The Mechanical Properties of Functionalised MWCNT Infused Epoxy Resin: A Theoretical and Experimental Study

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Abstract*-- Carbon nanotubes are considered to be one of the strongest and stiffest engineering materials available, possessing a calculated tensile strength of $\sigma_{TS} \approx$ 11- 200 GPa and Young's modulus E >1.4 TPa. In the context of manufactured engineering composites, epoxy resin is commonly used as a matrix material for many aerospace and oil field, and other, industrial applications. This paper reports the initial findings of a study, which considered the effects of small additions of two types of multi-wall carbon nanotubes, nickel coated MWCNTs (Ni-MWCNTs) & carboxyl acid surface activated MWCNTs (COOH-MWCNTs) on the mechanical properties of an epoxy resin matrix. To successfully incorporate these particles into the matrix materials, with good dispersive properties, standard mixing techniques using an ultrasonic bath were used during the manufacture of appropriate specimens for testing. The tensile strength properties of these specimens, as well as the microstructure, were then evaluated and studied. Scanning Electronic Microscope (SEM) was used to visualise the degree of dispersion of the MWCNT's in the matrix material. The results obtained indicated that the mechanical properties of epoxy resin can be improved by the addition of the both type of MWCNT's. In particular, the addition of Ni-MWCNT's increased the tensile strength by approximately 19% and the tensile modulus by 28%. While for COOH-MWCNTs the increase was 20.6% for tensile and 27.5% for the modulus. It is suggested that these improvements, seen with the MWCNT's particles, were due to an increase in the degree of interfacial bonding between MWCNT and epoxy, so leading to the improved mechanical properties of the nanocomposite observed. Theoretical modelling, using ANSYS finite element analysis, also showed good correlation with the experimental results obtained.

***Index Term*-- Ni-MWCNTs, COOH-MWCNTs, Epoxy resin, ANSYS**

I-INTRODUCTION

Carbon nanotubes (CNTs) were first observed by Iijima in 1991 [1] and are considered to be very effective additions to many engineering materials. CNTs have very good mechanical properties such as a high elastic modulus E ≈ 270-1400 GPa, and a high tensile strength up to 200 GPa [2]. In addition, carbon nanotubes have a low density value which varies from 1.2 g/cm^3 for single wall carbon nanotubes (SWCNTs) up to 2.1 g/cm^3 for MWCNTs[3]. These properties give carbon nanotubes a high specific modulus and high specific strength, which make them promising and ideal nanoparticles to reinforce and improve the mechanical properties of a range of organic matrix composites. In recent years, many researchers have sought to incorporate carbon nanotubes into polymers to fabricate a variety of nanocomposite such as epoxy resin based CNTs [4-17]. In particular, epoxy resins have been used in many manufacturing and industrial fields such as oil, aerospace and automobile applications since these important thermosetting polymers possess good chemical resistance, high adhesion, low weight, and very low shrinkage after curing process. All of these attributes make them promising engineering materials. However, after curing process, epoxy resin can become brittle and have a relatively low tensile and flexural strength. These poor properties limit many of their possible engineering applications. For these reasons, CNTs provide an excellent candidate nano-filler material to improve the mechanical properties of epoxy resin especially to enhance and modify their surfaces. There are two main property challenges that need to be solved when using CNTs in nanocomposite applications [4, 5, 18, 19] . The first challenge is that the agglomeration of CNTs due to their high aspects ratios and their high Van der Waals force of attraction between particles. Both of these lead to an inhomogeneous dispersion of the carbon nanotubes in the polymer matrix. The second problem is that of the interfacial bonding characteristic between CNTs and matrix material this is weak and so prevents effective load transfer between the carbon nanotubes and the matrix material. Better interfacial bonding and better dispersion of carbon nanotubes inside the nanocomposite will enhance the

final properties of CNT/epoxy composites. To improve these properties, the functionalization of carbon nanotubes is very a useful way to enhance the interfacial bonding between the carbon nanotubes and the matrix. This also helps to improve the dispersion of carbon nanotubes [14, 20, 21].

The aim of this research is an experimental and numerical study 'using ANSYS software' of the effect of two type of MWCNTs (Ni-MWCNTs and COOH-MWCNTs) on the mechanical properties of a standard epoxy resin. To this end, epoxy resin filled with different amount of MWCNTs was prepared and from this appropriate test specimens were manufacture. Tensile tests were performed on unmodified epoxy and on modified MWCNT/epoxy resin nanocomposites, respectively. Finally, the fracture properties of the nanocomposites, and dispersion of MWCNTs in the matrix, were studied using scanning electron microscopy (SEM).

Table I
Specifications of the as-received MWCNTs.

Properties	**COOH-MWCNTs**	**Ni-MWCNTs**
	Value	
Density (g/cm3)	2.1	2.6
Purity (%)	>95	>98
Outside/ Inside diameter (nm)	(5-15) / (3-5)	
Length (μm)	50	
Electrical conductivity s/cm	>100	N/A
Tensile strength/ Young's (GPa)	150/(270-1200)	
Content of COOH/ MWCNTs	2.56/ >97 wt.% (XPS & Titration)	N/A
Content of Ni/ MWCNTs	N/A	>60 / >38 wt.% (XPS & Titration)

The epoxy resin used in this study was purchased from Easy Composites LTD (U.K). This is a slow curing time Epoxy Infusion Resin. This was used as a matrix material in the present work. Table II shows the specification of the matrix materials. The hardener (AT30) was added to the matrix (resin) in a 10:3 by weight ratio.

III- NANOCOMPOSITE PREPARATION

In this study a direct ultrasonic method for mixing the Ni-MWCNTs with epoxy was used. During the preparation the variables which can affect the dispersion of MWCNTs in the resin are temperature, the right mixing order and the time to better homogenised during the sonication process. The mixing of the epoxy resins and the Ni-MWCNTs was carried out in a glass beaker. An appropriate amount of Ni-MWCNTs (0.1 wt.%, 0.2 wt.%, 0.3 wt.%, 0.4 wt.%, and 0.5 wt.%) was initially

II-MATERIALS AND METHODS

Both types of multi-wall carbon nanotubes (Ni-MWCNTs and COOH-MWCNTs) were supplied by US Research Nanomaterials., Inc. The method that was used to fabricate the MWCNTs was chemical vapor deposition (CVD). Table 1 shows the specifications of the as-received MWCNTs powders. A sample SEM micrograph of the as-received MWCNTs is shown in Figure (1a, b). The tendency for MWCNT's to agglomerate can be seen in figure. As states earlier this is due to their length and high aspect ratio the van der Waals forces of attraction which exist between them. In the high-resolution image, no amorphous layers of carbon on the outer surface of the MWCNTs are visible.

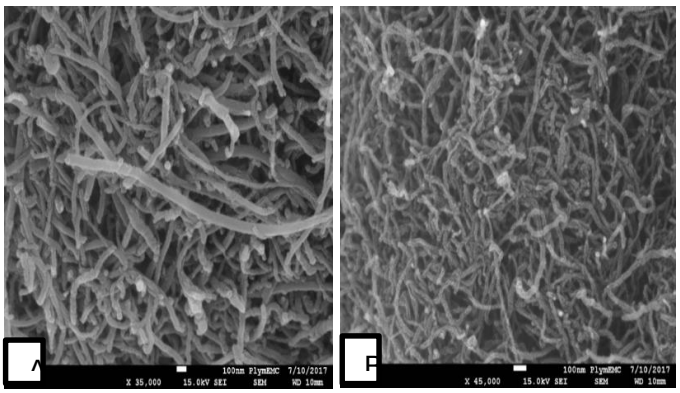


Fig. 1. SEM image of as-received (a) Ni-MWCNTs, (b) COOH-MWCNTs powder.

dispersed in a small quantity of resin using magnetic stirrer for 15 minutes. This mixture was then placed in an ultrasonic bath at 40 C° for 30 minutes. After this the solution was then mixed with the resin to the required volume and stirred for further 15 minutes at 1800 rpm at room temperature. The temperature of the mixture was kept cool by placing the container in a cooled water bath as shown in Figure 2. After degassing under vacuum, the mixture was poured into a silicon mould. The mould was made according to the BS EN ISO 527 standard [22]. The moulds used are shown in Figure 3. The mixture was kept for 24 hrs at room temperature to ensure complete curing. After solidification the samples were placed in an oven at 70°C for 6hrs for post curing. For comparison the control specimens were made from pure epoxy resin with only hardener added. The same procedure described above was repeated again for COOH-MWCNTs and again for a control mixture of epoxy resin with hardener.

Table II
Specification of epoxy resin and the hardener

Type	Viscosity (mPa.s) at (25°C)	Density (g/cm^3)
Epoxy resin	500 - 800	1.08 - 1.18
Hardener	10 - 20	1.07 - 1.13
		1.08

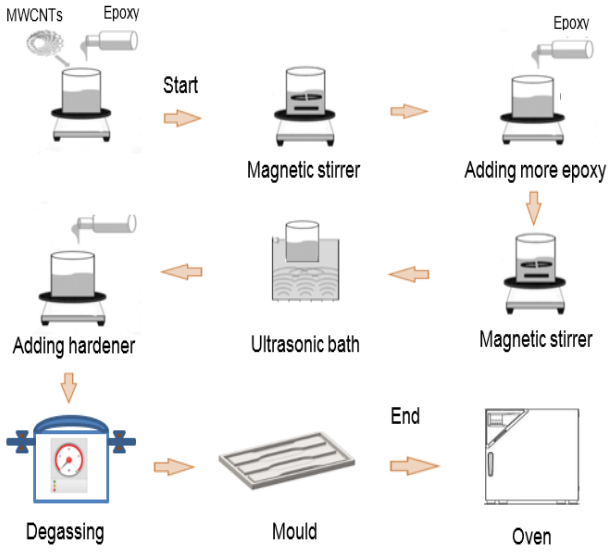


Fig. 2. Main steps of the nanocomposite preparation

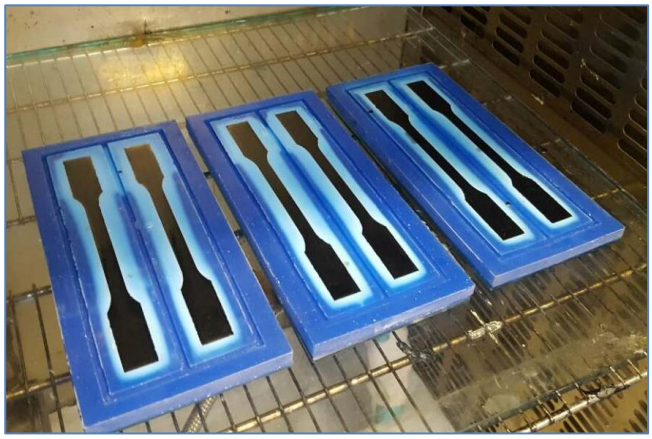


Fig. 3. Silicon moulds used for casting the tensile specimens

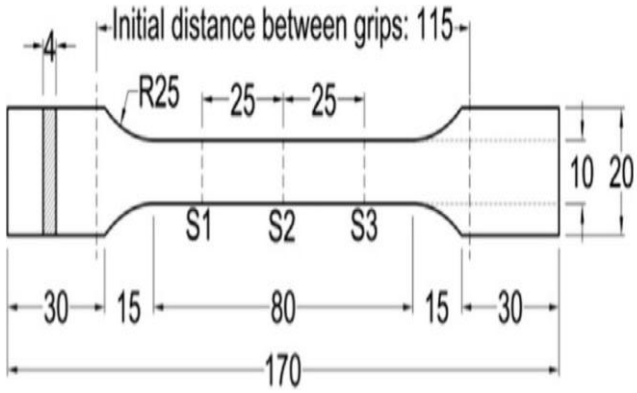


Fig. 4. Dimensions of the BS EN ISO 527 tensile test specimen (all dimensions are in mm)

IV- Mechanical Properties

A-Tensile Tests

Tensile testing was carried out on the epoxy based two type of MWCNTs nanocomposites specimens. Standard ″dog-bone″ shaped tensile specimens were manufactured according to the BS EN ISO 527-1 standard [22] as shown in Figure 4. The testing was carried out using an Instron model (5582/UK195) 100KN universal testing machine. The crosshead test speed r was initially set at 1mm/min. The same testing procedure was used for all of the five specimens. The elastic modulus (E) was determined over a strain range of 0.05-0.25 %. The mean values and their standard deviations (SD) were also calculated to evaluate the accuracy of the results obtained.

B-Fracture Characteristics

The microstructural characteristics of the fracture surface of the specimens and the extent of the dispersion of two type of MWCNTs in the epoxy resin matrix were observed using Scanning electron microscopy (SEM) on a JEOL JSM-5600 instrument. All SEM samples were gold-sputtered before being viewed in the SEM.

V- Theoretical Model

The Halpin-Tsai Equations [23] are mathematical equations which are used to model the strength and modulus of elasticity of fibre reinforced matrix and other properties [24]. This model was also modified by Yeh et al. [25] and applied to a PF/650 phenolic resin-multi wall carbon nanotube composite at various volume fractions of CNTs between 0 and 4 wt%. Overall, they found close agreement between the model calculations and the experimental result of tensile strength values. However in this study, the multi-wall carbon nanotubes distribution was not studied indetail of used to evaluate results. With respect to incorporating CNTs in a nanocomposite, then the Halpin-Tsai equation can be used to evaluate the results . The equation is expresed as

$$\sigma_c = \frac{1+\varepsilon\eta\, Vf}{1-\eta Vf}\ \sigma_m \qquad (1)$$

Where; σ_c= strength of composite, Vf= volume fraction of fibres, σ_m= strength of matrix, $\varepsilon = strain\ rate$, η= depends on the ratio of strength of fibre to strength of matrix (σ_f/σ_m):

$$\eta = \frac{\alpha\left(\frac{\sigma_f}{\sigma_m}\right)-1}{\alpha\left(\frac{\sigma_f}{\sigma_m}\right)+\xi} \qquad (2)$$

The dispersion of CNTs within the matrix is influenced by the shape factors α and ξ. Where for randomly orientated of the fibres in three dimensions these shape factors are then α = 1/6 and ξ = 2(l/d). Here l and d represent length of fibre and diameter respectively. These can be used if the fibre length is much less than the sample thickness (such as CNTs case). Coleman [26] also applied Halpin-Tsai model to polymer-carbon nanotube composites and found that there was close correlation between the calculated strength result and experimentally obtained values, particlarly when the carbon nanotube concentrations were lower than 10 wt.%. The Halpin-Tsai equation has also been used to calculate the modulus of elasticity of the final resulting composite when randomly oriented carbon nanotubes are used [27-29]. Voigt-Reuss [30] developed a micromechanical model to estimate the modulus of elasticity of short fibre composites, this is given below;

$$E = \frac{3E_l}{8} + \frac{5E_t}{8} \qquad (1)$$

Where; E_l, E_t indicate the longitudinal and transverse elastic modulus respectively. The above equations can be also modified for the MWCNTs composite case as given below[30];

$$E_C = \left[\frac{3}{8} * \frac{1 + 2\left\{\frac{l_{NT}}{d_{NT_o} - d_{NT_i}}\right\}\eta_L V_{NT}}{1 - \eta_L V_{NT}} + \frac{5}{8} * \frac{1 + 2\eta_T V_{NT}}{1 - \eta_T V_{NT}}\right] \mathrm{E}_m \qquad (2)$$

Where; d_{NTo}, d_{NTi} were the outer and inter of carbon nanotube diameter. Some assumptions such improved matrix/MWCNTs preoperties were used to promote a good adhesion between the MWCNTs and matrix, so that good bonding exists.

VI-Simulation

The ANSYS workbench software is considered to be one of the most effective tools available for property and design analaysis. This software uses the finite element method (FEM) to provide numerical solutions to highly complex structural problems. Using FEM the structure is divided into small parts (elements) which are then reassembled for analysis. Partial differential equations are then used to translate the finite element method into linear algebraic equations according to the function shows in the Eq.(1).

$$[\mathrm{K}] * \{\mathrm{q}\} = \{\mathrm{F}\} \qquad (3)$$

Here, K is the stiffness matrix, F is nodal vector force and q is the nodal displacement vector.

To conduct this FEM analysis Young's modulus, density, Poisson's ratio, load conditions and boundary conditions were

applied in order to simulate the experimental conditions. Solid elements were used during the analysis. Typically a 20-node brick element, as shown in Figure 5, was used during modelling. This is considered to be the most effective element for linear elastic calculations because of the location of the integration points and stress concentrations at the surface of a structure are well captured.

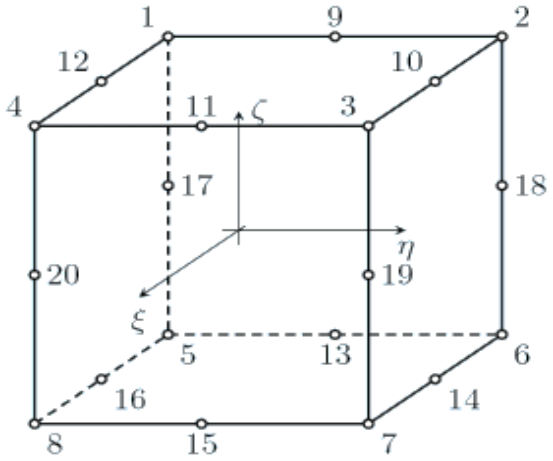


Fig. 5. 20-node brick element (60 DOF)

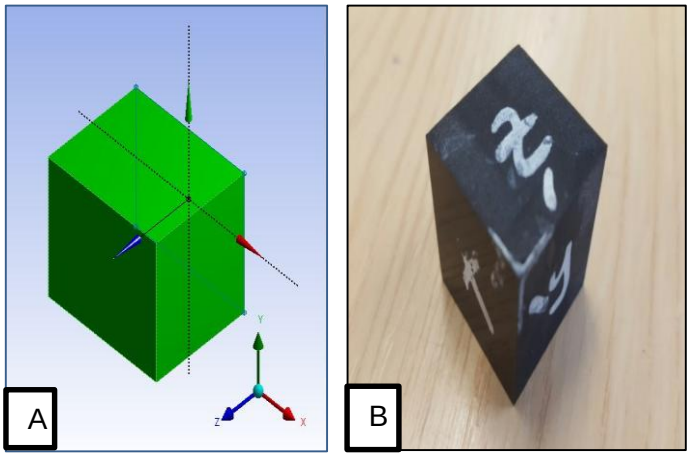


Fig. 6. A cubic 20×20×20 mm^3 specimen used during isotropic compression testing, 3D design used in FEA analysis and the test specimen with the major directions marked on the surface (b)

In this type of a 20 node element was used with each node having three degrees of freedom allowing translation in the x, y, z directions and rotation about x, y, z axes. In this analysis a fine meshe was generated and used. In this analysis. The MWCNTs and the epoxy resin nanocomposite were considered to be homogeneous isotropic materials as shown in Figures 6,7 and Table 3.

Table III
Results from compression tests

Type	Specimen No.		
	$\bar{E}_{X1\dot{\rightarrow}5}$	$\overline{E_{Y1}}\dot{\rightarrow}_5$	$\bar{E}_{Z1\dot{\rightarrow}5}$
Modulus (GPa)	0.876	0.822	0.820
Mean (overall)	0.840		
Standard Deviation (overall)	3.4%		

The behaviour of the nanocomposite was assumed to be linearly elastic with perfect bonding between the material and the Ni-MWCNTs. In addition, compression testing was done to determine (E) values. Figure 7 shows the typical results obtained.

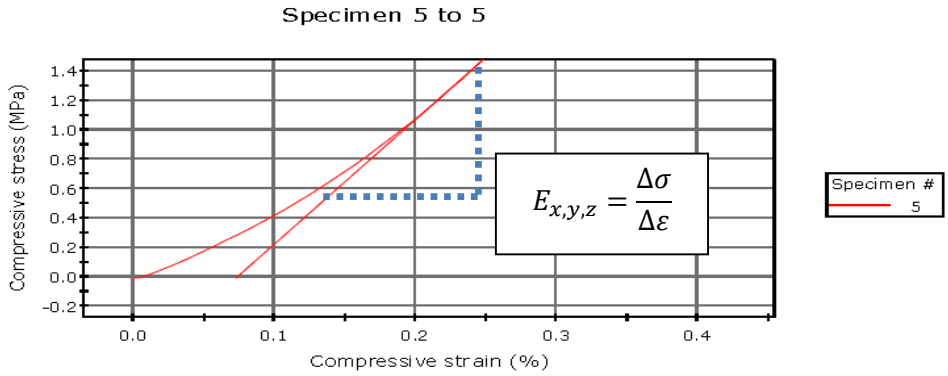


Fig. 7. The compression stress-strain curves for modulus characterisation of epoxy resin

Based on these assumptions, the nanocomposite material is transversely isotropic in both compounds and can be defined by the following compliance tensor equation (2):-

$$\begin{bmatrix} \frac{1}{E_x} & -\frac{v_{xy}}{E_x} & -\frac{v_{xz}}{E_x} & & & & 0 & 0 & 0 \\ -\frac{v_{yx}}{E_y} & \frac{1}{E_y} & -\frac{v_{yz}}{E_y} & & & & 0 & 0 & 0 \\ -\frac{v_{zx}}{E_z} & -\frac{v_{zy}}{E_z} & -\frac{1}{E_z} & & & & 0 & 0 & 0 \\ & & & \frac{1}{G_{xz}} & 0 & 0 & & & \\ 0 & 0 & 0 & 0 & \frac{1}{G_{yz}} & 0 & & & \\ 0 & 0 & 0 & 0 & 0 & \frac{2(1+v_{xy})}{E_x} & & & \end{bmatrix} \quad (2)$$

Where; $\frac{v_{zx}}{E_z} = \frac{v_{xz}}{E_x} = \frac{v_{zy}}{E_z} = \frac{v_{yz}}{E_y}$ and $E_x = E_y = E_z$, the passion ratio v_{xy}=$v_{yz} = v_{zx}$, the shear $G_{xz} = G_{yz}$

The rule of mixture (ROM) was used to calculate the density and the Poisson ratio of nanocomposite and the modulus of elasticity was calculated using the Halpin-Tsai equation with different weight fractions of MWCNTs (i.e 0.1 wt.%, 0.2 wt.%, 0.3 wt.%, 0.4 wt.%, and 0.5 wt.%). The physical and mechanical properties of the prepared nanocomposite are as shown in Table 4. The analysis parameters are shown in Table V.

Table IV Elastic modulus, density and the Poisson ratio for the two type of MWCNTs reinforced epoxy resin

Filler type	wt.%	$E_{Halpin-Tsai}$ (GPa)	Poison ratio	Density (g/cm^3)
Ni-MWCNTs	0	2.79	0.3750	1.1
	0.1	2.84	-	1.1009
	0.2	2.88	-	1.1018
	0.3	2.91	-	1.1027
	0.4	2.95	-	1.1036
	0.5	2.98	-	1.1045
COOH-MWCNTs	0.1	2.99	0.3750	1.1005
	0.2	3.18	-	1.1010
	0.3	3.38	-	1.1016
	0.4	3.57	0.3749	1.1021
	0.5	3.77	-	1.1026

Table V
ANSYS Evaluation Parameters

Name	Symbol	Value	Source
Outside diameter of MWCNTs (nm)	Do	10	Present study
Inside diameter of MWCNTs (nm)	Di	4	Present study
Length (μm)	L	50	Present study
Young's modulus of nanotube (GPa)	E_{cnt}	1000	Calculated
Density of nanotube(g/cm3)	ρ_{cnt}	2.1	Present study
Poisson's ratio of nanotube	υ_{cnt}	0.35	[23, 31, 32]
Young's modulus of unmodified epoxy (GPa) (tensile)	E_{epoxy}	2.79	Experimental
Poisson's ratio of unmodified epoxy	υ_{epoxy}	0.375	[33]
Density of unmodified (g/cm3)	ρ_{epoxy}	1.1	Present study
Young's modulus of nickel (GPa)	E_{nickel}	207	[34]
Poisson's ratio of nickel	υ_{nickel}	0.31	[35]
Density of nickel (g/cm3)	ρ_{nickel}	8.9	[35]

VII-Results and Discussions

This study investigated the mechanical properties of an experemental nanocomposite material maufactured from epoxy resin containing MWCNTs. The test results were evaluated and compared with simulation results as shown in table 6. Here ANSYS (version 16.2) was used to estimate the mechanical properties of the nanocomposite before and after adding a different weight fraction (0.1 wt.%, 0.2 wt.%, 0.3 wt.%, 0.4 wt.%, 0.5 wt.%) of Ni-MWCNTs. In this analysis, the specimen thickness is small compared to its length so that it is assumed to be a thin plate. Hence, a condition of plane stress will apply. The applied loads were based on the experimental work conducted and the maximum normal in (x-direction) stress value were obtained for the nanocomposites at different weight fractions. It must be noted that the tensile strength is a measure of the maximum stress which the material can withstand just prior to fracture. The maximum stress indicated by FEA can be considered to be the axial tensile stress. An Example of the axial tensile stress distribution for 0.3 wt.% as shown in figure 11. then this stress can be considered, for comparison purposes, to be also equivalant to the tensile strength.

The result obtained are shown in Figure 8. After adding the nanoparticals to the unmodified epoxy resin Figure (9), it can be seen that the tensile strength increases with increasing additions of Ni-MWCNTs reaching a maximum value by approximately 19% at 0.3 wt.% and with a slight decrease therfafter probably due to agglomeration [36] effects as shown in Figure 10a. This increase can be explained by considering; the reinforcement effect of the Ni-MWCNTs as providing an effective load transfer mechanism from the Ni-MWCNTs to the adjacent epoxy matrix region.

Therefore, a good dispersion of Ni-MWCNTs into the epoxy resin, as shown in Figure (10,b) with strong interfacial adhesion between the matrix and the reinforcement, will generate the increase shown. However, this reinforcment increase effect appears to be depend upon the observed inter particale spacing. When this spacing is reduced (by increasing the wt.%.) beyond a certain value then the effect is lost due to an increased agglomeration. The obtained experimental results were generally very close to the theoretical results obtained using ANSYS and the Halpin-Tsai equation as shown in figure 11. These results are in good agreement with the results published in the literature [8, 16, 18, 37].

Table VI
Experimental & theoretical Maximum Tensile stress results of nanocomposite

Type of content	wt.%	Tensile strength (MPa)	$E_{exp.}$ (GPa)	Tensile strength by (ANSYS)(MPa)
Ni-MWCNTs	0	58.47	2.79	62.92
	0.1	65.79	3.01	72.22
	0.2	67.38	3.26	74.46
	0.3	69.57	3.58	75.84
	0.4	67.44	3.33	74.32
	0.5	66.68	3.13	72.12
COOH-MWCNTs	0.1	68.78	3.21	77.04
	0.2	70.56	3.55	78.27
	0.3	68.33	3.28	74.43
	0.4	67.18	3.21	73.33
	0.5	64.23	3.05	69.41

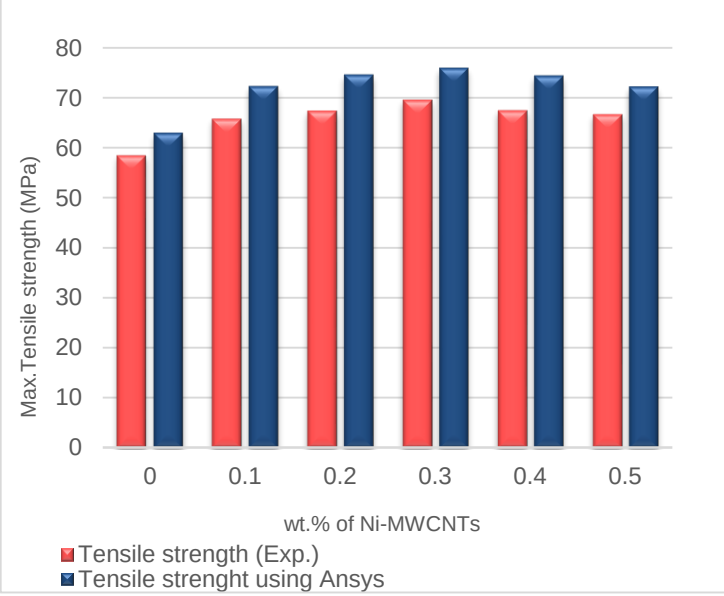


Fig. 8. The effect of Ni-MWCNTs content on tensile strength

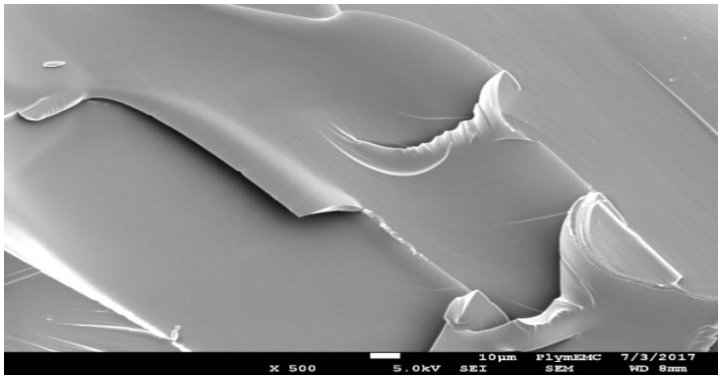


Fig. 9. Surface topology of the unmodified epoxy resin

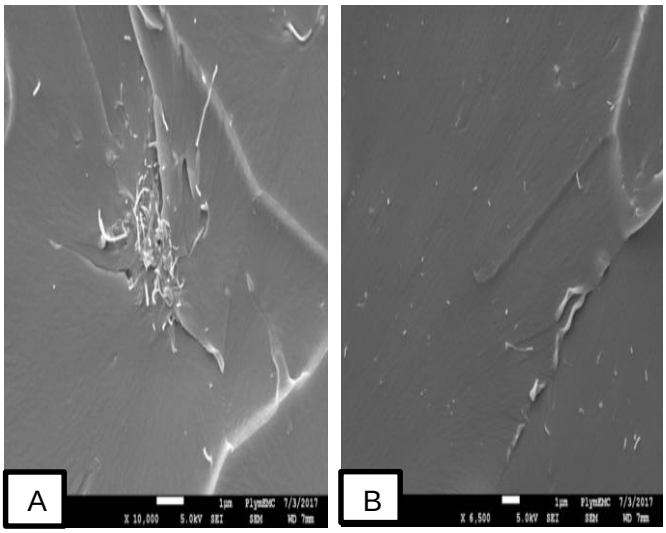


Fig. 10. Ni-MWCNTs agglomeration at 0.5 wt.% (a) and dispersion at 0.3 wt.% (b)

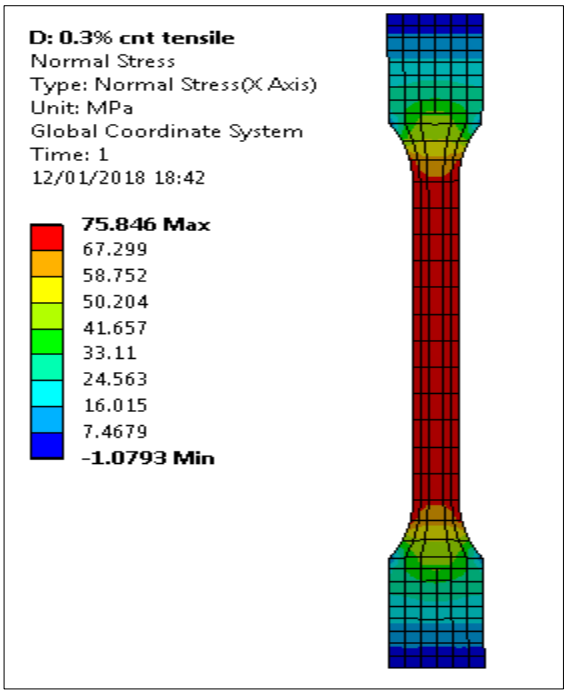


Fig. 11. FEA simulation result for 0.3 wt.% Ni-MWCNTs

It can be noted that when the amount of COOH-MWCNTs < 0.2 wt.% will improve the tensile and modulus of the nanocomposite, while will it reduced with with a COOH-MWCNTs content > 0.2 wt.% as shown in figure 12 showed a reduction. This enhancement effect caused by adding a small amount of MWCNTs was studied by Konnola, R., and K. Joseph [8]. It can be also noted from the table (6) that the highest tensile strength and modulus was obtained when 0.2 wt.% COOH-MWCNTs was added. This might be due to the good dispersion of the filler inside the matrix and is in agreement with Kim *et al* [38]. The SEM images shown were taken from the fracture surfaces and confirmed that for 0.2 wt.% of COOH-MWCNTs the good dispersive properties were obtained, see figure (13,a) and a strong interfacial adhesion between them was ensured [39]. However, both were reduced at 0.5 wt.% of COOH-MWCNTs [40], probably due to some agglomeration [36] as shown in the figure (13,b).

The experimental results obtained for the nanocomposite where again compared with the numerical results obtained using the Halpin-Tsai model during the ANSYS analysis as shown in figure 15. The maximum experimental tensile strength obtained was 70.56 MPa and whilst the maximum ANSYS tensile stress obtained was 78.27 MPa. It is revealed from these analysis results, the experimental tensile strength had a very good correlation with the ANSYS numerical results.

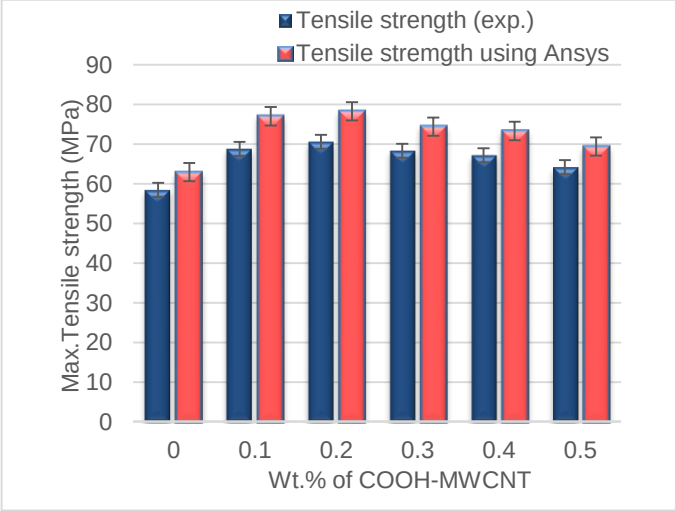


Fig. 12. The effect of COOH-MWCNTs content on the tensile strength

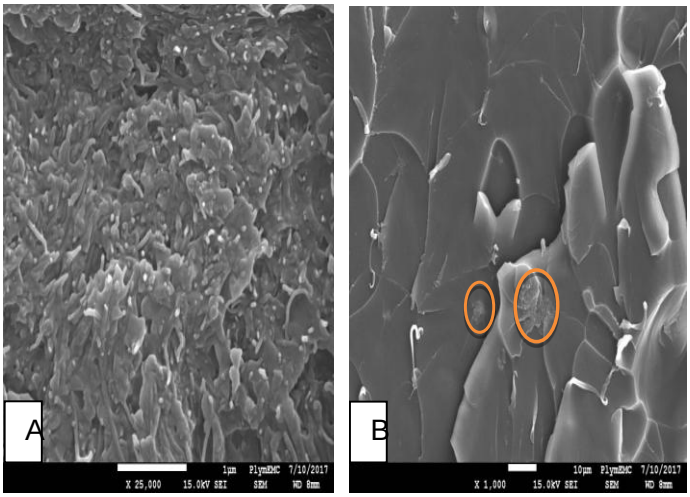
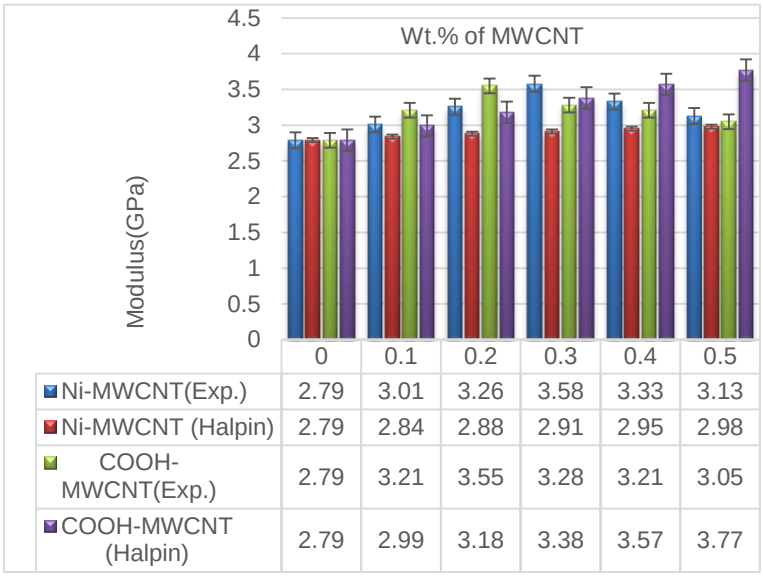


Fig. 13. Dispersion of the nanoparticles at 0.2 wt.% (a) and agglomeration at 0.5 wt.% inside the matrix (b)

With regards to the moduli obtained during testing and from the Halpin-Tsai equation, it is clear from the Figure12, that a noticeable improvement can be achieved for the nanocomposite with a 0.3 wt% of Ni-MWCNTs reinforcement. This is in agreement with the findings of Kim *et al* [38]. A small reduction was also noticed at 0.5 wt% MWCNTs [40]. It is very noticeable that the tensile modulus for the Ni-MWCNTs modified epoxy resin reached a maximum value at 0.3 wt.% before tailing off thereafter. Once again this effect could be due to agglomeration of Ni-MWCNTs as shown in figure (10, a) so leading to some reduction in the observed mechanical properties. This improvement with the addition of a small amount of Ni-MWCNTs was also seen by Konnola, R., and K. Joseph [8]. The Young's modulus of a nanocomposite with randomly oriented of Ni-MWCNTs was also theoretically estimated using the Halpin-Tsai model as shown in Table 4. The theoretical estimation of Young's modulus (E) for nanocomposite shows some agreement with the experimental results. Here the slight differences observed could be due to an orientation effect in the x-direction of the sample. On other hand, all the theoretical modulus values were less than experimental values. With respect to COOH-MWCNTs fillers, the modulus for experimental work was 3.55 GPa and 3.18 GPa for the numerically predicted value, a significant difference (~ 10.4 wt.%). This difference could due to the assumptions used during the ANSYS modelling, such as stating that the interface bonding between the COOH-MWCNTs and the matrix was ideal with good dispersion. This may or may not be there. Also up to 0.2 wt.% the experimental result was greater than the theoretical values. Whilst for the Ni-MWCNTs case all the experimental results were greater than the theoretical values. These results are also in close agreement with [8, 16, 18, 37].



	0	0.1	0.2	0.3	0.4	0.5
Ni-MWCNT(Exp.)	2.79	3.01	3.26	3.58	3.33	3.13
Ni-MWCNT (Halpin)	2.79	2.84	2.88	2.91	2.95	2.98
COOH-MWCNT(Exp.)	2.79	3.21	3.55	3.28	3.21	3.05
COOH-MWCNT (Halpin)	2.79	2.99	3.18	3.38	3.57	3.77

Fig. 14. The effect of MWCNTs on the modulus

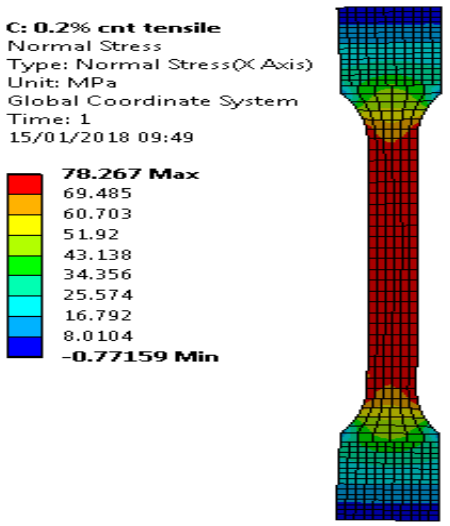


Fig. 15. FEA simulation results for 0.2 wt.% COOH-MWCNTs

VIII- Conclusions

In this study commercially available functionalised MWCNTs nano-reinforcements (Ni-MWCNTs and COOH-MWCNTs) were used in epoxy resin matrix. The aim was to improve the dispersion of the MWCNTs by applying enhanced mixing processes and to maintain the load transfer between the matrix and the filler through interfacial interactions between them. The mechanical test results and simulated properties were compared for both MWCNT types and discussed in this paper, while the following observations can be concluded:

1. The reinforcing effect of the Ni-MWCNTs and COOH-MWCNTs led to an improved tensile strength and Young's modulus (stiffness).
2. The greatest improvements were obtained at 0.3 wt.% inclusion of Ni-MWCNTs in the matrix and at 0.2 wt.% of COOH-MWCNTs, for both the strength and the stiffness.
3. Increasing beyond 0.3 wt.% of Ni-MWCNTs and at 0.2 wt.% of COOH-MWCNTs caused a decreased in both the strength and stiffness relative to the maximum values reached.
4. It is considered that these improved mechanical properties are due to good distribution of the nanoparticles in the matrix material.
5. Agglomeration of the nanoparticles became most evident beyond the maximum values indicated, thus causing the observed reduction in properties.
6. It is speculated the improving processing parameters will further improve the observed properties (tensile strength and stiffness).
7. The ANSYS theoretical results showed good correlation with the experimental results obtained. In most cases this difference was less than ~8.7 wt.% in term of Ni-MWCNTs and less than ~8.9 wt.% for COOH-MWCNTs.
8. The maximum difference between the measured and the theoretical properties (tensile modulus) occurred at 0.2 wt.% for both types of fillers. This was possibly due to nanoparticles shape and orientation effects not taken in account by the FEM analysis.

The results of this study showing improved properties of the epoxy resin. Therefore, the functionalised MWCNT infused epoxy may find its application in durable paints, where corrosion prevention is highly important (e.g. oil industry). However, the price of functionalised MWCNTs are relatively high but only very small quantities (0.2…0.3 wt.%) are required to achieve the mentioned properties. The various stages of the mixing process adding extra cost to the product, so in industrial scale a more efficient way needs to be investigated.

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