in the different responses of the composite to the same solvent vapor.

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Effectiveness of using carbon nanotubes as nano-reinforcements for advanced composite structures

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Carbon nanotubes exhibit many unique mechanical and electrical properties depending on their sizes, chirality and orientations. Recently, carbon nanotubes have been used as extremely strong nano-tubular-reinforcements, like fibres, for making nano-composites [1–3], which possess extraordinary high strength with low weight and moderate electrostatic discharge properties [4]. These nano-reinforcements could be used for improving the tensile properties and increasing the fracture energy once a crack is initiated in the composites. Some recent research has shown that the use of nanotubes, which are aligned perpendicularly to the cracks are able to slow down the crack propagation process by bridging up the crack faces [5,6]. The nanotubes, like conventional fibres can reinforce the polymer matrix to form advanced nano-composite materials. Ideally, these materials may be used to improve the out-of-plane and interlaminar properties of current advanced composite structures by increasing the matrix strength and linking up individual laminar layers with these tiny pin-like structures.

The mechanical properties of conventional reinforced fibres used in large-scale advanced composites are homogenous throughout their length. However, the mechanical performances of nanotube composites using either single-walled or multi-walled nanotubes in polymer matrices are doubtful. Although the tensile strength and modulus of the single-walled nanotubes have been measured to be as high as 200 GPa and 1 TPa, respectively, the exact stresses which are borne by these high strength nanotubes are unknown because of the uncertainty in the bonding between the nanotubes and the surrounding matrix. A sufficient stress transfer length is also important to allow all the stress to be transferred from the matrix to the nanotubes. According to the figures shown in [1,4,5], it is obvious that the nanotubes had a poor interfacial bonding strength with the polymer matrices since all the nanotubes were pulled out. In Fig. 1, local deformations of the matrix adjacent to stiff nanotubes and a longest pulled-out nanotube after a three point bend test of a nanotube/epoxy bar with 2 wt.% nanotubes are shown. The flexural strength diagram shown in Fig. 2 also reveals that a low flexural strength of the nanotube/epoxy bar compared with a bar made with pure epoxy was measured. Obviously, the stiff nanotubes were pulled out and, because of their great stiffness, in the process they deformed the surrounding

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matrix, thus enlarging the holes from which they came. Therefore, in order to effectively use the nanotubes as intrinsic reinforcements for composite structures, the first critical issue that must be solved is to improve the weak bonding between the nanotubes and surrounding matrix systems. Otherwise, the use of nanotubes in polymer-based structures exhibits no benefit and potentially weakens their mechanical performance.

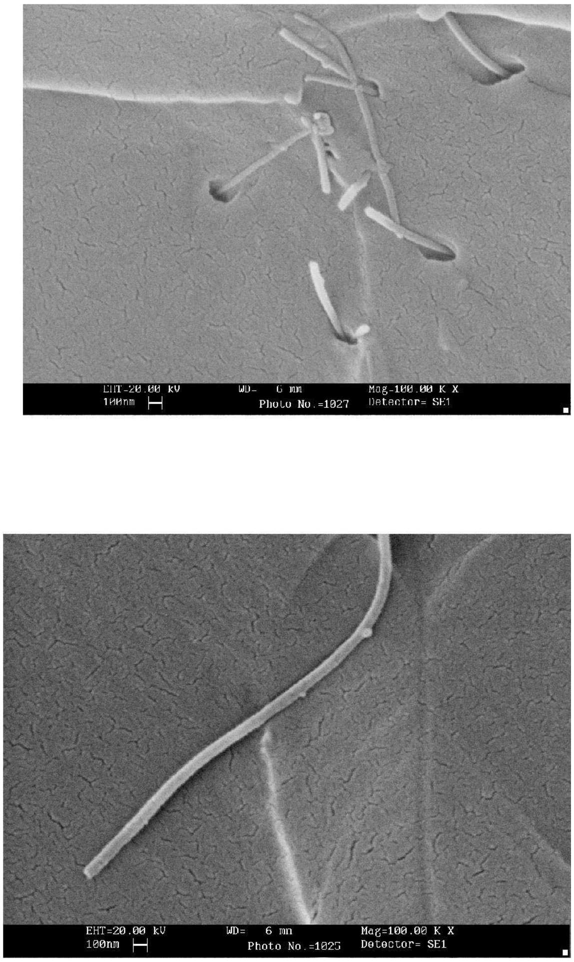

Fig. 1. (a) All nanotubes were pulled out after three point bending test. (b) A longest nanotube after being pulled out.

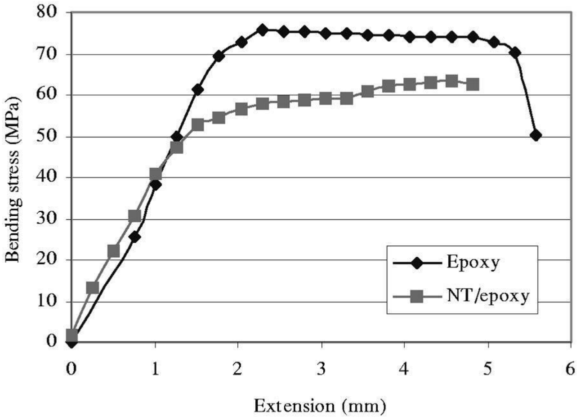

Fig. 2. The results from the flexural strength test.

A second issue is the effectiveness of using multi-walled nanotubes for composite applications. In the aforementioned problem, the interfacial bonding properties between the nanotubes and matrix are shown to be a critical issue that must be solved. However, that issue only affects the structural problem of the outer shell of the nanotubes. For multi-walled nanotubes, only very weak van der Waals forces exist to link the individual graphene shells together [7]; all inner shells can rotate and slide freely without the need of imposing any large forces. Therefore, using multi-walled nanotubes as intrinsic reinforcements for composite structures may not allow the maximum strength to be achieved since non-uniform axial deformations inside the multi-walled nanotubes may exist (Fig. 2). Each individual shell of the nanotubes may take different levels of stress or it is possibly that only the outer shell takes up all the load while the inner shells remain in an almost unloaded state. Eventually the mechanical properties of the structures may deteriorate.

There are therefore two critical issues related to the use of nanotubes to form advanced composites. To fully achieve the maximum strength of the nanotube composites attention must be paid to two critical issues: (1) an in-depth investigation on the interfacial bonding characterisation of the nanotubes to different types of polymer matrices and (2) the use of single-walled nanotubes may be more beneficial than the use of multi-walled structures.

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