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RESEARCH PAPER

An arm-like electrothermal actuator based on superaligned carbon nanotube/polymer composites

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Abstract: A superaligned carbon nanotube film embedded in polymers shows promising applications in the fields of electrothermal actuation because of their homogenous conductivity, good biocompatibility and mechanical properties. We fabricated a simple U-shaped gadget from the composite to investigate the electrothermal actuation mechanism. The gadget can curl to 730°, which is several times larger than existing actuators. A helix-shaped arm-like actuator (artificial arm) was also made from the composite, which exhibited a large twisting deformation (more than 700° twisting, 49.2% length constriction and 26.4% diameter constriction) when driven with low electrical fields (less than 500 V/m or 41 V). The actuation of the U-shaped gadget and the artificial arm can be precisely controlled by the applied voltage or electrical power. The gripping force of the clenched arm is about 4 g, 26 times its own weight. This points to a new way for manipulating objects and its potential application in the biomimetic field.

Key Words: Composite materials; Electrothermal; Twisting; Actuator; Application

1 Introduction

Actuator materials can convert different types of energies, such as thermal, light, electric energies, to mechanical energy[1-3]. These conversions are very desirable in many areas, such as soft-robots, medical applications, optical devices and biomimetic fields[4-7]. In some aspects, the muscle-like responses have already exceeded the natural muscles[8, 9]. Among them, electroactive polymers (EAPs) are intensively studied owing to their excellent performances such as flexibility, easy operation, low cost and lightness[4, 9-11]. The EAPs have been divided into two major groups: electronic and ionic[6, 10]. The electronic EAPs are mostly actuated by the Coulomb forces, and have the advantages of high speed, large-strain and high energy densities[12, 13], but it requires an extremely high driving electrical field (about 130 MV m^{-1})[14]. In contrast with the electronic EAPs, the ionic EAPs can work under relative low driving electrical fields (less than 600 V m^{-1})[15, 16], but it requires an electrolyte environment. Therefore, the ultra-high driving electrical fields or electrolyte-indispensable environment largely limits the widespread utilizations of these EAPs.

Recently, electrothermal actuators have attracted more and more attentions[17-19]. They can work under a relative low driving voltage (< 200 V/m) in the air, overcoming the main disadvantages of the traditional EAPs[14, 15]. Carbon nanotube (CNT)/polymer composites are mainly discussed in this field as they have the advantages of the CNTs (good conductivity, excellent chemical and thermal stability) and the polymers (good biocompatibility, proper strains and high stress)[20-23]. The electrothermal actuators usually have a one-layer, bimorph or sandwich structure[17, 24-26]. The one-layer actuator is very simple, and it is a uniform conductive composite that can expand or contract with the variation of the temperature[17]. The actuation of the bimorph structure actuator is based on the different thermal expansion coefficients (CTEs) between the two layers. The embedded superaligned carbon nanotube (SACNT) films can reduce the CTE of the polymer matrix by two orders of magnitude (from 3.1×10^{-4} K^{-1} down to 6×10^{-6} K^{-1})[27]. When it is electrically heated, the actuator could bend to the side that has a smaller thermal expansion. For the sandwich-structure actuator, the actuation is based on the thermal gradient along the thickness direction[24]. The carbon nanotubes are dispersed on both the upper and the lower surface of the polymer matrix. When one surface is electrically heated, the higher-temperature side will get a larger expansion. In our previous work, we reported a round-shaped bimorph-structure actuator[7]. It turns to a distinctive convex shape and shows the potential usages in the optical areas. Nevertheless, the configurations of the existing electrothermal actuators are still monotonous and the corresponding actuations are simple bending movements. Few

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complex and functional devices have been reported. Therefore, there is huge room for the improvements of the electrothermal actuators, and new kinds of actuators with sophisticated structures which are more functional and fit for practical applications should be developed.

In this work, we introduce a simple approach to fabricate high-deformation bimorph actuators based on the strong SACNT film and a high-strength silicone elastomer. A simple U-shaped gadget was designed to show the large curling deformation and the curling angle can reach 730° in 5 s, which is much quicker and several times larger than the former actuators[28, 29]. Then, a helix-shaped arm-like actuator based on the SACNT/polymer composite is elaborately designed. It shows a distinctive large twisting deformation (more than 700° twisting and 49.2% height constriction) when electrically heated, and the twisting process seems like the clenching arm. The gripping force is about 4 g (26 times of its own weight). The actuation speed and the deformation can be controlled by the voltage (or electrical power) precisely. With the advantages of large twisting deformation, large gripping force, low driving electrical fields (500 V/m or < 41 V) and long service life (> 5000 times), the arm-like actuator shows a new way for manipulating objects.

2 Experimental

2.1 Fabrication of the SACNT/SG3010 composite film

The SACNT arrays were first synthesized on an 8-inch silicon in a low-pressure chemical vapor deposition system by using Fe as the catalyst and acetylene as the precursor[30-32]. Then the SACNT sheet can be easily and continuously drawn from the "CNT forest" due to the weak van der Waals force between CNTs[33, 34]. The sheet was rolled up by a cylindrical steel roller to form a thin SACNT film, and the thickness of the film can be controlled by the rotation number. Then the SACNT film was peeled after an axial cut, and the well-prepared SACNT film is shown in Fig. 1a. After that, the SACNT film was supported tightly upon a petri dish, as shown in Fig. 1b. Then the silicone precursor (a high strength polymer: SG3010, Beijing Hangtongzhou Technology Co., Ltd. China, component A:B=1:1 by weight) was partially cured (30 min at 80°C, 0.26mm thickness) on another petri dish. We put the SACNT film on the upper surface of the polymer, and the partially cured precursor infiltrated the SACNT film very soon to shape the composite layer, as illustrated in Fig. 1c. After the final curing, the well-prepared composite film can be easily peeled from the petri dish, and Fig. 1d is the optical image of the film. In this work, SACNT film with 80 sheets was used for fabricating the U-shaped gadget and the arm-like actuator.

2.2 Fabrication of the U-shaped gadget

A U-shaped structure gadget with 40 mm long and 7 mm wide was made from the composite film. The U-shaped conducting channel was made by cutting off the middle part (1 mm wide) of the composite, and then the vacant part was refilled by the pure SG3010 precursor. At both ends of the channel, copper electrodes were fixed. After cured, the gadget had a thickness of 0.26 mm. The aligned direction of CNTs was chosen as the length direction of the gadget in order to show the largest deformation. Some silver paste was used for avoiding the local overheating. For deformation comparison, some other gadgets with different thicknesses or CNT directions were also made.

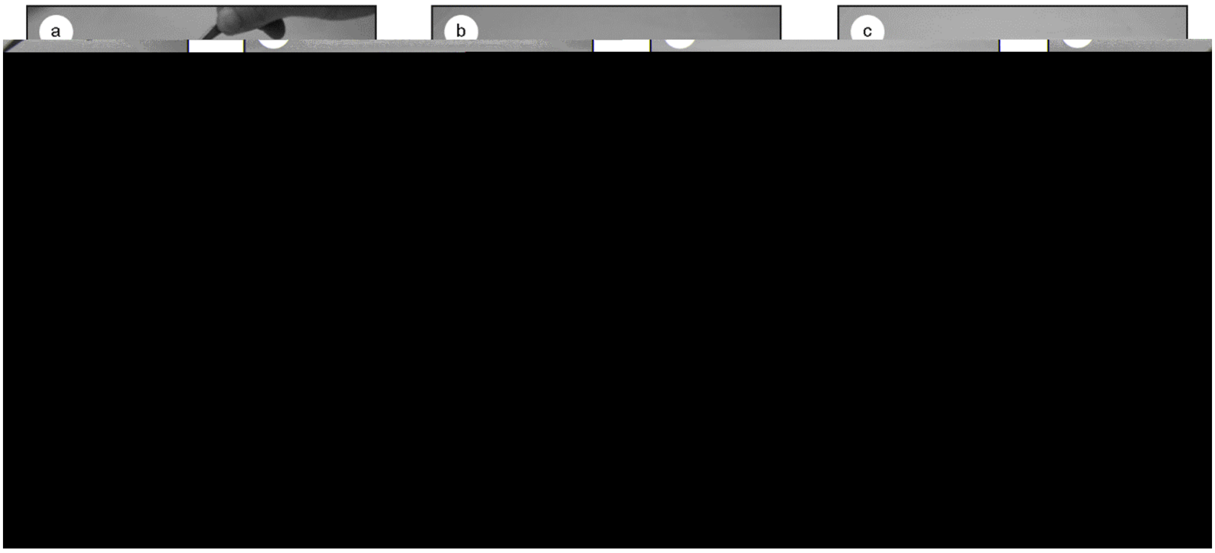

Fig.1 Fabrication of the SACNT/SG3010 composite: (a) The 80-layer SACNT film; (b) The SACNT film with a supporting petri dish; (c) Attach the SACNT film to the upper surface of the partially cured polymer; (d) The well-prepared composite film; (e) SEM image of the surface of the composite film (SACNT side); (f) cross-sectional SEM image of the composite film.