carbon structures through pyrolysis. This capability of making three-dimensional carbon polyhedra could open new ways to fabricate complex structures of different material and surface properties through techniques such as electroplating and electroless deposition.

Keywords: Origami, three-dimensional carbon structures, elastocapillarity, cross-linking, photolithography

INTRODUCTION

Microparticles are used in multiple timely applications including drug delivery [1], bioimaging [2] and diagnostics [3]. Recent studies have quantified how the physical parameters of microparticles such as size, shape, strength, and deformability contribute to their functionality [2], [4]. Several naturally existing particles, such as living cells, possess shape-based advantage. For instance, the shape of viruses and bacteria aids them in preventing immune response on the host. Findings on the effect of shape on the properties/behavior of microparticles have led to more research on the subject. However, studies were majorly confined to the shapes that are derivative of spheres, since they are easy to fabricate using microfluidic techniques [5], [6]. A folding-based fabrication technique, origami, can overcome this limitation [7], [8].

Various conventional fabrication techniques are adopted to make origami shapes. Differential thermal expansion, melting of folding hinges, and application of pre-strain are some of the techniques that have been explored to fold patterned two-dimensional sheets into three-dimensional shapes [9]–[11]. However, these methods demand multilayer photolithography. Alternatively, an elastocapillary-based folding using droplets can be used to make three-dimensional shapes by folding a single layer polymer material utilizing surface tension [12]. Although this method enables the use of a single layer polymer sheets for the fabrication of three-dimensional shapes, the folded particles return to their original flat configuration once the droplet evaporates. This reversibility is because the method often uses sheets made of elastomers. Also, for the fabrication of accurate three-dimensional shapes, folds and faces of the origami should have different properties, with folds being relatively soft, to get sharp bending at these locations; and faces should be stiff, to resist the bending. Attaining this contrast in material properties is challenging when a single material is used for elastocapillary-based folding. Moreover, elastocapillary-based folding generally is demonstrated on polydimethylsiloxane, which is challenging to be patterned into the desired two-dimensional sheets.

Here, we present an elastocapillary-based folding of photo-patternable materials to fabricate three-dimensional shapes using lithography involving only a single layer of polymer. The use of a photopolymer enables facile fabrication of two-
dimensional unfolded shapes. It also allows for the patterning of faces of the shapes with ease. Moreover, distinct material properties are introduced for folds (compliant) and faces (stiff) by controlling the level of cross-linking and the temperature of the sheets.

**EXPERIMENTAL PROCEDURE**

The planar sheets used for the fabrication of origami polyhedra are created using photolithography as illustrated in Fig. 1(a). A thin film of SU8-2050 (MicroChem) is spin-coated on a silicon wafer at 1500 rpm. Soft baking for 15 minutes at 85°C is performed to remove the solvent from the SU8 film. This soft baking duration and temperature are lower than the recommended values (20 minutes and 95°C), ensuring a weak adhesion between the SU8 film and the wafer, enabling the later release of the finalized patterned sheets from the wafer. After soft bake, a photomask that completely exposes the origami sheets, including folds and faces (but not the holes patterned in the faces), is used to irradiate such regions for 40 seconds using a 2 mW/cm² UV light source (Fig. 1(a)). Following the first exposure, a mask that exposes only the face regions, but not the folds or the patterned holes in the faces, is aligned on top of the first mask to exclusively irradiate the faces for another 40 seconds. The maximum exposure duration (80 seconds) used here is less than the recommended period (120 seconds) for the photolithography process. This reduced exposure duration allows for a straightforward release of the sheets from the wafer. The period of the post-exposure bake (PEB) is also reduced from 10 minutes (recommended period) to 5 minutes for the same reason. The sheets are released from the silicon substrate after the PEB by developing using acetone or SU8 developer. The released patterned sheets are later separated from the developer by carefully draining the developer, cleaning them with isopropyl alcohol (IPA), and then drying.

The patterned SU8 sheets are folded inside a silicone oil bath as shown in Fig. 1(b). A water droplet is placed on top of the sheet, and then the oil bath is heated up to 105°C, causing the sheets to become more compliant. These softened sheets are consequently folded by capillary forces induced by the droplet. The initial volume of the deposited droplets is at least 1.5 times larger than the volume of the target polyhedral shape to ensure that the droplets enter in contact with all the faces of the sheet during capillary folding. At this point, the polyhedral shape is partially open. Heating continues until the excess liquid is evaporated, forming a fully closed polyhedral structure. The silicone oil bath is then cooled to room temperature to lock the sheet in its folded polyhedral shape.

SU8 strips (2.5 mm × 25 mm × 0.053 mm) are characterized using dynamic mechanical analysis

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**Figure 1** (a) Steps to fabricate patterned origami sheets with patterned holes at the faces using photolithography. (b) Capillary folding of the patterned sheets into three-dimensional shapes.
(DMA) to find the effect of exposure energy and the temperature of the sheets on their elastic properties. A tensile preload of 0.001 N is applied to prevent compressive buckling of the specimens. The characterization is performed by applying a sinusoidal force. The temperature of the specimen is changed from 40°C to 90°C at a temperature ramp of 3°C/min.

RESULTS AND DISCUSSION

SU8, the photopolymer used in this study, undergoes cross-linking when it is irradiated with UV light. The level of cross-linking can be adjusting by controlling the exposure duration. Here, the faces of the target polyhedral shapes are exposed for a longer duration than the folds. The difference in total exposure time leads to dissimilar levels of cross-linking at the folds and faces. Additionally, holes of different shapes can be patterned on the faces by not exposing selected regions within them (Fig 1(a)). When thermally treated, the SU8 sheets are softened, with the less-cross linked fold regions softening more than the more-cross linked face regions (Fig. 2(a)). The characterization study performed with dynamic mechanical analysis showed that the storage modulus (the dynamic modulus that represents the elastic behavior of the material) correlates directly with the exposure density (Fig. 2(a)). This correlation indicates a direct relationship between the exposure energy and the degree of crosslinking.

The compliant patterned sheet is folded when a liquid droplet is placed on it. This folding occurs by the minimization of the total energy of the droplet-sheet system. That is, the addition of the surface energy of the droplet and the elastic strain energy of the sheet. Depending on the original sheet pattern, different final polyhedral shapes can be achieved (Fig. 2(b) and (c)). The difference in the modulus along the planform ensures a folding response in good agreement with theoretical assumptions. Such assumptions require the folds to be highly flexible (less cross-linked) and the
faces to be stiff (more cross-linked). The contrast in the material properties at the folds and the faces also enable the folding of the same final polyhedral shape from its multiple unfolded configurations, as shown in Fig. 3. The shapes that are made of polymers with carbon-rich backbones can be converted to an isometrically shrunken carbon through pyrolysis, as shown in Fig. 4.

CONCLUSION
Fabrication of three-dimensional polymer and carbon shapes was achieved by adjusting the material properties of photopolymer films along their planform and utilizing the enhanced surface tension effect at small length scales. Complex geometries with patterned walls were fabricated by implementing capillary folding on a photopatternable material. Pyrolysis was used to make carbon structures from the folded patterned sheets. This fabrication method for carbon and polymer origami could potentially contribute to many fields, including drug delivery and biosensing.

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References
BIOGRAPHY

Derosh George is currently pursuing a Ph.D. degree in Mechanical and Aerospace Engineering at the University of California, Irvine. He received his Bachelor’s and Master’s degrees in Mechanical Engineering from the Indian Institute of Technology (IIT) Madras. Afterwards, he joined General Electric (GE), where he was a part of the Edison Engineering Development Program (EEDP) in the Gas Turbine—New Product Introduction team until 2015. Following this stint at GE, he worked as a research fellow at IIT Madras for over a year. His current research interest is in the development of novel fabrication techniques for carbon origami and carbon nanowires.

Edwin A. Peraza Hernandez is an Assistant Professor of Mechanical and Aerospace Engineering at the University of California, Irvine. He obtained his Ph.D. and B.S. degrees in Aerospace Engineering from Texas A&M University in 2016 and 2012, respectively. His research integrates structural mechanics, design optimization, active materials, and principles of origami and tensegrity. He is the author of one book and more than 38 technical publications in archival journals and conference proceedings. The overarching goal of Hernandez’s research is the development of aerospace structures with optimal properties such as minimal mass, minimal energy usage, and tailorable stiffness.

Marc Madou was the Vice President of Advanced Technology with Nanogen, San Diego, CA, USA, before joining the University of California at Irvine as the Chancellor’s Professor of Mechanical and Aerospace Engineering. He specializes in the application of miniaturization technology to chemical and biological problems (BIO-MEMS). He has authored several books in this burgeoning field and has helped pioneer both in academia and industry. He founded several micromachining companies and has been on the board of many more. He was the Founder of the Department of Microsensor, SRI International, Menlo Park, CA; the Founder and President of Teknekron Sensor Development Corporation, Menlo Park; a Visiting Miller Professor with the University of California at Berkeley, Berkeley, CA; and is the Endowed Chair with Ohio State University (Professor of Chemistry and Materials Science and Engineering), Columbus, OH, USA.