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Mechanical behavior of phenolic-based composites reinforced with multi-walled carbon nanotubes

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Abstract

Two types of carbon nanotubes (CNTs), the network multi-walled nanotubes (MWNTs) and the dispersed MWNTs, were used for fabricating MWNTs/phenolic composites. The MWNTs were synthesized using the floating catalyst method through the chemical vapor deposition process. The effects of the MWNT content on the mechanical properties of the composites were investigated. Modified Halpin–Tsai equation was proposed to evaluate the Young's modulus and tensile strength of the MWNTs/phenolic composites by adopting an orientation factor and an exponential shape factor in the equation. It is found that the results obtained from the modified Halpin–Tsai equation on tensile strengths and Young's moduli fit successfully the experimental ones. The tensile fracture surfaces of MWNTs/phenolic composites were examined using field emission scanning electron microscope to study the failure morphologies of the MWNTs/phenolic composites.

Keywords: Carbon nanotubes; Resins; Mixing; Scanning electron microscopy; Mechanical properties

1. Introduction

Since Iijima discovered the carbon nanotubes (CNTs) made by the arc-discharge method in 1991 [1], CNTs with excellent mechanical, electrical, chemical resistance, and electromagnetic properties have been reported in many CNTs-related applications, such as nanoelectronics, field emission display, hydrogen storage, nanodevices, etc. On the mechanical properties of CNTs, Yu et al. [2] reported that a multi-walled nanotube (MWNT) has Young's modulus of 270–950 GPa; while a single-walled nanotube (SWNT) has Young's modulus of 1–1.2 TPa [3,4]. Since the CNTs have better mechanical properties than those of the traditional carbon fibers, the development of CNTs as reinforcement for polymer matrices is quite promising.

Wagner et al. [5] found that the stress transfer efficiency in multi-walled nanotubes/polymers is at least one order of magnitude larger than that of conventional fiber-based composites. Zeng et al. [6] reported a 50% increase in Young's modulus in CNTs/PMMA composites when 5.0 wt% carbon nanofibers were introduced into the composites. Allaoui et al. [7] found twice and triple improvement on Young's modulus and yield strength respectively, when 1.0 wt% MWNTs was added to epoxy matrix. However, Lau and Shi [8] reported a negative effect on the mechanical property of MWNTs/epoxy composites due to a poor interaction between the MWNTs and the epoxy matrix. Other researches on carbon nanofiller/polymer composites [9–11] reported increases in mechanical properties with increasing amount of CNTs. Tai et al. [12] showed a double improvement in tensile strength of the MWNTs/phenolic composites when

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3.0 wt% carbon nanotube network was introduced into the phenolic matrix.

Several models were proposed to evaluate the mechanical properties of the composites as a function of the volume fraction of the reinforcement. Cox [13] found an orientation factor to take account of the randomness of the discontinuous fibers in composites; and Bai [14] used the orientation factor in the rule of mixture to handle the randomly oriented CNTs in polymer matrix. In addition, the in-plane randomly-oriented discontinuous fiber lamina model [15], the modified Cox model [6], the Mori–Tanaka method [16,17], and the Halpin–Tsai equation [18] were used to fit the experimental results. The Mori–Tanaka method and Halpin–Tsai equation were suggested by Fornes and Paul [17] to evaluate the mechanical properties of nylon 6/clay composites.

In this paper, the dispersed and the network MWNTs were mixed with thermosetting resol-type phenolic resin to form composites. Tensile tests were performed to obtain the mechanical properties of the composites with different contents of MWNTs. The Halpin–Tsai equation [18] was modified by adding an orientation factor and an exponential shape factor, and the results fitted the experimental data successfully. The morphologies of the fracture surfaces of MWNTs/phenolic composites were studied and the failure mechanisms of MWNT/phenolic composites were discussed.

2. Experimental

2.1. Synthesis and characterization of MWNTs

The MWNTs were produced using the floating catalyst chemical vapor deposition (CVD) method, which has the advantages of low cost, high yield, and being easily controlled in experiments. Benzene, ferrocene, thiophene, and hydrogen were used as the precursor, catalyst, promoter, and carrier gas respectively. Thiophene was added into benzene at a ratio of 1:230 by volume. Hydrogen was used to bubble the precursor to produce the hydrocarbon gas, and the gas was channeled into a reservoir where ferrocene was placed. Then the mixtures were conducted into a 1.0 m long tube furnace with the temperature maintained at 1250 °C. In the furnace, the reaction pressure was kept at 700 ± 10 mbar. Fig. 1 shows the image of as-fabricated MWNTs obtained from field emission scanning electron microscope (FESEM). The as-fabricated MWNTs twist together into a network and are denoted as the network MWNTs. The diameter of MWNT was found statistically in the range of 15–40 nm with a mean value of 23.63 nm, as shown in Fig. 2. Since the portion of the network MWNTs tangled and curved into the matrix has no direct effect on the tensile mechanical properties of the MWNTs/phenolic composites, the apparent length of the network MWNTs in Fig. 1 was estimated and was used in this study. The apparent length of the network MWNTs is denoted as the effective length which is in the range of 10–25 μm with a mean value of 17.57 μm as shown in Fig. 3. Fig. 4 shows the FESEM image of the MWNTs after milling which are denoted as the dispersed MWNTs. In Fig. 4, MWNTs aggregate together with little amorphous carbon on the surface, which is different from the morphology of the network MWNTs. The length of the dispersed MWNTs is between 2.0 and 4.5 μm with a mean value of 3.07 μm as shown in Fig. 5.

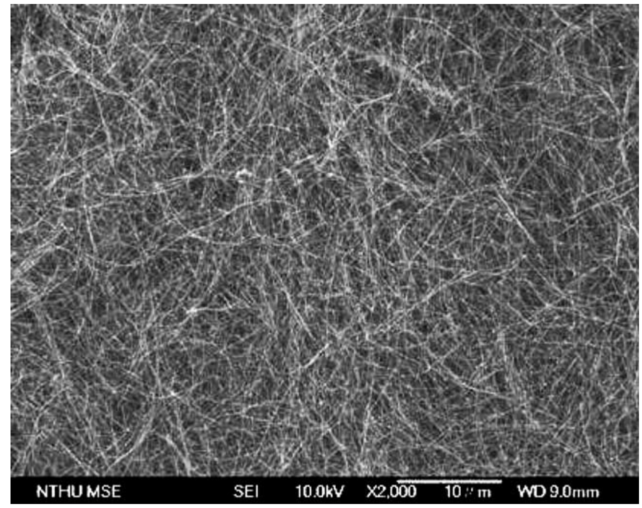

Fig. 1. SEM image of network MWNTs.

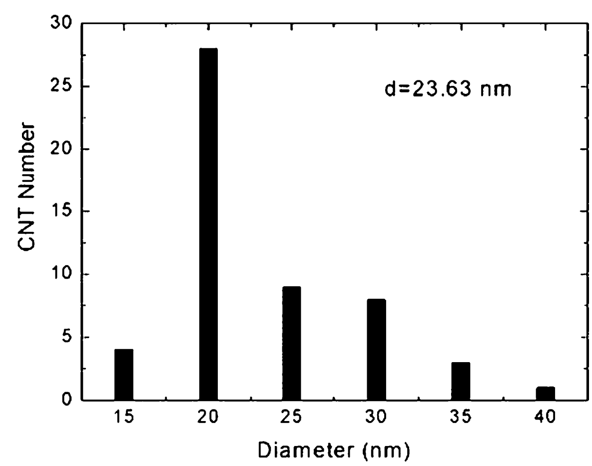

Fig. 2. Number of network MWNT with different diameters.

2.2. Fabrication and characterization of MWNT/phenolic composites

Two different types of MWNTs, the network MWNTs and the dispersed MWNTs, were used to reinforce the PF-650 phenolic resin provided by Chang-Chun Co., Taiwan. For the same weight of MWNT, the network MWNT with cotton-like structure has low-