academicJournals

Vol. 8(4), pp. 31-36, July 2017
DOI: 10.5897/JCEMS2016.0281
Articles Number: E3E4D8665364
ISSN 2141-6605

http://www.academicjournals.org/JCEMS

Journal of Chemical Engineering and Materials Science

Full Length Research Paper

Effect of nano-carbon percentage on properties of composite materials

Ali Anvari

Department of Mechanical and Aerospace Engineering, University of Missouri-Columbia, USA.

Received 28 December 2016; Accepted 6 July 2017

The presented study aims to investigate the role of nano-carbon percentage on material properties of different composites. Recently, nano-carbon composites are used in different industries like aerospace. Thus, it seems necessary to determine the best amount of nano-carbon in composite materials. The best percentage of nano-carbon can be defined as the amount that causes an increase in some of the useful materials' properties to the highest level. These useful characteristics may be Young's modulus, tensile strength, yield strength, and fatigue life. In the presented research, by using the experimental data and applying analytical method, equations are developed to determine the best amount of nano-carbon in composite materials including CNT/2009 Al, epoxy SC-15 with MWCNT-COOH, glass fiber reinforced polymer, and graphene nanocomposites. Based on the results of this study, it appears that the best amount of nano-carbon for every composite material is different. Furthermore, it seems that even for each composite material's property, the best amount of nano-carbon varies. Nevertheless, it appears that, it is possible to approximately distinguish the best amount of nano-carbon in composite materials in an especial environmental condition like a determined temperature.

Key words: Nano carbon, composite properties, strength, fatigue.

INTRODUCTION

Carbon nanotubes (CNTs) are a new Nano scale material discovered by Lijima. A significant body of theoretical and experimental work is developed to this special material. These studies show impressive physical properties such as high stiffness, high strength, low density, and excellent thermal conductivity, suggesting a role in light-weight high strength material applications" (Qian et al., 2003). Many investigators have endeavored to fabricate advanced CNT composite materials that exhibit one or more of these properties (Mirik et al., 2016).

Among the related works about the properties of composite materials, "carbon nanotube polymer composites", is submitted by Andrews and Weisenberger (2004), "a review on study of composite materials in presence of cracks" is developed by Abhijeet et al. (2015), and "interaction of thermal loading on the damage evolution of composite materials" is provided by Moufari and Bakkali (2015). Based on both prior works mentioned above, damage and cracks in composites are important to estimate because they have serious effect. It is also significant to determine the amount of CNT in composites that can reduce the damage and cracks in different loading conditions. These mitigations of cracks

*Corresponding author. E-mail: aabm9@mail.missouri.edu Tel: +1 (573) 529-4426.

Table 1. Yield strength (MPa) of CNT/2009Al composites tested at different temperatures (Liu et al., 2012).

Temperature	CNT (vol.%) 0	CNT (vol.%) 1.5	CNT (vol.%) 4.5
T = 293 K	300 MPa	380 MPa	430 MPa
T = 423 K	290 MPa	340 MPa	350 MPa
T = 473 K	270 MPa	300 MPa	290 MPa
T = 573 K	180 MPa	210 MPa	160 MPa

on the properties of composite materials. In this area, “crack growth as a function of temperature variation in carbon fiber/epoxy”, is recently presented by Anvari and damage in nano-composites’ materials might lead to better materials’ properties like; higher modulus and strength, and fatigue life extension.

Furthermore, the role of carbon, carbon nanotubes, and nano-particles, in different composite materials’ properties is investigated by Saleh (2013), Machado et al. (2014), Vallet et al. (2015), Gomez et al. (2016), Alswat et al. (2016), Wang et al. (2016), Saleh (2016) and Moyo et al. (2013).

Many attempts have been done to determine the mechanical properties and behaviors of Nano-composites’ materials in different conditions. Among those, “inter-laminar fatigue crack growth behavior of MWCNT/carbon fiber reinforced hybrid composites monitored via newly developed acoustic emission method” is presented by Romhany and Szebenyi (2012), “specific heat and thermal expansion of polyester composites containing single wall, multiwall, and functionalized carbon nanotubes” is provided by Ciupagea et al. (2013), and “thermal fatigue and hypothermal atomic oxygen exposure behavior of carbon nanotube wire” is submitted by Misak et al. (2013).

As mentioned, several efforts are performed to investigate the composites and Nano-composites properties. Moreover, many experiments are implemented to determine the best amount of CNT in Nano-composite materials. Nevertheless, it appears that there are no models that can exactly represent the role of CNT in Nano-composites properties.

In the presented study, by using experimental data (Liu et al., 2012; Salam et al., 2013; Genedy et al., 2015) and employing analytical method, equations are achieved to determine the best amount of CNT in Nano-composite materials. These equations are developed by using the experimental tests data as boundary conditions. Furthermore, in obtaining the best amount of CNT in each nano-composite material, derivation is employed.

EXPERIMENTAL PROCEDURES FOR COMPOSITE MATERIALS’ PREPARATION AND EVALUATION

“1.5 vol.% and 4.5 vol.% carbon nanotubes reinforced 2009 Al (CNT/2009Al) composites with homogeneously dispersed CNTs and reinforced matrix grains, were fabricated using powder metallurgy (PM) followed by 4-pass friction stir processing” (Liu et al., 2012).

In addition, for obtaining flexural test results of epoxy SC-15 samples with different wt. % of MWCNT-COOH “Functionalized multi-walled carbon nanotubes were dispersed in an epoxy resin system (SC-15) at room and elevated temperatures using a combination of sonication and high shear mixing methods to determine optimal mechanical properties” (Salam et al., 2013).

Furthermore, for evaluation of tensile strength and fatigue performance of glass fiber reinforced polymers (GFRP) composite Using CNTs, “GFRP coupons were fabricated and tested under static tension and cyclic tension with mean fatigue stress equal to 40% of the GFRP tensile strength. Microstructural investigations using scanning electron microscopy (SEM) and Fourier Transform Infrared (FTIR) spectroscopy were used for further investigation of the effect of MWCNTs on the GFRP composite” (Genedy et al., 2015).

Moreover, to obtain the results of Young’s Modulus (YM) and tensile strength (TS) of graphene nanocomposites in different amount of carbon atoms, “In order to synthesize bulk quantities of exfoliated graphene sheets and to effectively disperse these sheets in polymer composites a technique pioneered by Aksay and coworkers is used. Crack-opening test on compact tension samples were performed to measure the Mode I fracture toughness” (Rafiee et al., 2010).

APPLYING ANALYTICAL METHOD

Yield strength of CNT/2009Al composite in elevated temperature

In Table 1 (Liu et al., 2012), yield strengths (YS) of CNT/2009Al composites tested at different temperatures are indicated. The determined yield strength in Table 1 is indicated as a function of the amount of CNT (CNT (vol. %)) (Liu et al., 2012). As can be observed in Table 1, there are three points in each temperature. By employing of three points for each temperature, one equation can be achieved. As an instance, in Table 1, at temperature of 293K, there are these three boundary conditions: (CNT (vol. %) = 0 and YS = 300 MPa), (CNT (vol. %) = 1.5 and YS = 380 MPa), and (CNT (vol. %) = 4.5 and YS = 430 MPa). By using the three boundary conditions and three unknown constants (a, b, and c), one equation to determine the YS as a function of CNT content (wt.) at each temperature, is possible.

Table 2. Flexural test results of epoxy SC-15 samples with different wt. % of MWCNT-COOH and MWCNT-NH_2 (Salam et al., 2013).

Materials	Young's Modulus (GPa) % change
Neat Epoxy SC-15_RT	2.12
0.1% CNT-NH_2_RT	2.62
0.2% CNT-NH_2_RT	2.72
0.3% CNT-NH_2_RT	2.45

Table 3. Tensile strength (MPa) for individual GFRP coupons (Genedy et al., 2015).

Neat	0.5 wt% MWCNTs	1.0 wt% MWCNTs
703	904	714

Table 4. Fatigue life (Number of cycles until failure) for individual GFRP coupons (Genedy et al., 2015).

Neat	0.5 wt% MWCNTs	1.0 wt% MWCNTs
87,513	1,087,482	950,713

Therefore, at the zero wt. in Nano-composite, the YS is equal to 300 MPa, so

$$300 = a(0)^2 + b(0) + c \quad (1)$$

and at 1.5% wt, YS is equal to 380 MPa, so

$$380 = a(0.015)^2 + b(0.015) + c, \quad (2)$$

moreover, at 4.5% wt, YS in sample is, 430 MPa. As a result

$$430 = a(0.045)^2 + b(0.045) + c, \quad (3)$$

thus, by solving the three Equations ((1), (2), and (3)), three unknown quantities (a, b, and c), equation (4) is obtained that indicates the YS of CNT/2009Al composite as a function of wt., exposed to 293 K.

$$YS = -81481.467(wt)^2 + 6555.555(wt) + 300. \quad (4)$$

In the presented study, this process is repeated to obtain the equations for each temperature in this section, and other properties of Nano-composites in other sections. All of the equations that are obtained by this procedure are indicated in the results' section of this research.

Young's modulus of CNTs composites

In Table 2 (Salam et al., 2013), there are some results related to CNTs composite Young's Modulus (YM) in presence of different amounts of CNTs. As can be observed, YM of CNTs composite in room temperature (RT) and at 0, 0.1, 0.2 and 0.3% CNT are: 2.12, 2.62, 2.72 and 2.45 GPa, respectively (Salam et al., 2013). Here, by using the average amount of CNTs composite between the 0.1 and 0.2% CNTs content in CNTs composite from Table 2, the YS for 0.15% CNTs composite is equal to 2.67 GPa.

Following the above procedure, there are three boundary conditions; (YM = 2.12 GPa and CNT content = 0), (YM = 2.67 GPa and CNT content = 0.0015), and (YM = 2.45 and CNT content = 0.003). Consequently, by applying these boundary conditions like the method that is used to derive the Equation 4, Equation 5 can be achieved. This equation can represent the YM of CNT composite at RT in different wt. of CNT.

$$E = -171133.333(wt)^2 + 623.4(wt) + 2.12. \quad (5)$$

Tensile strength and fatigue performance of glass fiber reinforced polymers (GFRP) composite Using CNTs

In this part of the presented research, the effect of the CNT content on Tensile Strength (TS) and Fatigue performance of glass fiber reinforced polymers (GFRP) is investigated. In order to do this procedure, experimental results data from Tables 3 and 4 is used (Genedy et al., 2015). In Tables 3 and 4, TS and fatigue life for different amount of CNT in GFRP composite material are indicated respectively. By using the mean numerical values of TS and fatigue life in composite material at different CNT contents, three boundary conditions from each Table is obtained. From the Table 3, the three boundary conditions are: (TS = 703 MPa and CNT content = 0), (TS = 904 MPa and CNT content = 0.005), and (TS = 714 MPa and CNT content = 0.01). In addition, from the Table 4, the three boundary conditions are: (Fatigue life = 87,513 cycles and CNT content = 0), (Fatigue life = 1,087,482 cycles and CNT content = 0.005), and (Fatigue life = 950,713 cycles and CNT content = 0.01). By employing these two sets of boundary conditions and the method that is used to obtain the Equation 4, Equations 6 and 7 are achieved. These two equations are able to determine the numerical value of TS and Fatigue life for the GFRP in

Table 5. YM and TS of graphene nanocomposites in different amount of carbon atoms (Rafiee et al., 2010).

Material	0.125% weight FGS	0.1% weight FGS
Young's Modulus (Gpa)	4.1	4.15
Tensile Strenght (MPa)	82.5	79

Table 6. Comparison of fatigue lifetimes for glass fiber composites with and without CNTs (Grimmer and Dharan, 2009).

Cyclic stress amplitude/MPa	Fatigue life of glass fiber composites/cycles	Fatigue life of glass composites with the addition of carbon nanotubes/cycles	Improvement factor in life
98.0	1,473	2,091	1.4
85.0	3,238	3,813	1.2
65.0	11,488	18,517	1.6
44.0	109,055	316,227	1.9

different CNT content, respectively.

$$TS = -7820000(wt)^2 + 79300(wt) + 703, \qquad (6)$$

$$N = -2.273476e{+}10(wt)^2 + 313667600(wt) + 87513, \qquad (7)$$

RESULTS AND DISCUSSION

Here, we attempt to investigate the best amount of CNT in composite materials and compares the results of this research with the experimental data from other nano-carbon composite materials (Rafiee et al., 2010; Grimmer and Dharan, 2009). In order to do this purpose, derivative of the presented equations are used and indicated in Table 8. The derivative of the equation can contribute to determine the best amount of CNT in composite materials. All the results from derivatives can be observed in Table 8. It seems necessary to mention that the best CNT content is the percent amount of CNT in nano composite materials that can reflect the highest value of material property in nano composite material. This nano composite property can be YS, TS, fatigue life, or other material properties.

"The improvement in fatigue life with the addition of CNTs increases as the applied cyclic stress is reduced, making the effect most pronounced at high cycles. At a cyclic stress of 44 MPa, the addition of 1wt% of CNTs results in almost a 3 times improvement in the fatigue life" (Grimmer and Dharan, 2009).

By comparison, between Tables 5 and 8, it can be observed that the best nano-carbon content in Graphene Nano composites based on YM and TS (Table 5 for Graphene nanocomposites) are 0.001 and 0.00125, respectively, and the best CNT content for CNT composite (Table 8) based on YM and TS are 0.0018 (for MWCNT – COOH - Resin) and 0.0051 (for GFRP – MWCNTs), respectively. The difference from this comparison may be due to the difference between these Nano composite materials. In Graphene nanocomposites, Graphene is a single-thick sheet of sp^2-bonded carbon nanoparticles (Rafiee et al., 2010). In addition, in MWCNT-COOH resin and GFRP – MWCNTs composites, there are no Graphene sheets. By comparison between these numbers, it appears that if Graphene is used in composite materials, the less amount of carbon wt. % is needed to have the highest YM and TS. Furthermore, on the contrary, it can be concluded that if MWCNTs are used in composites, more amount of carbon wt. % is required to have the highest YM and TS in composites in comparison with carbon wt. % used in Graphene nanocomposites. Nevertheless, the best amount of nano-carbon for the maximum YM in comparison is closer. Moreover, by comparison between the best CNT content for the highest fatigue life in glass fiber composites in Table 6 and 8, it can be observed that the two CNT content 0.01 (for GFRP – CNTs) and 0.0069 (for GFRP – MWCNTs) are also close numerical values, respectively.

Furthermore, by increasing the temperature from 293 K to 573 K, it is noticeability; that the best CNT content for the highest YS decreases from wt = 0.0402 to wt = 0.0187. It means that in order to have the highest YS in CNT composite, the CNT content has to be determined by the temperature that is supposed to be applied to the Nano composite material. However, it seems that by increasing temperature from 293 K to 573 K, the nanostructure of CNT/2009Al composite changes that cause YS_{max} to appear in lower amount of CNT. This structure change may be due to the melting temperature of Al that is closer to 573 K rather than in 293 K. This might be the case because in close to the melting point, the nanoparticles in Al are farther from each other due to the weaker bonds. Thus, bonding between Al nanoparticles and carbon nanoparticles may occur easier because they can connect to each other and as a result, with less amount of carbon, highest YS can be achieved.

Table 7. Equations to obtain the nano composites properties as a function of CNT content.

CNTs composite materials properties as a function of CNT content (wt.)	Equation number with composite name
$YS = -81481.467(wt)^2 + 6555.555(wt) + 300$, at $T=293\ K$ (Liu et al., 2012)	(4) CNT/2009Al
$E = -171133.333(wt)^2 + 623.4(wt) + 2.12$ (Salam et al., 2013)	(5) MWCNT-COOH
$TS = -7820000(wt)^2 + 79300(wt) + 703$ (Genedy et al., 2015)	(6) GFRP -MWCNT
$N = -2.273476e{+}10(wt)^2 + 313667600(wt) + 87513$ (Genedy et al., 2015)	(7) GFRP- MWCNT
$YS = -51851.867(wt)^2 + 3444.445(wt) + 290$, at $T=423\ K$ (Liu et al., 2012)	(8) CNT/2009Al
$YS = -51851.867(wt)^2 + 2777.778(wt) + 270$, at $T=473\ K$ (Liu et al., 2012)	(9) CNT/2009Al
$YS = -88888.889(wt)^2 + 3333.333(wt) + 180$, at $T=573\ K$ (Liu et al., 2012)	(10)CNT/2009Al

Table 8. Amount of CNT content for gaining the highest values of material properties in nano composites that are obtained by using the derivation of equations that are achieved from the analytical method in this research indicated in Tables 1, 2, 3, 4, 5 and 6.

Equation number	Derivation of equations equal to zero	Best CNT content	Highest material properties
(4)	$\frac{\partial YS}{\partial wt} = -162962.933(wt) + 6555.555 = 0$	wt = 0.0402	$YS_{max} = 431\ MPa$ for CNT/2009Al
(5)	$\frac{\partial E}{\partial wt} = -342266.667(wt) + 623.4 = 0$	wt = 0.0018	$E_{max} = 2.686\ GPa$ for MWCNT - COOH
(6)	$\frac{\partial TS}{\partial wt} = -15640000(wt) + 79300 = 0$	wt = 0.0051	$TS_{max} = 904\ MPa$ for GFRP - MWCNT
(7)	$\frac{\partial N}{\partial wt} = -4.546952e{+}10(wt) + 313667600 = 0$	wt = 0.0069	$N_{max} = 1{,}169{,}417$ Cycles for GFRP -MWCNT
(8)	$\frac{\partial YS}{\partial wt} = -103703.733(wt) + 3444.445 = 0$	wt = 0.0332	$YS_{max} = 347\ MPa$ for CNT/2009Al
(9)	$\frac{\partial YS}{\partial wt} = -103703.733(wt) + 2777.778 = 0$	wt = 0.0268	$YS_{max} = 307\ MPa$ for CNT/2009Al
(10)	$\frac{\partial YS}{\partial wt} = -177777.772(wt) + 3333.333 = 0$	wt = 0.0187	$YS_{max} = 211\ MPa$ for CNT/2009Al

Conclusions

In the presented study, by using three experimental procedures data that are performed on CNT composites and an analytical method, new equations are obtained to compare the material properties between the different Nano composites. The results of this research have indicated that CNT content in composite materials can have serious effect on the properties of the composite materials. Furthermore, based on the results that are obtained in this study, it seems that for all of the mechanical properties of Nano composite materials, there is a determined CNT content that can improve that property to the highest amount. In the presented research, the best CNT content used in Nano composite materials for gaining the highest YM, TS, YS, and fatigue life is calculated by using the suggested new equations and are indicated. These results can contribute to estimate the best CNT content in Nano composite materials for different conditions. In order to calculate the best CNT content, first it has to be determined that which Nano composite property is required to be highest in that condition for obtaining the best results.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

ACKNOWLEDGEMENT

The author would like to appreciate the guidance of advisors. All the funding related to this research is provided by the presented author.

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