3D Printing System of Magnetic Anisotropy for Artificial Cilia

Seiji Azukizawa¹, Hayato Shinoda¹, Kazuki Tokumaru¹, and Fujio Tsumori²*

¹Department of Mechanical Engineering, Graduate School of Kyushu University, ²Department of Mechanical Engineering, Kyushu University, 744, Motooka, Nishi-ku, Fukuoka-city, 819-0395, Japan *tsumori@mech.kyushu-u.ac.jp

In this paper, we developed a new 3D-printing system for magnetic elastomer, and demonstrated to fabricate artificial cilia. Natural cilia are hair-like organ found in nature. They are effective fluidic system in the natural world that are widely observed on surfaces of microorganisms of creatures, such as Paramecium and throat surface of mammals. Recently, the motion of cilia has been analyzed and mimicked for developing soft actuator, for example, some studies on artificial cilia driven magnetically have been reported. They are small soft actuators, and there are various manufacturing methods for these actuators depending on materials and products. Among them, authors have already developed the concept of a printing system that not only forms a three-dimensional object but also prints out the deformation of the structure. This system can fabricate various shapes of soft actuators without any assembly. In this report, we utilized UV-curable urethane acrylate as a more flexible material than that used in the previous reports, and fabricated artificial cilia by the printer. We set magnetic anisotropy to each cilium and mimicked a metachronal wave, sequential action of plural cilia that causes effective flow.

Keywords: 3D-printing, 4D-printing, Magnetic anisotropy, Soft actuator, Artificial cilia

1. Introduction

In this paper, we demonstrated a new 3D-printing system using magnetic particles for artificial cilia. Natural cilia are known as an effective fluidic device, and the motion of cilia has been researched to realize bio-mimic soft actuators [1-16]. Several studies on artificial cilia driven magnetically have been reported [6-14].

Reported artificial cilia could be called small soft actuators. There are various methods of fabricating soft actuators depending on the structures [15,16]. Recently, additive manufacturing approach has been widely used for this area [17]. The 3D-printer has been used for not only industrial products but also personal uses. This process has advantages of manufacturing complicated objects in short time without any assembly. In addition, some innovative printers have been developing recently, which not only fabricate the form of a three-dimensional structure but also print out the deformation of the structure. S. Tibbits at Massachusetts Institute of Technology initially proposed this epoch-making concept for additive manufacturing in 2014 [18] and named “4D printing”. Several energy sources for manipulating soft actuators could be considered for the 4D-printer, such as pH, solvent, heat, electric field, magnetic field, light and swelling of materials. A research group in Harvard University developed a new type of printer for biomimetic structures that could output composite hydrogel architectures with using anisotropic swelling of materials [19]. It is noted that this research utilized anisotropy using dispersing nano-fibers in a polymer material. This anisotropy is essential to design and control the deformation after printing. However, the printing systems based on swelling have some disadvantages; the deformation speed of the structure is slow; the structure can only deform in water; and, the deformation is irreversible.

We focused on magnetic elastomer as a candidate
material for the 4D-printer. The magnetic elastomer is composed of polymer material dispersed with magnetic powder, which is a functional materials used for actuator, control of visco-elastic properties, and power generation [20-22]. We already proposed this new printing system [23,24]. Figure 1 shows a simple schematic of the proposed system. We used a UV-curable resin dispersed with magnetic particles. A magnetic field was applied to construct chain-like particle clusters in the structure. After curing, the chain clusters were fixed in the elastic medium that set magnetic anisotropy. These chain clusters will cause the rotational moment to be parallel to the magnetic flux line under an applied magnetic field [25]. Therefore, we can control overall deformation of a soft actuator by print this magnetic anisotropy in each portion of the printed structure. In this process, we use 3 design parameters \((x, y, z)\) in fabricating the shape of a structure and 2 more parameters \((\theta, \psi)\) in aligning magnetic chain clusters, so we use 5 design parameters \((x, y, z, \theta, \psi)\) at the same time, so that the system can be called “5D-printing”. In our last report, we proposed this new printing system and demonstrated using commercial UV resin as material [25]; however, the material was not enough flexible. Thus, in this report, we employed more flexible polymeric materials for a larger deformation of a printed structure.

In this paper, we demonstrated the present system for biomimetic field. The biomimicry is the most popular for the super-hydrophobic surface [26,27], and is also useful to develop soft actuators. The target of this work is the special movement of natural cilia, which is called a metachronal wave that is sequential action of plural cilia that causes effective flow [28-31]. The artificial cilia is expected for the micro pumping system for the μTAS (micro total analysis systems). The μTAS is a growing field, in which new features or devices are actively developing [32,33].

2. Materials and printing system

We employed UV-curable urethane acrylate for the experiment. Two materials, urethane acrylate monomer (UA-W2A, Shin-Nakamura Chemical Co., Ltd.) and 2-hydroxy-2-methylpropionic acid (Irgacure1173, BASF) as initiator, were mixed at a rate of 99:1. Carbonyl iron powders (median diameter: 4.36 μm) were dispersed as magnetic particles at a rate of 10 mass%. All materials were mixed by a planetary centrifugal mixer (Kakuhunter, Shashin Kagaku Co., Ltd.).

Figure 2 shows the flow of the present printing system, which was based on the conventional stereolithography. We utilized an ultraviolet laser system (CONQUEROR 355_2, Compact Laser Solutions) with a galvanometer scanner. The wavelength of the laser was 355 nm and the spot diameter was about 10 μm. In this study, we set laser power 5 mW, scanning speed 1 mm/s, and oscillation frequency 50 kHz. The prepared mixed material was poured into a pool. Surface of the printing stage was set in the pool at the depth of one layer. Next, a magnetic field was applied by the permanent magnet under the pool. The direction of the permanent magnet was set to obtain a proper magnetic field at the curing point. Then, UV laser scanned to cure the designed portion of the resin layer. The table went down by a layer-pitch, and the same procedure was repeated.

3. Experimental

3.1. Fabrication and actuation of single beam

In this section, simple beam structures were printed and actuated. We designed 3 beam structures with different magnetic anisotropies. The length of the beam was set to 3.0 mm. Magnetic field of 10 mT was applied for 180 s before printing to generate chain clusters of magnetic particles in the pool. After curing, the stage was taken out and the cured structure was rinsed by water. Subsequently, the sample was dried in an oven at 40 °C for \(1.8 \times 10^3\) s.

![Fig. 1. Schematic illustration of experimental flow; fabrication process and actuation.](image-url)
Figure 3 shows optical microscopy of printed samples with different orientation of chain clusters; parallel, in a 45 direction, and normal to the beam. Chain clusters, which were almost parallel to the applied magnetic field, were clearly observed in each sample. The beam width was about 200 μm, and the aspect ratio of the beam structure was about 15. The side edges of some samples became wavy, especially in the case of the chain clusters were normal to the beam. The chain clusters in the resin might disperse UV light, that would result non-flat cured surfaces.

The printed samples were set under an applied magnetic field of 90 mT for actuation. The magnetic direction was changed from -90° to 90°. Figure 4 shows an image of an actuated sample that had chain clusters parallel to the beam. Nine images were taken changing an applied magnetic field, and were superimposed into one image. The deformation angle of the beam was about from -60 to 60°. Note that the structure was enough flexible to use as an artificial cilium. Relationship between the deformations of the 3 kinds of beam and the applied magnetic field was summarized in Fig. 5. The horizontal displacement of the beam tip was shown. Three lines were almost similar, and shifted to horizontal direction by 0°, 45°, and 90°, respectively.

3.2. Artificial cilia with metachronal wave

Here, we demonstrate how the anisotropy works for the present 4D-printing system. It is necessary to deform each portion of a soft magnetic structure

Fig. 3. Optical microphotography of chain clusters. (a) parallel, (b) 45°, and (c) normal to the beam.
differently with various motion even in the same applied magnetic field. We showed bending behavior of 3 beams with different chain clusters in the previous section. It is clear that they deformed differently, for example, if the magnetic field was applied in the direction of 45°, one was not bent and the others were bent to opposite directions.

If we put the soft magnetic beam structure in a rotational magnetic field, it repeated sweeping motion like a natural cilium. The motion was asymmetric, and consisted of effective and recovery strokes as reported in the reference [7,10]. The phase of this repeated motion could be shifted by the orientation of the magnetic anisotropy. Next, we put several beams changing the orientation of the magnetic anisotropy by the position to propagate the

Fig. 4. Image of an actuated beam with chain clusters parallel to the beam. Numbers in the figure show the angle of the applied magnetic field. 9 photos are superimposed into one image.

Fig. 5. Relationship between angle of applied magnetic field and the tip displacement of the pillar.

Fig. 6. Deformation of 8-cilia array under a rotational magnetic field. Background color corresponds to the displacement of each cilium.
phase shift of the motion. This propagation is called a metachronal wave. It is observed in the nature, such as, on the surface of Paramecium and Tetrahymena. It is reported that the metachronal wave improves flow efficiency by the computational simulation [31].

We printed 8 beams with magnetic anisotropy as an example of one-dimensional array of the artificial cilia. Four orientations were set to each beam; parallel to the beam, -45°, normal, 45°, and were located periodically as schematically shown in the top of Fig. 6. The length of the beam was set to 3.0 mm, and the pitch was 2.0 mm. The fabrication conditions were the same as the previous section.

The obtained artificial cilia were located under magnetic field of 90 mT changing the magnetic direction rotationally. Figure 6 shows snapshots of the 8-cilia array under a rotational magnetic field. Background color corresponds to the displacement of each cilium; green shows deformation to the right, and red shows to the left. Each cilium repeated the deformation from left to right with a period of 180° as rotating the applied magnetic field. The difference of the phase of this cycle between 2 neighboring cilia was shifted by 45°, as the orientation of the magnetic anisotropy was set by 45° to the neighbor. Thus, the orange bands moved to right with rotation of the applied magnetic field as shown in Fig. 6; that means a metachronal wave was generated.

4. Conclusion

We proposed 3D-printing system with magnetic anisotropy, for developing a new 4D-printer. We choose more flexible UV-curable resin, which worked well for the present system. As a demonstration, we fabricated artificial cilia with magnetic anisotropies by the present printer. A designed metachronal wave of the cilia was successfully generated, that was an effective example of the present system. The present 4D-printing system could be a powerful tool to realize various bio-mimic soft actuators.

Acknowledgements

This work was supported by JSPS KAKENHI Grant Numbers JP15H01600 and 17K18830.

References
1. C. Eloy and E. Lauga, Phys. Rev. Lett., 109 (2012) 038101.
2. N. Osterman and A. Vilfan, Proc. Natl. Acad. Sci. USA, 108 (2011) 15727.
3. S. E. Spagnolie and E. Lauga, Phys. Fluids, 22 (2010) 031901.
4. S. Michelin and E. Lauga, Phys. Fluids, 22 (2010) 1119011.
5. E. M. Purcell, Proc. Biophysics, 94 (1997) 11307.
6. R. Marume, F. Tsumori, K. Kudo, T. Osada, and K. Shinagawa, Jpn. J. Appl. Phys., 56 (2017) 06GN15.
7. F. Tsumori, R. Marume, A. Saijou, K. Kudo, T. Osada, and H. Miura, Jpn. J. Appl. Phys., 55 (2016) 06GP19.
8. S. Hanasoge, M. Ballard, P. Hesketh, and A. Alexe, Lab Chip, 17 (2017) 3138.
9. Y. Wang, J. D. Toonder, R. Cardinaelsa, and P. Anderson, Lab Chip, 16 (2016) 2277.
10. F. Tsumori, A. Saijou, T. Osada, and H. Miura, Jpn. J. Appl. Phys., 54 (2015) 06FP12.
11. F. Tsumori, K. Hatama, H. Kang, T. Osada, and H. Miura, IEEE NEMS, (2013) 845.
12. K. Hatama, F. Tsumori, Yang Xu, H. Kang, T. Osada, and H. Miura, Jpn. J. Appl. Phys., 51 (2012) 06FL14.
13. S. Sareh, J. Rossiter, A. Conn, K. Drescher, and R.E. Goldstein, J. R. Soc. Interface, 10 (2012) 20120666.
14. F. Tsumori and J. Brunne, IEEE MEMS, (2011) 1245.
15. F. Tsumori, N. Miyano, and H. Kotera, J. Jpn. Soc. Powder Powder Met., 56 (2009) 133.
16. F. Tsumori, N. Miyano, and H. Kotera, J. Jpn. Soc. Powder Powder Met., 56 (2009) 127.
17. B. Gorissen, D. Reynaerts, S. Konishi, K. Yoshida, J. W. Kim, and M. De Volder, Adv. Mater., 29 (2017)1604977.
18. K. J. Cho, J. S. Koh, S. Kim, W. S. Chu, Y. Hong, and S. H. Ahn, Int. J. Precis. Eng. Manuf., 10 (2009) 171.
19. A. Zolfagharian, A. Z. Kouzani, S. Y. Khoo, A. A. Moghadam, I. Gibson, and A. Kaynak, Sens. Actuat. A: Phys., 250 (2016) 258.
20. S. Tibbits, Archit. Des, 84 (2014) 116.
21. A. S. Gladman, E. A. Matsumoto, R. G. Nuzzo, L. Mahadevan, and J. Lewis, Nat. Mater., 15 (2016) 413.
22. H. Shinoda and F. Tsumori, Jpn. J. Appl. Phys., in press.
23. D. Maede, F. Tsumori, T. Osada, and K. Kudo, IEEJ Trans. Sens. Micromach., 138 (2018) 48.
24. F. Tsumori, S. Echikawa, Y. Hiraibayashi, T. Nakatsuji, T. Osada, and H. Miura, Jpn. J. Appl. Phys., 61 (2014) 193.
25. S. Azukizawa, F. Tsumori, H. Shinoda, K.
Tokumaru, K. Kudo, and K. Shinagawa, *Micro TAS*, (2017) 623.
26. F. Tsumori, H. Kawanishi, K. Kudo, T. Osada, and H. Miura, *Jpn. J. Appl. Phys.*, 55 (2016) 06GP18.
27. J. Kim, S. E. Chung, S. E. Choi, H. Lee, J. Kim, and S. Kwon, *Nat. Mater.*, 10 (2011) 747.
28. F. Tsumori, L. Shen, T. Osada, and H. Miura, *Manufact. Rev.*, 2 (2015) 10.
29. Z. Guo and W. Liu, *Plant Sci.*, 172 (2007) 1103.
30. S. Zhang, Y. Wang, R. Lavrijsen, P. Onck, and J. D. Toonder, *Sens. Actuat. B: Chem.*, 263 (2018) 614.
31. J. Elgeti and G. Gompper, *Proc. Natl. Acad. Sci. USA*, 110 (2013) 4470.
32. F. Tsumori, S. Hunt, K. Kudo, T. Osada, and H. Miura, *J. Jpn. Soc. Powder Powder Met.*, 63 (2016) 511.
33. F. Tsumori, S. Hunt, T. Osada, and H. Miura, *Jpn. J. Appl. Phys.*, 54 (2015) 06FM03.