

Pneumatic artificial rubber muscle using shape-memory polymer sheet with embedded electrical heating wire

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Received 10 June 2014, revised 27 August 2014

Accepted for publication 16 September 2014

Published 16 October 2014

Abstract

Shape-memory polymer (SMP) can be deformed by applying a small load above its glass transition temperature (T_g). Shape-memory polymer maintains its shape after it has cooled below T_g and returns to a predefined shape when subsequently heated above T_g . The reversible change in the elastic modulus between the glassy and rubbery states of an SMP can be on the order of several hundred times. Based on the change in stiffness of the SMP in relation to the change in temperature, the present study attempts to evaluate the application of the SMP to soft actuators of a robot. In order to control the temperature of the SMP, we developed an SMP sheet with an embedded electrical heating wire. We formed a uniform, thin SMP sheet without air bubbles using a heat press. The SMP sheet with a heating wire can be heated quickly and can be maintained at a constant temperature. Moreover, the effects of the embedded wire on the mechanical properties in bending and tensile tests were small. Then, we applied the SMP sheet with the embedded electrical heating wire to a pneumatic artificial rubber muscle. The enhanced versatility of SMP sheet applications is demonstrated through a series of experiments conducted using a prototype. The initial shape and bending displacement of the pneumatic artificial rubber muscle can be changed by controlling the temperature of the SMP sheet.

Keywords: shape-memory polymer, pneumatic rubber muscle, shape fixity, Joule heat, shape recovery, glass transition temperature

(Some figures may appear in colour only in the online journal)

1. Introduction

In rapidly aging societies, several power-assist suits and power-assist apparatuses have been proposed as wearable robots for caregivers and rehabilitation systems [1, 2]. Many of these applications require soft actuators [1–3] rather than conventional actuators (e.g., electric motors). Soft actuators are lightweight and flexible and offer back-drivability. The characteristics of soft actuators, which ensure safety by minimizing the possibility of injury to the human body, make them an attractive choice for use in such applications.

Furthermore, soft actuators are also used in a variety of applications ranging from medical actuators in the human body to biomimetic robots [2, 3]. In the present study, we exploit the inherent advantageous properties of shape-memory polymers (SMPs) [4–15] for use in soft actuators.

As shown in figure 1, SMPs are often described as two-phase structures, comprising a lower-temperature ‘glassy’ hard phase and a higher-temperature ‘rubbery’ soft phase. The reversible change in the elastic modulus between the glassy and rubbery states of SMPs can be as high as several hundred times. Shape-memory polymers can be deformed above their

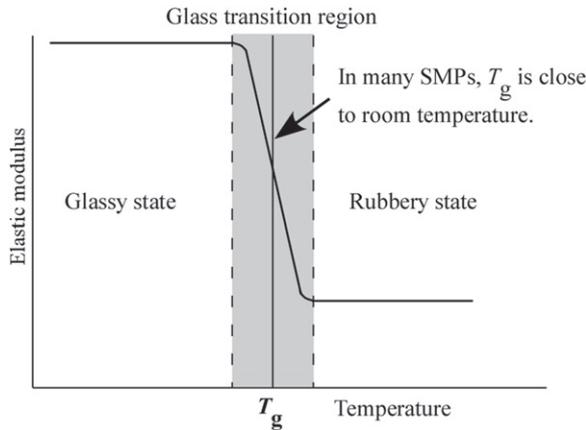


Figure 1. Relationship between the elastic modulus and the temperature of the SMP. The actual values of T_g and the elastic modulus are given in section 2.1.

glass transition temperature (T_g) by applying a small load. Moreover, SMPs maintain their shape after they have been cooled below T_g and are considered rigid in this state. When subsequently heated above T_g , they return to their initial shape and hence exhibit shape recovery. With these features in mind, we previously proposed a position-keeping module [4], soft actuators [5–7], and deployable structures [8] that use SMPs. For example, we developed a position-keeping module of a robot arm that uses an SMP [4]. We have also presented a new air muscle based on the enhancement of a McKibben actuator with SMPs that can transform between a deformable air muscle and a rigid structure [5]. A curved type artificial rubber muscle using SMP can change its direction of motion, the curvature of the artificial rubber muscle, and the actuation range of motion [6]. (See section 3.1 for more details on the typical operation of the artificial rubber muscle.)

However, in our previous studies, we encountered several problems, which are described in the following.

(1) Heating method

In our previous studies, hot air was used to heat the SMP. For example, the position-keeping module using an SMP [4] developed in our previous study was heated by supplying hot air into a tube-shaped SMP. However, since the supply of hot air requires a blower and a heater, which are bulky and noisy, the system is large. Therefore, in order to use this technology in a mobile robot, the entire system, including the pneumatic pressure source and the heat source, must be miniaturized. In particular, as the inner diameter of the SMP tube becomes smaller, the pressure loss in the tube becomes large, and so a large compressor is necessary. Moreover, the heating efficiency of hot air is low, and the use of air extends the heating time. For example, the heating time of the position-keeping module from room temperature to T_g is longer than one minute [4]. Therefore, it is difficult to apply a feedback control to the proposed actuators.

(2) Preparation of thin, uniform SMP sheets

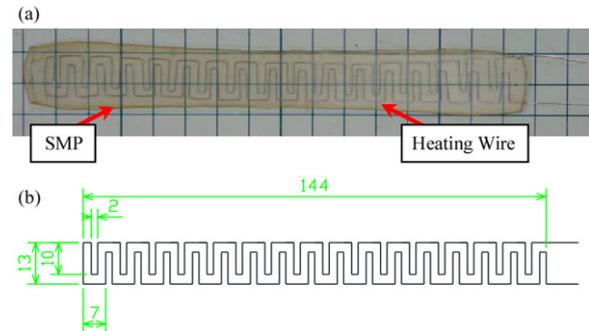


Figure 2. SMP sheet with embedded electrical heating wire (Length: 150 mm, Width: 20 mm, Thickness: 1.0 mm). (a) Photograph. (b) Dimensions of the electrical heating wire (unit: mm).

For example, before hardening, SMP was used to coat the braided mesh shell of a commercial McKibben artificial muscle in order to prepare a prototype McKibben artificial muscle using SMP [5]. The applied SMP was thick and not uniform. Moreover, numerous bubbles were observed in the SMP. Heating thick SMP in order to transition the SMP to the rubbery state could not be achieved quickly. Furthermore, it is difficult to uniformly heat an SMP sheet of non-uniform thickness. Therefore, it is necessary to prepare a thin uniform SMP sheet without bubbles.

In the present study, in order to solve the above-mentioned problems, we developed an SMP sheet with embedded electrical heating wire and evaluated the control of the SMP sheet temperature by Joule heat. A number of heat sources, including light illumination, electric current, and a hot saline solution, have been proposed for the SMP [9–12]. Joule heat is used for robotic applications of shape-memory materials such as shape-memory alloy and gel [16, 17]. We attempted to form a uniform thin SMP sheet without air bubbles using a heat press. Moreover, we evaluated the mechanical properties of the obtained SMP sheet. Finally, we applied the SMP sheet to a curved type pneumatic artificial muscle and evaluated the dynamic motion of the resulting actuator.

2. SMP sheet with embedded electrical heating wire

2.1. Prototype

The prototype SMP sheet with embedded electrical heating wire is shown in figure 2. In the present study, we chose a polyurethane shape memory polymer (SMP Technologies Inc., MP4510, $T_g = 45^\circ\text{C}$). The fundamental characteristics of this material are summarized in table 1. Two liquid components were prepared. They were vacuum-dried for 1 h or more and then mixed at the appropriate weight ratio, in a manner similar to that described in our previous studies [5, 6]. The mixture was poured onto a plate and cured. In this state, the SMP sheet was thick and non-uniform and included numerous bubbles. Therefore, in the present study, the SMP sheet was pressed in conjunction with heating (at 190°C to 200°C for 10 min, followed by natural cooling for 30 min or more), and the SMP sheet re-memorized a thin uniform shape.

Consequently, we obtained a uniform, thin SMP sheet without air bubbles. The reason for this is thought to be that secondary-shape forming with irrecoverable strain occurs when the SMP is maintained at high temperature above T_g for a long period of time [13, 14]. Furthermore, the heat would vaporize the water and the air in the bubbles, thereby removing the bubbles.

In order to heat the SMP sheet, we placed a heating wire made of Nichrome (outer diameter: 0.26 mm, electrical resistivity: $108 \pm 6 \times 10^{-6} \Omega\text{cm}$, Young's modulus: 214 GPa) between two pressed SMP sheets, which were cohered using a heat press (150 °C, 20 min). In a preliminary experiment, small bubbles nucleated near the heating wire during the curing of the SMP resin when the wire was placed in the mixture. The reason for this is thought to be that the residual air and water on the surface of the heating wire cause bubbles. The total electrical resistivity is approximately 20Ω . The heating wire is shaped into a square wave so as not to affect the mechanical properties of the SMP sheet in the tensile and bending directions (figure 2(b)). In the present study, we pressed MP4510 thermoset, supplied by the manufacturer as two liquids, in a manner similar to that described in our previous studies [5, 6]. However, the use of thermoplastic SMP MM4520 supplied in pellet form may be effective for this hot press method.

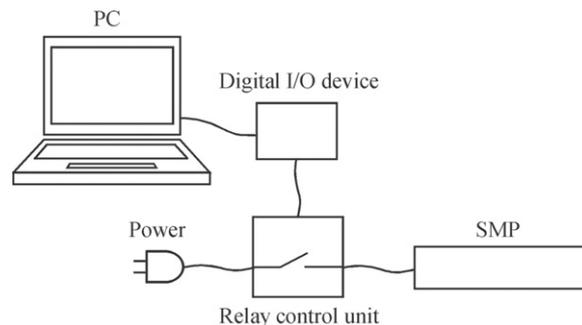


Figure 3. Schematic diagram of the temperature control system.

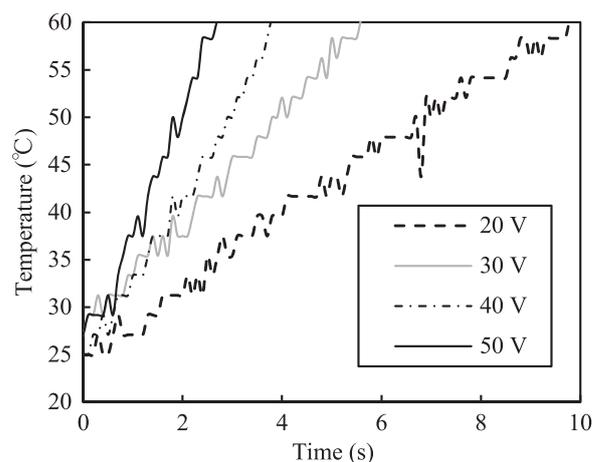


Figure 4. Transition of the surface temperature of SMP sheet.

Table 1. Characteristics of SMP MP4510.

Properties	MP4510
Tensile strength ($T < T_g$) (MPa)	30
Elastic modulus ($T < T_g$) (MPa)	1350 ^a
Elastic modulus ($T > T_g$) (MPa)	4.5 ^b
Elongation ($T < T_g$) (%)	300

^a Bending modulus.

^b 100% tensile in the machine direction.

2.2. Experiments

2.2.1. Temperature increase test. We measured the rising temperature of the SMP sheet when the applied alternating voltage on the heating wire was changed from ac 20 V to ac 50 V by a controller voltage. The surface temperature was measured using a digital infrared temperature sensor (Keyence Co., FT-H10).

2.2.2. Temperature retention test. We evaluated whether the SMP sheet can be fixed at a constant temperature. A schematic diagram of the temperature control system is shown in figure 3. A pulse width modulation (PWM) signal was output from a PC through a digital I/O device controlled by software developed in a LabVIEW (National Instruments Co.) environment. However, since the maximum output current from the digital I/O device is too small to heat the SMP sheet, we controlled the large-current relay using a relay

control kit, which included a transistor and a diode. A direct voltage of 18 V or an alternating voltage of 20 V was applied to the heating wire through the relay. We varied the temperature of the SMP sheet by changing the duty ratio from 10 to 25%. The time cycle was 1 s. The surface temperature and the temperature distribution were measured using the digital infrared temperature sensor, a type K thermocouple, and an infrared thermal camera (NEC Avio Infrared Technologies Co., Ltd, F30W).

2.2.3. Bending and tensile tests. The applied force was measured when the SMP sheet was deformed in the bending or tensile direction. First, the SMP sheet was bent at temperatures above and below T_g . We evaluated the relationship between the bending force and the displacement when a bending force was applied to the sensor by an indenter connected to a load cell (Kyowa Electronic Instruments Co. Ltd). The indenter was manually displaced using a stage. The distance between the fixed part and the indenter was 110 mm.

Second, the SMP sheet was pulled at a constant speed (strain rate: $5\% \text{ min}^{-1}$) by a universal tester, and the axial loading was recorded at room temperature. We performed these measurements on three SMP sheets (A, B, and C). The gauge lengths were 100 to 120 mm.

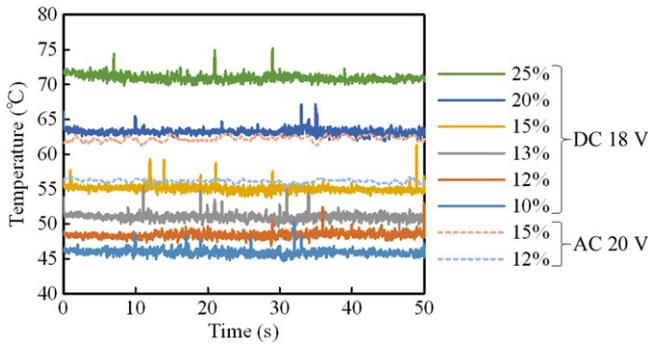


Figure 5. Transition of the surface temperature of SMP sheet.

2.3. Results and discussions

2.3.1. Temperature increase test. The transition of the SMP sheet temperature is shown in figure 4. The heating time became short and practical for the application. More specifically, the heating time from 40 °C to 50 °C (below and above T_g) was 1 s and 0.5 s by 40 V and 50 V, respectively. However, the distribution of the temperature in the thermograms was not uniform at the moment when the temperature reached 50 °C. Therefore, after the temperature increases, some time is required in order to equalize the temperature of the sheet.

2.3.2. Temperature retention test. In figure 5, the transition of the SMP sheet is shown when the temperatures of the SMP sheet became constant at the fixed duty ratio. We were able to control the SMP sheet at a constant temperature by PWM control. As shown in the thermograms of the SMP sheet (figure 6), the entire sheet was heated uniformly.

The incorporation of not only an electrical heating wire, but also particles such as carbon nanotubes [9–11] and nano-sized carbon [12], make the SMP electrically conductive and enable Joule heating of the SMP. However, the incorporation of particles also influences the mechanical properties of the SMP [9, 10] and may induce the initial bubbles. Therefore, we selected a more practical and applicable heating wire for use in the present study. The heating method proposed herein can also be used with the other conductive SMP samples that incorporate carbon nanotubes or nano-sized carbon.

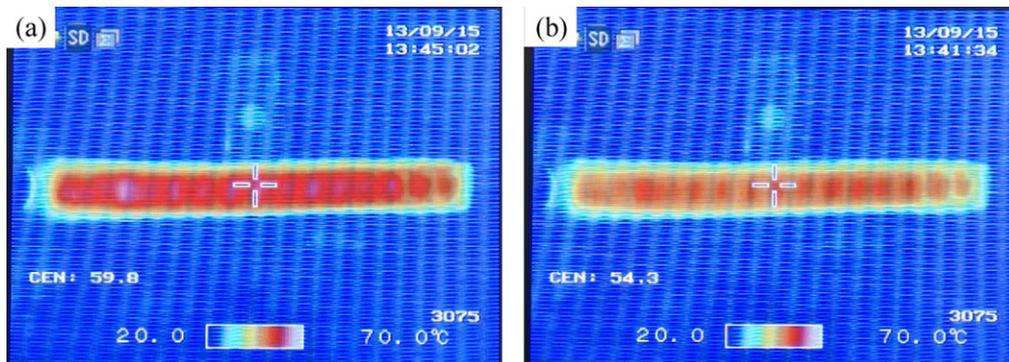


Figure 6. Thermographic images of the SMP sheet (AC 20 V). (a) 12%. (b) 15%.

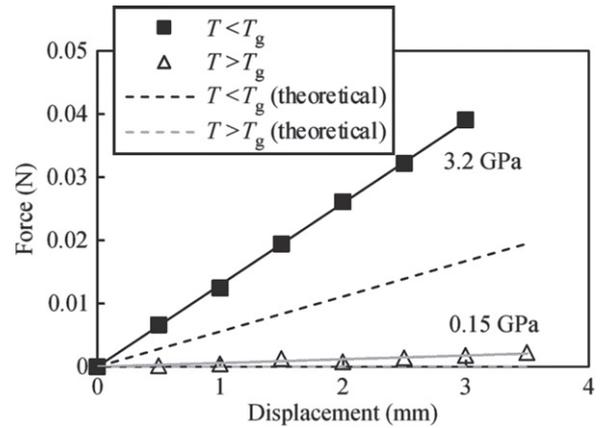


Figure 7. Relationship between the applied force and the displacement of the cantilever fixed SMP sheet.

2.3.3. Bending and tensile tests. The relationship between the applied bending force and the displacement at temperatures above and below T_g is shown in figure 7. In this figure, assuming an elastic cantilever, the theoretical values were calculated using the following equation:

$$W = \frac{3dEI}{l^3} \tag{1}$$

where d is the displacement, W is the applied load, and l , E , and I are the length, the elastic modulus shown in table 1, and area moment of inertia, respectively, of the SMP sheet. The values shown in this figure are the elastic modulus calculated using the slopes of the experimental results. We can vary the elastic modulus of the SMP sheet by as much as 2 000% according the temperature, although the SMP sheet includes metal wire, which is more rigid than the SMP.

The relationship between the applied tensile load and the displacement of the SMP sheet is shown in figure 8. The values shown in this figure are the elastic modulus calculated using a strain of less than 2.5%. The calculated tensile strength and elastic modulus are almost the same as those of the SMP itself, as illustrated in table 1.

As shown in this section, the effects of the embedded wire on the mechanical properties of the SMP sheet are small in the bending and tensile tests.

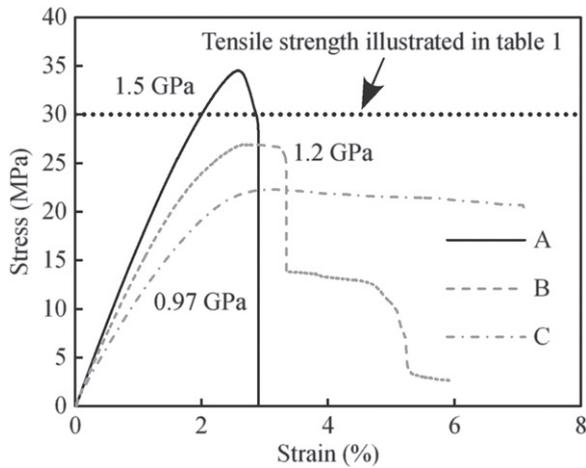


Figure 8. Relationship between the applied tensile load and the displacement of the SMP sheet ($T < T_g$).

3. Pneumatic artificial rubber muscle using SMP sheet with embedded electrical heating wire

3.1. Prototype

A linear type pneumatic rubber artificial muscle is composed of an internal bladder (e.g., rubber tube) covered by a bellows sleeve extending only in the axial direction [1]. When

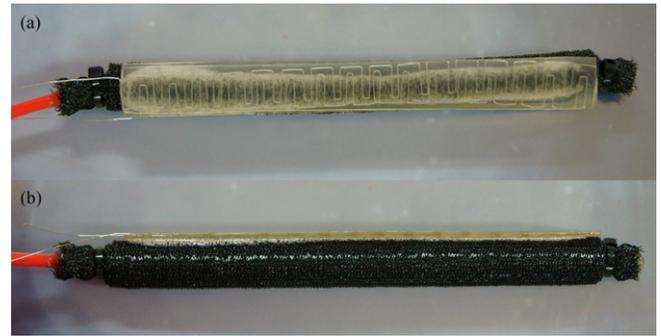


Figure 10. Curved type pneumatic artificial rubber muscle using SMP sheet with embedded electrical heating wire. (a) Front view. (b) Side view.

compressed air is introduced into the bladder, the actuator extends or contracts only axially. Moreover, in order to assist the rotational motion of a human joint with an artificial muscle, a curved type artificial rubber muscle, which is reinforced with fibers, was proposed [1]. By inhibiting the extension of one side using fiber reinforcement, bending motion toward the reinforcement direction occurs when compressed air is supplied to the bladder. However, once the fibers are fixed to the actuator, it is difficult to change the bending position, the direction, and the curvature of the actuator. Therefore, we developed a pneumatic artificial

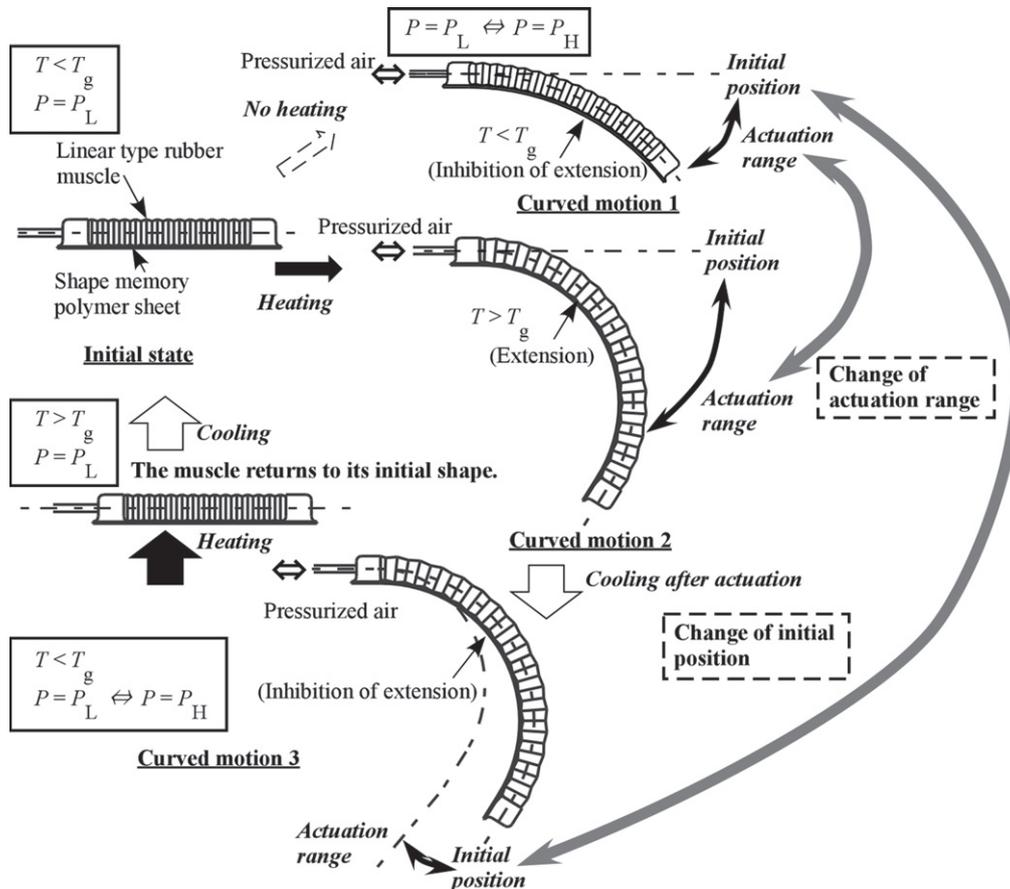


Figure 9. Schematic diagram of the curved type artificial rubber muscle that uses one SMP sheet (P : internal pressure, T : temperature, P_H : high pressure, P_L : low pressure).

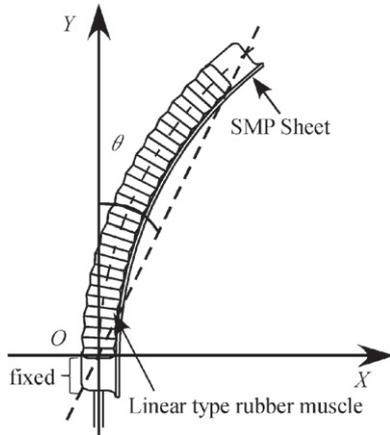


Figure 11. Positional relationship of artificial muscle.

rubber muscle using an SMP sheet [4]. The typical operation of the SMP curved type pneumatic actuator is shown in figure 9.

In this section, we applied the developed SMP sheet with an embedded electrical heating wire to a curved type pneumatic actuator. The prototype of the pneumatic artificial muscle using SMP sheet with embedded electrical heating wire is shown in figure 10. The SMP sheet was glued to one side of the linear type pneumatic actuator. The outer diameter

and the length of the artificial muscle are 15 mm and 150 mm, respectively.

3.2. Experiments

We evaluated the motion of the prototype actuator when the temperature of the SMP sheet was controlled by the temperature control system shown in figure 3. As shown in figure 11, the root of the actuator is fixed. We measured the trajectory of the tip using a video camera when compressed air (0.24 MPa) was supplied and exhausted. In figure 11, the origin represents the position at which the actuators were fixed. The prototype actuator moved in the XY plane. We calculated θ , which is the angle between the Y-axis and the line between the origin O and the tip of the prototype actuator.

We measured the motion of the prototype during the following actuations:

- (1) Supply of compressed air when the temperature of the SMP sheet is below T_g .
- (2) Exhaust of compressed air when the temperature of the SMP sheet is below T_g . Actuations (1) and (2) correspond to curved motion 1 in figure 9.
- (3) Supply of compressed air when the temperature of the SMP sheet is above T_g .

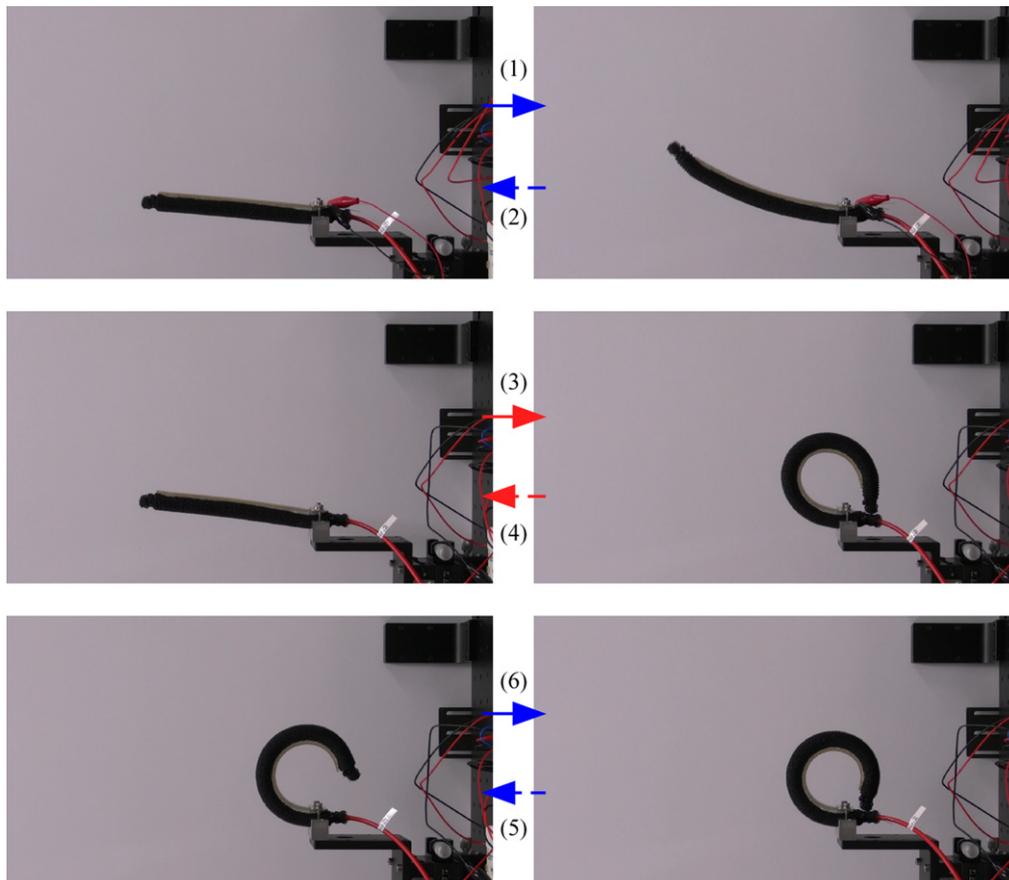


Figure 12. Photographs of the motion of a curved type artificial muscle using SMP sheet. Actuations (1) through (6) in this figure correspond to the respective actuations described in section 3.2.

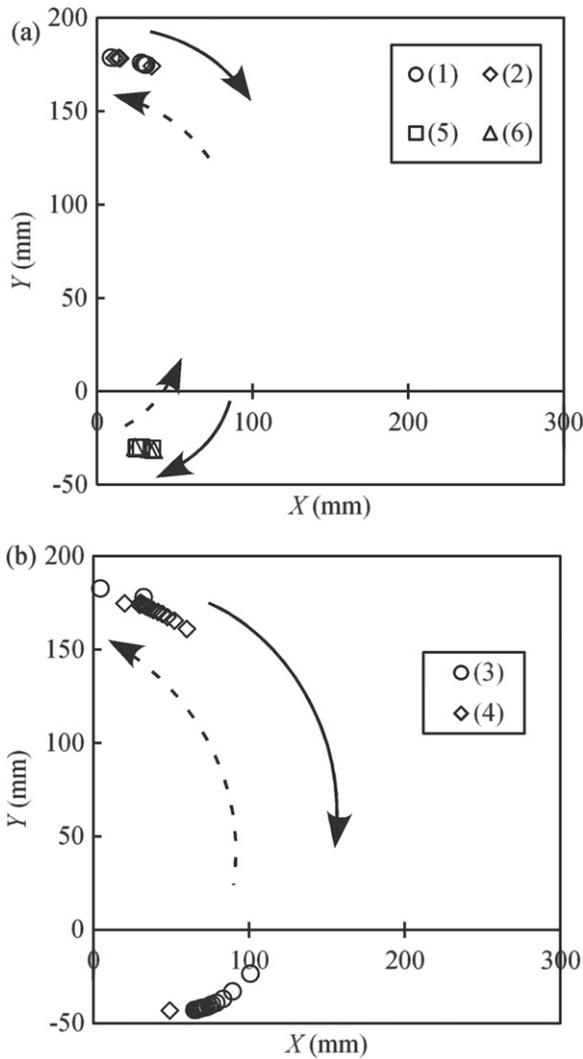


Figure 13. Trajectory of the curved type artificial muscle tip using SMP sheet. (a) $T < T_g$. (b) $T > T_g$. Actuations (1) through (6) in this figure correspond to the respective actuations described in section 3.2.

- (4) Exhaust of compressed air when the temperature of the SMP sheet is above T_g . Actuations (3) and (4) correspond to curved motion 2 in figure 9.
- (5) Exhaust of compressed air when the temperature of the SMP sheet is below T_g after actuation (3).
- (6) Supply of compressed air after actuation (5). Actuations (5) and (6) correspond to curved motion 3 in figure 9.

3.3. Results and discussions

The motion of the prototype using the SMP sheet is shown in figure 12. The trajectory of the tip of the prototype actuator is shown in figure 13. The transition of θ is shown in figure 14. Note that the inner pressure was changed at 0 s. As shown in figure 13, the prototype actuator can change the moving displacement and the initial position by controlling the temperature. For example, when the temperature increased, the deformation induced by the pressure variations increased. As shown in figure 14(a), when $T < T_g$, the prototype actuator

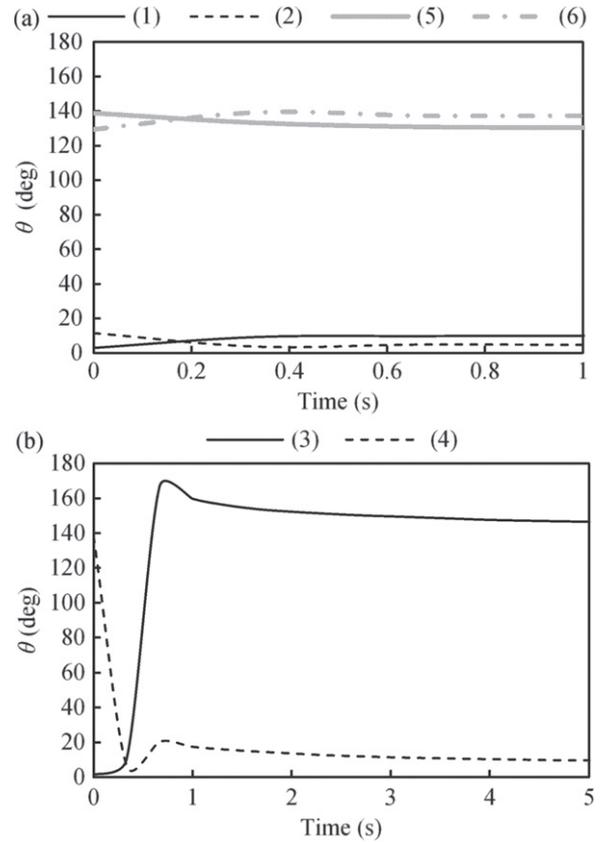


Figure 14. Motion of the curved type artificial muscle using SMP sheet. (a) $T < T_g$. (b) $T > T_g$. Actuations (1) through (6) in this figure correspond to the respective actuations described in section 3.2.

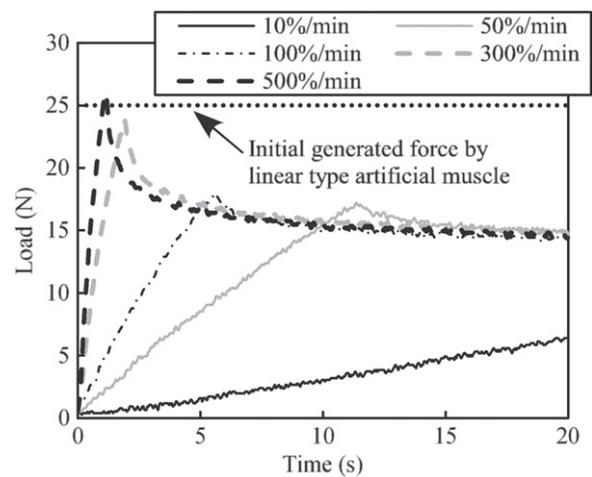


Figure 15. Tension–length relationship of the SMP sheet with an embedded electrical heating wire ($T > T_g$).

moved and stopped within approximately 0.5 s after the supply and exhaust of the compressed air. However, when $T > T_g$, the prototype actuator moved gradually even after 5 s (figure 14(b)). This may be due to the viscoelastic response of the SMP itself. Releasing or applying compressed air results in the sudden bending deformation of the SMP film actuator, and, due to this bending, stress is generated. Internal stress generated due to viscous deformation takes time to respond,

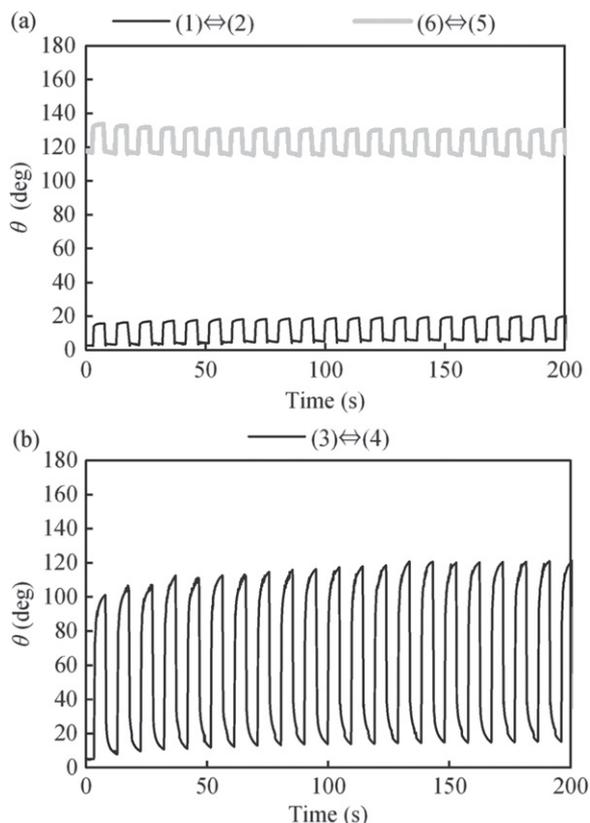


Figure 16. Motion of the prototype actuator when we applied a square wave pressure of 0.2 MPa (0.1 Hz). (a) $T < T_g$. (b) $T > T_g$.

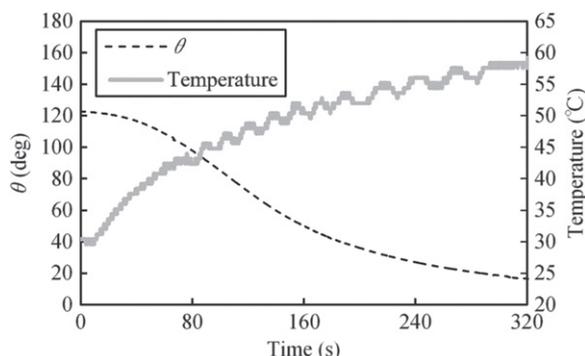


Figure 17. Motion of the prototype actuator when the actuator with a constant inner pressure (0 MPa) was heated.

and this viscous stress slows down gradually over time during relaxation. We checked the viscoelastic property of the SMP sheet with an embedded electrical heating wire by conducting a tensile test at a fast rate (strain rate: 10 to 500% min^{-1}) until a constant deformation (12 mm) was reached and then observing the behavior of the tensile stress over time (figure 15). The gauge length was 120 mm. As the deformation speed becomes large, the tensile stress becomes large and stress relaxation occurs according to the viscosity. In a preliminary experiment, the initial generated force by a linear type artificial muscle with an inner pressure of 0.24 MPa is approximately 25 N (corresponding to 1.25 MPa for the SMP sheet) in the axial direction of the actuator. Since this

instantaneous tensile stress applied by the actuator on the sheet is very large, the effects of the viscosity are large, as shown in figure 15. In order to eliminate the viscoelastic effects of the SMP sheet, it is necessary to cool the SMP sheet below T_g in order to fix the actuator at the desired position. Future research will consider the cooling method of the SMP sheet (e.g., a fan).

In order to check the repeatability and reproducibility of the proposed actuator, we applied a 0.2 MPa square wave pressure with a frequency of 0.1 Hz while varying the temperature of the actuator above and below T_g . Namely, the solenoid air valves were opened or closed every 5 s using a timer (0.1 Hz). The transition of θ for 20 continuous cycles (repetitions of actuations (1) and (2), (3) and (4), and (5) and (6), respectively) is shown in figure 16. As the bending motions are repeated, the positions changed gradually. In particular, when $T > T_g$, the fixed positions are gradually changed with the repeated motions according to the viscosity of the SMP sheet. Another reason may be that the change in the inner pressure (0.2 MPa) is too large for the bending stiffness of the SMP sheet. The optimization of the shape, such as the size of the SMP sheet, for each actuator and each motion range would be necessary.

After actuation (5), even though the internal pressure was low, the actuator does not bend and the temporary shape is fixed because the SMP is in the rigid state. After this actuation, we subsequently heated the actuator with no air and checked the motion. The transitions of θ and the temperature are shown in figure 17. As the temperature increased, the actuator returned to its initial position. This phenomenon demonstrates that the actuator can also be actuated thermally, given a pre-applied pressure in a manner similar to the prototype McKibben artificial muscle using SMP [5]. Note that this concept can be extended to other SMP state transition stimuli, including indirect heating, such as illumination with infrared light, a magnetic field, and lowering of T_g by water content [10].

Most of the present results can also be applied to the large-scale actuators, although the thermal properties, such as the thermal distribution, would change. Therefore, it may be useful to use several actuators and make them into a bundle if more force is necessary.

4. Conclusion

We have developed an SMP sheet with embedded electrical heating wire and applied the newly developed SMP sheet to a pneumatic artificial rubber muscle. In the present study, we confirmed that the temperature of the SMP sheet could be raised quickly and maintained at a constant temperature by controlling the voltage applied to the heating wire. We also evaluated the mechanical properties of the SMP sheet through bending and tensile tests and found the effects of the embedded wire to be small. By controlling the temperature of the SMP sheet, the bending motion of the actuator such as the initial position and the actuation range could be changed. When $T < T_g$, the prototype actuator moved and stopped

within approximately 0.5 s after the supply and exhaust of compressed air.

Acknowledgment

The present study was supported by a research grant from The Mazda Foundation.

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