Proceedings of the 2022 IEEE
International Conference on Robotics and Biomimetics
December 5-9, 2022, Xishuangbanna, China

Thermal Casting for Monolithic Soft Actuators

Huacen Wang, Boyu Yang, Junling Mei, Yujin Dai, Yixuan Xia and Hongqiang Wang*

Abstract—**Soft robotics has significantly impacted many fields in the last decades. However, their current fabrication methodologies are limited by the assemble complexity, limited materials, or long duration. A monolithic thermal casting method for fabrication of elastomer and soft robotics based on thermoset polymer is introduced. In this work, we used simple heating cores to manufacture elastomers and soft actuators. By controlling the heating current and duration, we can adjust the thermal field and consequently change the configuration of the generated elastomer. Due to its short duration (several minutes), this method can benefit the mass production of soft robots for high efficiency. Also, this work offers a new way to design soft robotics without complex molds.**

I. Introduction

Soft robotics are attracting increasing interest from researchers and developers due to their outstanding advantages, such as being safe, compliant, lightweight, and highly adaptive [1]-[3]. According to these features, they have been extensively studied in the last decades for the applications such as human-machine interaction [2][4], gripping of fragile objects [5]-[7], and inspection in a narrow space [8]-[11]. Although the soft actuators can depend on different principles [12]-[15], the fluid driven (pneumatic or hydraulic) soft actuator made from low Young's modulus materials (mainly silicone) are still dominant in this field, in which the pressure deforms the material to the desired shape to generate elongation, shrinkage, and bending [1][16][17].

Nevertheless, the fabrication of fluid driven soft actuators are still challenging in various aspects. Current most extensively applied fabrication method is mold casting [16][18][19]. This method usually generates the actuators by two halves and glues the two parts together finally, between which the low-strength of the bonding interface always causes an undesired burst on the actuators under a pressure lower than the expectation [20][21]. 3D printing is another common fabrication method [22]-[24], which can fabricate complex structures, but it possesses only a few materials (i.e., thermoplastic polymers) for printing, while the main materials for soft actuators are thermosetting materials (e.g., silicone). Considering the limitations of these fabrication methods, in the last decades, many researchers devoted themselves into developing novel solutions, including dip coating [25][26], bubble casting [27] and injection molding [28]. However, these methodologies are limited by long duration, complex principles, and extra components. More controllable and simple efficient fabrication methods for monolithic actuators are still highly desired in this field.

Fig. 1. The monolithic soft actuator made by the thermal casting method proposed in this work.

Here we introduce a novel method to generate the desired shape of soft actuators by regulating the temperature distribution in the space. In this method, we immerse the heating wires into the silicone precursor, and the silicone near the wires are cured since the polymerization highly depends on the temperature. By arranging the heating wires on purpose, we can control the generated soft actuator shape by the temperature field. This method has various advantages compared with previous methods. First, we use the thermal field to replace the laborious molds, which means we just need to change the configuration of the heating wires. Then the thickness of the silicone could be controlled by heating current and time. Moreover, the elastomer fabricated from thermal casting is monolithic, which makes fewer weak spots. The whole process of thermal casting is non-toxic and the materials used are eco-friendly.

The contributions of this work are as follows. We presented a novel methodology by tuning the thermal field by the heating wires' topology and preliminarily analyzed the model to explain the generation mechanism of the soft actuator. With this technology, we fabricated a monolithic pneumatic soft actuator (Fig. 1) by heating in only 5 minutes with wires, it

This work was supported in part by the National Natural Science Foundation of China under Grant 52275021, in part by the Natural Science Foundation of Guangdong Province of China under Grant 2020A1515010955, in part by the Science, Technology and Innovation Commission of Shenzhen Municipality under Grant ZDSYS20200811143601004, in part by the Natural Science Foundation of Liaoning Province of China (State Key Laboratory of Robotics joint funding, under Grant 2021-KF-22-11), and in part by Southern Marine Science and Engineering Guangdong Laboratory (Guangzhou), under Grant K19313901. (Corresponding author: Hongqiang Wang.)

Huacen Wang, Boyu Yang, Junling Mei, Yujin Dai and Yixuan Xia are with the Shenzhen Key Laboratory of Biomimetic Robotics and Intelligent Systems, Department of Mechanical and Energy Engineering, Southern University of Science and Technology, Shenzhen 518055, China (e-mail: 12132296@mail.sustech.edu.cn, 11913021@mail.sustech.edu.cn, 11910433@mail.sustech.edu.cn, 11910114@mail.sustech.edu.cn, 11910528@mail.sustech.edu.cn).

Hongqiang Wang is with the Shenzhen Key Laboratory of Biomimetic Robotics and Intelligent Systems, Department of Mechanical and Energy Engineering and Guangdong Provincial Key Laboratory of Human-Augmentation and Rehabilitation Robotics in Universities, Southern University of Science and Technology, Shenzhen 518055, China, and also with the Southern Marine Science and Engineering Guangdong Laboratory (Guangzhou), Guangzhou 510000, China (e-mail: wanghq@sustech.edu.cn).

2022 IEEE International Conference on Robotics and Biomimetics (ROBIO) | 978-1-6654-8109-0/22/$31.00 ©2022 IEEE | DOI: 10.1109/ROBIO55434.2022.10011742

could elongate about 10 mm and rotate axially about 10 degrees.

In the next section, the principle and model of thermal casting are described that show the thermal field distribution with electric heating. Section III describes the elastomer fabrication method and illustrates the details of the process. The results of thermal casting with different currents and time are demonstrated in Section IV, a monolithic linear soft actuator also demonstrated in this section.

II. Principle and Modeling

A. Principle

Most of the soft actuators are made from silicone due to their high stretch ratio [29]. The solid silicone is typically generated by mixing two parts and then thermally curing [30]. During the polymerization, the silicone precursor solidified exothermally by cross-linking curing reaction without generating by-products, and the synthesis process strongly depends on the temperature [31]. Thus, here we decide to control the distribution of the thermal field to generate the desired shape of the soft actuator.

Due to the thermal dissipation principle [32], the temperature drops drastically with respect to the heating source (as shown in Fig. 2a). Since the curing time of the silicone precursor at a higher temperature is less than that at a lower temperature, the silicone precursor close to the heating source becomes polymer in advance. Thus, for an electrically powered straight metal filament immersed in the precursor, a cylinder shape of silicone is generated after the heating. For different durations, the diameter of the cylinder varies.

The shape of the generated silicone can be further changed by tuning the thermal field, which is implemented by arranging the heating wires. Here, for example, if we immerse a spiral metal filament in the precursor, a hollow silicone cylinder will be generated (Fig. 2b) and the details are explained in the next part.

B. Modelling

To understand the phenomenon, first, we build an analytical model for the simplest situation with only one straight heating wire in the precursor. The heating wire could be considered as a constant heating source with the cylinder shape. Derived from the Fourier-Biot equation, the rate at which energy is generated per unit volume of the heating wire could be expressed as,

$$q_V = \frac{Q}{V}, \tag{1}$$

where Q is the heat energy generated from the supplied current, V is the volume of the heating wire, according to Joule's law,

$$Q = I^2 R, \tag{2}$$

where I is the constant current flowing through the heating wire, R is the resistance of the heating wire. The form could be expressed as the cylindrical heat equation,

$$\frac{1}{r}\frac{d}{dr}\left(r\frac{dT}{dr}\right) + \frac{q_V}{k} = 0, \tag{3}$$

where k is the liquid silicone rubber conductivity, then the model could be solved into a one-dimensional problem, and the temperature could be expressed as a function of radius,

$$r\frac{dT}{dr} = -\frac{q_V}{2k}r^2 + C_1, \tag{4}$$

$$T(r) = -\frac{q_V}{4k}r^2 + C_1 \ln r + C_2, \tag{5}$$

where C_1 and C_2 are the constants of integration.

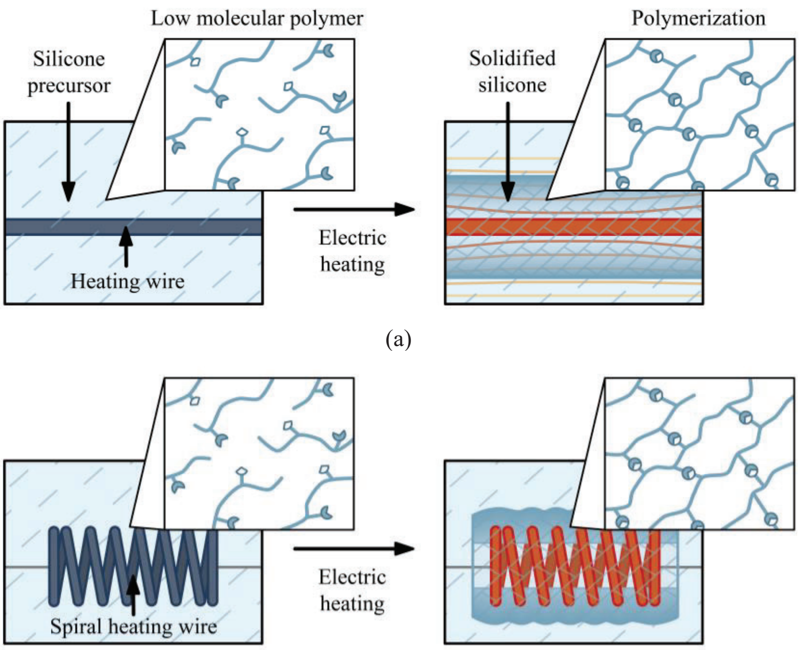


Fig. 2. The principle of thermal casting for a silicone cylinder using a straight heating wire (a) and for a hollow cylinder with a spiral wire (b), respectively.

The above analytical model can only explain the thermal distribution with a simple straight wire. For more complex cases, the thermal distribution in the precursor pool can be analyzed by FEA (finite element analysis) models. We used COMSOL (Multiphysics 5.6) to build the models. In the simulation, we built the heating wire (radius 0.3 mm, Ni-Cr alloy wire with 80% nickel and 20% chromium by mass, length 30 mm) and powered the heating wire with the current of 0.5 A. The heating wire was immersed in a regular box full of silicone precursor. About the Ni-Cr alloy heating wire, we set the thermal conductivity as $15\ \mathrm{W/(m \cdot k)}$, density as $8400\ \mathrm{kg/m^3}$ and resistivity as $0.00000109\ \Omega \cdot \mathrm{m}$. We considered the silicone precursor as solid with heat capacity at constant pressure as $1280\ \mathrm{J/(kg \cdot K)}$, density as $1900\ \mathrm{kg/m^3}$ and relative permittivity as 3.9.

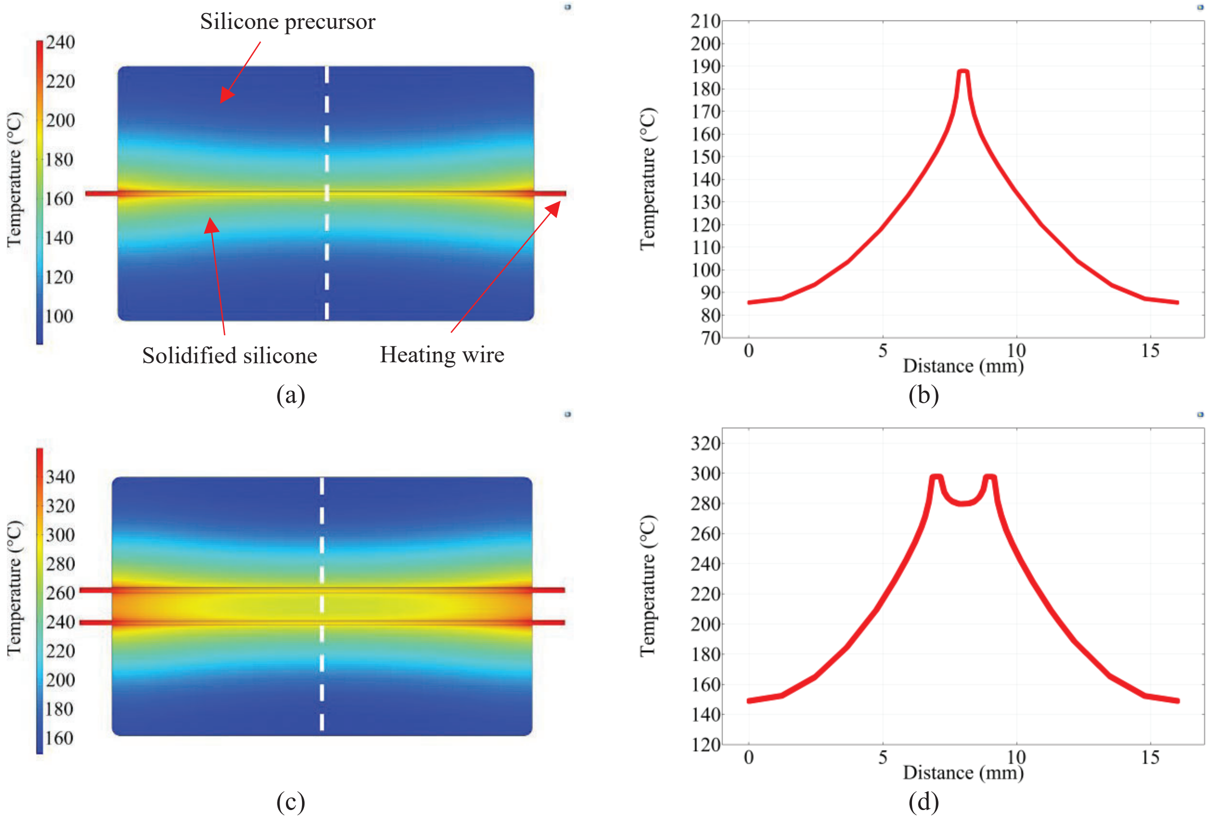


Fig. 3. The thermal analysis based on the FEA models. The thermal field for the precursor with a single heating wire (a) and two parallel wires (c), respectively. The temperature in the precursor at different positions on the dashed line using one wire (b) and two wires (d), respectively.

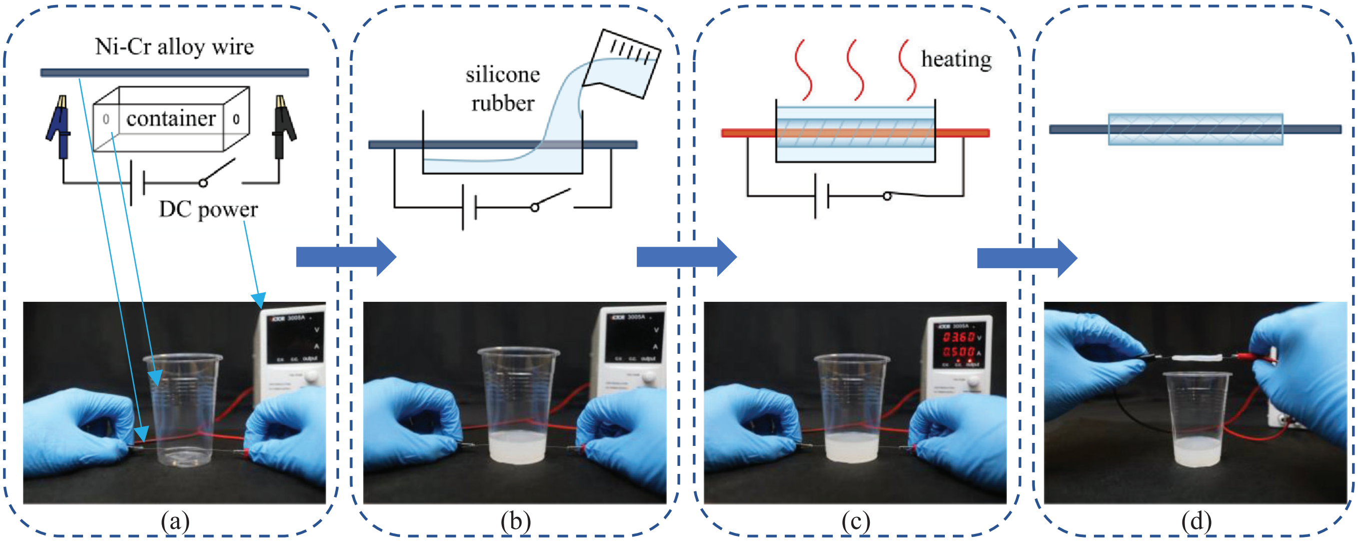


Fig. 4. The fabrication process of the elastomer cylinder. (a) Thread the heating wire through the cup and connect the wire to the DC supplier. (b) Pour over the silicone precursor. (c) The heating process. (d) The consequent elastomer.

Fig. 3a shows the temperature distribution of the precursor after 5 minutes. The temperature exponentially decreases if the distance is larger to the center of the heating wire. Thus the silicone is generated on the wire. Fig. 3c shows that if there are two parallel heating wires, the gap between them is heated by both the two wires and keeps its temperature at a high level. Thus the silicone is generated on the wires and between the wires.

III. Fabrication

As shown in Fig. 4a, we created the cylinder elastomer with a heating wire made from Ni-Cr alloy (diameter: 0.3 mm, length: 50 mm, resistance: 3 Ω), because of its high resistivity, which would produce large heat energy under relative low current based on Eq. (2). First, we inserted the heating wire in a plastic cup (two holes on the wall) (Fig. 4a). Then we poured the silicone precursor (Ecoflex 00-30) into the cup (Fig. 4b) and mixed it. The wire was then powered by a DC supplier (Victor 3005A) for several minutes.

To generate more complex shapes, we made the heating wire at the desired shape and then powered the wire. For example, to achieve a hollow cylinder for a soft actuator, we first bent the wire (diameter: 0.5 mm, material: stainless steel) into a spiral shape (diameter: 15 mm, pitch: 4 mm, length: 50 mm) as shown in Fig. 4a. After powering this spiral wire (1.6 Ω) for 1.5 minute under the current of 2.5 A, a hollow cylinder was generated, and then we picked out the heating wire and drained the precursor from the actuator (Fig. 5c). Then we cured the ends of the actuator in turn (Fig. 5d and Fig. 5e), and a monolithic soft actuator with chamber was manufactured.

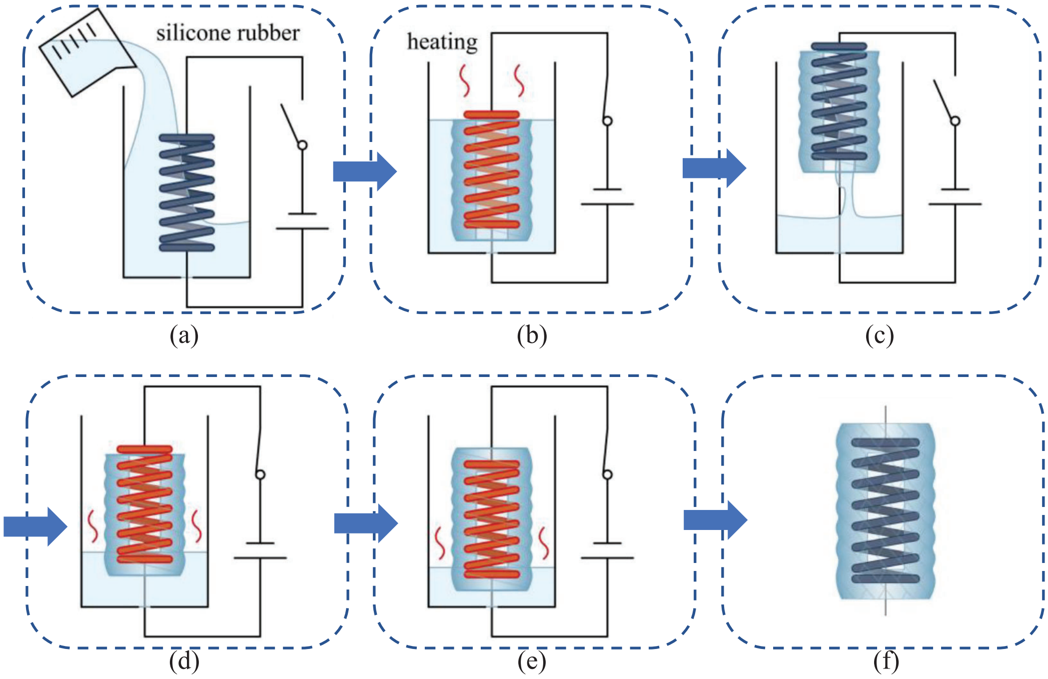


Fig. 5. The flow chart of the process in the fabrication of a soft actuator by thermal casting. (a) Pour the precursor into the container and immerse the wire in the precursor. (b) Heat the wire. (c) Leak redundant silicone. (d) Heat one end of the actuator. (e) Heat the other end of the actuator. (f) The finished product.

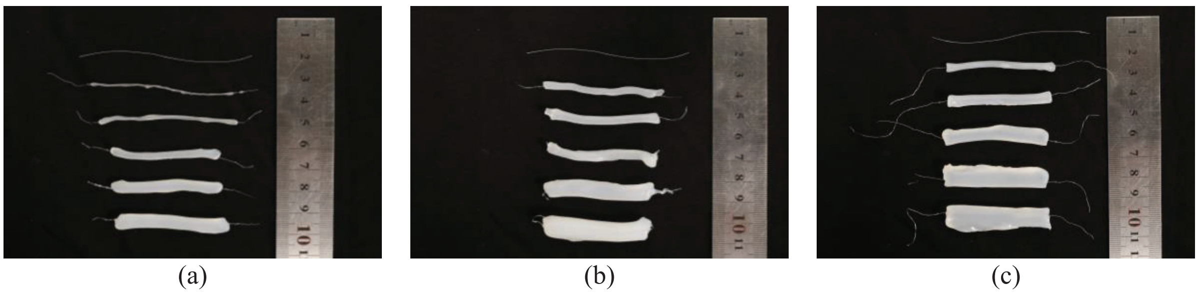


Fig. 6. The elastomers made by thermal casting with a straight heating wire. The heating current is (a) 0.5 A, (b) 0.6 A (c) 0.7 A, respectively. From the top to the bottom in each subfigure, the heating duration is 2, 3, 4, 5, and 6 minutes, respectively.

IV. Experiment

A. characterization of the silicone generated on a single heating wire

To verify the fabrication process, we immersed straight wires made from Ni-Cr alloy into the precursor pool. The wires were powered by the current of 0.5 A, 0.6 A, and 0.7 A, respectively, for the duration rating from 2 to 7 minutes. The resultant elastomer cylinders made by this method are shown in Fig. 6, and the corresponding diameter data is shown in Fig. 7. The diameter of the silicone generated from this process becomes higher when the current becomes larger and grows almost linearly with the heating duration. Therefore, we can adjust the consequent thickness of the silicone by controlling either the current or the heating duration.

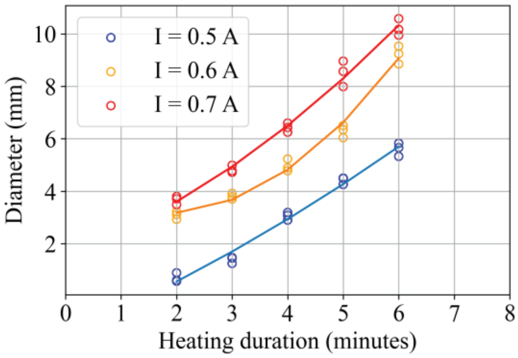


Fig. 7. The diameter of elastomer cylinders with different heating currents and heating duration

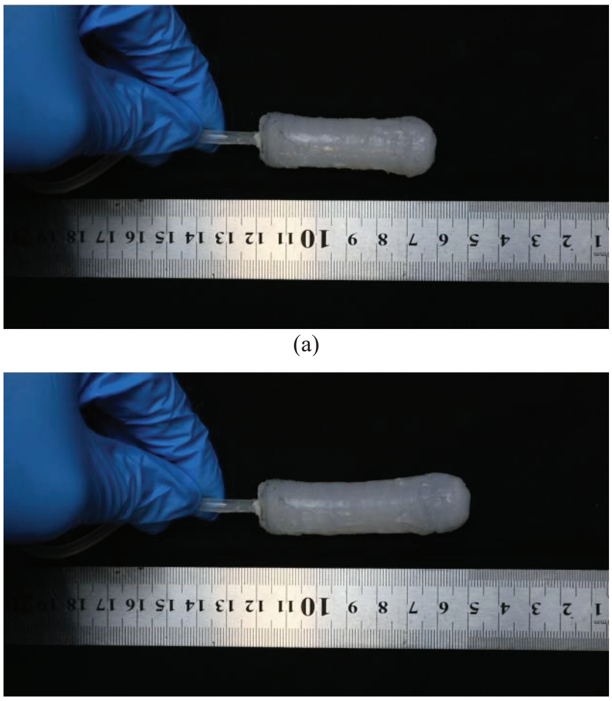
B. Monolithic pneumatic actuator

After fabricating the soft actuator with the method explained in Section III, we inserted a tube to connect the actuator to an air pump. The actuator had a spiral spring as embedded constraint, which resulted in a motion that combines extension and twisting [19]. Inflated by pressured air, the actuator elongated for about 10 mm and rotated axially for about 10 degrees, as shown in Fig. 8. This was because the spiral wire was working as a constrained layer. This layer limited the radial inflation and the rotation against the spiral direction but allowed the elongation and rotation along the spiral direction.

V. Conclusion

In this work, by controlling the configuration of heating wires, electrical current, and the heating duration, we fabricated soft robotics in several minutes. As verified by the FEA models, the temperature decreases exponentially when the distance increases, and the temperature between two wires can keep at a high temperature. Since both temperature and time benefit the polymerization of the precursor, we demonstrated that we generated different thicknesses of silicone by modulating the heating current and duration. Finally, with a spiral wire, we created a soft actuator within 5 minutes and displayed its operation by pressured air.

In the future, we could use metal 3D printing to fabricate more configurations of heaters to realize more soft robotics based on thermal casting.



(a)

(b)

Fig. 8. The demonstration of the monolithic soft actuator. The actuator before (a) and after (b) the inflation.

References

[1] G. M. Whitesides, “Soft Robotics,” Angewandte Chemie, vol. 130, no. 16, pp. 4336–4353, Apr. 2018, doi: 10.1002/ange.201800907.

[2] H. Zhao, J. Jalving, R. Huang, R. Knepper, A. Ruina, and R. Shepherd, “A helping hand: Soft orthosis with integrated optical strain sensors and EMG control,” IEEE Robotics and Automation Magazine, vol. 23, no. 3, pp. 55–64, 2016, doi: 10.1109/MRA.2016.2582216.

[3] H. Wang et al., “Biologically inspired electrostatic artificial muscles for insect-sized robots,” International Journal of Robotics Research, vol. 40, no. 6–7, pp. 895–922, Jun. 2021, doi: 10.1177/02783649211002545.

[4] P. Polygerinos, Z. Wang, K. C. Galloway, R. J. Wood, and C. J. Walsh, “Soft robotic glove for combined assistance and at-home rehabilitation,” in Robotics and Autonomous Systems, Nov. 2015, vol. 73, pp. 135–143. doi: 10.1016/j.robot.2014.08.014.

[5] D. Li et al., “A Soft Gripper Driven by Bellow Actuators and Twist Actuators for Dexterous Grasping,” in 2021 IEEE International Conference on Robotics and Biomimetics, ROBIO 2021, 2021, pp. 962–967. doi: 10.1109/ROBIO54168.2021.9739548.

[6] F. Ilievski, A. D. Mazzeo, R. F. Shepherd, X. Chen, and G. M. Whitesides, “Soft Robotics for Chemists,” Angewandte Chemie, vol. 123, no. 8, pp. 1930–1935, Feb. 2011, doi: 10.1002/ange.201006464.

[7] J. Zhou, S. Chen, and Z. Wang, “A Soft-Robotic Gripper with Enhanced Object Adaptation and Grasping Reliability,” IEEE Robotics and Automation Letters, vol. 2, no. 4, pp. 2287–2293, 2017, doi: 10.1109/LRA.2017.2716445.

[8] Y. Fu, H. Wang, Y. Zi, and X. Liang, “A multifunctional robotic system toward moveable sensing and energy harvesting,” Nano Energy, vol. 89, Nov. 2021, doi: 10.1016/j.nanoen.2021.106368.

[9] T. Jin et al., “Origami-Inspired Soft Actuators for Stimulus Perception and Crawling Robot Applications; Origami-Inspired Soft Actuators for Stimulus Perception and Crawling Robot Applications,” IEEE Transactions on Robotics, vol. 38, no. 2, 2022, doi: 10.1109/TRO.2021.

[10] R. F. Shepherd et al., “Multigait soft robot”, doi: 10.1073/pnas.1116564108/-/DCSupplemental.

[11] H. Wang, A. Yamamoto, and T. Higuchi, “A crawler climbing robot integrating electroadhesion and electrostatic actuation,” International

Journal of Advanced Robotic Systems, vol. 11, pp. 1–11, 2014, doi: 10.5772/59118.
[12] W. Wang, D. Fan, R. Zhu, P. Wang, Y. Zhao, and H. Wang, “Modeling and Optimization of Electrostatic Film Actuators Based on the Method of Moments,” Soft Robotics, vol. 8, no. 6, pp. 651–661, 2021, doi: 10.1089/soro.2020.0099.
[13] G. Li et al., “Self-powered soft robot in the Mariana Trench,” Nature, vol. 591, no. 7848, pp. 66–71, 2021, doi: 10.1038/s41586-020-03153-z.
[14] H. Na, Y.-W. Kang, C. Seo Park, S. Jung, H.-Y. Kim, and J.-Y. Sun, “Hydrogel-based strong and fast actuators by electroosmotic turgor pressure.” [Online]. Available: https://www.science.org
[15] Y. Chen et al., “Controlled flight of a microrobot powered by soft artificial muscles,” Nature, vol. 575, no. 7782, pp. 324–329, Nov. 2019, doi: 10.1038/s41586-019-1737-7.
[16] A. D. Marchese, R. K. Katzschmann, and D. Rus, “A recipe for soft fluidic elastomer robots,” Soft Robotics, vol. 2, no. 1, pp. 7–25, Mar. 2015, doi: 10.1089/soro.2014.0022.
[17] C. de Pascali, G. Adele Naselli, S. Palagi, R. B. N Scharff, and B. Mazzolai, “3D-printed biomimetic artificial muscles using soft actuators that contract and elongate,” 2022. [Online]. Available: https://www.science.org
[18] D. Fan et al., “Self-shrinking soft demoulding for complex high-aspect-ratio microchannels,” Nat Commun, vol. 13, no. 1, Dec. 2022, doi: 10.1038/s41467-022-32859-z.
[19] R. v. Martinez, C. R. Fish, X. Chen, and G. M. Whitesides, “Elastomeric origami: Programmable paper-elastomer composites as pneumatic actuators,” Advanced Functional Materials, vol. 22, no. 7, pp. 1376–1384, Apr. 2012, doi: 10.1002/adfm.201102978.
[20] B. Mosadegh et al., “Pneumatic networks for soft robotics that actuate rapidly,” Advanced Functional Materials, vol. 24, no. 15, pp. 2163–2170, Apr. 2014, doi: 10.1002/adfm.201303288.
[21] M. A. Bell et al., “Echinoderm-Inspired Tube Feet for Robust Robot Locomotion and Adhesion,” IEEE Robotics and Automation Letters, vol. 3, no. 3, pp. 2222–2228, Jul. 2018, doi: 10.1109/LRA.2018.2810949.
[22] H. K. Yap, “High-Force Soft Printable Pneumatics for Soft,” vol. 3, no. 3, pp. 144–158, 2016, doi: 10.1089/soro.2016.0030.
[23] M. A. Skylar-Scott, J. Mueller, C. W. Visser, and J. A. Lewis, “Voxelated soft matter via multimaterial multinozzle 3D printing,” Nature, vol. 575, no. 7782, pp. 330–335, Nov. 2019, doi: 10.1038/s41586-019-1736-8.
[24] Bartlett, Nicholas W., et al. "A 3D-printed, functionally graded soft robot powered by combustion." Science 349.6244 (2015): 161-165.
[25] K. P. Becker, Y. Chen, and R. J. Wood, “Mechanically Programmable Dip Molding of High Aspect Ratio Soft Actuator Arrays,” Advanced Functional Materials, vol. 30, no. 12, pp. 1–11, 2020, doi: 10.1002/adfm.201908919.
[26] W. Xi et al., “Soft tubular microfluidics for 2D and 3D applications,” Proc Natl Acad Sci U S A, vol. 114, no. 40, pp. 10590–10595, Oct. 2017, doi: 10.1073/pnas.1712195114.
[27] T. J. Jones, E. Jambon-Puillet, J. Marthelot, and P.-T. Brun, “Bubble casting soft robotics,” Nature, vol. 599, no. 7884, pp. 229–233, 2021, doi: 10.1038/s41586-021-04029-6.
[28] M. A. Bell, K. P. Becker, and R. J. Wood, “Injection Molding of Soft Robots,” Advanced Materials Technologies, vol. 2100605, p. 2100605, 2021, doi: 10.1002/admt.202100605.
[29] M. S. Xavier et al., “Soft Pneumatic Actuators: A Review of Design, Fabrication, Modeling, Sensing, Control and Applications,” IEEE Access, vol. 10, pp. 59442–59485, Jun. 2022, doi: 10.1109/access.2022.3179589.
[30] S. C. Shit and P. Shah, “A review on silicone rubber,” National Academy Science Letters, vol. 36, no. 4. pp. 355–365, Aug. 2013. doi: 10.1007/s40009-013-0150-2.
[31] I. K. Hong and S. Lee, “Cure kinetics and modeling the reaction of silicone rubber,” Journal of Industrial and Engineering Chemistry, vol. 19, no. 1, pp. 42–47, Jan. 2013, doi: 10.1016/j.jiec.2012.05.006.
[32] C. Kittel, H. Kroemer, and H. L. Scott, “Thermal Physics, 2nd ed.,” American Journal of Physics, vol. 66, no. 2, pp. 164–167, Feb. 1998, doi: 10.1119/1.19072