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Equivalent circuit model for the strain sensing characteristics of multi-walled carbon nanotube/polyvinylidene fluoride films in alternating current circuit

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ABSTRACT

In this study, multi-walled carbon nanotube/polyvinylidene fluoride (MWCNT/PVDF) composite films fabricated by solution casting method were used to make composite sensors for large strain measurement. The strain sensing characteristics of the sensors in direct current (DC) and alternating current (AC) circuits were both investigated through experiment. It is observed that the piezoresistivity of the MWCNT/PVDF composite films in DC circuits can be used for strain sensing, but this type of application may be limited since the strain-resistance relationship of the films is highly nonlinear. On the other hand, in AC circuits, the change rate of the dielectric loss tangent (DLT) of the composite is also sensitive to the strain. Besides, the experimental results show that the dependence between the strain and the DLT change rate becomes linear if the MWCNT content and the AC frequency are chosen properly. In this work, an equivalent RLC circuit model of the MWCNT/PVDF composite was proposed to interpret the findings obtained from the experiment. The good agreement between the analytical results and the measurements indicates that the current research reveals a new mechanism for the design of high-performance strain sensors.

1. Introduction

Composites consisting of polymers and carbon nanotubes (CNTs) have been attracting more and more attention since they possess the advantages of both components. In general, polymers are insulation materials but CNT/polymer composites become conductive if there are enough CNTs in the matrices [1,2]. In literature, it was reported that the electrical properties of the CNT/polymer composites are very sensitive to some external stimuli such as temperature [3], humidity [4], vapor [5] and deformation [6–12]. As a result, CNT/polymer composites have been applied to make various sensors. Meanwhile, strain gauges are one of the most widely used sensors in engineering. As a matter of course, some meaningful efforts have been conducted to make use of CNT/polymer composites into stain detection. For instance, based on the piezoresistive behaviour induced by the “tunneling effect” [13], Hu et al. fabricated strain gauges using CNT/Epoxy composite films [14]. With certain CNT content, the sensitivity of the composite films can reach to 22, which is about 10 times higher than that of the conventional metal foil strain gauges. Besides the excellent performance under direct current (DC) condition, CNT/polymer composites also have special dielectric properties in alternating current (AC) circuits. For example, Yadav et al. pointed out that the dielectric loss tangent (DLT) of the single-wall CNT/styrene-b-(ethylene-co-butylenes)-b-styrene composite is proportional to the CNT content in the composite but inverse proportional to the AC frequency [15]. Similarly, in low-frequency region, the DLT of the MWCNT/polystyrene composite rises as the MWCNT weight fraction increases in the material [16]. On the other hand, although the dielectric properties of the CNT/polymer have been investigated in various aspects, very few studies focus on the relationship between the DLT and the mechanical strain of the CNT composites, except

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Alamusi et al. related DLT to strain gauge design [17]. In their study, they defined a new parameter called the "AC gauge factor" using the ratio of the DLT's change rate to the strain. The maximum value of the AC gauge factor is up to 256. Up to today, there is no doubt that both the DC and AC behaviour of the CNT/polymer composites can be adopted as the mechanism to make strain sensors. Unfortunately, as reported in Refs. [14] and [17], the composite gauges are extremely sensitive to the strain, but the relationship between the strain and the dependent parameters are highly nonlinear as well. In the present research, the authors fabricated MWCNT/PVDF composite films and tested their strain-induced electrical properties in both DC and AC circuits. It is found that the DLT-strain relationship of the MWCNT/PVDF composite can be represented by an equivalent RLC circuit model.

2. Experiment

2.1. Material and sample preparation

In this research, the MWCNT/PVDF composite consists of MWCNTs, PVDF and the solvent. The filler is MWCNTs-7, provided by Nano Carbon Technologies Co., Ltd, Japan. The purity of the material is 99.5%. The average diameter of the MWCNTs is 20–80 nm, and the aspect ratio of the tubes is larger than 100. The PVDF matrix is Kynar 740, manufactured by Arkema. The solvent is N, N-dimethylformamide (DMF) with a purity of 99.9%. The fabrication process for MWCNT/PVDF strain gauges is described in Fig. 1. Basically, the PVDF powder is dissolved into the DMF and the MWCNTs are dispersed into the PVDF paste through planetary mixer and ultrasonication. Then the liquid mixture is poured into a mould to make MWCNT/PVDF films by solution casting method. The composites films fabricated using the proposed process have excellent ductility. When in tension, the elongation of the material can achieve 20% without obvious damage. It should be mentioned that it is better to polish the films using sandpapers before applying silver paste to make electrodes. The average thickness of the films is 100 μm. The sizes of the composite strain gauges are shown in Fig. 1. For comparison, three batches of strain gauges with different MWCNT contents were fabricated. The weight fractions of the MWCNT in the three types of specimen are 0.6%, 0.8% and 1.0%, respectively.

In general, the distribution of the MWCNTs in the matrix affects the electrical conductivity of the MWCNT/polymer composite significantly. However, through the specific fabrication process illustrated in Fig. 1, the MWCNTs can be dispersed into the PVDF matrix evenly. Fig. 2 consists of the SEM photos of the cross section of a selected sample which was acryo-fractured in liquid nitrogen. The photos show that there is no obvious filler aggregation in the PVDF. It can also be seen from Fig. 2 (b) that the MWCNTs crisscross in 3-dimensional space to form a conductive network in the composite.

2.2. Experimental setup

Fig. 3 illustrates the self-developed test setup. In an experiment, the two electrodes of a composite strain gauge are clamped by insulated sliders that can move along the lead rails. A raster rule is used to read the displacement of the movable slider so the strain of the film can be calculated. During stretching, the resistance, DLT and other DC or AC properties of the specimen are measured by a LCR precision bridge tester. The voltage and the frequency of the circuit can be adjusted in case of need.

3. Results and discussion

Conventional strain gauges take the piezoresistivity of materials as the performance mechanism. Therefore, the change rates of the resistance of the composite films were investigated using the test setup. For convenience, it is defined that $\Delta R = R - R_0$ and $\alpha = \Delta R / R_0$, where R denotes the resistance and R_0 is its initial value at null strain state. As shown in Fig. 4, the change rate of the resistance of the MWCNT/PVDF film is dependent on the strain. Overall, when the strain is getting larger, the value of α becomes larger too. Actually, the monotonic relationship between α and ε is the

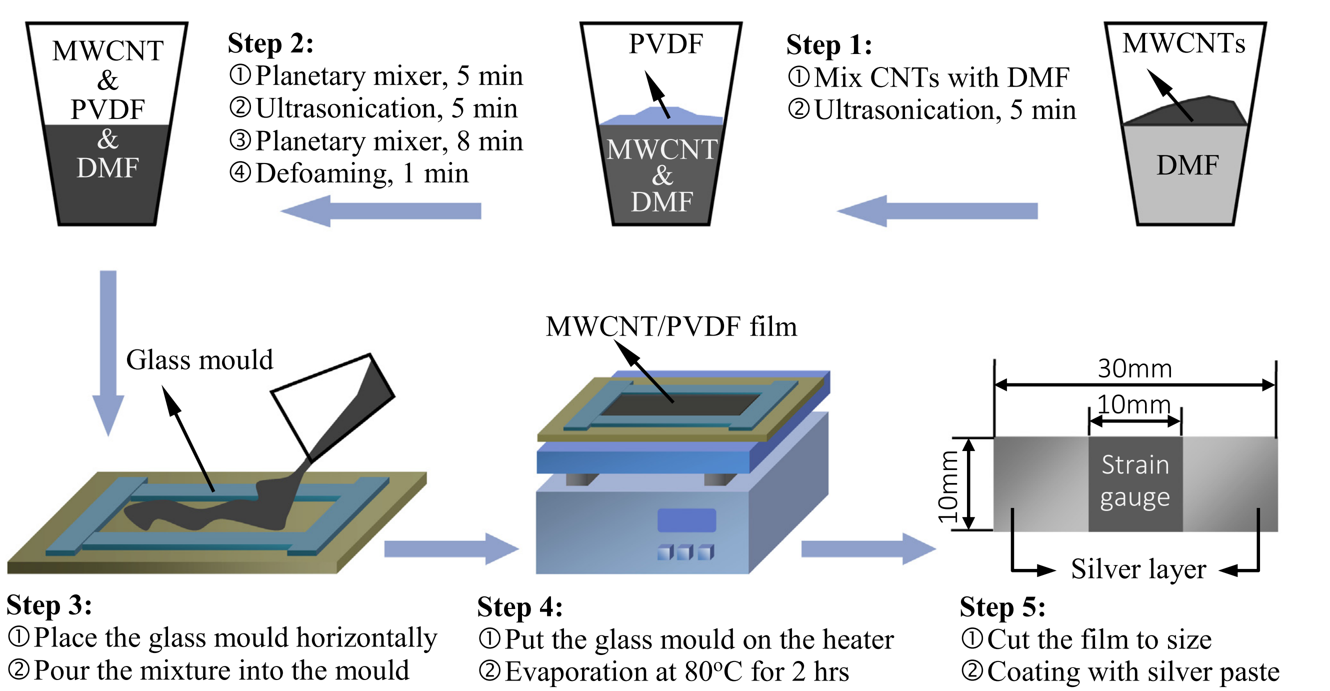

Fig. 1. Fabrication process of MWCNT/PVDF nanocomposite film. (A colour version of this figure can be viewed online.)