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A study of mechanical peeling behavior in a junction assembled by two individual carbon nanotubes

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A B S T R A C T

The mechanical characteristics of nano-scale interface between by carbon nanotubes (CNTs) play critical roles in macro-mechanical properties of CNT-based hierarchical composites. In this study, an in-situ peeling experiment for a sidewall-contacted junction assembled by two individual CNTs was achieved by using a force measurement system in the scanning electron microscope. The whole peeling mechanical behaviors were investigated by a typical peeling force-displacement curve combining with corresponding experiment video, and an interesting double peaks phenomenon about peeling force was observed. In order to further reveal this peeling process, a model of two-dimensional finite element analysis was developed, where an equivalence of rectangular sections to cylindrical sections of CNTs and a bilinear cohesive law were employed. The theoretical prediction of peeling behaviors was agreed with the experimental one. More importantly, by this model it is found that the double peaks of peeling force result from shape transition of CNTs from concave to arc, with an abruptly interface crack. This work could provide an in-depth understanding on mechanical behaviors of CNT-based hierarchical composites.

1. Introduction

Recently, hierarchical materials formed by carbon nanotubes (CNTs), such as CNT fibers, films and blocks (Fig. 1a–c), have been attracted much attention due to their outstanding mechanical, electrical and thermal properties [1–8]. In such materials, the CNT fibers are usually produced by spinning CNTs forests or CNT solutions, where the CNTs with limited length can be continuously drawn out via complex entanglements and attractive interactions of CNTs, thus forming macro-scale fibers (Fig. 1a) [9,10]. The CNT films can be obtained by drop-drying from solvent, airbrushing, and Langmuir-Blodgett deposition (Fig. 1b) [7]. The CNT blocks including aerogel and sponge are normally prepared by a chemical vapor deposition (CVD) process (Fig. 1c) [5,6]. The structural characteristics of CNT films and blocks are that the CNTs overlap in a disorderly fashion and uniform and homogeneous porous structures are formed. In general, basic configurations of these materials are the junctions self-assembled by CNTs, whose frameworks can be classified as sidewall-to-sidewall, end-to-end, end-to-sidewall and entanglement junctions, etc [11–15]. The interfacial bonding in CNT junctions is commonly based on van der Waals (vdW), chemical or covalent interactions between CNTs resulting from various treatment processes for CNTs. The macro-scale mechanical properties of this kind of hierarchical materials are highly dependent on the mechanical characteristics of nano-scale interfaces between CNTs, indicating that the CNT junctions play key roles in stress and energy transfer. Therefore, an investigation into mechanical characteristics of interface performances of the CNT junctions is very important for understanding mechanical behaviors and potential applications of these CNT-based hierarchical materials.

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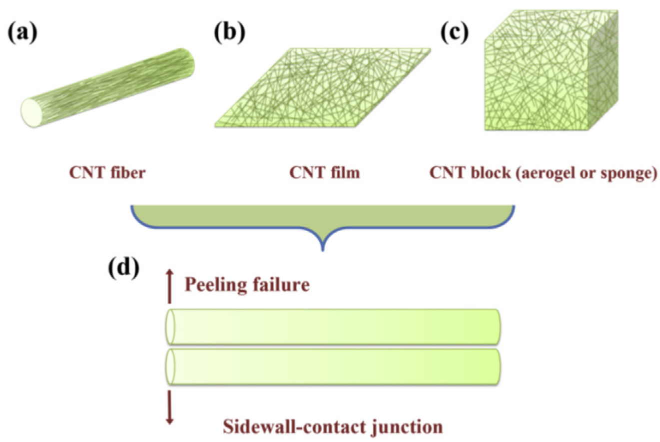

Fig. 1. Schematics of CNT-based hierarchical materials including (a) CNT fiber, (b) CNT film and (c) CNT block. (d) a schematic for a sidewall-contacted junction under peeling load. (A color version of this figure can be viewed online.)

Basic failure modes of sidewall-contacted CNT junctions include shearing and peeling failures. So far, the shearing failure behaviors have been studied by several research groups. For examples, Espinosa et al. [16] first performed an in-situ experiment in a scanning electron microscope (SEM) to carry out tension of a junction formed by two multi-walled CNTs with same outer diameters, by which the maximum tensile failure load was obtained. Combining with a continuum model, the interfacial shearing strength between CNTs was determined to be 30–60 MPa depending on the CNT chirality. In Wang et al.'s work [12], it is found that the maximum failure load is sensitive to outer diameter and wall numbers of CNTs. The main reason is that there is a typical radial deformation between two closed CNTs, which can enhance the interfacial shear force. This deformation increases with increase of outer diameter of CNTs, whereas decreases with increase of wall numbers of CNTs.

For peeling failure, most work is still suspended on peeling of single CNT from various two-dimensional (2D) substrates [17–26]. Strus et al. [21] carried out the mechanical peeling of a single CNT from a graphite substrate in the atomic force microscope (AFM), and the curve of peeling force versus displacement was extracted. Meanwhile, a theoretical model was established to predict it. Huang [26] conducted molecular dynamics simulation to investigate the mechanical behaviors of peeling CNTs from Au substrates, in which effects of CNT junction length, peeling velocity and binding energy on the peeling behaviors were studied. So far, only one literature referenced the peeling of CNT selves, where a single-walled CNT was peeled from a CNT bundle and the curvature deformations of CNTs, adhesion force and strength between CNTs in the CNT bundle were studied [27]. Although above studies can provide some insights on mechanical behaviors of CNTs during peeling to some extents, in-depth and full understanding on this peeling failure is still lacking. Up to date, to the best knowledge of authors, experimental and theoretical investigation on peeling a sidewall-contacted junction self-assembled by two individual CNTs has not been reported in open publications.

In this paper, an in-situ experiment performed in a SEM was conducted for peeling a sidewall-contacted junction self-assembled by two individual CNTs (Fig. 1d). After that, a 2D finite element analysis (FEA) model, where cohesive damage is considered, was developed to predict the peeling mechanical behaviors.

2. Experimental

2.1. Material preparation

In this study, we utilized a kind of hierarchical structure where the CNTs were grown on the carbon fiber (CF) surfaces by CVD to achieve the in-situ peeling of CNT junctions as shown in Fig. 2a. During CVD, with a high density of CNTs, parts of two close CNTs could naturally bond together to form sidewall-contacted junctions (Fig. 2b–c). Fig. 2d is the transmission electron microscope (TEM) image of a single CNT. There are two advantages using this hierarchical structure: (1) one can omit a difficult manipulation step for building a sidewall-contacted junction; (2) the interfacial characteristics between CNTs are same as those in most of the CNT-based hierarchical structures prepared by CVD. Therefore, the present investigation into peeling behaviors is universal and more helpful to understand mechanical properties of these CNT-based hierarchical materials. The length of as-grown CNTs ranges from 0.5 to 20 μm. The outer diameter is about 50–120 nm. The detailed preparation process can be found in the literatures [10,26].

2.2. In-situ experiment

Here, a sensitive force measurement system (FMS) (Kleindiek Nanotechnik, Germany) is used to perform the in-situ peeling test. The testing process is conducted in the chamber of a SEM, so that whole experimental process can be observed. The FMS mainly include a MM3A-EM nano-manipulator with an AFM tip (the cantilever length of AFM tip is 120 μm) and a force output system. The nano-manipulator can achieve three-dimensional moving with a minimum moving resolution of 0.25 nN. The measurement resolution and the maximum endurance force of AFM tip are ~1 nN and 80 μN, respectively. The force signal is output by the FMT-400 sensor, whose resistance is 500–650 Ω and sensitivity is 3.1×10^{-3} mV/nm at vbridge = 2.5 V. Before testing, the AFM tip is calibrated by a standard calibration cantilever (spring constant is 9.38 μN/μm) so that the data obtained is sufficiently accurate. See detailed experimental process and results in Subsection 4.1.

3. Theoretical peeling model

We employed a commercial FEA software MSC NASTRAN to simulate the peeling mechanical behaviors of sidewall-contacted junctions. In the FEA computation, an equivalent 2D peeling model with geometric and material nonlinearities was implemented. The 4-node isoparametric elements were used to mesh CNTs and 4-node interface elements with fully-nonlinear features were used to mesh interface. Linear elastic deformations in CNTs with large deflections are considered but a cohesive zone model is applied to the interface.

4. Results and discussion

4.1. Peeling mechanical behaviors of a sidewall-contacted CNT junction

4.1.1. In situ peeling the sidewall-contacted CNT junction

In order to carry out the in-situ peeling test, one CNT/CF hierarchical structure is first picked out from the CNT/CF bundles and cut into several segments with a length of 3 mm. One CNT/CF segment is then fixed on a metal holder using glue in the optical microscope, as shown in Fig. 3a. The prepared samples and the nano-manipulator are put into a chamber of SEM. The cantilever of AFM tip should be parallel to axial direction of the CF so that loading direction can be perpendicular to axial direction of the CNT.