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Fawad Inam
Glyndwr University, f.inam@glyndwr.ac.uk

Nataliia Luhyna

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Abstract

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Keywords

Carbon nanotubes (CNTs), CNT/ epoxy nanocomposites, Properties

Disciplines

Aerospace Engineering | Engineering | Engineering Science and Materials | Nanoscience and Nanotechnology

Carbon Nanotubes for Epoxy Nanocomposites: A Review on Recent Developments

Nataliia Luhyna, Fawad Inam

Advanced Composite Training and Development Centre and School of Mechanical and Aeronautical Engineering, Glyndŵr University, Plas Coch, Mold Road, Wrexham, LL11 2AW, UK

Abstract: Carbon nanotubes (CNTs) are one of the strongest and stiffest engineering fibres. Due to their unique combination of chemical and physical properties at an incredibly small size, they possess great potential to be used as nanofillers for many structural and functional materials, particularly in aerospace sector. Depending on the type, geometrical parameters, concentration, dispersion and many other factors, CNTs can significantly modify the mechanical, electrical and thermal properties of epoxy based materials. This review paper, covering methods of synthesis, composite processing techniques and properties, presents an overview of developments in the field of CNT/ epoxy nanocomposites in recent years.

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1. Introduction and historical perspective

The relatively recent discovery (Iijima, 1991) of carbon nanotubes (CNTs) has opened new possibilities for the production of advanced novel materials. Due to their unique mechanical, electrical and the thermal properties, CNTs is subject of intense research, which is evident from a growing number of publications in this area. CNT based materials possess potential to be used in almost any of the leading industries such as aeronautics, electronics, optics, medicine, architecture/ construction, automotive, mechatronics and biotechnology to name a few (Endo et al., 2004).

CNTs were discovered accidently in 1991 (Iijima, 1991). CNTs were formed at the cathode during sputtering of graphite by electronic arc. Derived nanotubes were multi-walled nanotubes (MWNTs) with an inner cylindrical diameter about 4 nm (Iijima, 1991). After two years, Iijima and his colleagues synthesised single-walled carbon nanotubes (SWNTs). SWNTs were prepared using the method originally researched by Iijima (1991), but with the addition of metal particles on the carbon electrodes (Bethune et al., 1993).

The discovery of CNTs belongs to the most remarkable achievements of modern science and technology. This form of carbon structure is intermediate between graphite and fullerene. However, many properties of CNTs have nothing in common either with graphite or fullerene, which explains uniqueness of CNTs in many ways.

This review paper has two parts. In the first part, it elucidates the properties, synthesis and uniqueness of CNTs. The second part provides a summary of recent development in the field of CNT/ epoxy nanocomposites.

2. Classifications and types of CNTs

CNTs have chicken-wire structures with an incredibly small size (diametre: 0.1 nm to 100 nm). CNTs are extended cylindrical structures composed of collapsed sheets of graphene (Geim and Novoselov, 2007). The main unit of graphene sheets is hexagon with carbon atoms arranged at the corners (Fig. 1).

Chirality or helicity is an important property, indicating the incompatibility of the object with its mirror image. It is characterised by two integers (n, m), which indicate the location of the hexagonal grid (Belin and Epron, 2005). Chirality of the nanotube can also be uniquely determined by the angle α, formed by the folding direction of the nanotube. The value of (n, m) determines the chirality of CNT, which affects the optical, mechanical and electronic properties (Fig. 2).

Subject to the chirality, SWNTs possess electrical properties of semiconductors as well as that of metals (Belin

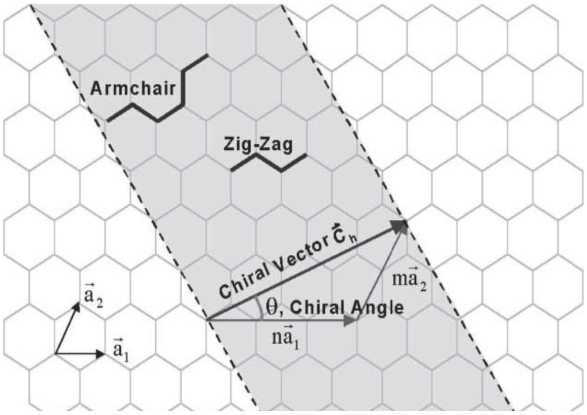

Figure 1. Schematic diagram showing how a hexagonal sheet of graphite is 'rolled' to form a carbon nanotube (Thostenson et al., 2001).

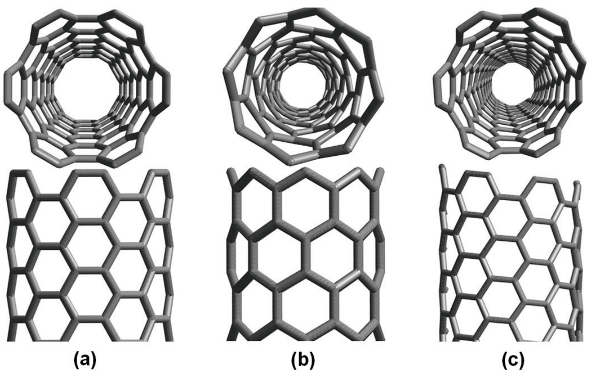

Figure 2. Different types of CNTs based on their chirality: a) armchair (metallic); b) zigzag (metallic or semiconducting); and c) chiral (metallic or semiconducting).

and Epron, 2005). As evident from Fig. 2, the parameters (n, m) can change the type of CNTs, i.e.

1) Direct (achiral) nanotubes:
   a) "Armchair" with values $n = m = 0$ and the angle $\alpha = 0$;
   b) "Zigzag" with $m = 0$ or $n = 0$ and the angle $\alpha = 30$.
2) Helical (chiral) nanotube with an angle α of 0 to 30.

Other than chirality, CNTs can be synthesised in many different physical forms, i.e. short, long, thick, thin, single wall, multi wall, functionalised, open, capped, stacked, containing different structural defects and rolling structures. Depending of number of rolled graphene shells, CNTs can be classified as single walled nanotubes (SWNTs), double walled nanotubes (DWNTs) and multi walled nanotubes (MWNTs). They can also be further classified depending on the structure - straight, branched, curled, cup-stacked and herringbone; and variety of the crystalline structure - well aligned and distorted (Hayashi and Endo, 2011). Each type has its own advantages and disadvantages and possesses potential to be used for different types of applications.

Fig. 3 shows two of the most common type of CNTs. SWNT is a rolled up sheet of graphene, which is having half hemisphere fullerene molecule (Fig. 3a). The ends of the CNT are not always closed as shown in Fig. 3b. MWNT (Fig. 3b) possess cylinders, inserted one into each other of SWNTs. The number of cylinders can be from 2 to 30 and the outer diameters are around 3-100 nm (Fig. 3b).

3. Properties of CNTs

A perfectly crystalline CNT possesses excellent electrical conduction similar to that of copper. CNTs also have tensile strengths 100 times greater than steel having nearly 1/6 the density of steel (Zolotuchin, 1999). Apart from this, CNTs were also found to have thermal conductivity higher than the purest diamond (Holister et al., 2003). These unique properties of nanotubes and small sizes make them indispensable materials for modern nanotechnology (Breeuer and Sundararaj, 2004, Holister et al., 2003). Tab. 1 shows a basic comparison of CNTs with graphite, where CNTs are distinguished by their excellent mechanical, thermal and electrical properties.

As compared to SWNTs, DWNTs are distinguished by their heat-stable properties. Upon heating to temperatures of 2000 °C (in vacuum), they maintain their crystallinity and cylindrical structure. When heated above 2000 °C the outer layers of CNTs start degrading. The mechanical properties of the DWNT are superior as compared to SWNT and MWNTs, which makes them an excellent filler/reinforcement material for nanocomposites (Hayashi and Endo, 2011).

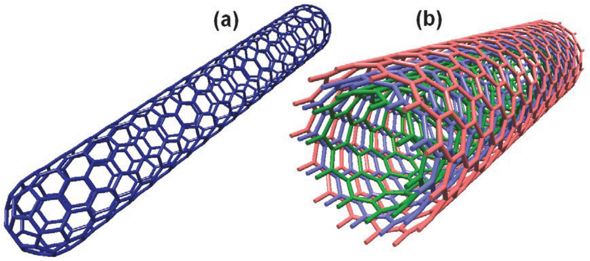

Figure 3. Different types of CNTs based on the number of graphene layers/ cylinders: (a) capped SWNT; and (b) open MWNT.

Depending on the type, CNTs could be both conductors and/ or semiconductors. It is related to the topological defects in the structure (Xie et al., 2005). CNTs with metallic properties conduct electricity at absolute zero temperature, whereas the conductivity of semiconducting nanotubes is zero at absolute zero and increases with increasing temperature. Different types of metallic and semiconducting CNTs are shown in Fig. 2.

Diamond is another allotropic form of carbon. It has lower modulus (20 GPa) than graphite (1000 GPa). However, compressive strength of diamond is 14 GPa and of graphite is 105 MPa (Smith, 1987). As compared to diamond and graphite, the higher values of the elastic modulus and compressive strengths of CNTs allows possibility of creating a composite material with very different set of mechanical properties. Such combination of superior properties cannot be observed for any other allotropic form on carbon (Xie et al., 2005). Tensile strength of CNTs is significantly higher (i.e. 11 to 63 GPa) than any of the known engineering materials (Yu et al., 2000). This is explained by the lack of micro-defects in the CNT crystal structure and high degree of interaction forces between the atoms in its crystal lattice.

Graphite is thermodynamically more stable than diamond at room temperature, and diamond is thermodynamically more stable at high pressure. In terms of thermodynamic stability, CNTs stand in between. Because of large specific surface area (up to 2600 m^2g^{-1}) of CNTs (Eletskii, 2007), they possess unique absorption capabilities for different types of gases.

The rigidity of CNTs under radial compression is much lower than the longitudinal compression or tension (Hertel et al., 1998). Therefore, the tubular structure may

Table 1
Properties of carbon nanotubes (Xie et al., 2005, Sengupta et al., 2011, Li et al., 2008)

Property	CNTs	Graphite
Specific gravity	0.8 g/cm^3 for SWCNT; 1.8 g/cm^3 for MWCNT (theoretical)	2.26 g/cm^3
Elastic modulus	1 TPa for SWCNT; 0.3–1 TPa for MWCNT	1 TPa (in-plane)
Tensile strength	50–500 GPa for SWCNT; 10–60 GPa for MWCNT	130 GPa
Resistivity	5–50 μΩcm	50 μΩcm (in-plane)
Thermal conductivity	3000 W/ mK (theoretical)	3000 W/ mK (in-plane), 6 W/mK (c-axis)
Magnetic susceptibility	22×10^6 EMU/g (perpendicular with plane), 0.5×10^6 EMU/g (parallel with plane)	
Thermal expansion	Theoretically negligible	-1×10^{-6} 1/K (in-plane), 29×10^{-6} 1/K (c-axis)
Thermal stability	>700 °C (in air); 2800 °C (in vacuum)	450–650 °C (in air)
Specific surface area	10–20 m^2/g	7 m^2/g

be distorted under the influence of van der Waals forces with the substrate or as a result of exposure of nanotubes to each other. Such radial defects increase with the increase in the diametres of CNTs. The deformation of MWNTs decreases with increasing the inner layers of the nanotube and vice versa.

4. Synthesis of CNTs

The most common methods for producing CNTs are the arc discharge method, the laser ablation, the gas phase catalytic growth, and chemical vapor deposition (CVD). During synthesis, impurities from the catalyst particles, amorphous carbon, and tubular fullerenes are produced. Gas phase methods are more suitable for large scale production of CNTs since it is necessary to receive a good amount of reinforcement materials for composite materials (Thostenson et al., 2001).

For producing CNTs, arc discharge technique involves thermal decomposition of graphite electrodes in arc discharge plasma. It occurs in the helium atmosphere under a very high voltage. It is important to use anode and cathode of high-purity graphite rods. The final dimensions of CNTs depend on various process parameters. During combustion plasma, there is an intensive thermal evaporation of the anode, resulting in a build-up formed at the cathode which generates CNTs (Journet et al., 1997). The production yield is highest when the plasma current is minimal, and its density is around 100 A/cm^2 (Zolotuchin, 1999).

In laser ablation method, a laser is directed to the target for producing CNTs. It is usually performed in a horizontal tube furnace in a stream of inert gas (with pressure) at a temperature of around 1200 ^{o}C. The target is usually of the carbon origin and CNTs are deposited on one of the ends. Like other synthesizing methods of CNTs, the quality and type of CNTs depend on the type of employed catalysts (Rinzler et al., 1998).

Both techniques, arc discharge and laser ablation are restricted in terms of the production quantity. When using the arc discharge method, the limitation is the size of the anode and in the laser ablation it is the graphite target. Also, there are issues with the purification of CNTs, which need to be integrated with the primary synthesis methods (Thostenson et al., 2001). Elimination of such drawbacks is possible by employing CVD method, in which nanotubes are formed by decomposition of carbon containing gases like ferrocene (Singh et al., 2002). The method is based on the deposition of CNTs on a catalytic substrate with a constant controlled flow of hydrocarbon gas. CNTs are obtained by the decomposition of carbon containing gas at 700-900 ^{o}C and nanotubes are subsequently grown on the metallic catalyst (Khare and Bose, 2005). This method also offers the advantage of controlling the length and diametre of CNTs with no side additives. Therefore, CVD method is an ideal way for mass production of CNTs (Ren et al., 1998).

5. CNTs vs. carbon fibres

Carbon fibers used to reinforce materials such as polymers, carbon-carbon composites and carbon fiber reinforced materials (Smith, 1987). These micro-sized fibers have high specific strength and specific modulus which make them ideal for many applications. Carbon fibers are also significant for their excellent thermal and electrical conductive properties, and low coefficient of thermal expansion (Donnet et al., 1990). Materials based on carbon fibers are widely used in aeronautical applications, because of its high strength, stiffness, durability, low weight and most important reliability (Chand, 2000). All this make carbon fibres one of the light-weight reinforcements for epoxy matrix, especially for new aerospace initiatives like Boeing 787 and Airbus A350 programmes.

As compared to carbon fibres, CNTs are unique for having smaller dimensions which makes them supplementary for filling carbon fibre reinforced epoxy composites (Inam et al., 2010). It is not possible to substitute CNTs with well-matured carbon fibre for aerospace technology at this stage. This is because of the issues with the mass production of long and perfectly crystalline CNTs. Currently, it is not possible to produce defect-free long CNTs. Some attempts have been made for synthesizing CNT ropes (Kis et al., 2004, Koziol et al., 2007, Liu et al., 2010, Zhang et al., 2002), but it is still subject of intense research. Therefore, CNTs cannot be substituted against well matured micro-carbon fibre technology. However, CNTs may offer some added advantages to carbon fibre reinforced composites like enhanced adhesion between matrix and carbon fibre and improved matrix-dominated properties (Qian et al., 2010, Hayashi and Endo, 2011, Kim et al., 2011). For example, 0.2 wt.% CNTs were added to woven carbon fibre reinforced epoxy and significant improvements in strengths and modulus were reported (Kim et al., 2011). A comprehensive study was conducted by Inam et al. (2010), where the concept of multi-scale hybrid CNT/ carbon fibre reinforced epoxy micro-nanocomposite was thoroughly discussed.

6. CNT filled epoxy nanocomposites

CNTs are currently widely used as reinforcements for various matrices such as ceramics, polymers and metals. However, significant interest can be observed in the field CNT filled epoxy matrices (Kim et al., 2008). The main objectives of these researches have been to improve the manufacturing CNT reinforced epoxy composites, deagglomeration of CNT bundles, homogenous CNT dispersion, CNT alignment and interfacial bonding between the nanotubes and the matrix (Breeuer and Sundararaj, 2004, Quin et al., 2010).

It is now well established that CNTs influence the curing of thermoset polymers (Hussain et al., 2006). Vega et al. (2009) studied the influence of CNTs on the curing of epoxy nanocomposites. During curing, it was found that the time to gelation (t_{gel}) and time to vetrification (t_{vit}) is slightly higher for neat epoxy samples as compared to CNT/ epoxy nanocomposites (Tab. 2). The addition of 0.2 wt.% CNTs with the matrix does not significantly affect the gelation and vitrification times, however it was pointed that further increase in CNT concentration could affect these parameters significantly. There was not much difference in the glass-transition temperature. Furthermore, it was shown that thermal compressive strain developed in the epoxy above the glass transition temperature (T_g) was due to the presence of CNTs.

Table 2
Curing parameters of the CNT/ epoxy nanocomposites
(Vega et al., 2009)

System	CNT (wt.%)	t_{gel} (min)	t_{vit} (min)	T_g (°C)
Epoxy system 1	0	36.3 ± 0.8	69.4 ± 1.1	130 ± 0
	0.2	36.1 ± 0.7	68.5 ± 2	128.5 ± 1.3
Epoxy system 2	0	59.5 ± 4.9	106 ± 0	177.0 ± 0.1
	0.2	59.0 ± 5.6	95.5 ± 0.7	176.9 ± 0.9
Epoxy system 3	0	~880	~980	26
	0.2	~850	~970	26

6.1. Mechanical properties of CNT/ epoxy nanocomposites

It is well known that it is very difficult to achieve a good homogenisation of CNTs in epoxy matrix, therefore the properties of composites are often lower than expected. Significant research has been carried out on the manufacturing techniques to produce good composite materials. Resin transfer moulding (RTM) is one of the most common ways of producing CNT/ epoxy nanocomposites. RTM consists of pouring mould with liquid resin under high pressure and then it is lead to subsequent curing. The method allows manufacturing complex shape and large size in shorter durations. Cheng et al. (2009) evaluated the mechanical and physical properties of the CNT composites with a high concentration of CNTs (up to 16.5 wt.%) which was prepared by RTM method. MWNT/ epoxy materials were recently prepared using hot melt prepreg method (Ogasawara et al., 2011). High tensile strength and Young's modulus were achieved for samples prepared with hot melt prepped method as compared to composites prepared by conventional methods. For hot melt prepreg technique, a very good penetration (wet-out) between the matrix and CNTs was observed. This method of producing composite materials showed excellent output results and it can be applied for mass production as well. Experiments have confirmed that mechanical and electrical properties of nanocomposite were improved with the increase in CNT dispersion temperature (Martone et al., 2010). Glaskova et al. (2012) researched the effects of parameters like ultrasonication duration, temperature and power level and reported significant differences in the final properties of the nanocomposites. Among these processing variables, temperature and duration of the ultrasonication were found to be the major positive contributors.

Table 3
Effect of CNT concentration on the mechanical properties of epoxy based materials (Montazeri and Montazeri, 2011)

Material	Elastic module (MPa)	Ultimate tensile strength (MPa)	Ultimate tensile strain (%)
Epoxy	3430	64	6.1
0.1 wt. % MWNT	3458	67	5
0.5 wt. % MWNT	3705	69	4.45
1 wt. % MWNT	3951	71	5
2 wt. % MWNT	4225	75	7.5

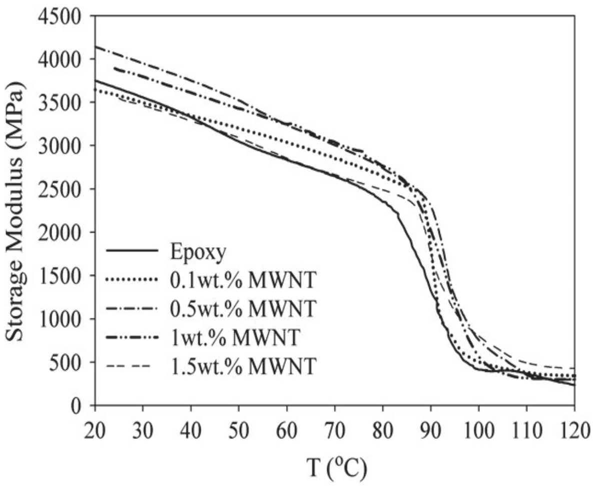

Figure 4. Storage modulus for epoxy and nanocomposites with different weight percent at 10 Hz frequency (Montazeri et al., 2012).

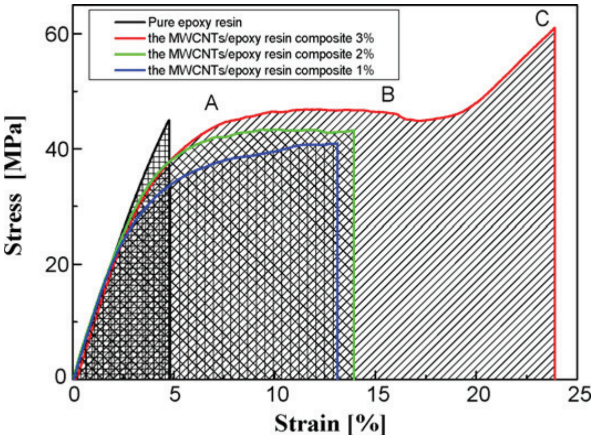

Figure 5. Stress–strain curves of pure epoxy resin and MWNT/ epoxy composites (Guo et al., 2009).

Recently, Montazeri and Montazeri (2011) conducted the investigation on viscoelastic and tensile properties of MWNT/ epoxy composites. The study showed a major influence of CNT concentration (0.1, 0.5, 1 and 2 wt.%) on the mechanical properties of the nanocomposites. The tensile properties of composites with different amount of CNTs are presented in Tab. 3. It was also reported that with addition of CNTs, epoxy composites became more brittle. Recently, Montazeri et al. (2012) also reported the effect of CNTs on the storage modulus of the composite (Fig. 4).

Guo et al. (2009) investigated the interphase between CNTs and epoxy and reported increase in the strength and toughness (Fig. 5). Fracture elongation and ultimate tensile strength (UTS) were increased with the increase in MWNT concentration (i.e. 1 wt.%, 2 wt.%, 3 wt.% of CNTs). Prolongo et al. (2011) reported the presence of good adhesion between CNTs and matrix were the main attributes for these results. To form a strong interface, amino functionalised MWNTs were dispersed in epoxy matrix. It was evident that the functionalisation treatment increased thermo-mechanical and flexural properties of the nanocomposite (Prolongo et al., 2011). The thermally pre-cured samples (with 0.25 wt.% functionalised CNTs) showed 58% improvement in the flexural strength, whereas samples having non-functionalised CNTs showed only 45% improvement as compared to the pure resin (Prolongo et al., 2011). Therefore, functionalisation of CNTs has significant positive effect on the mechanical properties of the epoxy nanocomposites.

Epoxy nanocomposites processed with acid treated CNTs showed have higher tensile strength and fracture strain (Montazeri et al., 2010). Moreover, untreated MWNT/ epoxy were found to be brittle. Montazeri et al. (2010) investigated the properties of MWNT/ epoxy composites reinforced with CNTs treated with nitric and sulfur acids. Young's modulus is higher in the untreated samples, possibly due to the aggregation of carbon nanotubes. The purified or acid treated MWNTs have modified interface as compared to the original nanotubes. After modification and acid treatment of CNTs, they have excellent structure and found to be adhering well with the matrix. It was shown by Montazeri et al. (2010) that the composites with purified CNTs have capability of absorbing greater stresses (i.e. higher fracture elongation and ultimate tensile strength), which is due to good interfacial adhesion between CNTs and the matrix. Modifying surfaces of CNTs based pre-pregs also contribute in achieving superior mechanical properties. Chen et al. (2010) showed that the modified CNT-added nano-prepreg sheets have better properties due to superior dispersion and the absence of CNT clusters. Tensile strength, flexural strength and impact strength were improved with the increase in CNT content. Moreover, the modified composite material exhibits high electrical conductivity compared to the unmodified, and it can be further increased with the addition of CNTs.

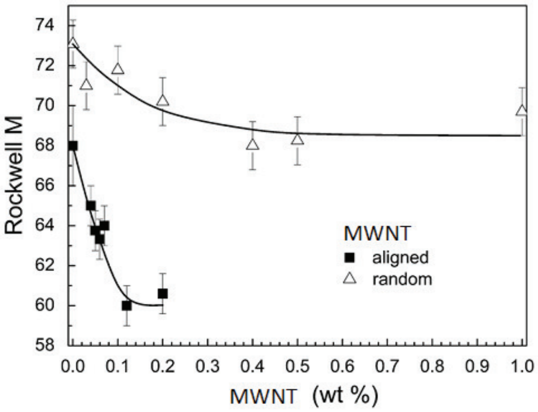

Figure 6. Rockwell hardness of aligned and randomly oriented CNT/ epoxy nanocomposites (Felisberto et al., 2011).

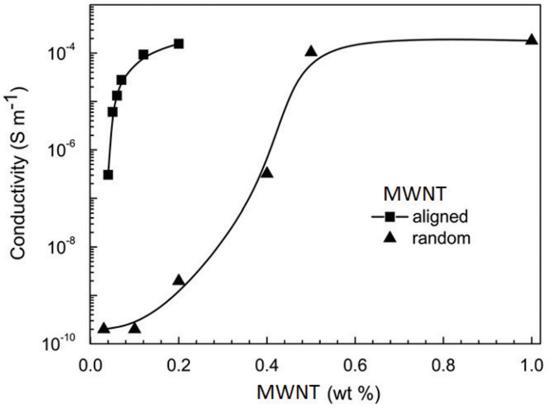

Figure 7. Electrical conductivity of aligned and randomly oriented CNT/ epoxy nanocomposites (Felisberto et al., 2011).

Currently, it is difficult to align CNTs in epoxy matrices because of the dimensions of CNTs. Uncontrolled orientation is responsible for low degree of dispersion. Thus, the resulting composite indexes of properties were found to be much lower due to these deficiencies (Cheng et al., 2009). However, for some properties, like hardness random oriented CNTs contribute positively as reported by Felisberto et al. (2011) in Fig. 6.

6.2. Electrical and thermal properties of CNT/epoxy nanocomposites

To achieve good dispersion and electrical/ thermal properties, optimal resin viscosity is essential. Recently, Pereira et al. (2010) reported significant increase in the electrical and thermal conductivity by incorporating MWNTs in low-viscosity epoxy composite. Such improvements are only possible when CNTs are thoroughly de-bundled and homogenously dispersed as demonstrated by Pereira et al. (2010). Just like hardness (Fig. 6), there is a strong dependence of composite’s electrical conductivity on the alignment of nanofillers, as seen in Fig. 7. Recently, Inam et al. (2011) reported the dependence of CNT aspect ratio on the percolation threshold and electrical conductivity of the CNT/ epoxy nanocomposites. It was found that CNTs having higher aspect ratios have lower percolation threshold for electrical conductivity and vice versa (Inam et al., 2011).

CNT is an interesting material to research. Recently, Felisberto et al. (2011) analysed the electrical conductivity of CNT nanocomposites during curing. The results showed that CNTs were mobile at ~60 ^{o}C because of the decrease in viscosity. This increased the number of pathways and subsequently increased electrical conductivity of the composite. After 50 mins of processing, the resin viscosity raised sharply which stopped CNT mobility and stabilised electrical conductivity. In this way, CNT mobility can be monitored during different stages of curing CNT/ thermoset nanocomposites. This approach can also be used to characterise curing cycles of new thermoset formulations.

Recently, Chang et al. (2012) produced CNT nanocomposites by using microwaves for curing. The group also reported improved thermal and mechanical properties of microwaved composites as compared to the samples prepared by conventional oven heating. Microwave curing imparted very high dielectric constant and low dielectric loss to the samples. Using microwaves for curing CNT/ epoxy nanocomposites nanotubes is also advantageous because of shorter curing durations. This would help in reducing re-agglomeration during curing as reported by Inam and Peijs (2006). As a result, Chang et al. (2012) reported superior dispersion of carbon nanotubes in epoxy matrix, which contributed towards significantly increasing the electrical conductivity of the nanocomposite. Therefore, good dispersion and consistency in the direction of the nanotubes provides high dielectric properties to the

Table 4
Room temperature two-probe electrical and thermal conductivity of 60±5 wt.% CNT/ epoxy composites at its highest value (Park et al., 2012).

CNT sheet for epoxy composite	Electrical conductivity (S/cm)	Thermal conductivity (W/mK)
Random short-MWNT	100	6
Random long-MWNT	640	55
25% stretched long-MWNT	1300	83
40% stretched long-MWNT	800	103
Functionalised long-MWNT	160	22

Table 5
CTEs of the neat epoxy and the nanocomposite samples (Abdalla et al., 2010).

Sample	CTE (ppm/^{o}C), n = 5
Neat epoxy system	74.04 ± 3
1% MWNT/ epoxy (random)	65.43 ± 2
1% MWNT/ epoxy (perpendicular magnetic field)	66.57 ± 2
1% MWNT/ epoxy (parallel magnetic field)	64.71

nanocomposite. A comprehensive review of dispersion of CNT in polymers was presented by Xie et al. (2005).

Park et al. (2012) dispersed different types of CNTs into epoxy to study electrical and thermal conductivities. In order to improve these properties, CNT/ epoxy nanocomposite sheets were mechanically stretched and aligned. It was shown that the thermal conductivity increased with the increase in temperature, and the highest electrical and thermal conductivities were observed for 40% stretched samples (Tab. 4).

Abdalla et al. (2010) cured CNT/ epoxy nanocomposites in the presence of magnetic field and reported thermal properties. CNTs were aligned perpendicularly and parallel to the magnetic field during curing. For these anisotropic nanocomposites, mechanical properties were also found to vary significantly in different directions. In the parallel direction, modulus increased to 72% compared with a net resin, in the perpendicular - up to 24%, and in a random direction, it rose to 32%. It was also found that thermal diffusivity and conductivity are strongly dependent on the alignment of CNTs. CNTs were also responsible for decreasing co-efficient of thermal expansion for epoxy matrices as shown in Tab. 5.

7. Conclusions

This paper provides detailed introduction of CNTs and a review of the recent developments in the field of CNT/ epoxy nanocomposites. Because of their unique properties, CNTs are indispensable nanofillers for novel and advanced epoxy nanocomposites. Significant developments have been made recently in the field of CNT/ epoxy composites. CNT/ epoxy materials have remarkably high thermal and electrical conductivities. Such composites also have improved strength, ultimate tensile strength, viscoelastic properties and thermo mechanical characteristics. Because of their low densities, CNTs reinforced epoxy nanocomposites possess great potential to be used for many aerospace applications. Carbon fibre is a well-mature technology and replacing them with CNTs is not feasible at this stage. More development is required in the field of CNTs before they can be substituted against carbon fibre. However, CNTs certainly offer many supplementary benefits to carbon fibre reinforced epoxy composites. Recent research reported that CNTs' types, properties and dispersion profile have a strong effect on the final mechanical, electrical and thermal properties of the CNT/ epoxy composites.

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