BRIEF PAPER *Special Section on Recent Progress in Organic Molecular Electronics*

Effect of Temperature on Electrical Resistance–Length Characteristic of Electroactive Supercoiled Polymer Artificial Muscle

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SUMMARY It is found that the electrical resistance–length characteristic in an electroactive supercoiled polymer artificial muscle strongly depends on the temperature. This may come from the thermal expansion of coils in the artificial muscle, which increases the contact area of neighboring coils and results in a lower electrical resistance at a higher temperature. On the other hand, the electrical resistance–length characteristic collected during electrical driving seriously deviates from those collected at constant temperatures. Inhomogeneous heating during electrical driving seems to be a key for the deviation.

key words: *actuator, supercoiled polymer artificial muscle, twisted and coiled polymer actuator, electrical resistance, mathematical model*

1. Introduction

Since the discovery of the supercoiled polymer artificial muscle, which is also known as the twisted and coiled polymer actuator or the nylon muscle, by Haines et al., [1] lots of research efforts have been devoted to the applications of the device such as humanoid hand [2] and power-assist system [3]. The actuation principle of the device is the contraction upon heating, and the device made from conductive sewing thread can be directly driven by electrical power. The electroactive supercoiled artificial muscle seems to be highly attractive compared to other electrically driven artificial muscles in numerous factors such as durability and cost.

The modeling of an artificial muscle is indispensable for the precise control of it. Most researchers tackling the problem have paid little attention to the electrical resistance of electroactive supercoiled artificial muscle in operation [4], [5]. The electrical resistance is still important because the input power is in inverse (direct) proportion to it under constant voltage (current) application. We have recently pointed out that the electrical resistance of the supercoiled polymer actuator shows considerable reduction upon contraction due to Joule heating [6], [7]. Here, the effect of temperature on the electrical resistance–length characteristic of the electroactive supercoiled artificial muscle is studied.

Manuscript received June 1, 2020.
Manuscript revised September 23, 2020.
Manuscript publicized October 6, 2020.
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DOI: 10.1587/transele.2020OMS0002

2. Experimental

The supercoiled artificial muscle used in this study was prepared from a nylon monofilament fishing line of 0.81 mm in diameter manufactured by TOA-Strings. The insertion of a twist to a thread 16 cm in length with a suspended weight of 500 g at room temperature resulted in a supercoiled artificial muscle approximately 4 cm in length with approximately 30 coils. After annealing at 140 °C for 0.5h in an oven to fix the shape, the artificial muscle was coated with Du Pont PE872 silver paste.

The length of the artificial muscle was changed by changing the suspended weight to collect length–electrical resistance characteristics. The temperature of the sample was changed by a Yamato Scientific IN804 incubator.

The change in the length of the artificial muscle with a suspended weight of 500 g at room temperature driven by a 1/180 Hz square current wave of 0.8 A with 1/3 duty cycle, which made the temperature of the artificial muscle 20/40 °C at the end of off /on state, was measured by an Optex FA CD22-100 laser displacement sensor. The temperature of the artificial muscle is measured by a type-K thermocouple attached to the center of the sample. The data including the voltage applied to the artificial muscle were collected by a Graphtec GL240 data logger. The thermograph of the artificial muscle is collected by a FLIR ETS320 thermal camera.

3. Results and Discussion

Both length and electrical resistance monotonically increased by increasing the suspended weight. The electrical resistance–length characteristic is shown in Fig. 1 (a). An electroactive supercoiled artificial muscle has the lowest electrical resistance in its shortest form since the neighboring coils are fully contacted and the artificial muscle is considered as a cylindrical resistor. The contact area between the neighboring coils in the artificial muscle reduces by elongation, giving increased electrical resistance. At a certain degree of elongation, the neighboring coils are separated and the artificial muscle becomes a spiral line resistor. Further elongation virtually retains the electrical resistance. Thus, the conductive supercoiled artificial muscle shows S–shaped electrical resistance–length characteris-

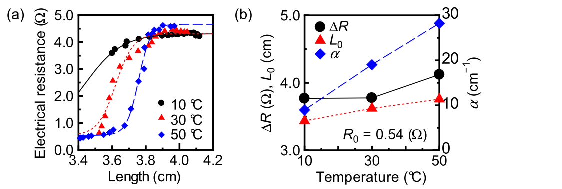

Fig. 1 (a) Electrical resistance–length characteristics of the electroactive supercoiled polymer actuator at various temperatures. Lines show fitting curves using Eq. (1). (b) Dependence of fitting parameters on temperature.

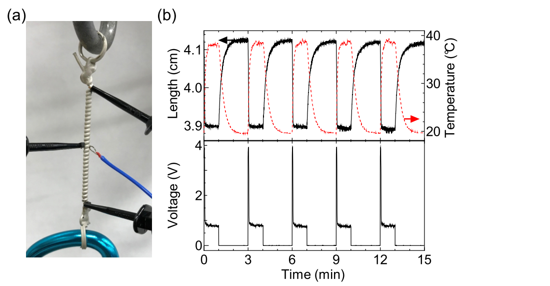

Fig. 2 (a) Photograph of the electroactive supercoiled artificial muscle under electrical driving. (b) Temporal change of the length, the temperature, and the voltage of the electroactive supercoiled artificial muscle during 5 cycles of the electrical driving.

tics [7]. Interestingly, the electrical resistance at a constant length, say 3.7 cm, strongly depends on the temperature. This may come from the thermal expansion of coils in the artificial muscle, which increases the contact area of neighboring coils and results in a lower electrical resistance at a higher temperature.

As mentioned in the previous report [7], a simple expression for electrical resistance R as a function of length L using a logistic function

$$R(L) = R_0 + \frac{\Delta R}{1 + \exp(-\alpha(L - L_0))} \tag{1}$$

can reproduce the experimental data. As shown as curves in Fig. 1 (a), Eq. (1) successfully reproduces the experimental data. The temperature dependences of fitting parameters are shown in Fig. 1 (b). It is found that all parameters, say ΔR, L_0 and α increase as increasing the temperature.

Figure 2 (a) shows a photograph of the experimental setup for the electrical driving of the electroactive supercoiled artificial muscle. Figure 2 (b) shows 5 cycles of the temporal change of the length, the temperature, and the voltage under the electrical driving. The sample used for this experiment is the same one used for the results mentioned above. Similar to our previous reports [6], [7], the voltage and thus the electrical resistance seriously drop upon the Joule heating.

The electrical resistance of the artificial muscle as a function of length during electrical driving is plotted in Fig. 3 (a). Because the temperature range during the experiment is between 10 and 50 °C, the data for the electrical driving are expected to be mapped into the area bounded by the electrical resistance–length curves for 10 and 50 °C. However, the data for the electrical driving deviate from the

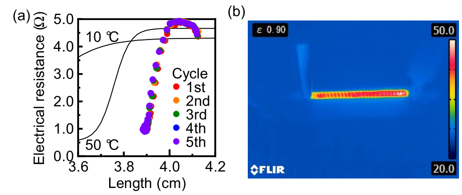

Fig. 3 (a) Electrical resistance–length characteristics of the electroactive supercoiled artificial muscle from Fig. 2 (b). Lines show the fitting curves that appeared in Fig. 1 (a) at 10 and 50 °C. (b) Thermograph of an electroactive supercoiled artificial muscle under the constant current application.

area. Inhomogeneous heating during electrical driving, a typical case is shown in Fig. 3 (b), seems to be a key for the deviation.

In conclusion, the electrical resistance–length characteristic in an electroactive supercoiled polymer artificial muscle strongly depends on the temperature. The thermal expansion of coils in the artificial muscle, which may increase the contact area of neighboring coils and results in a lower electrical resistance at a higher temperature. The electrical resistance–length characteristic collected during electrical driving seriously deviates from those collected at constant temperatures, which may come from inhomogeneous heating during electrical driving.

Acknowledgments

This work was partially supported by the Hyogo Science and Technology Association.

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