The Effect of Carbon Nanotube Wall Thickness on Elastic Modulus of Nanocomposite

N. Kordani[1*], R. Adibipour[2], A. Sadough Vanini[2]
[1]Department of Mechanical Engineering, University of Mazandaran, Mazandaran, Iran
[2]Department of Mechanical Engineering, Amirkabir University of Technology, Tehran, Iran

Abstract- *This paper focuses on effect of carbon nanotubes physical parameter on elastic modulus of nanocomposites. The remarkable properties of at least some of nano particles have led to high research in the field of nanocomposites, especially carbon nanotubes. In this paper, polymer matrixes and carbon nanotubes are interest. At the nano scale, the structure of the carbon nanotube strongly influences the overall properties of the composite. Some well-known theories such as Halpin-Tsai equation, shear lag model and modified mixture of low were employed to consider the efficient of carbon nanotubes physical parameter on elastic modulus of nanocomposites. According to the results, addition of volume fraction of carbon nanotubes caused a reduction of elastic modulus. The nanocomposite elastic properties are particularly sensitive to the nanotube diameter, with increasing on diameter and wall thickness of carbon nanotube the elastic modulus decreases and when length of carbon nanotube is increasing, the elastic modulus increases.*

Keywords: *Mechanical Properties, Nanocomposites, Polymer Matrix Composites, Aspect Ratio, Carbon Nanotube*

1. Introduction

The development of nano-particle reinforced polymer composites is newly one of the most favorable approaches in the field of future engineering applications. The remarkable properties of at least some of these nano particles have led to high research in the field of nanocomposites, especially carbon nanotubes (Sreejarani & Ray, 2011; Baharvandi & et. al., 2017; Kordani & Sadough, 2014).

Of the various nano-particles, carbon nanotubes (CNTs) have attracted great interest newly as structural reinforcements because of their unique properties. CNTs with their notable mechanical properties such as low density, high aspect ratio, high strength and stiffness, excellent electrical and chemical resistance are a potential candidate as reinforcement for polymeric materials. The addition of only small quantity of nano particle (specially CNTs) leads to improved mechanical properties of matrix (Baharvandi & et. al., 2016; Guozhong, 2004; Harris, 1999). The most important of properties of Single-Walled Carbon Nanotubes (SWCNT) and Multi-Walled Carbon Nanotubes (MWCNT) are collected on Table 1.

Table 1 Typical properties of SWCNT and MWCNT.

Property	*SWCNT*	*MWCNT*	Ref.
Diameter (nm)	0.4-5	5–50	(Micah & et.al, 2009)
Aspect ratio	100–10,000	100–10,000	(Saleh & Sundararaj, 2011)
Density (g/cm^3)	~1.3	~1.75	(Saleh & Sundararaj, 2011)
Tensile strength (GPa)	50–500	10–60	(Saleh & Sundararaj, 2011)
Elastic modulus (TPa)	~1 (from 1 to 5)	0.2-0.95	(Meo & Rossi, 2006; Yu & et.al, 2000)

Corresponding Author:naser.kordani@umz.ac.ir

Failure strain (%)	$\sim 5-10$	10.5, up to 12	(Liu & et.al, 2005; Chowdhury & et.al, 2012)

CNTs have many structures, differing in length, diameter, thickness, spiral types and number of layers that are used to modify the other materials. MWNTs and SWNTs are the most popular type of CNTs. In 1991, MWNTs consist of many coaxial graphite cylindrical tubes and in 1993, SWNTs with one graphite cylindrical tube were discovered by Iijima. MWCNTs and SWCNTs were discovered in the soot of the arc-discharge method and using of metal catalysts in the arc-discharge method (Natsuki & Tantrakan, 2004; Khare & Bose, 2005). TEM micrograph of a MWNT is shown in figure 1.

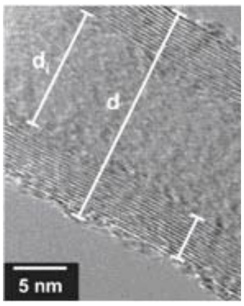

Figure 1 TEM micrograph of a MWNT with measurements of outside diameter, inside diameter and wall thickness (Thostenson & et. al, 2001).

2. Influence of Physical parameters of CNTs on Elastic modulus of nanocomposite

At the nano scale, the structure of the carbon nanotube strongly influences the overall properties of the composite. For design purposes, we need to have simple and rapid calculative procedures for estimating the effective properties. Some well-known theories such as Halpin-Tsai equation, shear lag model and modified mixture of low were used. Their equations depend on a parameter which is considered, table. 2.

Table 2 Theories on mechanical properties of nanocomposite with their parameter

Model	Equation	Ref.
Halpin-Sai	$E_c = E_m(\frac{1+\zeta\eta v_f}{1-\eta v_f}), \eta = \frac{\frac{E_f}{(E_m)}-1}{\frac{E_f}{(E_m)}+\zeta}, \zeta = {}^{2l}/_{d}$	(Halpin & Tsai, 1967)
Shear-Lag	$E_c = \eta E_f v_f + E_m.(1-v_f),$ $\eta = 1-\frac{\tanh(k\frac{l}{d})}{k\frac{l}{d}}, k = \sqrt{\frac{2E_m}{E_f(1+\nu)\ln({}^{1}/_{V_f})}}$	(Kashyap & et.al, 2011)
Modified Mixture Low	$E_c = X_1\eta E_f v_f + E_m v_m,$ $\eta = 1-\frac{tanh(k\frac{l}{d})}{k\frac{l}{d}}, X_1(2D,3D) = 3/8,1/5$	(Crutis & et.al, 1978)

Where E_c, E_f, E_m are the modulus of nanocomposite, *CNTs* and matrix. ζ is called shape factor that is depend on the particular elastic property. L is average length and d is average diameter of nanotube and ν is poisson ratio. υ_f is volume fraction.

Base on experimental results, Thostenson and Chou ploted a linear line through the data that shows relationship between the nanotube diameter and wall thickness, figure 2. According their study at smaller nanotube diameters this relationship between the nanotube diameter and wall thickness begins to deviate from the linear curve fit (Thostenson & et. al, 2001).

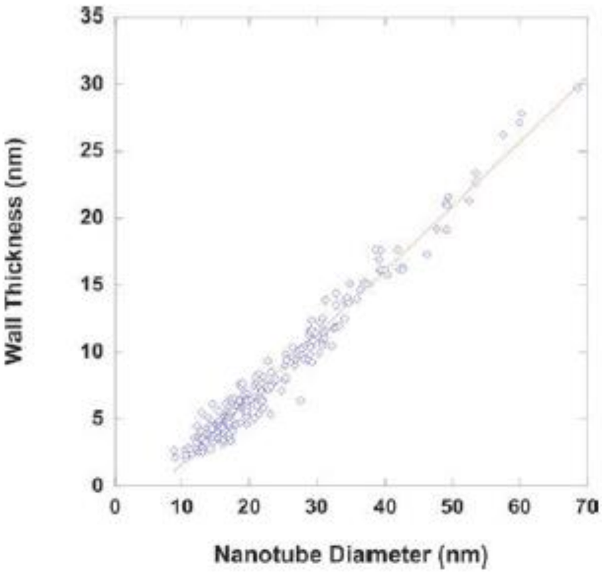

Figure 2 linear relationship between wall thickness and nanotube diameter by (Thostenson & et. al, 2001).

$$T = -3.0793 + 0.4796d,\ R = 0.98687 \tag{1}$$

In which, *T* is wall thickness and *d* is Nanotube diameter. *R* is the error of this curve fitting. Eq. (1), Substituted into shape factor of Halpin-Tsai equation to show the effective of wall thikness on elastic modulus of nanocomposite.

$$\zeta = \frac{0.9592l}{T + 3.0793} \tag{2}$$

We also used Eq. (2) for other theories to consider the effect of wall thickness of *CNTs*. Halpin-Tsai equation and experimental results by Montazeri et al. (2010), were used to consider the influence of nanotube diameter, length and volume fraction on the elastic modulus of nanocomposite. Results are shown in figures 3 and 4. As shown in figures 3 and 4, increasing on diameter and wall thickness make the elastic modulus of nanocomposite decreases and increasing on weight percent and wall length of *CNTs* make the elastic modulus of nanocomposite increases.

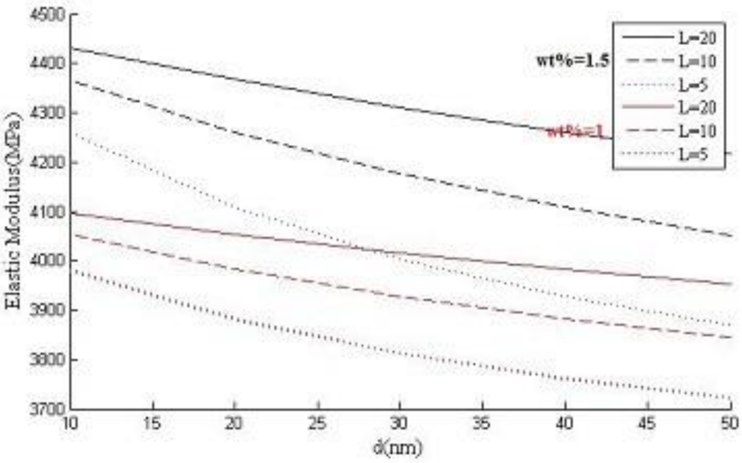

Figure 3 The effect of nanotube diameter, *d*, length, *L* and weight percent, *wt%* on the elastic modulus of nanocomposite.

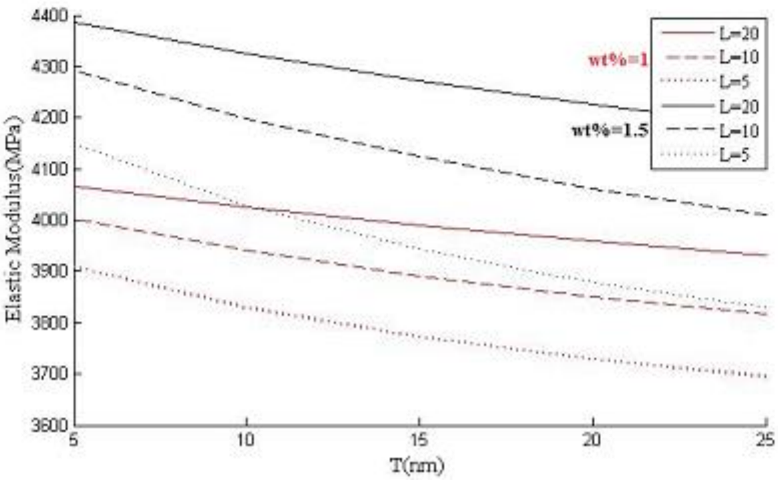

Figure 4 The effect of nanotube wall thickness, *T*, length, *L* and weight percent, *wt%* on the elastic modulus of nanocomposite.

By using the theories on table 2 and experimental results by (Montazeri & et al., 2010), effect of diameter on the composite elastic modulus of nanocomposite are predicted, and results are shown in figure 5. Modified mixture of low in 2D and 3D are inefficient to consider the wall thickness of CNTs on elastic modulus of nanocomposite.

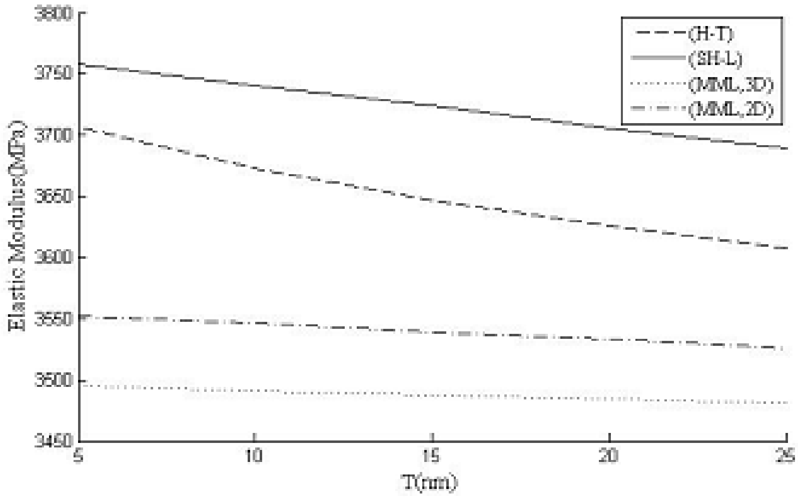

Figure 5 Effect of diameter on the elastic modulus of nanocomposite by using Halpin-Tsai equation (H-T), shear-Lag theory (SH-L), and modified mixture of low in 2 dimension(MML,2D) and 3 dimension(MML,3D).

3. Conclusion

In this paper by using the experimental data, Halpin-Tsai Equation, shear lag model and modified mixture of low, effects of reinforcement, length and diameter of carbon nanotube on the mechanical properties were investigated.

According to the results, additional CNTs weight percent caused an increase on elastic modulus. The elastic properties of nanocomposite are particularly sensitive to the nanotube diameter. By increasing the diameter and wall thickness of carbon nanotube, the elastic modulus decreases and when length of carbon nanotube is increasing, the elastic modulus increases. Effect of geometry parameter on elastic properties of nanocomposite is better shown by Halpin-Tsai equation and shear-Lag theory.

References

Al-Saleh, M.H., Sundararaj, U. (2011). Review of the Mechanical Properties of Carbon Nanofiber/Polymer Composites. Composites, Part A 42, 2126–2142.

Baharvandi, H., Alebooyeh, M., Alizadeh, M., Saeedi Heydari, M., Kordani, N. & Khaksari, P. (2016). The influences of particle–particle interaction and viscosity of carrier fluid on characteristics of silica and calcium carbonate suspensions-coated Twaron® composite. Journal of Experimental Nanoscience, VOL. 11, NO. 7, 550_563.

Baharvandi, H., Saeedi Heydari, M., Kordani, N., Alebooyeh, M., Alizadeh, M., Khaksari, P. (2017). Characterization of the rheological and mechanical properties of shear thickening fluid-coated Twaron® composite. The Journal of the Textile Institute, Vol. 108, no. 3, 397-407.

Chowdhury, S.C., Haque, B.Z., Okabe, T., Gillespie, J.W. (2012). Modeling the Effect of Statistical Variations in Length and Diameter of Randomly Oriented CNTs on the Properties of CNT Reinforced Nanocomposites. Composites,Part B 43,1756–1762.

Crutis, P.T., Bader, M.G., Bailey, J.E. (1978). The Stiffness and Strength of A Polyamide Thermoplastic Reinforced With Glass and Carbon Fibers. Journal of Material Science, 13, 377-390.

Guozhong, C. (2004). Nanostructures and Nanomaterials: Synthesis, Properties and Applications. Imperial College Press, London.

Halpin, J. C., Tsai, S.W. (1967). Environmental Factors in Composite Materials Design. US Air Force Technical Report AFML TR, 67–423.

Harris, P., F. J. (1999). Carbon Nanotubes and Related Structures: New Materials for the 21st Century. Cambridge University Press.

Kashyap, K.T., Koppad Praveennath, G., Puneeth, K.B., Aniruddha Ram, H.R., Mallikarjuna, H.M. (2011). Elastic Modulus of Multi-Walled Carbon Nanotubes Reinforced Aluminium Matrix Nanocomposite. Computational Materials Science, 8, 2493-2495.

Khare, R., Bose, S. (2005). Carbon Nanotube Based Composites- A Review. Journal of Minerals & Materials Characterization & Engineering, 4, 31-46.

Kordani, N., Sadough, A. (2014). Different Method to make laminates by Shear Thickening Fluid. Science and Engineering of Composite Materials (SECM), Vol. 21, No. 3, 421-425.

Liu, L., Barber, A.H., Nuriel, S., Wanger, H.D. (2005). Mechanical Properties of Functionalized Single-Walled Carbon-Nanotube/Poly (Vinyl Alcohol) Nanocomposites. Advanced Functional Materials, 15, 975-980.

Meo, M., Rossi, M. (2006). Prediction of Young's Modulus of Single Wall Carbon Nanotubes by Molecular-mechanics-based Finite Element Modeling. Composites Science and Technology, 66, 1597–1605.

Micah, J., Green Behabtu N., Pasquali, M., Wade Adams, W. (2009). Nanotubes as Polymers. Polymer, 50, 4979–4997.

Montazeri, A., Javadpour, J., Khavandi, A., Tcharkhtchi, A., Mohajeri, A. (2010). Mechanical Properties of Multi-Walled Carbon Nanotube/Epoxy Composites. Materials and Design, 31, 4202–4208.

Natsuki, T., Tantrakan, K.M. (2004). Effects of Carbon Nanotube Structures on Mechanical Properties. Applied Physics, 79, 117-124.

Sreejarani, K., Pillai Ray, S.S. (2011). Epoxy-based Carbon Nanotubes Reinforced Composite. National Centre for Nano-Structured Materials, CSIR, South Africa, 726-792.

Thostenson, E.T., Ren, Z., Chou, T.W. (2001). Advances in the Science and Technology of Carbon Nanotubes and Their Composites: A Review. Composites Science and Technology, 61, 1899–912.

Yu, M.F., Lourie, O., Dyer, M.J., Moloni, K., Kelly, T.F., Ruoff, R.S. (2000). Strength and Breaking Mechanism of Multiwalled Carbon Nanotubes under Tensile Load. Science, 287, 637–640.