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Static and dynamic mechanical properties of polydimethylsiloxane/carbon nanotube nanocomposites

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ABSTRACT

The purpose of this study is to investigate the static and dynamic mechanical properties of polydimethylsiloxane (PDMS) and the mixture of PDMS and carbon nanotubes. The PDMS/CNT nanocomposites were stirred by an ultrasonic instrument to prevent agglomerations. The tested specimens of nanocomposites were manufactured by using the thermoforming method at 150 °C for 15 min. A micro tensile tester was adopted in this testing system with a maximum load of 500 mN and a crosshead extension of 150 mm. The static elastic modulus can be calculated by means of a tensile test and the average elastic modulus of pure PDMS is 1.65 MPa. In addition, the Nano Bionix tensile tester was also used to perform the dynamic mechanical analysis. Its dynamic frequency range is from 0.1 Hz to 2.5 KHz. The dynamic properties of PDMS/CNT nanocomposites such as storage and loss modulus can be obtained by this system. The storage modulus increased with the CNT content and also with the higher frequencies. Finally, the nanoindentation measurement system was employed to characterize the mechanical properties of PDMS and PDMS/CNTs. The measurement results of elastic modulus by a nanoindentation test have the similar trend with the results obtained by the tensile test method.

1. Introduction

Polydimethylsiloxane (PDMS) silicon-based organic polymer is composed of a repeating $[SiO(CH_3)_2]$ unit. It is in the rubber state at room temperature because it has a glass transition temperature of less than −120 °C. In addition, it possesses hydrophobic, non-conductive and bio-compatible properties and is applied in casting molds and microfluidic devices [1,2]. As is well known, carbon nanotubes (CNTs) were found by Iijima in 1991 [3]. CNTs exhibit excellent mechanical and electrical properties such as light weight, high stiffness, premium thermal conduction and electric conductivity. By micro-Raman spectroscopy, Lourie et al. [4] found that the Young's moduli of single-walled carbon nanotube (SWCNT) and multi-walled carbon nanotube (MWCNT) were 3.58 TPa and 2.24 TPa, respectively when the temperature gradient was −122 K. In 1999, Salvetat et al. [5] showed that the Young's modulus of single-walled carbon nanotube was 1 TPa by using the transmission electron microscopy (TEM) technique.

In the meantime, many researchers [6–8] have also found that adding proper CNTs into polymers or epoxy resins can enhance the strength and elastic modulus of polymers. Allaoui et al. [7] added one weight percentage of MWCNTs to an epoxy resin and found that the Young's modulus and yield strength of nanocomposites had been doubled and tripled respectively, compared to the pure epoxy resin. In 2006, Yeh et al. [8] found that the tensile strength and Young's modulus of MWCNTs/phenolic composites increased with the addition of MWCNTs.

It was also found that the elastic modulus and strength of the PDMS/CNT nanocomposites were enhanced by adding MWCNTs [9]. However, there are fewer investigations of the dynamic behavior of PDMS/CNT nanocomposites. To comprehend the static and dynamic properties of these composites, the Nano Bionix universal testing system (MTS Systems Corp., Oak Ridge, TN, USA) was employed to analyze the elastic modulus, storage and loss modulus of PDMS/CNT nanocomposites. The testing system possesses the ability of continuous dynamic analysis (CDA) which is different from the traditional dynamic mechanical analysis (DMA). In addition, the nanoindentation technique [10,11] has been widely used to measure the mechanical properties of thin films in recent years. As a comparison, the elastic modulus of PDMS/CNTs polymeric nanocomposites can be determined by a commercial Nano Indenter. The TriboIndenter (Hysitron Inc., MN, USA) was adopted to characterize the mechanical properties of PDMS and nanocomposites.

2. Elastic, storage and loss modulus

The static elastic modulus (E) is the ratio of stress (σ) to strain (ε) within the range of elastic limit. The value can be obtained by

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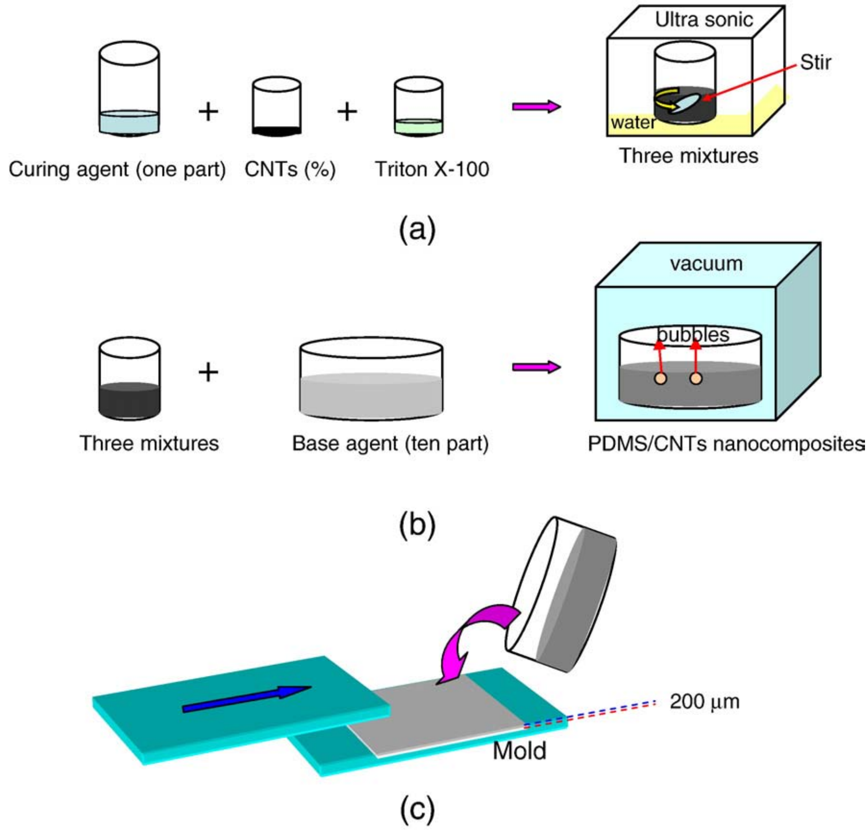

Fig. 1. Manufacturing procedure of the PDMS/CNT nanocomposites.

calculating the slope of the stress–strain curve resulting from the tensile test. For simplification, the engineering stress and strain was adopted to determine the elastic modulus in this study.

On the other hand, the dynamic behavior of PDMS/CNT nanocomposites was tested on the CDA option of Nano UTM by using a frequency sweep method. The complex modulus of the nanocomposites can be calculated from applying harmonic force and oscillation amplitude. If a linearly viscoelastic material is subjected to an oscillatory strain (input), then the dynamic strain (ε_d) is expressed as follows.

$$\varepsilon_d = \varepsilon_0 e^{i\omega t} \tag{1}$$

where ε_0 is the dynamic strain amplitude, ω is the frequency, and t is time.

Then dynamic stress (output) can be expressed as,

$$\sigma_d = \sigma^* e^{i\omega t} \tag{2}$$

where $\sigma^* = \sigma_0(\cos\delta + i\sin\delta) = \sigma_0 e^{i\delta}$, σ_0 is the dynamic stress amplitude, δ is the phase lag angle between strain and stress at the same frequency.

Substituting (1) and (2) into the general constitutive equation of the viscoleastic material,

$$[p_0 + p_1\partial_t + \ldots]\sigma_d = [q_0 + q_1\partial_t + \ldots]\varepsilon_d \tag{3}$$

In which p_0, p_1..., q_0, q_1 ... are material constants.

Then the ratio of the stress (σ^*) to strain (ε_0) can be defined as complex relaxation modulus $G^*(\omega)$ as follows,

$$G^*(\omega) = \frac{\sigma^*}{\varepsilon_0} = \frac{\left[q_0 + (i\omega)q_1 + (i\omega)^2 q_2 + \ldots\right]}{\left[p_0 + (i\omega)p_1 + (i\omega)^2 p_2 + \ldots\right]} \tag{4}$$

$$G^*(\omega) = \frac{\sigma^*}{\varepsilon_0} = \frac{\sigma_0}{\varepsilon_0}(\cos\delta + i\sin\delta) = G' + iG'' \tag{5}$$

Therefore, the real part of the complex relaxation modulus is called storage modulus $G' = \frac{\sigma_0}{\varepsilon_0}(\cos\delta)$ and the image part is called loss modulus $G'' = \frac{\sigma_0}{\varepsilon_0}(\sin\delta)$.

In addition, the ratio of storage to loss modulus can be defined as the loss tangent ($\tan\delta$),

$$\tan\delta = \frac{G''}{G'} \tag{6}$$

The storage modulus represents the elastic portion of stored energy and the loss modulus illustrates the dissipated energy of a material (i.e. viscous portion). The loss tangent is the ratio of elastic to viscous portion and would change with the storage and loss modulus.

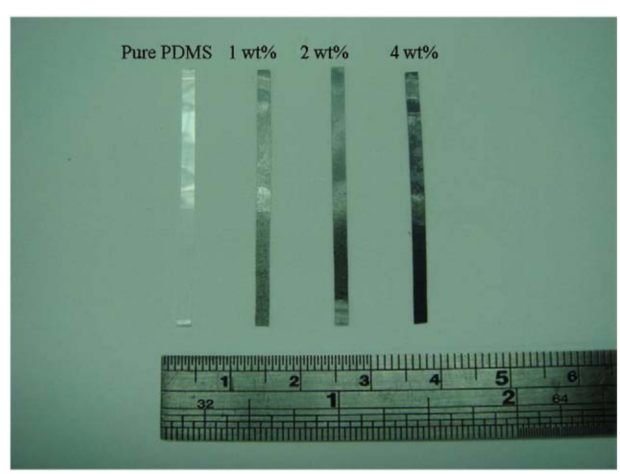

Fig. 2. The specimen of pure PDMS, 1.0 wt.%, 2.0 wt.% and 4.0 wt.% CNT nanocomposites.