NANO CARBON MATERIAL BASED ELECTROCHEMICAL ACTUATORS

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1 Introduction
Actuators change electrical or electrochemical energy into mechanical energy and ideally produce high power using a small volume of material. Researchers have been trying to overcome the limitation of either the small strains or small forces produced by smart materials. With the help of nanoscale materials like carbon nanotube (CNT), there is the potential to develop new actuators that will provide higher work per cycle than previous actuator technologies, and generate much higher mechanical strength [1]. The first actuator made of CNTs was published by Ray Baughman in 1999, and others followed [1-7]. This actuator produced strain due to the change in dimension of the nanotube in the covalently bonded axial direction caused by an applied electric potential. The charge injection leads to a change in the dimension of the nanotube paper causing the assembly to bend. This excess charge is compensated at the nanotube-electrolyte interface by electrolyte ions forming a double layer. To overcome the applications of aqueous working environment of the carbon nano actuator, soft and flexible dry actuators that can work in air have been developed with solid polymer electrolyte [8-10].

2 Experimental

2.1 Preparation of the actuator film
Different actuator films were fabricated with carbon nanomaterials involving ionic conducting host polymer Nafion by using of traditional solution-casting techniques. Composite of Nanfion and nano carbon materials were prepared by the dispersion of the carbon nanomaterials in appropriate amount of solvent to achieve polymer membranes. In nano carbon materials, individual nanomaterials exist as a form of bunch or aggregation due to the Vander Waals force, which is a strong binding force between molecules. The aggregation prevents the forming of a three dimensional network structure in the fabrication of composites, which improve electric and physical properties. If carbon nanomaterials are not uniformly dispersed in the matrix of polymers, it is difficult to present the characteristics of nano filler well. Thus, a dispersion process of the carbon nanomaterial is an important step in fabricating nano composites.

The appropriated amounts of dispersed carbon nanomaterials were mixed with the Nafion (Aldrich, 274704) in order to achieve wt. 90% of carbon nanomaterials/Nafion composites. The carbon nanomaterials-Nafion solutions were homogenized for 2 hours until highly homogeneous solution resulted. As bulk materials were hardly achieved with carbon nanomaterials except single-wall carbon nanotube (SWCNT), we added a Nafion to fabricate the bulk electrode. In general, the van der Walls force interacting among the individual carbon
nanomaterials is not enough to form a film. Nafion not only combines nanotubes as a matrix but it also greatly improves the electrochemical activity.

2.2 The nano carbon actuation in an aqueous electrolyte

The electrochemical nano carbon actuator is a strain induced one by volume change, i.e. the volume of nano carbon materials can be expanded by ion exchange when it is immersed in an electrolyte. If a voltage source is connected to the nano carbon, because of the electrical charging effect, anions and cations in an electrolyte would attach on the surface of cathode nano carbon and anode nano carbon respectively. To achieve the actuation of nano carbon material, actuator film was immersed into an aqueous electrolyte and AC voltage was applied to the film as a power source. The basic experimental setup is provided in Figure 1.

Figure 2 shows an experiment of CNT bi-morphing actuator made of Nafion coated SWCNT which is actuating in 5M aqueous NaCl electrolyte. The actuation amplitude is 5 mm when driven by the square wave and it can vibrate at frequencies up to 15 Hz.

Since multi-wall carbon nanotube (MWCNT) has been reported to be difficult to produce macroscopic sheet, its actuation property has not been studied well. Only forest-like aligned MWCNT actuator in aqueous electrolyte has been demonstrated [2]. The aligned MWCNT arrays actuation has been reported as an electrical repulsion among nano tube forests which means a rather different actuation mechanism than SWCNT. The carbon nanofiber (CNF) sheet manufacturing process was developed and it can be used for MWCNT actuator as well. Figure 3 shows a manufactured CNF adding Nafion (wt. 90/10) and its actuating with volume expansion similar with SWCNT actuator. Because of poor electrochemical and electrical properties, the bending occurs mostly near the top of the film.

Because of the Nafion infiltration, MWCNT and CNF can bind with hydrogen bonding and it helps to bind the tubes each other to make a film type. Since Nafion also has an actuation property dues to redox mechanism [6, 7], this study had validated that the actuation property does not owing to the Nafion actuation.
Recently, we fabricated a novel nano carbon film with graphene/Nafion composite and tested its actuation property in a saline electrolyte. The graphene film also has electrochemical actuation property like other nano carbon however it requires rather higher driving voltage due to its high surface resistivity along the film. The high resistivity of the film may degrade not only the efficiency of electrochemical actuation and also electrical driving efficiency. We can deduce that the electrochemical actuation can be achieved by various porous nano carbon materials from the experiments. The ions of electrolyte forming double layer may make dimensional changes of the film surface [1] and this principle maybe available to the nano carbon based electrochemical actuators.

2.3 The strain output model for electrochemical actuator

The natural phenomenon of electrochemical CNT actuation will be modeled to optimize the design of the actuator with respect to stress, strain and applied voltage. A theoretical background for the actuator is given in terms of the electrochemical constitutive equations in an electrolyte environment. Actuation is proportional to charging transfer rate, and the electrolysis with an AC voltage input has very complex characteristics. The CNT actuator charges and discharges under an AC environment which means we can model this effect as an impedance element even though this system is an electrolysis mechanism. The electrolyte and CNT contact act as a resistance and the interface between the polymer and the electrolyte is modeled as the double layer capacitance which is attributed to the entire polymer volume, $C_s$, and the overall diffusion element. The relationship between mechanical properties and electrical properties can be expressed by:

$$\varepsilon(s) = \alpha(s) \cdot \rho(s) + \sigma(s) / S(s)$$

which is a nonlinear equation, or a linear equation can be written as;

$$\varepsilon(t) = \alpha \cdot C_s \cdot V + \sigma(t) / E$$

Here, $\varepsilon$ is the output strain, $\rho$ is the charge per unit volume, $\sigma$ is stress, $V$ is input voltage, $s,t$ are the Laplace variable and time, $\alpha$ is the empirically derived constant of proportionality referred to as the strain to charge ratio, $E$ is the elastic modulus, and $S(s)$ is the frequency dependent stiffness. Most of the parameters should be determined by experiments and would be derived in further study.

3. Summary of Results

The electrochemical actuation property of nano carbon films was studied and graphene actuator was shown for the first time by fabrication of a Nafion host film. The strain output model was studied based on electrochemical effects between the nano carbon films and the electrolyte. On the basis of the obtained results regarding the all experiment, we may affirm that the electrochemical actuation mechanism based on the expansion of carbon nanomaterials due to the ions attachment of the film surface is available to most of nano carbon porous films immersed in an electrolyte. Since the nano carbon actuator is made of nano size material, it could be manufactured at the micro or nano scale. MEMS may be required to control the micro and nano motion of devices. A nano carbon actuator may be available to control micro or nano scale structure. And it only need a small voltage and simple circuit to control, it would be fabricated with simple devices for MEMS and Nano scale applications.

References


