Three dimensional orientation angle distribution counting and calculation for the mechanical properties of aligned carbon nanotube/epoxy composites

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Abstract

This paper presents effects of carbon nanotube (CNT) orientation angle distribution on elastic moduli of aligned CNT/epoxy composites that were fabricated with various volume fractions using hot-melt prepreg method. Tensile testing was conducted to evaluate the composites' mechanical properties. The composites' Young's moduli increased with increasing CNT volume fraction. Scanning electron microscopy (SEM) revealed CNT orientation angle distribution data for the surface and through-thickness planes. The standard deviation of CNT orientation angle distribution was about 30 deg for the surface, and 22.5 deg for the through-thickness plane. The effective Young's modulus of CNT was estimated using the equivalent inclusion theory (Eshelby/Mori-Tanaka theory) incorporating a three-dimensional

CNT orientation distribution function. The CNT Young's modulus was approximately 800 GPa, which agrees with reported theoretical and experimental values.

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Introduction

Numerous studies of the mechanical properties of composites, including interlaminar reinforcement properties using carbon nanotubes (CNTs) or vapor grown carbon fibers (VGCFs) have been conducted over the last decade because of CNTs' extremely high strength and elastic modulus [1–14]. However, the mechanical properties of the CNT/ polymer composites are much lower than the theoretically predicted values [1–7]. Insufficient mechanical properties of CNT/polymer composites result from the random orientation, inadequate dispersion such as agglomerations of CNTs, low volume fraction, low aspect ratio of CNTs and weak CNT/matrix interfacial strength [1, 15].

To control the CNT orientations in composites, Thorstenson and Chou proposed “microtome cutting method” [15]. Using this technique, the CNT alignment can be controlled. The standard deviation of the orientation angle distribution was within 15 degree for arbitrary aligned direction. Nevertheless, applying this method to actual engineering products is difficult for three reasons; the sample becomes smaller, the system requires specific facilities, which makes costs prohibitively high.

Application of CNT bucky paper as a stiffener and increase of the CNT volume fraction in composites have been attempted [9]. In fact, CNT/polymer composites with high CNT volume fraction (> 10 vol.%) were produced using bucky papers. Randomly oriented CNT sheets for the surface direction were obtained using this method. Nevertheless, the problem for the orientation angle of CNTs remains unresolved.

Recently, the application of vertically grown multi-walled CNT (MWNT) has been attempted to achieve

high CNT volume fractions, high aspect ratios and better orientation in the CNTs/polymer composites.

Several technologies used to produce vertically grown multi-walled CNT (MWNT) have been established in recent years [16–18]. For example, Bradford et al. produced highly oriented CNT sheets and CNT/epoxy composites by pushing down the CNT-array in the diagonal direction [18]. They reported that CNT/epoxy composites exhibit high tensile strength of 402 MPa and Young's modulus of 22.3 GPa by adding a 32% weight fraction of CNT, which values are about 8.5 times and 6 times higher than those of pure epoxy. This method has been demonstrated for the reproduction of high elastic modulus and strength with higher volume fraction than that of existing CNT composites. Thermal and electrical properties of CNT papers were also evaluated by another group [19]. However, the size of the produced CNT sheets is restricted by the size of the substrate used for CNT production.

Zhang et al. proposed a better method to produce aligned CNT sheets from CNT forests in 2005. Horizontally aligned CNT sheets were obtained easily by drawing CNTs horizontally from a vertically grown CNT forest [20,21]. This method might be applicable for mass production of large lots. Cheng and Fan have reported similar studies related to aligned CNT sheet composite [22–24]. For example, they reported 16.5 wt.% CNT/epoxy composites, tensile strength of 230 MPa, and elastic modulus of 20.4 GPa.

For the effective production of aligned CNT sheets from CNT forests, it is necessary to grow a CNT forest with high efficiency. Inoue et al. proposed an efficient technique to grow a multi-walled CNT forest

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3 of high quality using iron chloride as a catalyst precursor [25]. They can grow CNTs to a length of several
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6 millimeters in only 20 min using thermal chemical vapor deposition (CVD) [26].
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10 Manufacture and evaluate the mechanical properties of aligned CNT sheet/ epoxy composites has
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12 been conducted, of which CNT forests were produced by Inoue et al. [27,28]. Stable production of
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15 CNT/ epoxy composites with easy control of the volume fraction of CNT became possible by
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18 application of hot-melt method using the uncured resin film as a matrix. This manufacturing process is
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21 surprisingly easy, producing high-quality CNT/ epoxy composites. The highest mechanical properties of
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24 our composites to date are the tensile strength of 239 MPa and Young's modulus of 89.6 GPa achieved by
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27 adding 32.8% weight fraction of CNT [28]. These values are 4.4 times and 37.6 times higher than the
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30 tensile strength and Young's modulus of epoxy polymer. Generally, mechanical properties of dispersed
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33 type CNT (10–20 vol.%)/ polymer composites increases at most around several tens of percent [6,7],
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36 which implies that the aligned CNT sheet / epoxy composites are extremely effective for the
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39 improvement of composites' mechanical properties. However, the estimated Young's moduli of CNTs
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42 from the tensile testing are 230–380 GPa, which value is lower than the actual Young's modulus of
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45 CNTs (500–1500 GPa) reported from application of theoretical and experimental methods [28–36].
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51 These mismatches are thought to result from the CNT orientation distribution and interfacial shear
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54 strength between CNT and polymer. For the quantitative evaluation of interfacial shear strength for
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57 MWNT/PEEK and the MWNT/ epoxy composite, so-called “nano-pullout testing” using a nano-pullout
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3 machine was previously conducted [37]. The average interfacial shear strength (IFSS) between
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6 MWNT and epoxy was about 20 MPa, which is smaller than that of ordinary CFRP composites (in the
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9 range of 25-90 MPa [38-41]). However, alignment effects of CNTs in the polymer for mechanical
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12 properties of composites remain ambiguous.
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16 This study specifically addressed the orientation angle of CNT in the composites. The production
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18 method of aligned CNT sheet composites strongly affects their mechanical properties. For instance, Wang
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20 et al. produced a 60 wt.% aligned CNT by stretching from randomly dispersed CNT "buckypaper", and
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22 fabricated aligned CNT/ bismaleimide (BMI) composites. The tensile strength and Young's moduli are,
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24 respectively, 2.1 GPa, and 169 GPa [23]. In contrast, Wang et al. produced 60 wt.% aligned CNTs by
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26 stretching from aligned CNT sheet. The CNT/bismaleimide (BMI) composite showed strength of 3.8 GPa,
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28 and Young's modulus of 239 GPa [24], which suggests that the CNT orientation in the composites
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30 influences their mechanical properties. However, no report has described a study undertaken for the
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32 quantitative evaluation of orientation angles of CNTs, assessing the actual reinforcement effects of
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34 CNT/epoxy composites.
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47 Previous study specifically addressed the two-dimensional alignment angle of CNTs by evaluating the
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49 surface alignment, of which the Young's modulus of CNT was about 680 GPa [28]. However evaluation
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51 of the alignment of the thickness direction is yet to be conducted.
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57 The primary objective of this study is to evaluate the quantitative effects of the orientation distribution
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of CNTs in the composites. Composites with a higher volume fraction of CNTs were fabricated and mechanical properties were evaluated. The quantitative evaluation for orientation angle distribution of CNT was expanded for three dimensions. Orientations for the surface direction and thickness direction of the specimen were obtained experimentally. Effective young's modulus of CNT was estimated by application of equivalent inclusion theory (Eshelby/Mori-Tanaka theory [42,43])

2. Experiments

2.1 Aligned CNT sheets

Aligned CNT sheets used for this study were produced from vertically aligned CNT arrays (forests). Synthesis methods for producing vertically aligned MWNTs using iron chloride powders as precursors of catalysts were established by Inoue et al. [25,26]. Aligned MWNT sheets were drawn easily from the MWNT forest. The respective MWNT lengths and diameters were about 1 mm and 50–70 nm [25,26].

2.2 Processing aligned CNT sheet/epoxy composites

The procedure used for molding CNT/epoxy prepreg has been reported elsewhere [27]. The B-stage cured epoxy resin with release paper was obtained from a commercial prepreg company (Arisawa Mfg. Co., Ltd. Japan). The epoxy resin consists of bisphenol-A type epoxy/ novolac type epoxy/ aromatic diamine curing agent. The areal weight of the epoxy resin film is controlled as 30 g/m², with thickness of

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3 about 25 μm . A CNT sheet that is 20 mm wide and 45 mm long was put on a polytetrafluoroethylene
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6 (PTFE) sheet (2 mm thickness), and was covered with epoxy resin film with a release paper. Epoxy resin
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9 was impregnated into the CNT sheet at 90°C for 3 min. After molding the prepreg sheet becomes 25–40
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12 μm thick, which depends on the CNT areal weight. After peeling off a prepreg sheet from the release
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15 paper, the prepreg sheet was cured at 130°C, 2.0 MPa for 1.5 h using the hot press [27].
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19 The weight fraction of CNTs was measured using thermogravimetric analysis (TGA). Each sample was
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22 heated to 800°C under argon gas flow. The weight fraction was calculated from the weight loss of the
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25 composites. The volume fraction of CNTs was recalculated from the weight fraction of CNTs under the
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28 assumption of 1.2 g/cm³ of density in epoxy and 2 g/cm³ in CNTs [27].
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35 **2.3 Tensile testing methods**

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38 Mechanical properties of composites for various volume fractions of CNT (Comp #1 ~7) were evaluated
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41 using tensile tests conducted on a screw-driven mechanical testing machine (Model 5966; Instron Corp.,
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44 USA) under a constant displacement rate of 0.2 mm/min at room temperature. The specimen shape is
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47 presented in Fig. 1. The specimen was 25–40 μm thick and 3 mm wide, with 45 mm overall length. The
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50 longitudinal strain was measured using a non-contacting video extensometer (AVE; Instron Corp., USA).
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53 Figure 2 depicts the tensile testing machine and video extensometer attached to it. Two white marker
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56 spots were painted on the specimen as gauge length (30 mm) target markers. The strain was measured by
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tracking the contrasting gauge marks placed on the specimen [27].

2.4 Evaluation of the CNT orientation

Tube structures of CNTs were neglected for simplicity of calculations. The CNTs in the composites produced show waviness and irregular orientation of CNTs. Evaluation of orientation angle was conducted from microscopic pictures of SEM. The orientation angle θ was evaluated as follows: first, a microscopic image of the composites at the surface ($12 \times 28 \mu\text{m}^2$) was obtained, as depicted in Fig. 3(a). The picture was divided into $2 \mu\text{m}$ lengths to obscure the waviness of CNTs, as depicted in Fig. 3(b), and Fig. 3(c). Finally, orientation angle θ was evaluated from each divided image ($12 \times 2 \mu\text{m}^2$) under the assumption that each CNT is straight.

A similar method was applied for evaluating alignment of CNTs in the thickness direction. Comp #7 was used for evaluation of the alignment to the thickness direction. For the thickness direction evaluation, a microscopic image of $6 \times 14 \mu\text{m}^2$ was obtained and divided into every $2 \mu\text{m}$. The orientation was also obtained using the same method. Each image was obtained from tensile specimens of Comp #1 – Comp #5 for obtaining the orientation angle of surface, and Comp #7 for obtaining the thickness direction.

3. Results and discussion

3.1 Stress–strain behavior of composites

Young's modulus, tensile strength and fracture strain of composites are presented in Table 1, and

representative stress–strain behavior of the composites are depicted in Figs. 4(a) and 4(b) (Fig. 4(b) for 0–1% strain). Young’s modulus and tensile strength were increased by adding aligned CNT sheets, however the fracture strain became smaller compared with pure epoxy.

The relations between the volume fraction of CNTs and Young’s moduli of composites and between the volume fraction of CNT and ultimate tensile strength of composites are shown respectively in Figs. 5(a) and 5(b). These results are compared with a result of the dispersed-type of CNT composite (CNT/ poly ether-ether-ketone (PEEK) composite [40]) in the figure. Both the Young’s modulus and ultimate tensile strength increased concomitantly with increasing volume fraction of CNTs. Additionally, they showed higher Young’s modulus and tensile strength than those reported from an earlier study [40]. These different results might be attributed to the better alignment of the CNTs and less agglomeration of CNTs in the polymer. However, in Comp #6, which has the highest volume fraction of CNT in this study ($V_f = 42.3$ vol.%), Young’s modulus of composites decreased compared with Comp #5 ($V_f = 32.8$ vol.%). This result is thought to derive from the insufficient impregnation of polymer. Figure 6 presents a fracture surface of composites viewed from the thickness direction. In most specimens, it seems that resin is adequately impregnated. However the so-called “CNT-rich region” and “inadequate molding region” are clearly visible in Comp #6. The stress concentration occurred there and mechanical properties consequently decreased. Probably, the result means that the upper limit of volume fraction is deduced using hot-melt method between 33–40 vol%.

The effective Young's modulus of CNTs (E_{eff}) is calculated from the law of the mixture (in this calculation orientations are neglected). Results show that E_{eff} = 250 GPa is obtained with a value higher than those of previous reports [27,40] but lower than the actual mechanical properties of CNTs [29–36]. The result suggests that excellent mechanical properties of CNT are not sufficiently reproducible in this composite, probably because of the waviness and orientation distribution of CNT in the composites.

Figures 7(a) and 7(b) show high magnification images of SEM at the fracture surface of composites. Figure 7(a) depicts microscopic observation results of CNT at the fracture surface. Many sword-in-sheath fractures of CNTs are visible, as reported already from previous studies [27]. Figure 7(b) shows many CNTs exposure at the fracture surface with length of 1.0–7.1 μm (4.0 μm average), which is much shorter than the actual CNT length and which suggests multiple fracture of CNTs.

3.2 Evaluation result of CNT orientation

Table 2 and Table 3 present the orientation evaluation results of Comp #1–#5 (for the surface direction), and Comp #7 (for the thickness direction). Figure 8 and Fig. 9 show representative histograms of the fiber distribution (Comp #1–#5 and Comp #7). The CNTs are aligned around the 0 deg direction (for tensile direction). The standard deviation of the fiber orientation is about 30 deg for the surface direction and 22.8 deg for the thickness direction. However, around 60–80 deg for the surface direction and 10–30 deg for the thickness direction shows higher frequency than the normal distribution graph. These outcomes

are thought to result from the CNT sheet misalignment. Approximate functions were obtained from these histograms.

3.3 Estimation for effective Young's modulus of CNT by Eshelby/Mori-Tanaka theory

The stiffness tensor $\{D\}$ was calculated from orientation functions obtained from microscopic observations. The Eshelby/Mori-Tanaka theory considering orientation angle distribution of CNTs was used for calculations [42,43]. In the coordinating system shown in Fig. 10, the stiffness tensor is calculated as

$$\{D\} = (v_0 D_0 + v_1 \{D_1 A_1\})(v_0 I + v_1 \{A_1\})^{-1} \quad (1)$$

$$\{D_{ijkl}\} = \int_{\phi} \int_{\theta} \int_{\varphi} D_{mnpq} l_{mi} l_{nj} l_{pk} l_{ql} n(\phi, \theta, \varphi) \sin \theta d\phi d\theta d\varphi \quad (2)$$

Here, $n(\phi, \theta, \varphi)$ are orientation functions satisfying the following equation:

$$\int_{\phi} \int_{\theta} \int_{\varphi} n(\phi, \theta, \varphi) \sin \theta d\phi d\theta d\varphi = 1. \quad (3)$$

The stress transformation tensor l_{ij} is written as shown below.

$$l_{ij} = \begin{pmatrix} \cos \phi \cos \theta \cos \varphi - \sin \phi \sin \varphi & \cos \phi \cos \theta \sin \varphi - \sin \phi \cos \varphi & \cos \phi \sin \theta \\ -\sin \phi \cos \theta \cos \varphi & -\sin \phi \cos \theta \sin \varphi + \cos \phi \cos \varphi & -\sin \varphi \sin \theta \\ -\cos \varphi \sin \theta & -\sin \varphi \sin \theta & \cos \theta \end{pmatrix} \quad (4)$$

A three-dimensional orientation function $n(\phi, \theta, \varphi)$ is obtainable as a multiplication of that for the surface direction and thickness direction under the assumption of independence for these directions.

In this case, the following equation can be written.

$$n(\phi, \theta, \varphi) = \frac{1}{A(\phi)B(\theta)} \int_{\phi} \int_{\theta} f(\phi)g(\theta)d\phi d\theta \quad (5)$$

Here the following definitions are used.

$$A(\phi) = \int_{\phi} f(\phi) d\phi \quad (6)$$

$$B(\theta) = \int_{\theta} g(\theta) d\theta \quad (7)$$

The effective Young's modulus of CNT was estimated from eq. (1).

Before calculating the effective Young's modulus, the CNT aspect ratio was determined. We couldn't assume the actual length (actual aspect ratio) of CNT, because waviness and entanglement within the composites must be taken into account and theoretical calculations became too complicated to solve. Multiple fracture of CNTs occurred during the tensile testing, which has already reported from our previous reports [45]. Therefore we assumed multiple fracture length as the effective length of CNT, which length can be obtained from fracture surface. As shown in Fig. 7(b), many CNTs are exposed at the fracture surface. The average length was about 4.0 μm , as explained earlier, which value is extremely short compared with the actual length of the CNT. Therefore, multiple fracture of CNTs occurred during the tensile process.

Between the exposed fiber length (L_{exposed}) and mean break length (L_{cr}), the following equation was established from Curtin's law [46]:

$$L_{\text{exposed}} = \frac{L_{\text{cr}}}{4} \quad (8)$$

Therein, the length of CNT exposed from the fracture surface was 4.0 μm . Then the CNT fracture length

was calculated as 16.2 μm . The aspect ratio becomes approximately 300, assuming an average diameter of CNT as 52 nm [28, 45]. Other mechanical properties of CNT and polymer used in the calculation are presented in Table 4 [36].

Calculation results obtained using Eshelby/Mori-Tanaka theory are presented in Fig. 11. The best fit of Young's modulus (axial direction) of CNT was obtained as $E_1 = 800$ GPa, which value is much higher than the calculation result by the law of mixtures ($E_{\text{eff}} = 250$ GPa) or of previous reports [23,27].

3.4 Discussion

For the reinforcement effect of CNT, the resultant effective Young's modulus of CNT was obtained as $E_1 = 800$ GPa under the assumption of three-dimensional alignment of CNT, which value was much higher than those of previous reports [23,27,28]. Such a high value can be achieved because the CNT aspect ratio is extremely high and the load transfer from the matrix to CNT through interfaces can be done efficiently in comparison with existing CNT composites (dispersed-type CNT composites).

Table 5 presents the Young's modulus of previous reports [28–36] and that obtained in this study. Compared with previous reports, the resultant Young's modulus of CNT is near the value reported from previous studies, which means that excellent mechanical properties of CNT can be reproduced in the composites. Nevertheless, it can be pointed out that that this excellent mechanical property can not emerge from the tensile direction because the CNT orientations are distributed in three dimensions. It can therefore be said that it is necessary to align the orientation of CNT unidirectionally to use this

reinforcement effect in the tensile direction more efficiently.

4. Conclusions

As described herein, tensile testing of aligned CNT sheet/epoxy composites were conducted for various volume fractions of CNTs. The reinforcement efficiency of CNTs is calculated quantitatively by evaluating the alignment of CNT by SEM microscopic observation to the surface direction and thickness direction, with application of Eshelby/Mori-Tanaka theory. The conclusions are presented below:

1. The resultant tensile strength and Young's modulus increase of aligned CNT sheet/epoxy composites showed much better efficiency than those of previously dispersed CNT type composites, which realized the highest mechanical properties for Young's modulus of 89.8 GPa, and ultimate tensile strength of 319 MPa for $V_f = 32.8$ vol.% composites. After tensile testing, sword-in-sheath fracture of CNT for length of several micrometers was observed, which means a multiple fracture of CNTs.

2. Quantitative evaluation for the alignment of CNT was conducted for the surface and thickness directions of composites. Results show that the orientation was distributed over a plane direction and thickness direction in the composites.

3. The effective Young's modulus of CNT was calculated using the Eshelby/Mori-Tanaka theory, which takes account of the three-dimensional orientation distribution of CNT. As a resultant value, $E_1 = 800$ GPa

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3 was obtained, which value was much higher than those of existing reports. This result is thought to derive
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6 from the high aspect ratio of CNT and the better alignment of CNT. Additionally, the orientation control
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9 in the tensile direction was shown to be indispensable for the improvement of mechanical properties.
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16 A method of controlling CNT alignment, for example, by stretching composites and enhancing
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19 mechanical properties of the composites and considering tubular structures of CNTs are our next steps.
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Fig. 1 Geometry and dimension of tensile test specimen (thickness: about 30 μm).

Fig. 2(a) Electrical material testing machine (5966R) and (b) video extensometer (AVE).

Fig. 3 Procedure to estimate fiber orientation angle: (a) SEM micrograph showing the CNT alignment, (b) divided SEM micrograph, and (c) result of measurement [28].

Fig. 4(a) Stress–strain behavior of epoxy and composites, (b) at the range of 0–1% strain [27,28].

Fig. 5(a) Young's modulus and (b) ultimate tensile strength as function of CNT volume fraction. Several experimental values include previous research data [27, 28, 44].

Fig. 6 SEM micrographs showing fracture surface of aligned CNT/epoxy composites after tensile testing: (a) Comp-#1, (b) Comp-#2, (c) Comp-#3, (d) Comp-#4, (e) Comp-#5, (f) high magnification of Comp-#5 (g) Comp-#6, (h) high magnification of Comp-#6, and (i) Comp-#7 after tensile testing

Notes: Comp #1 ~Comp #5 data was referred from [27,28].

Fig. 7(a) Sword-in-sheath fracture of CNT and (b) sword-in-sheath fracture at the fracture surface [28].

Fig. 8 Histogram of fiber orientation angles of 0–90 deg (for surface direction, under the assumption of Euler angle): (a) Comp #1, (b) Comp #2, (c) Comp #3, (d) Comp #4, and (e) Comp #5.

The histogram was obtained from ref. [26].

Fig. 9 Histogram of fiber orientation angles of 0–90 deg
(For thickness direction, under the assumption of Euler angle).

Fig. 10 Transformation of coordinate system.

Fig. 11 Experimental results compared with calculations

(Under the assumption of three-dimensional distribution of CNT). Best fit Young's modulus of CNT is $E_1 = 800$ GPa.

Table 1 Average mechanical property of aligned CNT/epoxy composites [27,28]

Notice: Epoxy and Comp #1 ~ Comp #4 is the previous data from ref. [27]. Comp #5 is the previous data from ref. [28]. Comp #6 resin was not impregnated adequately. Comp #7 specimen was polished.

Specimen	Test samples	Ply count	Weight fraction (M_f)	Volume fraction (V_f)	Young's modulus (GPa)	Tensile strength (MPa)	Failure strain (%)
Epoxy	2	-	-	0	2.5	54.7	3.05
Comp #1	3	20	7.3	4.5	18.8	97.4	0.503
Comp #2	3	50	13.2	10.5	27.8	153	0.545
Comp #3	2	100	31.3	21.4	50.1	181	0.36
Comp #4	2	150	41.3	29.6	73.4	193	0.22
Comp #5	3	200	44.8	32.8	89.8	217	0.237
Comp #6	3	700	55.6	42.3	82.9	319	0.404
Comp #7	3	50	23.2	15.3	42.9	230	0.526

Table 2 Results of counting orientation angles for the CNT (surface direction) [28].

	Comp #1	Comp #2	Comp #3	Comp #4	Comp #5
Ply count	20	50	100	150	200
V_f (%)	4.5	10.5	21.4	29.6	32.8
CNT count	225	455	1144	1160	1377
Standard deviation (deg)	34.7	31.9	30.7	32.3	32.5

Table 3 Results of counting orientation angle for CNT (thickness direction).

	Ply count	V_f (%)	CNT count	Standard deviation (deg)
Comp #7	50	15.3	644	22.8

Table 4 Mechanical properties of CNT and polymer used in the calculations.

(Stiffness of CNT is obtained from Ref. [36]; E_1 is variables)

	Stiffness (GPa)			Poisson's ratio (fixed)		Aspect Ratio (fixed)
	E_1	E_2	G_{12}	ν_{12}	ν_{23}	α
CNT [36]	Variables	410	540	0.28	0.28	300
Matrix [27]	2.5 (fixed)		0.961	0.3		

Table 5 Young's modulus and CNT strength reported by previous reports.

Type of CNT	Young's modulus (TPa)	Measurement method
MWNT	0.40–4.15 (avg. 1.8)	CNT vibration [29]
MWNT	1.28 (± 0.59)	Direct measurement [30]
MWNT	1	Bending observation [31]
MWNT	0.81 (± 0.41)	Direct measurement [32]
MWNT	0.27–0.95	Direct measurement [33]
MWNT	0.91 (± 0.18)	Direct measurement [34]
MWNT	0.45 (± 0.23)	Direct measurement [35]
SWNT	1.19	Empirical force constant model [36]
MWNT	0.68	Eshelby/Mori-Tanaka theory (two-dimensional) [28]
MWNT	0.8	Eshelby/Mori-Tanaka theory in this study (three-dimensional)

Captions

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