Microorigami: Fabrication of Small, Three-Dimensional, Metallic Structures

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Microcontact printing (μCP) and wet chemical etching generated two-dimensional (2D) patterns in thin silver films. Electroplating silver onto these patterns increased the structural integrity of the metal layer. Separating the metal film from the substrate resulted in free-standing, 2D structures. Folding of these structures along predesigned “hinges” produced three-dimensional (3D) objects. Additional electrodeposition of nickel welded hinges into position, strengthened the structure, and joined separate pieces. By printing onto cylindrical surfaces, it was possible to generate complex shapes efficiently and to minimize joining steps.

Results and Discussion

Folding of a Planar Object into a 3D Structure and Consolidation of this Structure by Electrodeposition. Figure 1 illustrates the general strategy of microorigami. Microcontact printing (μCP) using an elastomeric stamp transfers a layer of hexadecanethiol to a silver-coated substrate. The hexadecanethiol forms a self-assembled monolayer (SAM) on the surface of the silver. This SAM acts as a nanoscopic resist to subsequent wet chemical etching using aqueous ferricyanide solution. The resulting patterned, interconnected, conductive, thin silver film serves as the cathode in an electrodeposition step. An electroplated layer of silver ~25 μm thick strengthens the patterned film and enables removal of the planar, silver object from the surface of the substrate.

The object comprises a single-layer array of rigid plates fabricated in a ductile metal film (silver) connected by weaker, perforated lines of the same metal. This type of structure folds easily at the perforated lines; that is, these lines act as “hinges.” The folds can generate either of two types of topographies: a “ridge fold” results in a convex crease that bends outward and forms a ridge; a “valley fold” results in a concave crease that bends inward like a groove. A series of folds transforms the planar film into a 3D object. A final electrodeposition step using a structural metal (nickel, for example) “welds” the hinges in place, joins elements that are separated in the starting pattern, heals any stress-induced fissures, and consolidates the structure.

Microorigami using Planar Substrates: the Arch and Bird. As demonstrations, we have prepared two microorigami figures, the “arch” and the “bird” (Figure 2). The arch requires a transformation from a plane to a quasi-hemicylindrical shell. The uniformity of folding angles and panel sizes/shapes results in a symmetrical structure. The corrugation developed in this object on folding increases the structural stability of the metal film. The final silver arch is shown in Figure 3. The bird illustrates that a range of folding angles and panel sizes/shapes can produce more elaborate structure (Figure 2). In this origami figure, some panels have been folded under others. These
the gaps between perforations and increases the overall film over the entire surface of a folded bird. This operation closes nipulators will require careful design. Accomplishing these types of folds using automated micromas-

“pushed” folds introduce multiple layers into the object that increase the complexity beyond that of a simple shell structure (Figure 3). Pushed folds also increase the complexity of the fabrication process and require finesse to achieve manually. Accomplishing these types of folds using automated micromanipulators will require careful design.

Figure 3 also shows the effect of electroplating a metal shell over the entire surface of a folded bird. This operation closes the gaps between perforations and increases the overall film thickness. Since nickel is stiffer and less ductile than silver, the nickel-coated structures are much stronger than their silver precursors.

Microorigami using Cylindrical Substrates: the Torus. To produce an object that encloses space (e.g., a continuous shell) from a planar template, the template must wrap around and connect to itself at some point. For example, a toroidal shell can be thought of as a cylindrical shell connected end-to-end. The cylindrical shell can be further decomposed into a planar sheet rolled and joined along a seam. Cylindrical shells with more complex topographies—for example, a chain of tetrahedral shells—require multiple connecting points (qQ, rR, ...) to be joined after initial folding of a planar sheet (Figure 4a). The alignment required for this joining is difficult. These connections can, however, also be made before the sheet is folded (Figure 4b). Using this strategy, we first rolled the planar sheet into a cylinder and then joined the connecting points (qQ, rR, ...) along the seam. Crimping of the cylinder in two orthogonal directions that are both orthogonal to the axis of the cylinder produces a tetrahedral shell.15 A series of such crimps along the length of the cylinder results in the desired chain of tetrahedral shells.

Implementing the strategy described in Figure 4b involves an initial transfer of a planar pattern directly to a cylindrical substrate using μCP (Figure 5). This printing step is topologically analogous to rolling a sheet into a cylinder. After the cylindrical substrate makes one entire rotation across the stamp, the pattern meets along its edge, and all necessary interconnects form in one simple step. Wet chemical etching develops the pattern, electroplating strengthens the patterned metal film, and dissolution of the cylindrical substrate releases the free-standing, quasi-3D template. Crimping of this template along the specified perforated hinges produces the desired chain of tetrahedral shells. Suturing the chain end-to-end with platinum wire followed by an electroplating step joins the ends and completes the toroidal shell.

Conclusions

The method described provides a strategy for fabricating tessellated, 3D, metallic surfaces, but uses planar methods of lithography (high-resolution printing,16 photolithography, soft lithography, electrodeposition) that make the fabrication of even very complex 2D patterns straightforward. Microelectrochemistry enables joints and joins to be welded and heals defects introduced during bending or crimping. The use of nonplanar substrates with suitable topographies/symmetries can, in some instances, enable difficult interconnects to be made simply and directly on the substrate.

The range of microsurfaces that can be formed using the strategy described here is large: conformal mapping17—the mapping of 2D patterns onto 3D surfaces—and cylindrical buckling18 have been extensively studied. The major limitations to this method are practical ones: the difficulties of folding and connecting. In its present configuration, we fold the structures manually, and the method is thus limited to tessellations having millimeter dimensions. We can envision using microtools19,20 to manipulate hinges and assemble components. We21,22 and others23,24 have also developed methods of self-assembly that use minimization of surface free energy to accomplish folding. These methods are particularly attractive for their simplicity and for their ability to scale to small dimensions. We suggest that they will be useful in fabricating small, lightweight structures: components of MEMS, small antennas, components of micro air vehicles, and microchemical reactors.
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Supporting Information Available: All experimental details, including preparation of glass substrates, microorigami using planar substrates, and microorigami using cylindrical substrates. This material is available free of charge via the Internet at http://pubs.acs.org.

References and Notes


Figure 4. Two strategies for converting a planar sheet into a chain of interconnected tetrahedral shells. (a) Interconnects made after the folding step. Introduction of the indicated folds causes the sheet to curl along its long axis. Points q and Q, and r and R, can be joined to form the array of tetrahedra. (b) Interconnects made before the folding step. Points q and Q, and r and R, meet along the seam of the rolled sheet; joining of the edges along the seam forms a cylinder. Crimping at the locations and in the directions indicated by the arrows creates the concave folds shown by the dash–dotted lines. Simultaneously, the crimping induces the formation of convex folds along the dotted lines. This strategy results in the formation of the desired array of tetrahedral shells.

Figure 5. Microorigami using cylindrical substrates. Microcontact printing of hexadecanethiol on the surface of the silver film was achieved by rolling the capillary across the surface of a poly(dimethyl siloxane) (PDMS) stamp “inked” with an ethanolic solution of hexadecanethiol. Careful alignment of the capillary with the stamp ensured that the printed pattern matched with an error of <5 μm along the “seam”, and a continuous, interconnected, patterned SAM resulted. The SAM acted as a resist against subsequent wet chemical etching of areas of derivatized silver using an aqueous ferricyanide solution. A brief, subsequent etch in 1% aqueous HF solution removed exposed areas of the titanium adhesion layer. Electrodepositing additional silver strengthened the patterned metal film. Dissolving the glass capillary in 49% aqueous HF solution released the free-standing, quasi-3D template. Crimping the cylinder along orthogonally oriented, perforated hinges using tweezers shaped the tetrahedral shells (as described in Figure 4b). The ends of the chain of tetrahedra were sutured together using a fine wire and welded by electrodeposition of an additional layer of silver over the entire structure.