Study on the impedance of aligned carbon microcoils embedded in silicone rubber matrix*

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(Received 29 January 2010; revised manuscript received 23 June 2010)

This paper reports that carbon microcoils are grown through a chemical vapour deposit process, they are then embedded in silicone rubber, and manipulated to parallel with each other along their axes in the resulting composite. The impedance $|Z|$ as well as phase angle θ of both the original carbon microcoil sheets and the aligned carbon microcoil/silicone rubber composites are measured. The results illustrate that carbon microcoils in different forms show different alternating current electric properties. The aligned carbon microcoils in the composites show stable parameters for $f < 10^4$ Hz but a sharp decrease in both $|Z|$ and θ for frequencies $> 10^4$ Hz, which will also change as the carbon microcoils are extended. But, the original sheets have a pure resistance with their parameters stable throughout the entire alternating current frequency range investigated.

Keywords: carbon microcoils, impedance, alignment

PACC: 6148, 7360T, 8160H

1. Introduction

Developing intelligent nano/micro functional apparatus[1−4] is one of the major challenges that today contemporary scientists are facing up. Carbon microcoils (CMCs) have drawn scholars' attention for their unique physical properties and potential application at micron level. A great quantity of CMCs can be synthesized by means of catalyst chemical vapour deposition (CCVD) or arc discharge process[5,6] and they present different shapes shown as difference in diameter, coil pitch and section. The typical properties of CMCs such as their tensile strength, extension, bending and conductance, etc. have been thoroughly studied.[7−10] The composite made up of CMC/polymer matrixes has also been widely explored. Yang *et al.*[11] and Chen *et al.*[12] claimed that they have synthesized CMC/elastomer composite which, they think, is likely to be employed to make tactile sensors for its property of high sensitivity. Yoshimura *et al.*[13] have made a thorough study of the mechanical properties of the composite which is formed by imbedding CMCs into a polymer matrix. Katsuno *et al.*[14,15] stated that they had measured the electrical parameters (impedance and phase angle) as a function of the CMC content in matrix. But, these CMCs in the matrix were in disorder.

In this report, the aligned CMCs embeded in silicone–rubber matrix have been successfully prepared, and their AC electrical properties were measured and compared with those of as-grown CMCs. The results showed that the impedance of the as-grown CMCs was almost not influenced by the AC frequency and their phase angle was zero. But for the aligned CMCs, their impedance and phase angle strongly depended on the AC frequency and also relied on the extension states of CMCs in matrix. The CMC states with their inductance and capacitance, which may dominate the properties of the samples, were investigated. These findings should be valuable for designing micro-circuit and tactile sensors.

2. Experiment

The CMCs used in the study were synthesized by the CCVD process using acetylene as a carbon source under the temperature of 780–800 °C. The as-grown CMCs were deposited on silicon substrates and gathered in the shape of sheets. These sheets were cut into rectangular strips, which then were put on with a special device so that the CMCs in the sheets were aligned. The aligned CMCs were processed in silicon–rubber solution that contained 5% hardener. The polymer solution was spin-coated onto the CMCs at 500 rpm for 60 s, so that the CMC/silicon–rubber

*Project supported by the Natural Science Foundation of Jiangsu Province of China (Grant No. BK2008129).

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composites were obtained. The composites have approximate sizes of 28 mm×5.5 mm×0.6 mm, in which the weight ratio of CMCs is around 10%. The composites and the as–grown CMC sheets are separately placed on two copper electrodes with a separated distance of 3 mm. The AC electrical parameters of all samples were measured with an impedance measurement unit (ZAHNER ELEKTRIC, IM6ex) in the frequency range from 100 Hz to 1 MHz. These samples were observed by a scanning electron microscope (SEM, S–520) and an optical microscope (Guangzhou, L–2020A). And their impedance spectra were analysed with software (ZSimpWin).

3. Results and discussion

The morphology of the representative CMCs in the as-grown sheets is shown in Fig. 1(a). These CMCs, which are very pure, overlap each other and arrange in a random manner. Figure 1(b) shows the morphology of the aligned CMCs imbedded in silicon–rubber matrix, which is extending under a certain drawing force. Almost no fracture of CMCs exists in the composite.

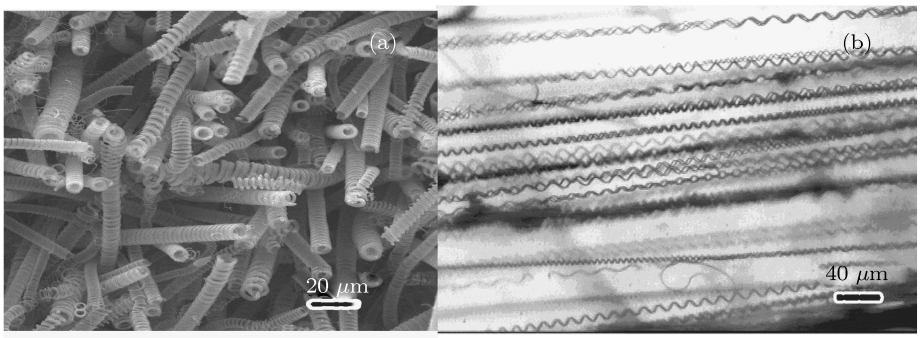


Fig. 1. (a) The SEM image of as-grown CMCs, and (b) the optical image of an aligned CMC/silicone–rubber composite.

The impedance spectrum of the as-grown CMCs was measured as shown in Fig. 2(a).

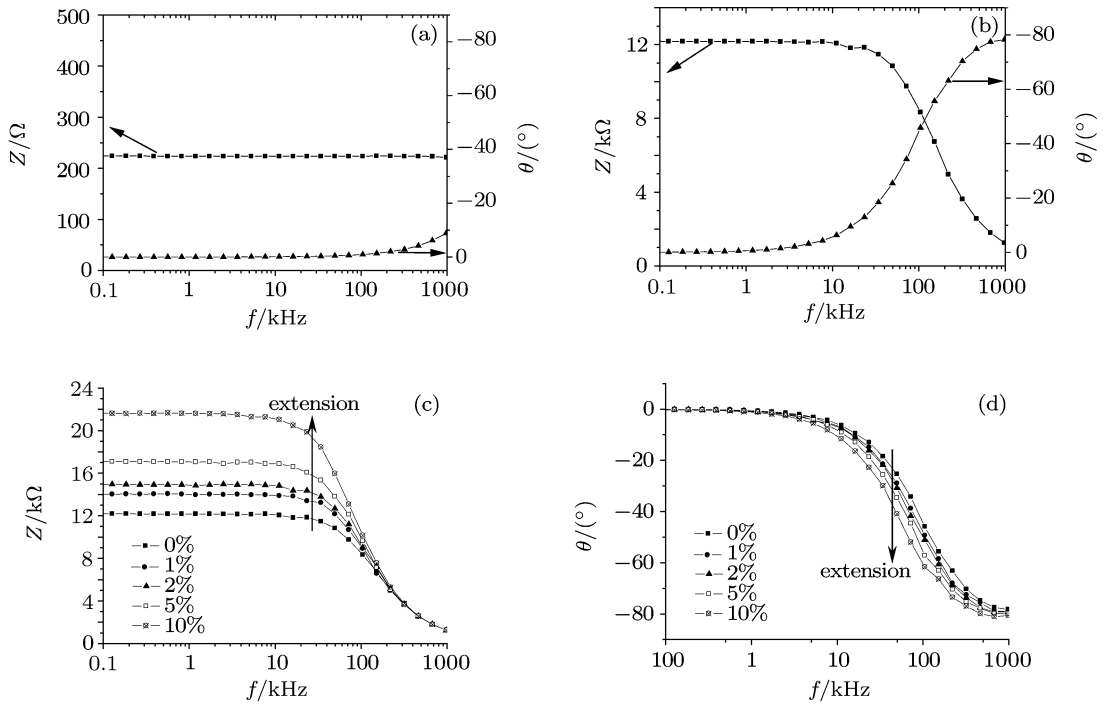


Fig. 2. The dependence of electrical parameters ($|Z|$ and θ) on frequency for (a) as-grown CMCs, (b) an aligned CMC/silicon–rubber composite, (c) the impedance $|Z|$, and (d) the phase angle θ depending on frequency as a function of CMC extension for the aligned CMC/silicon–rubber composite. The composite is extended from 0% to 10% longer than its original length.

The experimental dots being in a horizontal line mean that the as-grown CMCs with their impedance are not influenced by the AC frequency and act like pure resistance. This can be explained as follows: the as-grown CMCs contact with each other to form a net structure in a disordered manner, which leads to the electromagnetic induction effect from each coil induced by AC being cancelled out.[10] These random CMCs were measured with a value of 200 Ω and 0° of both $|Z|$ and θ, respectively.

Using silicon–rubber as matrix, we find that the CMCs are controllable in parallel with each other, and their AC properties are studied. Figure 2(b) depicts the impedance spectrum of a composite, where the CMCs are in alignment and not stretched. The obtained experimental data are wholly different from the former. During $f < 10^4$ Hz, the composite shows a stable characteristics of its AC parameters. During AC frequency $f > 10^4$ Hz, its $|Z|$ value and phase angle θ sharply decrease from 12 kΩ to less than 2 kΩ and 0 to −80°, respectively. Exerting a force on the composite pulled the aligned CMCs to different lengths. The extension ratio was controled from 0% to 10%. The impedance spectra are measured for different extensions and are shown in Fig. 2(c). It can be seen that the larger the extension, the bigger the $|Z|$ value in the frequency range from 10^2 Hz–10^4 Hz, but above 10^4 Hz the values are almost the same. Figure 2(d) shows that its phase angle θ is influenced by the extension ratio. It decreases with increasing the ratio over a wider range of frequency area, but tends to 0 below 10^3 Hz.

The aligned CMCs should dominate the composite with its AC property. Because of the coil structure like spring, each of these aligned CMCs can behave like a micro-inductance but has a small value of inductance for its micro size in diameter. These aligned CMCs can be regarded as many micro-inductances in series parallel and their impedance can be expressed as

$$Z = Z_1 + \mathrm{j}X_1, R_2 + \mathrm{j}X_2, \ldots, R_i + \mathrm{j}X_i \ldots), \quad (1)$$

where, the index i refers to the i-th CMC and R_i and X_i are the real part and imaginary part of the impedance of the i-th CMC respectively; $X_i = 2\pi f L_i$ (L_i represents the inductance of the i-th CMC). Based on Eq. (1), small L_i and low frequency will lead to $X_i \ll R_i$ and $|Z| \approx |Z(R_1, R_2, \ldots, R_i, \ldots)|$, so the impedance of composite is mainly decided by the self-resistance of the coils under low frequency, which is not influenced by the frequency. As the AC frequency is high enough, X_i will be much bigger than R_i and $|Z| \approx |Z(X_1, X_2, \ldots, X_i, \ldots)|$, which causes that the impedance depends on the frequency strongly. As the aligned CMCs are extended, their self-resistance rises, so the impedance spectrum increases.

The phase angle θ of the composite approaches −80° as the AC frequency becomes big and arrives at 1 MHz (as shown in Fig. 2(b)), which means that the capacitance component produced from the aligned CMCs should be considered. We have designed an equivalent circuit (shown in Fig. 3(b)), which has the very similar impedance spectra with the composite (see Fig. 3(c)), to analyse the capacitance in the composite. We can see that each of the aligned CMCs is equivalent to a parallel connection of a capacitor and an inductor taking with resistance as Fig. 3(a).

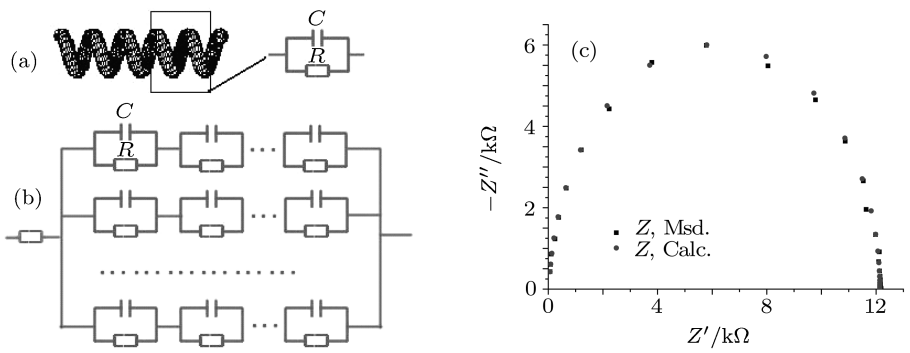


Fig. 3. (a) The sketch of a single coil. (b) The equivalent circuit mode of an aligned CMC composite. (c) The real part (Z') and imaginary part (Z'') of the impedance of an aligned CMC composite (measured, Msd.) in comparison with that of its equivalent circuit (calculated, Calc.).

So, it is proposed that

$$X_i = \left(\frac{1}{2\pi f L_i} + 2\pi f C_i\right)^{-1}, \quad (2)$$

when frequency $f > 10^4$ Hz. In Eq. (2), X_i will be decided mainly by the capacitance C_i in high frequency area, which leads to the phase angle tending to $-80°$ with AC frequency increasing high enough as shown in Fig. 2(d).

4. Conclusions

We reported the AC properties of aligned CMC/silicon–rubber composites. Their impedance were measured. The results showed that the impedance of the as-grown CMC sheets is independent of the AC frequency all the while, but that of the composites with content of aligned CMCs strongly depends on the AC frequency above 10^4 Hz. The aligned CMCs in the composites can be regarded as capacitors, inductances and resistances in series parallel. When the AC frequency is high, their impedance will be chiefly decided by the capacitance of the CMCs, which showed a strong dependence on the frequency, and the phase angles tend to 80° at high frequency end. The aligned CMCs are extended to lead to their self-resistance rising, so that their impedance spectra shift up.

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