SELF-ROLLING UP MICRO ASSEMBLY USING TEMPERATURE - RESPONSIVE HYDROGEL SHEET WITH RIGID PLATE ARRAY

Yoshitaka Iwata[1], Shuhei Miyashita[2], and Eiji Iwase[1*]*
[1]Department of Applied Mechanics, Waseda University, Tokyo, Japan
[2]Department of Electronic Engineering, University of York, York, United Kingdom

ABSTRACT

We propose a design method of a micro self-rolling up structure using a temperature-responsive hydrogel sheet with rigid plate array. Our self-rolling up is a method for developing a micro three-dimensional (3D) structure performed by rolling up a two-dimensional (2D) flat sheet, like making a croissant, through a continuous self-folding. The local curvature of the self-rolled up structure could be controlled by the length of rigid plates. By controlling the local curvature, we designed and developed self-rolled up structures with or without gaps between the self-rolled up layers, such as cylindrical and croissant-like ellipsoidal structures. In addition, all the structures demonstrated repetitive deformation of forward and backward rolling up by changing a temperature of water.

INTRODUCTION

In a fabrication method at a microscale, self-folding is an especially useful method to easily fabricate a small 3D structure from a 2D flat sheet [1-2]. In the previous works, a bilayer structure is usually used for developing self-folded structures. A difference of stress between two layers, such as shrinking and/or swelling of hydrogel [3], deposition of metal [2], etc., causes self-folding. These structures are, however, hard to change local curvature of the folding. Because the difference of stress has one stable state, it produces one stable local curvature. Controlling local curvature is useful for developing cylindrical structures. When self-folding is placed continuously in line, it can produce a cylindrical structure without or with gaps between the self-rolled up layers by controlling the local curvatures.

The objective of this research is to build a design method of local curvature for developing micro self-rolling up structures without or with gaps (Figure 1). Figure 1 shows the concept of the self-rolling up deformation. We used a hybrid hydrogel sheet consists of the temperature-responsive hydrogel sheet and the rigid plate array. Poly(N-isopropylacrylamide-co-acrylic acid) (pNIPAM-AAc) is used for the temperature-responsive hydrogel (dot patterned and blue region in Figure 1), and SU-8 is used for the rigid plate array (white region in Figure 1). The pNIPAM-AAc layer shrinks or swells by temperature, but the SU-8 plate does not. Using swelling or shrinking of pNIPAM-AAc layer, we can get self-rolling up deformation deformed to forward or backward directions. In this work, we evaluated self-folding deformation by local curvature. By controlling the curvature of self-folding continuously, we designed and fabricated self-rolling up structures without gaps (Figure 1(a)) or with gaps (Figure 1(b)). Our self-rolling up structures is used for soft robots or actuators. For example, it can be used for a medical patch [4] moving in the body and deploying at the targeted region. The self-rolling up method can make the medical patch smaller despite having a larger area.

PRINCIPLE AND FABRICATION PROCESS

Our self-rolling up deformation is generated using the continuous self-folding of the hybrid hydrogel sheet.

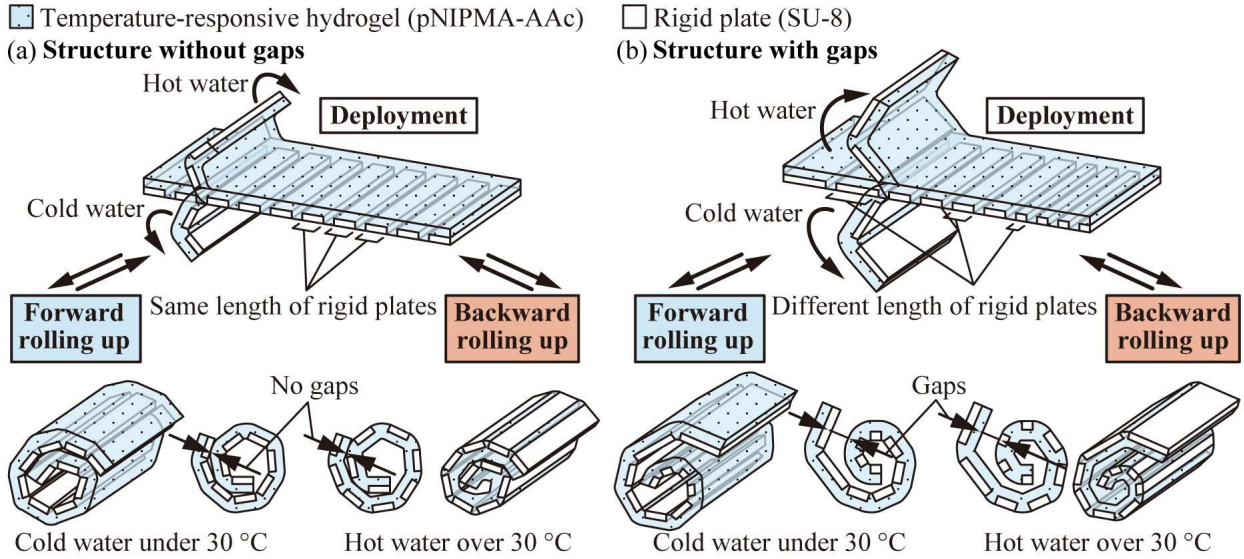

Figure 1: Concept of the self-rolling up deformation using a temperature-responsive hydrogel sheet with a rigid plate array. Deformation of temperature-responsive hydrogel develops forward rolling up in cold water and backward rolling up in hot water. (a) Self-rolled up structure without gaps. (b) Self-rolled up structure with gaps.

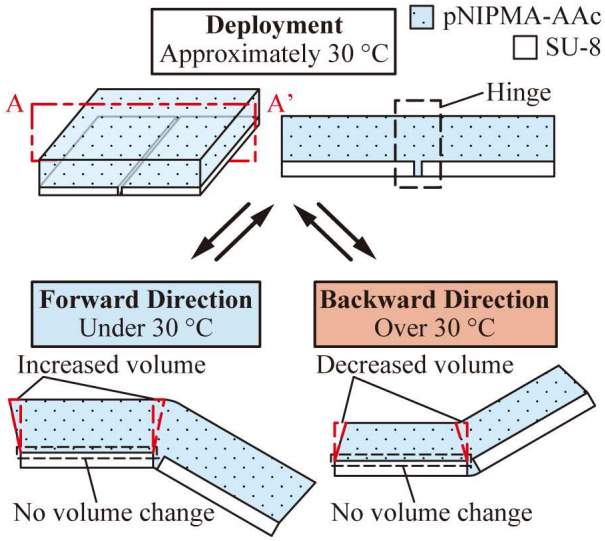

Figure 2: Principle of self-folding using hybrid hydrogel sheet. Swelling of pNIPAM-AAc layer in cold water produces forward rolling up, and shrinking of pNIPAM-AAc layer in hot water produces backward rolling up.

Figure 2 shows a general principle of the self-folding. The hybrid hydrogel sheet is composed of pNIPAM-AAc (dot patterned and blue region in Figure 2) and SU-8 (white region in Figure 2). pNIPAM-AAc is a stimuli-responsive hydrogel, and it has responsiveness to temperature and/or pH. SU-8 is an epoxy resin, and it does not have responsiveness to these stimuli. Basically, the self-folding occurs at hinges between rigid SU-8 plates. In a water under 30 °C, pNIPAM-AAc layer swells by absorbing water, and a volume of pNIPAM-AAc is increased at a top surface of the pNIPAM-AAc layer. However, at a bottom surface, a volume of pNIPAM-AAc does not change, because swelling of pNIPAM-AAc is prevented by SU-8. As a result, there is a difference of volume between the top and bottom surfaces, and self-folding to the forward direction is generated. On the other hand, in water over 30 °C, pNIPAM-AAc layer shrinks and a difference in volume changes between the top and bottom surfaces causes self-folding to the backward direction as well as swelling. In a water approximately 30 °C, pNIPAM-AAc layer causes neither swelling nor shrinking, and there is no self-folding with resulting in a deployed state. Therefore, our self-rolling up deformation is generated using the self-folding caused by swelling and shrinking of the pNIPAM-AAc layer.

Next, we fabricated the hybrid hydrogel sheet consisted of pNIPAM-AAc and SU-8. Before moving to the fabrication, we prepared and synthesized following materials. Poly(vinyl alcohol) (PVA, Mw 9,000-10,000, 80% hydrolyzed) (360627) was purchased from Sigma-Aldrich. SU-8 3025 and SU-8 primer (OmniCoat) were purchased from MicroChem. pNIPAM-AAc solution was synthesized by following a previously reported method [5]. Figure 3 shows the fabrication process of the hybrid hydrogel sheet. Details of the fabrication process for the hybrid hydrogel sheet is shown to our previous work [6]. PVA solution adjusted to 20 wt.% was spin-coated on 2 inch Si wafer and dried. In the same way,

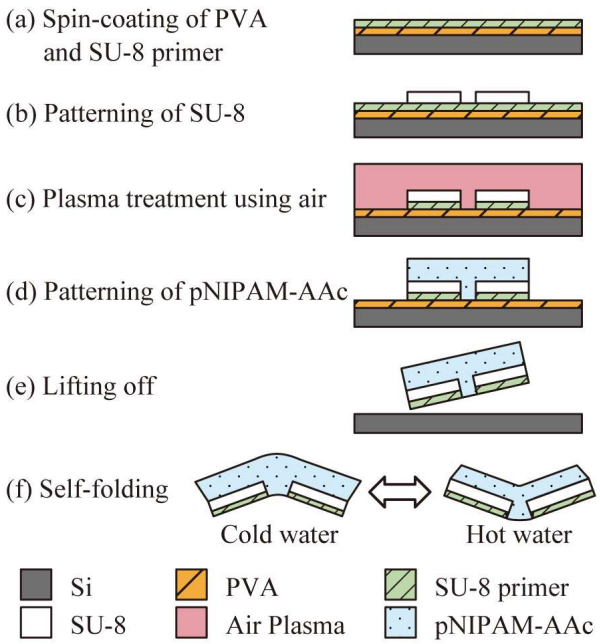

Figure 3: Fabrication process of the hybrid hydrogel sheet.

SU-8 primer was spin-coated on the PVA layer to improve an adhesion between PVA and SU-8 layer (Figure 3(a)). Then, SU-8 layer with 30 μm in thickness was patterned on SU-8 primer layer using photolithography (Figure 3(b)). After providing the layer, air plasma treatment was applied to the wafer (Figure 3(c)). The plasma treatment removed the residual SU-8 primer layer, and it improved an adhesion between SU-8 and pNIPAM-AAc layers. Next, we patterned a pNIPAM-AAc layer (Figure 3(d)). A UV light was exposed to pNIPAM-AAc solution through a dark field mask. pNIPAM-AAc layer was developed and rinsed using acetone and isopropyl alcohol (IPA), and the layer was approximately 95 μm in thickness. Finally, the wafer was put into hot water set to approximately 30 °C, and the hybrid hydrogel sheet was lifted off (Figure 3(e)). Swelling in cold water or shrinking in hot water of pNIPAM-AAc layer leaded to self-folding to forward or backward direction (Figure 3(f)).

EXPERIMENTS

We evaluated a basic characteristic on the local curvature of self-folding using the hybrid hydrogel sheet to realize the self-rolling up deformation, and to design self-rolling up structures. Figure 4 shows the basic characteristic of local curvature using the hybrid hydrogel sheets. The hybrid hydrogel sheets with different SU-8 lengths L [μm] (from 100 μm to 1000 μm) were put into 20 °C cold water and 40 °C hot water, respectively. Figure 4(a) shows actual images of self-folded hybrid hydrogel sheets with 300 μm, 600 μm, and 900 μm of SU-8 plates in length. Figure 4(b) shows the characteristic of local curvature produced by the hybrid hydrogel sheets with different SU-8 lengths. The vertical axis shows curvature 1/R [mm^{-1}], and the horizontal axis shows SU-8 length L [μm]. We measured folding angle θ [rad] from the actual images, such as Figure 4(a), using a microscope unit (VHS-2000 and VH-Z20W, KEYENCE), and calculated

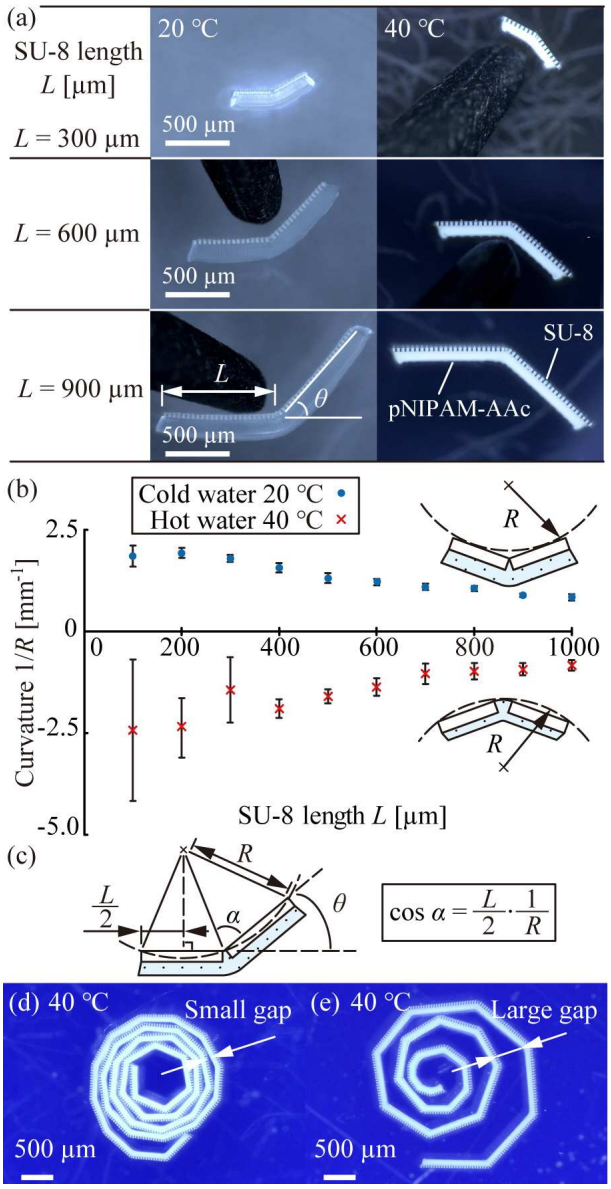

Figure 4: Basic characteristic of the self-folding using the hybrid hydrogel sheet. (a) Images of the fabricated hybrid hydrogel sheets, put into 20 °C and 40 °C water. (b) Characteristic of local curvature produced by different length of SU-8 plates (N=5). (c) Geometry for providing local curvature. (d) The structure with small gaps between each SU-8 plates, produced by same length of SU-8 plates. (e) The structure with large gaps between each SU-8 plates using various local curvatures, consisted of different length of SU-8 plates.

the local curvatures geometrically (Figure 4(c)) using below equation.

$$\frac{1}{R} = \frac{2}{L} \cdot \cos\left[(\pi - \theta) \cdot \frac{1}{2}\right] \qquad (1)$$

Figure 4(b) shows that curvature of the hybrid hydrogel sheet decreased gradually as the length of SU-8 became longer. It describes that controlling the self-folding curvature is possible by changing the length of SU-8 plate. Based on this result, we could design and develop not only a structure with small gaps between the rolled-up sheets (Figure 4(d)), but also a structure with large gaps (Figure

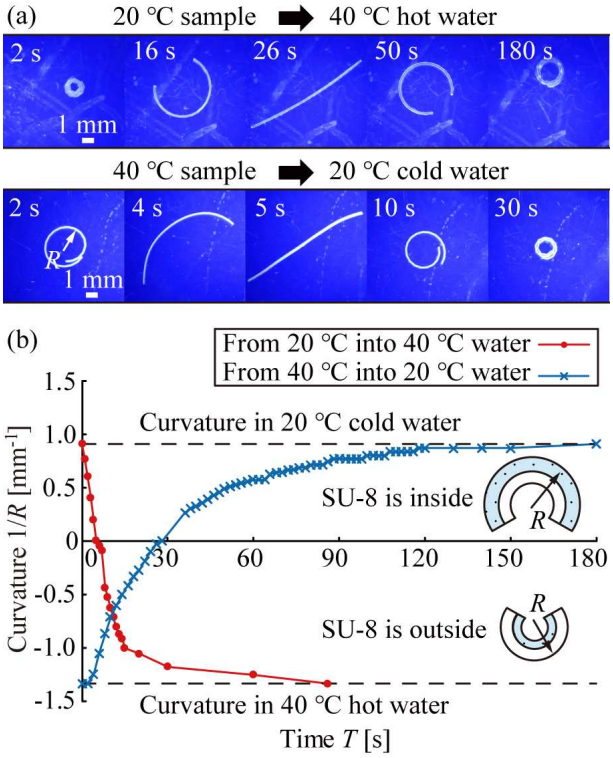

Figure 5: Time responses of the hybrid hydrogel sheet. (a) Images of procedure with self-rolling up and deployment in 20 °C and 40 °C water. (b) Time responses evaluated by curvature of the self-rolled up structure.

4(e)) by changing the local curvatures. The structure with small gaps developed using same local curvatures continuously. On the other hand, the structure with large gaps developed by combining different local curvatures.

In addition, time responses of the self-rolling were evaluated to confirm the repetitive deformation. As shown to figure 5(a), a cylindrical hybrid hydrogel sheet kept in 20 °C cold water was dipped into 40 °C hot water. Similarly, the sheet kept in 40 °C hot water was dipped into 20 °C cold water. Figure 5(b) shows the measurement result of self-rolling up curvature. The vertical axis shows curvature 1/R [mm^{-1}], and the horizontal axis shows time T [s]. In case of increasing water (shrinking hydrogel), the time response resulted in approximately 2 times faster than that when decreasing water (swelling hydrogel).

Finally, we demonstrated micro 3D structures using self-rolling up deformation. Figure 6(a) shows a cylindrical structure without gaps between the rolled-up sheet. A hybrid hydrogel sheet consisted of 100 SU-8 plates, with 200 μm in width and 3 mm in length having 15 μm interval of creases between each SU-8 plates, was developed. In 20 °C cold water, pNIPAM-AAc swelled and SU-8 layer existed in inside of the self-rolled up structure. Then, there was no gaps between layers with colliding the layers. On the other hand, in 40 °C hot water, pNIPAM-AAc shrank and SU-8 layer existed in outside of the self-rolled up structure. As well as cold water, there was no gaps in the structure. In addition, the cylindrical structure had small internal hollow region with 180 μm in diameter. This result shows it can produce small structure with large area, and could be used for the medical patch driving in a body. As shown in figure 6(b), our self-rolling

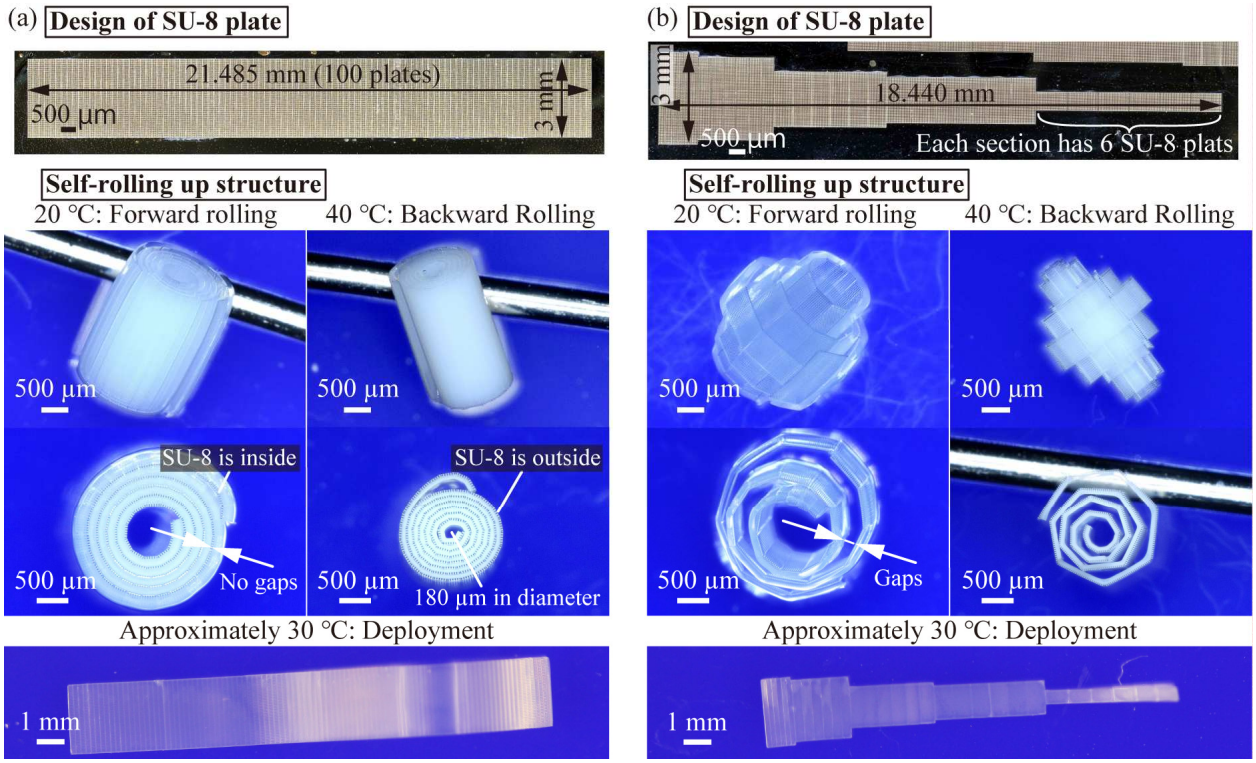

Figure 6: Designs and 3D structures fabricated using self-rolling up deformation. (a) Cylindrical structure without gaps between layers. (b) Croissant-like ellipsoidal structure with gaps between layers.

method could also produce a structure with gaps by controlling local curvatures. A croissant-like ellipsoidal structure was fabricated by changing the length and width of SU-8 plates stepwise. A hybrid hydrogel sheet consisted of 30 SU-8 plates, with different length of SU-8 plates (from 200 µm to 1000 µm by 200 µm stepwise), was developed. In both 20 °C cold and 40 °C hot water, we could see gaps between layers, because the local curvatures were controlled by changing the length of SU-8 plates.

CONCLUSIONS

We proposed the design method of local curvature using self-rolling up deformation with hybrid hydrogel sheet consisted of pNIPAM-AAc and SU-8. Characteristic of local curvature produced by self-folding was first evaluated. The result showed that designing the length of SU-8 plates made the local curvature controlled. Then, time responses of the self-rolling was evaluated, and the structure developed by shrinking of pNIPAM-AAc layer was approximately 2 times faster than swelling. Finally, cylindrical structure without gaps and croissant-like ellipsoidal structure with gaps were developed by controlling local curvatures, and showed repetitive deformation in 20 °C and 40 °C water. The self-rolling up deformation controlled by local curvature could be useful for soft robots or actuators.

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CONTACT

*Y. Iwata, +81-3-5286-2741, iwata5116@ruri.wasda.jp
E. Iwase, +81-3-5286-2741, iwase@waseda.jp