Mechanics and Mechanical Engineering
Vol. 21, No. 3 (2017) 549–568

Reasons of Adding Carbon Nanotubes into Composite Systems – Review Paper

Elias Randjbaran
Rizal Zahari
Dayang L. Majid
Mohamed T. H. Sultan
Norkhairunnisa Mazlan
Department of Aerospace Engineering
Faculty of Engineering
Universiti Putra Malaysia
43400 Serdang, Selangor Darul Ehsan, Malaysia
Aerospace Manufacturing Research Centre (AMRC)
Level 7, Tower Block, Faculty of Engineering
43400 UPM, Serdang, Selangor, Malaysia
Elias@gmx.co.uk

Received (10 August 2017)
Revised (25 August 2017)
Accepted (28 August 2017)

The Inclusion of CNT in the laminated composite system was found to increase the energy absorption of the whole composite after impact. The main important criteria is happened CNTs, which have good interfacial adhesion strong bonding with the matrix. Thus, it will be improve the properties/performance of the composite. Therefore, in current review paper the concentration/amount of the CNT, in term of loading, affect the performance of the composite and the mechanism on how the presence of CNT tends to absorb high amount of energy after impact have been discussed.

Keywords: carbon nanotube, ballistic impact, van der Waals, microstructure.

1. Introduction

1.1. *General review*

Carbon-Kevlar is a mixture of carbon fibre with Kevlar, resulting in a less breakable construction. This is among other things used in lightweight fuel tanks and road motorcycles, in which pure carbon fibre would damage too easy. And Carbon-Kevlar/epoxy with CNT are a new material in area of ballistic impact, especially in term of oblique impact. This attempt can be an innovation in this regard [1]. Epoxy is widely used in industry with an estimated world market of $15 Billion [2]. Epoxy formulations are used as adhesives, paints, coatings, and composites [3].

Epoxy is increasingly being used within composite materials as an alternative to traditional materials such as metals, metal alloys and wood [4]. The objective of the CNT epoxy program has been to reinforce epoxy with carbon nanotubes (CNTs) to take advantage of CNTs mechanical properties while reducing the weight of materials needed for a specified application. The challenges for developing an enhanced CNT epoxy nanocomposites are the dispersion of the CNTs, strong bonding with the epoxy, transformation of mechanical properties' improvement to the fibre reinforced plastics, and enhanced results in an application. By adding CNT solved these issues and can get a good result in uniform dispersion of CNTs throughout the epoxy, filling in the epoxy/resin gaps to create significant improvements in strength, toughness, durability, vibration damping and other mechanical properties. The results of the epoxy enhancements translate to the carbon or glass fibre reinforced prepared and to the final composite application [5–27].

Material scientists and engineers are excited by the possibilities for creating superstrong, high-performance polymer composite materials using carbon nanotubes. Since carbon nanotubes (CNTs) are five times less dense than steel and approximately 30 times stronger this makes them the ultimate mechanical filler for reinforcing polymers, with very low densities, and Young module (the measurement of stiffness of a material) superior to all other carbon fibres [28–29].

Currently, all existing methods of fabricating CNT-polymer composites involve quite complicated, expensive, time-demanding processing techniques such as solution casting, melting, moulding, extrusion, and in situ polymerization. In all of these techniques, nanotubes must either be incorporated into a polymer solution, molten polymer or mixed with the initial monomer before the formation of the final product (e.g. yarn, ribbon or film). In addition, these methods cannot be applied in the case of insoluble or temperature sensitive polymers, which decompose without melting [28–36].

Commercially sourced Kevlar yarns were placed in stable suspensions of multiwalled CNTs in a selected organic solvent. These Kevlar-nanotube mixtures were processed using an ultrasonic bath for an optimized period at ambient temperature. This processing resulted in swelling of Kevlar and in an uptake of nanotubes inside Kevlar fibres [37–40].

Gun'ko says that, when they performed mechanical testing of these Kevlar-CNT composites, they found considerable increases in all mechanical parameters of the nanocomposites material compared to the original Kevlar fibres, e.g.: Young's modulus, from 115 to 207 GPa; strength, from 4.7 to 5.9 GPa; strain at break, from 4.0 to 5.4%; toughness, from 63 to 99 J/g [37–42].

These improvements have been achieved at only 1 - 1.75 wt% of carbon nanotube content. This can be considered a quite significant advancement in the area of nanotube-polymer composites [40–42].

"It is clear that the new approach of incorporating nanomaterial into polymer macro materials by swelling could be expanded and utilized for many other Nano systems and polymer materials," says Gun'ko. "For example, it can be used to incorporate various nanoparticles, nanotubes, nanowires etc. inside pre-fabricated polymer fibres, yarns, films, ribbons etc. These can open up completely new opportunities in the large and important area of polymer nanocomposites." He also points out that one of the promising likely applications for their technique is the production of conductive CNT-polymer composites (films and wires), which could be potentially used as electrodes in flexible displays, electronic paper, solar cells and in different electronic devices [43–45].

According to Gun'ko, another very promising area of future research involves the reinforcement of various polymer fibres and films using carbon nanotubes as reinforcing additives. Potential applications of new ultra-strong polymer-nanotube materials would include bullet-proof vests, protective clothing, high-performance composites for aircraft and automotive industries, for example, seat belts, cables, reinforcement of tires, break linings, bumpers, et cetera [42–47].

1.2. *Interlocking*

Yielding is an increased in interfacial shear strength, it means that 15% measured improvement with the CNTs previously mentioned [48]. Other mechanisms for the increase in strength might be mechanical interlocking of the CNTs with the epoxy and/or the neighbouring fibres and a reduction in stress gradients in which the CNTs may be seen as an interlayer of intermediate modulus between the stiff advanced fibre and the compliant matrix [49–53].

1.3. *Pull-out*

No noticeable CNT pull out from the epoxy was observed in the CNT/epoxy slices after microtoming, and most of the CNTs remained in the epoxy, suggesting good adherence of the epoxy to CNT. The authors tried to explain the observed CNT-epoxy adhesion by proposing mechanical interlocking as a possible mechanism. However, the local non-uniformity along a CNT, such as varying diameter and bends (due to non-hexagonal defects), contribute to mechanical interlocking, and so, extra energy is needed to deform the epoxy causing CNT-pull out. A molecular model of CNT with diameter variation embedded in an array of linear polyethylene illustrated this mechanism [54–58].

1.4. *Van der Waals Forces*

The van der Waals' forces (or van der Waals' interaction) are the residual attractive or repulsive forces between molecules or atomic groups that do not arise from a covalent bond, or electrostatic interaction of ions or of ionic groups with one another or with neutral molecules. The resulting van der Waals' forces can be attractive or repulsive. Van der Waals' forces include attraction and repulsions between atoms, molecules, and surfaces, as well as other intermolecular forces. They differ from covalent and ionic bonding in that they are caused by correlations in the fluctuating polarizations of nearby particles [59–62].

Nano composites possess a large amount of interfaces due to the small (nanometer) size of reinforcements. The interface behavior can significantly affect the mechanical properties of Nano composites. For example, carbon nanotubes in general do not bond well to polymers, and their interactions result mainly from the weak van der Waals forces. Consequently, CNTs may slide inside the matrix and may not provide much reinforcing effect. It is, however, important to assess whether the poor interface behavior is indeed responsible for the short fall of CNT-reinforced composites in order to reach their expected properties [63–66].

1.5. *Agglomeration*

The tiny size of the nanostructures intensifies their tendency to form agglomerates, and their large surface area per unit volume yields an augmented influence of the interfacial bonding on the effective properties of the composite. Because of the intrinsic van der Waals attraction of the CNTs to each other and high aspect ratio, tubes are held together as bundles and ropes having very low solubility in most solvents. When blended with the epoxy, CNTs remain as entangled agglomerates, which prevent homogeneous dispersion of the filler into the epoxy matrix. Again, the smooth non-reactive CNT surface limits the load transfer from the matrix to nanotubes. Additional processing problem arises due to the increase in viscosity when the CNTs are added directly to the epoxy [67–70]. For CNT-composites, the problem is aggravated by the influence of tube morphology and content of amorphous carbon and metal impurities normally contained in the as-produced CNTs. These impurities, synthesized along with CNTs, are frequently removed (or at least reduced) by oxidative processes, which may lead to structural and morphological changes in the tubes [71–73]. Given the potential of the CNTs as reinforcement agents, several researchers have aggressively pursued their use in epoxies Nano composites: either thermoplastics or thermosettings [74–76].

1.6. *Chemical reaction*

The carbon is extruded from the catalyst particles, which remained attached to the fibre base. The pitting also indicates that the CNTs were attached to the fibre surface via etching or some other chemical reaction between the catalyst and the substrate [77–79]. Covalent modification attaches a functional group onto the carbon nanotube. The functional groups can be attached onto the side wall or ends of the carbon nanotube The end caps of the carbon nanotubes have the highest reactivity due to its higher pyrimidization angle and the walls of the carbon nanotubes have lower pyrimidization angles which has lower reactivity [80-82] Although covalent modifications are very stable, the bonding process disrupts the sp^2 hybridization of the carbon atoms because a σ-bond is formed The disruption of the extended sp^2 hybridization typically decreases the conductance of the carbon nanotubes [83–87].

1.6.1. *Oxidation*

The purification and oxidation of carbon nanotubes (CNTs) has been well represented in literature [88–91]. These processes were essential for low yield production of carbon nanotubes; where carbon particles, amorphous carbon particles and coatings comprised a significant percentage of the overall material and are still important for the introduction of surface functional groups [92–94]. During acid oxidation, the carbon-carbon bonded network of the graphitic layers is broken allowing the introduction of oxygen units in the form of carboxyl, phenolic, and lactone groups [95–97], which have been extensively exploited for further chemical functionalisations [98–100].

1.6.2. *Non-covalent modifications*

Non-covalent modifications utilize van der Waals forces and $\pi - \pi$ interactions by adsorption of polynuclear aromatic compounds, surfactants, polymers or biomolecules. Non-covalent modifications do not disrupt the natural configuration of carbon nanotubes with the cost of chemical stability, and is prone to phase separation, dissociation in between two phases, in the solid state [101–103].

1.6.3. $\pi - \pi$ *stacking and electrostatic interactions*

Molecules that have bi-functionality are used to modify the carbon nanotube. One end of the molecule is polyaromatic compounds that interact with the carbon nanotube through $\pi - \pi$ stacking [103–105]. The other end of the same molecule has a functional group such as amino, carboxyl, or thiol [106–108]. For example, pyrene derivatives and aryl thiols were used as the linkers for various metal nanobeads such as gold, silver, and platinum [109–111].

2. Results and discussion

2.1. *Microscopic discussion*

Adding CNT into the epoxy has a range, and this range in each composite system might be different to another system [112]. Adding less amount of CNT can have poor impact on micro-mechanical interlocking, chemical bonding between the nanotubes and the matrix, and van der Waals bonding between the fibre and the matrix [113]. On the other hand, adding much more amount of CNT can show the negative results [114]. Because of characteristics and properties of carbon atomic network, it behaves as a brittle material and high concentrations of can be happen the CNT [115]. Moreover, some noticeable works mentioned that the optimal amount of the CNT is 0.3% [116].

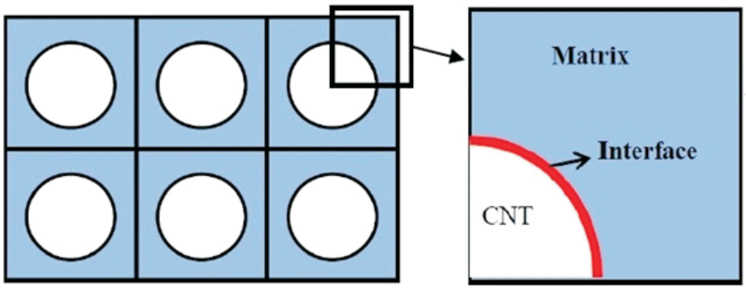

Figure 1 Carbon nanotube (CNT) is considered promising to reinforce materials because of its extraordinary mechanical properties. To describe the interface behaviour between CNTs and the matrix more precisely, a nonlinear cohesive law is being devised in order to consider van der Waals interaction between carbon atoms and atoms in the matrix [113]

Carbon nanotubes are members of fullerene family and have a hollow cylindrical structure. Based on the number of graphene layers forming a tube, carbon nanotubes can be classified as single walled and multiwalled carbon nanotubes [90,

100–107]. The extraordinary intrinsic properties like high melting point, high mechanical strength [11–38], high surface area and electrical conductivity [55-78] and thermal conductivity [32–45] created a gold rush amongst the researches to explore new potentials of CNT. It has been found that CNT's have a young's modulus of 270—950 GPa and a tensile strength of 11—63 GPa [12] and high aspect ratio (100—1000) [18] . The large aspect ratio and high surface area is due to Van der Waals forces of Carbon nanotubes.
However, the effective utilization of carbon nanotubes in composite applications depends strongly on the ability to homogeneously disperse them throughout the matrix without destroying their integrity [79–88]. Furthermore, good interfacial bonding is required to achieve load transfer across the CNT–matrix interface, a necessary condition for improving the mechanical properties of the composite [34–39]. Load transfer from matrix to CNTs plays a key role in the mechanical properties of composites. If the adhesion between the matrix and the CNTs is not strong enough to sustain high loads, the benefits of the high tensile strength of CNTs are lost. Load transfer depends on the interfacial shear stress between the fibre and the matrix [90–98].

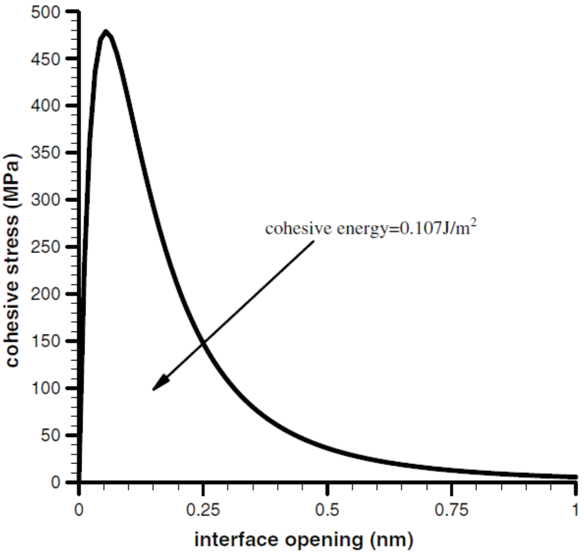

Figure 2 The cohesive law for a carbon nanotube and epoxy matrix established from the van der Waals interactions at the nanotube/matrix interface. The normal cohesive stress ^{int} is shown versus the interface opening displacement (u) for a carbon nanotube and polyethylene matrix [91]

For carbon nanotubes not well bonded to polymers, Jiang et al. in 2006 established a cohesive law for carbon nanotube/epoxy interfaces. The cohesive law and its properties (e.g. cohesive strength, cohesive energy) are obtained directly from the Lennard–Jones potential from the van der Waals interactions [60]. Such a cohesive law is incorporated in the micromechanics model to study the mechanical behaviour of carbon nanotube-reinforced composite materials. Carbon nanotubes indeed improve the mechanical behaviour of composite at the small strain [77–89]. However, such improvement disappears at relatively large strain because the completely deboned nanotubes behave like voids in the matrix and may even weaken the composite. The increase of interface adhesion between carbon nanotubes and epoxy matrix may significantly improve the composite behaviour at the large strain [11–37].

CNT reinforced epoxy composites are seen as a potentially fruitful area for new, tougher or fatigue resistant materials. Although various studies have provided some insights into the nature of CNT–epoxy interactions at the interface, the physics of CNT–epoxy interactions still await further elucidation, both qualitatively and quantitatively. A relevant question is, will the high modulus and strength predicted for nanotubes be available when used as fillers. MWNTs are generally entangled in the form of curved agglomerates and SWNTs are produced as bundles. In order to achieve optimal enhancement in the property of the CNTs/epoxy composites, there are several key issues to be resolved, i.e. improved dispersion of CNTs, alignment of CNTs in the epoxy resin and functionalisations of CNTs surface for good adhesion. A good CNT/matrix interfacial bonding and a perceptible reinforcement of the matrix with the nanotubes can bring improvement to the fracture strength of the composite by ensuring a shear stress transfer to the reinforcement [95–101].

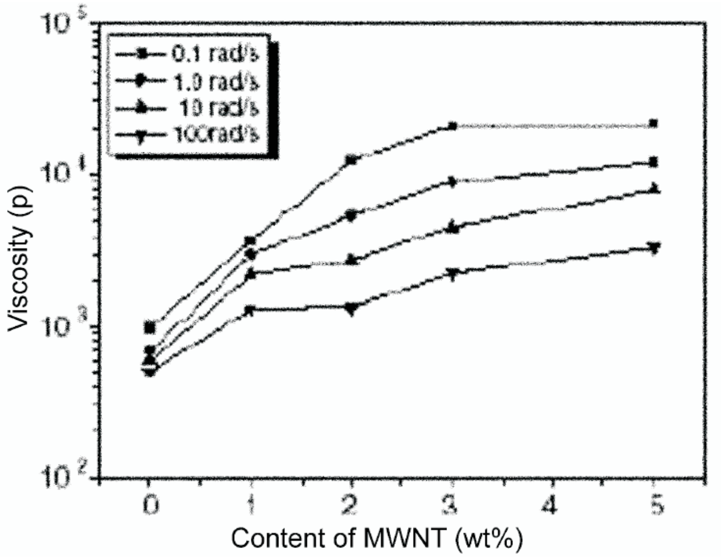

Figure 3 Viscosity of MWNT/PP composites as a function of CNT content [107]

The tensile modulus of the composites is found to enhance much less as compared to the enhancement in the compression modulus of the similar system. Some works have attributed the differences, between the tensile and compression strain cases, to the sliding of inner shells of the MWNTs when a tensile stress is applied. In cases of SWNT epoxy composites, the possible sliding of individual tubes in the SWCNT rope, which is bonded by van der Waals forces, may also reduce the efficiency of load transfer. It is suggested that for the SWNT rope case, interlocking using epoxy molecules might bond the SWCNT rope more strongly [112–114].

However, the potential of using CNTs as reinforcements has not been realized mainly because of the difficulties in processing and the limitation on load transfer. The tiny size of the nanostructures intensifies their tendency to form agglomerates, and their large surface area per unit volume yields an augmented influence of the interfacial bonding on the effective properties of the composite. Because of the intrinsic van der Waals attraction of the CNTs to each other and high aspect ratio, tubes are held together as bundles and ropes having very low solubility in most solvents. When blended with the polymer, CNTs remain as entangled agglomerates, which prevent homogeneous dispersion of the filler into the epoxy matrix. Again, the smooth non-reactive CNT surface limits the load transfer from the matrix to nanotubes. Additional processing problem arises due to the increase in viscosity when the CNTs are added directly to the epoxy [56–61].

Sandler and co-workers [67–81] studied the effect of processing conditions on the degree of dispersion of MWCNTs in epoxy matrix. The aligned CVD-grown MWCNTs with loading of 0.001–1 wt. percentage were used for composites preparation [23–29]. For the preparation of composite, required amounts of CNTs were dispersed in a bisphenol-A resin (Araldite LY 556) by shear-intensive mechanical stirring using a dissolver disk. The mixture was then stirred at RT for an hour at 2000 rpm. After reducing the resin temperature with dry ice in order to increase the viscosity (shear force), the mixture was again stirred for 1 h at 2000 rpm. Finally, the resin temperature was raised to 80°C and equilibrated for 10 min. After addition of the hardener at this temperature, the mixtures were stirred for 1 min at 500 rpm followed by 4 min at 50 rpm to allow for a homogeneous dispersion of the hardener and to enhance the nanotube agglomeration process. The moulded composites were cured at 140°C for 8 h. SEM and optical microscopy images of the fractured composite surface revealed that though the procedure led to very good dispersion of low wt. percentage of aligned CNTs in the epoxy matrix, agglomeration occurs from 0.025 wt. percentage onwards. The processing found to be much more difficult with entangled CNTs, as the densely packed tubes increased the viscosity of the resin even at low CNTs content [39–46].

Hierarchical analysis of the fracture toughness enhancement of carbon nanotube (CNT) reinforced hard matrix composites is carried out because of shear-lag theory and facture mechanics. It is found that stronger CNT/matrix interfaces cannot definitely lead to the better fracture toughness of these composites, and the optimal interfacial chemical bond density is that making the failure mode just in the transition from CNT pullout to CNT break. For hard matrix composites, the fracture toughness of composites with weak interfaces can be improved effectively by increasing the CNT length. However, for soft matrix composite, the fracture toughness improvement due to the reinforcing CNTs quickly becomes saturated with an increase in CNT length. The proposed theoretical model is also applicable to short fibre-reinforced composites [114–117].

Introduction Carbon nanotubes (CNTs) possess exceptionally superior physical and mechanical properties, such as high strength, low density, high flexibility, and high toughness and therefore hold great promise for employment as reinforcements in advanced composites [70–81]. However, experimental and numerical studies show that the performance of such composites depends critically on the CNT/matrix interfacial characteristics [31–43]. Interface strength and interface length are two of the most important factors that affect the mechanical properties of CNT-reinforced composites and therefore have drawn the attention of many researchers. Ensure efficient load transfer from the matrix to the fibre, the interfacial bonding between the epoxy matrix and the carbon nanotubes is necessary to prevent fibre pull out [87–91].

The strength and effect of surface van der Waals forces on the shape of multiwalled and single-walled carbon nanotubes is investigated using atomic-force microscopy, continuum mechanics, and molecular-mechanics simulations [90–93].

Carbon-epoxy composites consist of carbon fibres, unidirectional, woven, knitted, or 3-Dimensional embedded in a composite matrix. The composite matrix can be either a thermosetting resin such as epoxy or a thermoplastic resin such as PEEK. While woven carbon fibre is available un-coated for use in wet lay-up manufacturing, the majority of carbon fibre is pre-coated or pre-impregnated (pre-preg) with the composite: Carbon-carbon composites consist of highly ordered graphite fibers embedded in a carbon matrix. C-C composites are made by gradually building up a carbon matrix on a fiber preform through a series of impregnation and pyrolysis steps or chemical vapor deposition. C-C composites tend to be stiffer, stronger, and lighter than steel or other metals. Because only weak Van der Waals bonds bond the graphite ribbons to each other perpendicular to the fibres, the ribbons must be reoriented to increase the tensile strength of the fiber to a useful level. This is accomplished through the application of tension at some point in the stabilization or pyrolysis phases, the exact time depending on the precursor material. Increased axial orientation increases the fiber's tensile strength by making better use of the strong covalent bonds along the ribbons of graphite plates [41–44].

There are three main mechanisms of load transfer from a matrix to filler:

a) Micro-mechanical interlocking:

This could be difficult in nanotube composites due to their atomically smooth surface. Local non-uniformity along a CNT, including varying diameter and bends/kinks at places as a result of non-hexagonal defects, contribute to CNT–epoxy adhesion by mechanical interlocking [39].

b) Chemical bonding between the nanotubes and the matrix:

This improves interfacial interaction through ionic or covalent bond that enables a stress transfer [44].

c) Weak van der Waals bonding between the fibre and the matrix:

Under no chemical bonding between CNT– polymers, the origins of CNT–epoxy interactions are electrostatic and van der Waals forces [72].

Nano composites possess a large amount of interfaces due to the small (nanometre) size of reinforcements. The interface behaviour can significantly affect the mechanical properties of nanocomposites. For example, carbon nanotubes in general do not bond well to polymers, and their interactions result mainly from the weak van der Waals forces. Consequently, CNTs may slide inside the matrix and may not provide much reinforcing effect. It is, however, important to assess whether the poor interface behaviour is indeed responsible for the short fall of CNT-reinforced composites in order to reach their expected properties [32–36].

Nano-particles, in general, and carbon nanotubes, in particular, are desirable particles to modify material properties of polymers. In order to disperse CNTs in the epoxy homogeneously, the entanglement of CNTs produced by the synthesis and agglomerates of CNTs caused by the intermolecular van der Waals force must be broken for homogenization that will make more filler surface area available. A further enhancement of the compatibility to the composite material could be achieved by a chemical functionalization of the carbon nanotube surface, through covalent or ionic bonds to the polymeric matrix. These bonds enable a stress transfer between the epoxy and CNTs, which leads to improved interfacial interactions. Again, the covalent bonding is stronger as physical interactions and simulations predict a negligible influence on the mechanical performance of CNTs. Therefore, the chemical surface functionalisations of CNTs along with perceptible dispersion of nanotubes in the matrix are the key issues in developing CNT/epoxy composites [65-69].

2.2. *Energy absorption*

The damage tolerance concept in aerospace structures relates to their ability to conform to required standards within damage limits. Since damage can never be entirely avoided, composite structures should be designed to function safely despite the presence of flaws. In this respect, damage tolerance is the main design criterion for composite structures, which are exposed to a number of events during in-service loading, which in their turn, may cause damage initiation and structural degradation. Impact (low or high velocity) during service is a common phenomenon for aerospace composite structures. Upon impact, the incident energy is absorbed by a variety of mechanisms [48]. In order to produce an impact resistant component, the impact-induced damage should be minimized. In general, the initial failure event during impact is the formation of matrix cracks within the plies. These cracks are due to the through-thickness shear stresses, which are generated by the out-of-plane impact forces. However, the dominant failure mode during low-velocity impact is delamination. Impact phenomena induce blind delaminations, which are usually initiated by the extension and the bridging of matrix cracks due to opening forces. Delamination growth is mainly driven by interlaminar shear stresses (mode II) induced by the bending of the laminate during the impact event. Finally, fibre fracture can be a significant energy absorbing mechanism, particularly at high velocities, and is generated by the high through-thickness forces generated during impact. Fibres can either fail in tension due to the membrane forces generated during impact, or by shear-out during penetration of the projectiles [67].

Carbon nanotubes (CNTs) have demonstrated unique mechanical properties similar to those found in various fibrous materials, exhibiting excellent compression capability combined with extreme structural flexibility and recovery from mechanical deformation. As such, arrays or forests of vertically aligned CNTs have been considered for ultra-light weight shock absorbing material. In addition, CNTs incorporate multifunctional properties, including excellent electrical and thermal conductivity. These properties then allow layers formed for energy absorption to monitor in situ strain loading. The utilization of vertically oriented CNT arrays for mechanical energy absorbing benefits from fundamental understanding of stress wave mitigation ad deformation mechanisms in fibre reinforced composites or porous foam-like materials where layered structures of materials have been adopted for shock and vibrational damping [86].

Characterization of the multilayer structure under quasi-static and dynamic loading demonstrated the energy absorbing capacity of the materials exhibiting foam-like properties. The structures were able to sustain large compressive deformations up to ~0.8 strain, exhibiting nearly complete recovery. The structures reached a steady state response to the compression after the first two cycles, suggesting that any irreversible damage to the structure occurs during the first couple deformation cycles. Additionally, it was observed that the electrical conductivity of the vertically aligned CNT arrays increased after the first couple compressive cycles, suggesting a rearrangement of the CNTs within each array. The energy absorbing properties for the epoxy-CNT multilayer architecture were estimated to be at least three orders of magnitude larger than that of natural and synthetic cellular foam materials having comparable densities. Thus, an innovative method to create multi-layered, hierarchical structures of epoxy-CNT foams has been demonstrated, providing unique properties for impact and vibrational protection applications [91–98].

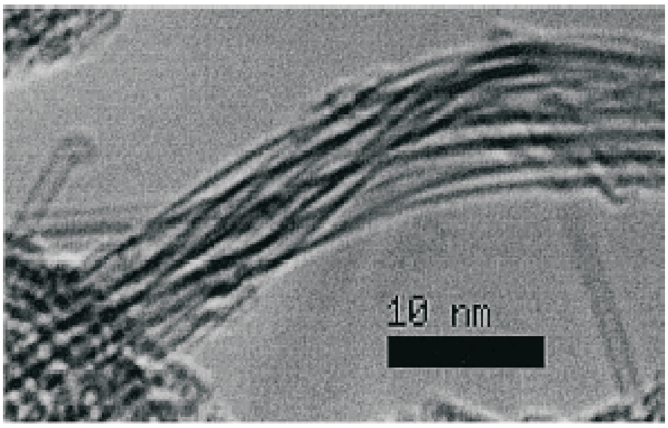

Figure 4 TEM image of partially exfoliated single-wall carbon nanotubes showing the rope-like structure [51]

However, Colloidal materials such as carbon nanotubes do not spontaneously suspend in polymers, thus the chemistry and physics of filler dispersion become a major issue. In the case of polymers filled with carbon nanotubes, the research challenge is particularly tremendous due to the unique character of these unusual materials. Due to strong attractive interaction, nanotubes aggregate to form bundles or “ropes” that are very difficult to disrupt [81-84]. In case of single nanotubes, they are only 1-3 nm in diameter, however, since they like to assemble into ropes, which consist of many nanotubes, are most likely 10-200 nm in diameter. Furthermore, ropes are tangled with one another like spaghetti or polymers. With high shear, these ropes can be untangled, but it is extremely difficult to further disperse at the single tube level [95-98].

Due to the low entropy of mixing, rigid molecules of high molecule weight require strong attractive interactions to disperse. Since the connectivity and rigidity of macromolecules drastically reduces the number of configurations available in the dispersed state, mixing becomes a problem. In the case of rigid fillers dispersed into stiff polymers, the problem is compounded in that neither species gains entropy on dispersion [89-93].

3. Conclusion

Carbon fiber reinforced epoxy composites show good energy absorption behaviour. By using CNTs, the matrix would be more conducting and to provide with some mechanical strength and to make the strong interface which inhibits higher mechanical properties. Carbon nanotube reinforced composites exhibits much better mechanical properties than CFRP. Moreover, CNTs generally exhibit high stiffness and extraordinary thermal and electrical conductivity. These superior properties are generally attributed to presence of strong sp2 carbon-carbon network in their outer shells, which makes them thermally and chemically stable. It is widely known that CNTs improves the mechanical, tribological, and functional properties of hosting matrices; exempli gratia, polymers, metal matrices, et cetera.

References

[1] **Cha, J., Jin, S., Shim, J. H., Park, C. S., Ryu, H. J. and Hong, S. H.**: Functionalization of carbon nanotubes for fabrication of CNT/epoxy nanocomposites, *Materials & Design*, 5, 95, 1–8, **2016**.

[2] **Ramanathan, M., Shanov, V., Kumta, P. N.**: Carbon Nanotube-Based Impedimetric Biosensors for Bone Marker Detection, Mitali Patil Department of Bioengineering, Swanson School of Engineering, University of Pittsburgh, Pittsburgh, Pennsylvania, USA, *Advances in Materials Science for Environmental and Energy Technologies IV: Ceramic Transactions*, 253, 187, **2015**.

[3] **Pradhan, S., Pandey, P., Mohanty, S. and Nayak, S. K.**: Insight on the Chemistry of Epoxy and Its Curing for Coating Applications: A Detailed Investigation and Future Perspectives. *Polymer-Plastics Technology and Engineering*, 55, 8, 862–77, **2016**.

[4] **Hünnekens, B., Peters, F., Avramidis, G., Krause, A., Militz, H. and Viöl, W.**: Plasma treatment of wood–polymer composites: A comparison of three different discharge types and their effect on surface properties, *Journal of Applied Polymer Science*, 133, 18, **2016**.

[5] **Bonduel, D., Kchit, N. and Claes, M.**: Use of carbon nanotubes in structural composites, *Smart Intelligent Aircraft Structures (SARISTU), Springer International Publishing*, 755–762, **2016**.

[6] **Chen, Y., Zhang, H. B., Yang, Y., Wang, M., Cao, A. and Yu, Z. Z.**: High-Performance Epoxy Nanocomposites Reinforced with Three-Dimensional Carbon Nanotube Sponge for Electromagnetic Interference Shielding, *Advanced Functional Materials*, 26, 3, 447–55, **2016**.

[7] **Islam, M. S., Deng, Y., Tong, L., Faisal, S. N., Roy, A. K., Minett, A. I. and Gomes, V. G.**: Grafting carbon nanotubes directly onto carbon fibers for superior mechanical stability: Towards next generation aerospace composites and energy storage applications, *Carbon*, 96, 701–10, **2016**.

[8] **Tornabene, F., Fantuzzi, N., Bacciocchi, M. and Viola, E.**: Effect of agglomeration on the natural frequencies of functionally graded carbon nanotube-reinforced laminated composite doubly-curved shells, *Composites Part B: Engineering*, 89, 187–218, **2016**.

[9] **Gómez-del Río, T., Salazar, A., Pearson, R. A. and Rodríguez, J.**: Fracture behaviour of epoxy nanocomposites modified with triblock copolymers and carbon nanotubes, *Composites Part B: Engineering*, 87, 343–9, **2016**.

[10] **Fujigaya, T., Saegusa, Y., Momota, S., Uda, N. and Nakashima, N.**: Interfacial engineering of epoxy/carbon nanotubes using reactive glue for effective reinforcement of the composite, *Polymer Journal*, 48, 2, 183–8, **2016**.

[11] **Zhou, H. W., Mishnaevsky, L., Yi, H. Y., Liu, Y. Q., Hu, X., Warrier, A. and Dai, G. M.**: Carbon fiber/carbon nanotube reinforced hierarchical composites: Effect of CNT distribution on shearing strength, *Composites Part B: Engineering*, 88, 201–11, **2016**.

[12] **Randjbaran, E., Zahari, R., Abdul Jalil, N. A. and Majid, D. L.**: Hybrid composite laminates reinforced with kevlar/carbon/glass woven fabrics for ballistic impact testing, *The Scientific World Journal*, **2014**.

[13] **Randjbaran, E., Zahari, R., Majid, D. L., Jalil, N. A., Vaghei, R. and Ahmadi, R.**; The effects of stacking sequence layers of six layers composite materials in ballistic energy absorption, *International Journal of Material Science Innovations*, 1, 6, 293–305, **2013**.

[14] **Randjbaran, E., Zahari, R., Majid, D. L., Jalil, N. A., Vaghei, R. and Ahmadi, R.**: The effects of stacking sequence layers of hybrid composite materials in energy absorption under the high velocity ballistic impact conditions: an experimental investigation, *Journal of Material Sciences & Engineering*, **2013**.

[15] **Randjbaran, E., Zahari, R., Majid, D. L., Jalil, N. A., Vaghei, R. and Ahmadi, R.**: Effects of Stacking Sequence on Compression Response Testing of Carbon Fibre and Hybrids: Fibrous-Glass/Carbon/Kevlar/Epoxy Composite Plates, *MATRIX Academic International Online Journal of Engineering and Technology*, 2, 1, 13–7, **2013**.

[16] **Randjbaran, E., Zahari, R., Majid, D. L., Jalil, N. A., Vaghei, R. and Ahmadi, R.**: Experimental Study of the Influence of Stacking Order of the Fibrous Layers on Laminated Hybrid Composite Plates Subjected to Compression Loading, *Journal of Science and Engineering*, 4, 1, 01–8, **2014**.

[17] **Randjbaran, E., Zahari, R., Vaghei, R. and Karamizadeh, F.**: A Review Paper on Comparison of Numerical Techniques for Finding Approximate Solutions to Boundary Value Problems on Post-Buckling in Functionally Graded Materials, *Trends Journal of Sciences Research*, 1, 1, 1–6, **2015**.

[18] **Randjbaran, E., Zahari, R. and Vaghei, R.**: Scanning Electron Microscopy Interpretation In Carbon Nanotubes Composite Materials After Postbuckling - Review Paper, *MATRIX Academic International Online Journal of Engineering and Technology*, 2, 2, 1–6, **2014**.

[19] **Randjbaran, E., Zahari, R. and Vaghei, R.**: Computing Simulation of Postbuckling in Functionally Graded Materials - A Review, *Indonesian Journal of Electrical Engineering and Computer Science*, 12, 12, 8344–8, **2014**.

[20] **Randjbaran, E., Zahari, R., Majid D. L., Sultan, M. T. H. and Mazlan, N.**: Effects of Carbon Nanotube on Mechanical Properties of Composite plates - A Review Paper, *MATRIX Academic International Online Journal of Engineering and Technology*, 3, 2, 1–8, **2015**. http://maioj.org/pub.aspx?PaperId=101503.

[21] **Reddy, P. R., Reddy, T. S., Srikanth, I., Madhu, V., Gogia, A. K. and Rao, K. V.**: Effect of viscoelastic behaviour of glass laminates on their energy absorption subjected to high velocity impact, *Materials & Design*, 98, 272–9, **2016**.

[22] **Saba, N., Paridah, M. T., Abdan, K. and Ibrahim, N. A.**: Dynamic mechanical properties of oil palm nano filler/kenaf/epoxy hybrid nanocomposites, *Construction and Building Materials*, 124, 133–8, **2016**.

[23] **Ostovan, F., Matori, K. A., Toozandehjani M., Oskoueian, A., Yusoff, H. M., Yunus, R., Ariff, A. H., Quah, H. J. and Lim, W. F.**: Effects of CNTs content and milling time on mechanical behavior of MWCNT-reinforced aluminum nanocomposites, *Materials Chemistry and Physics*, 166, 160–6, **2015**.

[24] **Shabaneh, A., Girei, S., Arasu, P., Mahdi, M., Rashid, S., Paiman, S. and Yaacob, M.**: Dynamic response of tapered optical multimode fiber coated with carbon nanotubes for ethanol sensing application, *Sensors*, 15, 5, 10452–64, **2015**.

[25] **Ramli, N. I., Rashid, S. A., Sulaiman, Y., Mamat, M. S., Zobir, S. A., Krishnan, S.**: Physicochemical and electrochemical properties of carbon nanotube/graphite nanofiber hybrid nanocomposites for supercapacitor, *Journal of Power Sources*, 328, 195–202, **2016**.

[26] **Ghaemi, F., Yunus, R., Salleh, M. A., Rashid, S. A., Ahmadian, A. and Lim, H. N.**: Effects of the surface modification of carbon fiber by growing different types of carbon nanomaterials on the mechanical and thermal properties of polypropylene, *RSC Advances*, 5, 36, 28822–31, **2015**.

[27] **Shojaei, T. R., Salleh, M. A., Sijam, K., Rahim, R. A., Mohsenifar, A., Safarnejad, R. and Tabatabaei, M.**: Fluorometric immunoassay for detecting the plant virus Citrus tristeza using carbon nanoparticles acting as quenchers and antibodies labeled with CdTe quantum dots, *Microchimica Acta*, 1-1, **2016**.

[28] **Lomicka, C. W., Thomas, J. A., LaBarre, E. D., Trexler, M. M, Merkle, A. C.**: Improving ballistic fiber strength: insights from experiment and simulation, *Dynamic Behavior of Materials, Springer International Publishing*, 1, 187–193, **2014**.

[29] **Randjbaran, E., Zahari, R., Majid, D. L., Sultan, M. T. H. and Mazlan, N.**: Effects of Sloped Armour in Ballistic Impact Resistance - A Review Paper, *MATRIX Academic International Online Journal of Engineering and Technology*, 4, 2, 19–26, **2016**. http://maioj.org/data/documents/oct2016/101603.pdf.

[30] **Shang, Y., Hua, C., Xu, W., Hu, X., Wang, Y., Zhou, Y., Zhang, Y., Li, X. and Cao, A.**: Meter-Long Spiral Carbon Nanotube Fibers Show Ultrauniformity and Flexibility, *Nano letters*, 16, 3, 1768–75, **2016**.

[31] **Wu, X., Morimoto, T., Mukai, K., Asaka, K. and Okazaki, T.**: Relationship between Mechanical and Electrical Properties of Continuous Polymer-Free Carbon Nanotube Fibers by Wet-Spinning Method and Nanotube-Length Estimated by Far-Infrared Spectroscopy, *J. Phys. Chem. C*, 120, 36, 20419–20427, **2016**

[32] **Liu, P., Fan, Z., Mikhalchan, A., Tran, T. Q., Jewell, D., Duong, H. M. and Marconnet, A. M.**: Continuous Carbon Nanotube-Based Fibers and Films for Applications Requiring Enhanced Heat Dissipation, *ACS Applied Materials & Interfaces*, 8, 27, 17461–71, **2016**.

[33] **Xu, W., Chen, Y., Zhan, H. and Wang, J. N.**: High-Strength Carbon Nanotube Film from Improving Alignment and Densification, *Nano letters*, 16, 2, 946–52, **2016**.

[34] **Zare, M., Rayegan-Shirazi, A., Rezaei, S., Sadat, S. A., Baneshi, M. M. and Randjbaran, E.**: Effects of Polychlorinated biphenyls compounds on the number of bacteria in the rhizosphere of sorghum and Onobrychis sativa, *Advances in Bioresearch*, 7, 3, **2016**.

[35] **Mirri, F., Orloff, N. D., Forster, A. M., Ashkar, R., Headrick, R. J., Bengio, E. A., Long, C. J., Choi, A., Luo, Y., Hight Walker, A. R. and Butler, P.**: Lightweight, flexible, high-performance carbon nanotube cables made by scalable flow coating, *ACS applied materials & interfaces*, 8, 7, 4903–10, **2016**.

[36] **Davaa, E., Safari, M., Randjbaran, E. and Randjbaran, S.**: The Factors That Influence Customer Satisfaction Level in the Mongolian Banking Industry, *Journal of Insurance and Financial Management*, 1, 3, **2016**.

[37] **O'Connor, I., Hayden, H., Coleman, J. N. and Gun'ko, Y. K.**: High-Strength, High-Toughness Composite Fibers by Swelling Kevlar in Nanotube Suspensions, *Small*, 5, 4, 466–9, **2009**.

[38] **Govarthanam, K. K., Anand, S. C. and Rajendran, S.**: 7 Technical textiles for knife and slash resistance, *Handbook of Technical Textiles: Technical Textile Applications*, 2, 193, **2016**.

[39] **Dwivedi, A. K., Dalzell, M. W., Fossey, S. A., Slusarski, K. A., Long, L. R. and Wetzel, E. D.**: Low velocity ballistic behavior of continuous filament knit aramid, *International Journal of Impact Engineering*, 96, 23–34, **2016**.

[40] **Yang, D. and Chen, X.**: Multi-layer pattern creation for seamless front female body armor panel using angle-interlock woven fabrics, *Textile Research Journal*, 0040517516631315, **2016**.

[41] **Lomicka, C. W., Thomas, J. A., LaBarre, E. D., Trexler, M. M. and Merkle, A. C.**: Improving ballistic fiber strength: insights from experiment and simulation, *Dynamic Behavior of Materials, Springer International Publishing* 1, 187–193, **2014**.

[42] **Sockalingam, S., Chowdhury, S. C., Gillespie, J. W. and Keefe, M.**: Recent advances in modeling and experiments of Kevlar ballistic fibrils, fibers, yarns and flexible woven textile fabrics–a review, *Textile Research Journal*, 004051751664603, **2016**.

[43] **O'Connor, I., Hayden, H., Coleman, J. N. and Gun'ko, Y. K.**: High-Strength, High-Toughness Composite Fibers by Swelling Kevlar in Nanotube Suspensions, *Small*, 5, 4, 466–9, **2009**.

[44] **Zheng, J., Duan, X., Lin, H., Gu, Z., Fang, H., Li, J. and Yuan, Y.**: Silver nanoparticles confined in carbon nanotubes: on the understanding of the confinement effect and promotional catalysis for the selective hydrogenation of dimethyl oxalate, *Nanoscale*, 8, 11, 5959–67, **2016**.

[45] **Haft, M., Grönke, M., Gellesch, M., Wurmehl, S., Büchner, B., Mertig, M. and Hampel, S.**: Tailored nanoparticles and wires of Sn, Ge and Pb inside carbon nanotubes, *Carbon*, 101, 352–60, **2016**.

[46] **Gun'ko, V. M. and Do, D. D.**: Characterisation of pore structure of carbon adsorbents using regularisation procedure, *Colloids and Surfaces A: Physicochemical and Engineering Aspects*, 193, 1, 71–83, **2001**.

[47] **Gun'ko, V. M. and Mikhalovsky, S. V.**: Evaluation of slitlike porosity of carbon adsorbents, *Carbon*, 42, 4, 843–9, **2004**.

[48] **Jiang, L. Y., Huang, Y., Jiang, H., Ravichandran, G., Gao, H., Hwang, K. C. and Liu, B.**: A cohesive law for carbon nanotube/polymer interfaces based

on the van der Waals force, *Journal of the Mechanics and Physics of Solids*, 54, 11, 2436–52, **2006**.

[49] **Wong, M., Paramsothy, M., Xu, X. J., Ren, Y., Li, S. and Liao, K.**: Physical interactions at carbon nanotube-polymer interface, *Polymer*, 44, 25, 7757–64, **2003**.

[50] **Liao, K. and Li, S.**: Interfacial characteristics of a carbon nanotube–polystyrene composite system, *Applied Physics Letters*, 79, 25, 4225–7, **2001**.

[51] **Veedu, V. P., Cao, A., Li, X., Ma, K., Soldano, C., Kar, S., Ajayan, P. M. and Ghasemi-Nejhad, M. N.**: Multifunctional composites using reinforced laminae with carbon-nanotube forests, *Nature materials*, 5, 6, 457–62, **2006**.

[52] **Wang, Y., Colas, G. and Filleter, T.**: Improvements in the mechanical properties of carbon nanotube fibers through graphene oxide interlocking, *Carbon*, 98, 291–9, **2016**.

[53] **Koizumi, R., Hart, A. H., Brunetto, G., Bhowmick, S., Owuor, P. S., Hamel, J. T., Gentles, A. X., Ozden, S., Lou, J., Vajtai, R. and Asif, S. S.**: Mechano-chemical stabilization of three-dimensional carbon nanotube aggregates, *Carbon*, 110, 27–33, **2016**.

[54] **Chowdhury, S. C. and Okabe, T.**: Computer simulation of carbon nanotube pull-out from polymer by the molecular dynamics method, *Composites Part A: Applied Science and Manufacturing*, 38, 3, 747–54, **2007**.

[55] **Li, Y., Liu, Y., Peng, X., Yan, C., Liu, S. and Hu, N.**: Pull-out simulations on interfacial properties of carbon nanotube-reinforced polymer nanocomposites. *Computational Materials Science*, 50, 6, 1854–60, **2011**.

[56] **Wagner, H. D. and Vaia, R. A.**: Nanocomposites: issues at the interface, *Materials Today*, 7, 11, 38–42, **2004**.

[57] **Wagner, H. D., Ajayan, P. M. and Schulte, K.**: Nanocomposite toughness from a pull-out mechanism, *Composites Science and Technology*, 83, 27–31, **2013**.

[58] **Esawi, A. M., Morsi, K., Sayed, A., Taher, M. and Lanka, S.**: Effect of carbon nanotube (CNT) content on the mechanical properties of CNT-reinforced aluminium composites, *Composites Science and Technology*, 70, 16, 2237–41, **2010**.

[59] **He, X. Q., Kitipornchai, S. and Liew, K. M.**: Buckling analysis of multi-walled carbon nanotubes: a continuum model accounting for van der Waals interaction, *Journal of the Mechanics and Physics of Solids*, 53, 2, 303–26, **2005**.

[60] **Jiang, L. Y., Huang, Y., Jiang, H., Ravichandran, G., Gao, H., Hwang, K. C. and Liu, B.**: A cohesive law for carbon nanotube/polymer interfaces based on the van der Waals force, *Journal of the Mechanics and Physics of Solids*, 54, 11, 2436–52, **2006**.

[61] **Tan, H., Jiang, L. Y., Huang, Y., Liu, B. and Hwang, K. C.**: The effect of van der Waals-based interface cohesive law on carbon nanotube-reinforced composite materials, *Composites Science and Technology*, 67, 14, 2941–6, **2007**.

[62] **Liu, X., Yang, Q. S., He, X. Q. and Liew, K. M.**: Cohesive laws for van der Waals interactions of super carbon nanotube/polymer composites, *Mechanics Research Communications*, 72, 33–40, **2016**.

[63] **Nagataki, A., Takei, K., Arie, T. and Akita, S.**: Carbon nanotube mechanical resonator in potential well induced by van der Waals interaction with graphene, *Applied Physics Express*, 8, 8, 085101, **2015**.

[64] **Zhang, X., Zhou, W. X., Chen, X. K., Liu, Y. Y. and Chen, K. Q.**: Significant decrease in thermal conductivity of multi-walled carbon nanotube induced by inter-wall van der Waals interactions, *Physics Letters A*, 380, 21, 1861–4, **2016**.

[65] **Chernozatonskii, L. A., Artyukh, A. A., Demin, V. A. and Katz, E. A.**: Bucky-corn: van der Waals composite of carbon nanotube coated by fullerenes, *Molecular Physics*, 114, 9, 92–101, **2016**.

[66] **Perebeinos, V. and Tersoff, J.**: Wetting transition for carbon nanotube arrays under metal contacts, *Physical review letters*, 114, 8, 085501, **2015**.

[67] **Tornabene, F., Fantuzzi, N., Bacciocchi, M. and Viola, E.**: Effect of agglomeration on the natural frequencies of functionally graded carbon nanotube-reinforced laminated composite doubly-curved shells, *Composites Part B: Engineering*, 89, 187–218, **2016**.

[68] **Kumar, A. A., Sundaram, R.**: Cure cycle optimization for the resin infusion technique using carbon nanotube additives, *Carbon*, 96, 1043–52, **2016**.

[69] **Kamarian, S., Salim, M., Dimitri, R. and Tornabene, F.**: Free vibration analysis of conical shells reinforced with agglomerated Carbon Nanotubes, *International Journal of Mechanical Sciences*, 108, 157–65, **2016**.

[70] **Rathore, D. K., Singh, B. P., Mohanty, S. C., Prusty, R. K. and Ray, B. C.**: Temperature dependent reinforcement efficiency of carbon nanotube in polymer composite, *Composites Communications*, 1, 29–32, **2016**.

[71] **Bautista-Quijano, J. R., Pötschke, P., Brünig, H. and Heinrich, G.**:Strain sensing, electrical and mechanical properties of polycarbonate/multiwall carbon nanotube monofilament fibers fabricated by melt spinning, *Polymer*, 82, 181–9, **2016**.

[72] **Herceg, T. M., Abidin, M. S., Greenhalgh, E. S., Shaffer, M. S., Bismarck, A.**; Thermosetting hierarchical composites with high carbon nanotube loadings: En route to high performance, *Composites Science and Technology*, 127, 134–41, **2016**.

[73] **Wang, J., Bahk, Y. K., Chen, S. C., Pui, D. Y.**: Characteristics of airborne fractal-like agglomerates of carbon nanotubes, *Carbon*, 93, 441–50, **2015**.

[74] **Moghadam, A. D., Omrani, E., Menezes, P. L., Rohatgi, P. K.**: Mechanical and tribological properties of self-lubricating metal matrix nanocomposites reinforced by carbon nanotubes (CNTs) and graphene–a review, *Composites Part B: Engineering*, 77, 402–20, **2015**.

[75] **Chen, S. J., Qiu, C. Y., Korayem, A. H., Barati, M. R.and Duan, W. H.**: Agglomeration process of surfactant-dispersed carbon nanotubes in unstable dispersion: A two-stage agglomeration model and experimental evidence, *Powder Technology*, 301, 412–20, **2016**.

[76] **Romanov, V. S., Lomov, S. V., Verpoest, I., Gorbatikh, L.**: Stress magnification due to carbon nanotube agglomeration in composites, *Composite Structures*, 133, 246–56, **2015**.

[77] **Balasubramanian, K., Burghard, M.**: Chemically functionalized carbon nanotubes, *Small*, 1, 2, 180–92, **2005**.

[78] **Wong, S. S., Joselevich, E., Woolley, A. T., Cheung, C. L., Lieber, C. M.**: Covalently functionalized nanotubes as nanometre-sized probes in chemistry and biology, *Nature*, 394, 6688, 52–5, **1998**.

[79] **Banerjee, S., Hemraj-Benny, T., Wong, S. S.**: Covalent surface chemistry of single-walled carbon nanotubes, *Advanced Materials*, 17, 1, 17–29, **2005**.

[80] **Bianco, A., Kostarelos, K., Prato, M.**: Applications of carbon nanotubes in drug delivery, *Current opinion in chemical biology*, 9, 6, 674–9, **2005**.

[81] **Spitalsky, Z., Tasis, D., Papagelis, K. and Galiotis, C.**: Carbon nanotube–polymer composites: chemistry, processing, mechanical and electrical properties, *Progress in polymer science*, 35, 3, 357–401, **2010**.

[82] **Salvetat, J. P., Bonard, J. M., Thomson, N. H., Kulik, A. J., Forro, L., Benoit, W. and Zuppiroli, L.**: Mechanical properties of carbon nanotubes, *Applied Physics A*, 69, 3, 255–60, **1999**.

[83] **Wei, B. Q., Vajtai, R. and Ajayan, P. M.**: Reliability and current carrying capacity of carbon nanotubes, *Applied Physics Letters*, 79, 8, 1172, **2001**.

[84] **Li, Q. W., Li, Y., Zhang, X. F., Chikkannanavar, S. B., Zhao, Y. H., Dangelewicz, A. M., Zheng, L. X., Doorn S. K., Jia, Q. X., Peterson, D. E. and Arendt, P. N.**: Structure-dependent electrical properties of carbon nanotube fibers. *Advanced Materials*, 19, 20, 3358–63, **2007**.

[85] **Dumitrica, T., Landis, C. M. and Yakobson, B. I.**: Curvature-induced polarization in carbon nanoshells, *Chemical physics letters*, 360, 1, 182–8, **2002**.

[86] **Zhang, H. W., Wang, J. B. and Guo, X.**: Predicting the elastic properties of single-walled carbon nanotubes, *Journal of the Mechanics and Physics of Solids*, 53, 9, 1929–50, **2005**.

[87] **Banhart, F.**: Interactions between metals and carbon nanotubes: at the interface between old and new materials, *Nanoscale*, 1, 2, 201–13, **2009**.

[88] **Jakubinek, M. B., Ashrafi, B., Zhang, Y., Martinez-Rubi, Y., Kingston, C. T., Johnston, A. and Simard, B.**: Single-walled carbon nanotube–epoxy composites for structural and conductive aerospace adhesives, *Composites Part B: Engineering*, 69, 87–93, **2015**.

[89] **Papadopoulos, A., Gkikas, G., Paipetis, A. S., Barkoula, N. M.**: Effect of CNTs addition on the erosive wear response of epoxy resin and carbon fibre composites, *Composites Part A: Applied Science and Manufacturing*, 84, 299–307, **2016**.

[90] **Fujigaya, T., Saegusa, Y., Momota, S., Uda, N. and Nakashima, N.**: Interfacial engineering of epoxy/carbon nanotubes using reactive glue for effective reinforcement of the composite, *Polymer Journal*, 48, 2, 183–8, **2016**.

[91] **Sun, Y., Lu, J., Ai, C., Wen, D. and Bai, X.**: Multilevel resistive switching and nonvolatile memory effects in epoxy methacrylate resin and carbon nanotube composite films, *Organic Electronics*, 32, 7–14, **2016**.

[92] **Ling, Y., Li, W., Wang, B., Gan, W., Zhu, C., Brady, M. A. and Wang, C.**: Epoxy resin reinforced with nanothin polydopamine-coated carbon nanotubes: a study of the interfacial polymer layer thickness, *RSC Advances*, 6, 37, 31037–45, **2016**.

[93] **Mei, H., Zhang, S., Chen, H., Zhou, H., Zhai, X. and Cheng, L.**: Interfacial modification and enhancement of toughening mechanisms in epoxy composites with CNTs grafted on carbon fibers, *Composites Science and Technology*, 134, 89–95, **2016**.

[94] **Wu, J., Chen, J., Zhao, Y., Liu, W. and Zhang, W.**: Effect of electrophoretic condition on the electromagnetic interference shielding performance of reduced graphene oxide-carbon fiber/epoxy resin composites, *Composites Part B: Engineering*, 105, 167–75, **2016**.

[95] **Umer, R., Li, Y., Dong, Y., Haroosh, H. J. and Liao, K.**: The effect of graphene oxide (GO) nanoparticles on the processing of epoxy/glass fiber composites using resin infusion, *The International Journal of Advanced Manufacturing Technology*, 81, 9-12, 2183–92, **2015**.

[96] **Schlagenhauf, L., Buerki-Thurnherr, T., Kuo, Y. Y., Wichser, A., Nuesch, F., Wick, P. and Wang, J.**: Carbon Nanotubes Released from an Epoxy-Based Nanocomposite: Quantification and Particle Toxicity, *Environmental Science & Technology*, 49, 17, 10616–23, **2015**.

[97] **Rafique, I., Kausar, A., Anwar, Z. and Muhammad, B.**: Exploration of Epoxy Resins, Hardening Systems, and Epoxy/Carbon Nanotube Composite Designed for High Performance Materials: A Review, *Polymer-Plastics Technology and Engineering*, 55, 3, 312–33, **2016**.

[98] **Schlagenhauf, L., Kuo, Y. Y., Bahk, Y. K., Nüesch, F. and Wang, J.**: Decomposition and particle release of a carbon nanotube/epoxy nanocomposite at elevated temperatures, *Journal of Nanoparticle Research*, 17, 11, 1–11, **2015**.

[99] **Gong, L. X., Zhao, L., Tang, L. C., Liu, H. Y. and Mai, Y. W.**: Balanced electrical, thermal and mechanical properties of epoxy composites filled with chemically reduced graphene oxide and rubber nanoparticles, *Composites Science and Technology*, 121, 104–14, **2015**.

[100] **Pathak, A. K., Borah, M., Gupta, A., Yokozeki, T. and Dhakate, S. R.**: Improved mechanical properties of carbon fiber/graphene oxide-epoxy hybrid composites, *Composites Science and Technology*, 135, 28–38, **2016**.

[101] **Wang, J., Zhao, Y., Ma, F. X., Wang, K., Wang, F. B. and Xia, X. H.**: Synthesis of a hydrophilic poly-L-lysine/graphene hybrid through multiple non-covalent interactions for biosensors, *Journal of Materials Chemistry B*, 1, 10, 1406–13, **2013**.

[102] **Tallury, S. S. and Pasquinelli, M. A.**: Molecular dynamics simulations of polymers with stiff backbones interacting with single-walled carbon nanotubes, *The Journal of Physical Chemistry B*, 114, 2, 9349–55, **2010**.

[103] **Pan, B. and Xing, B.**: Adsorption mechanisms of organic chemicals on carbon nanotubes, *Environmental Science & Technology*, 42, 24, 9005–13, **2008**.

[104] **Xu, Z., Wei, C., Gong, Y., Chen, Z., Yang, D., Su, H. and Liu, T.**: Efficient dispersion of carbon nanotube by synergistic effects of sisal cellulose nano-fiber and graphene oxide, *Composite Interfaces*, 1–5, **2016**.

[105] **Wang, Y. and Xu, Z.**: Interaction mechanism of doxorubicin and SWCNT: protonation and diameter effects on drug loading and releasing, *RSC advances*, 6, 6, 314–22, **2016**.

[106] **Hua, Z., Qin, Q., Bai, X., Huang, X. and Zhang, Q.**: An electrochemical biosensing platform based on 1-formylpyrene functionalized reduced graphene oxide for sensitive determination of phenol, *RSC Advances*, 6, 30, 25427–34, **2016**.

[107] **Wang, Y., Ren, P., Gu, X., Wen, X., Wang, Y., Guo, X., Waclawik, E. R., Zhu, H. and Zheng, Z.**: Probing the mechanism of benzaldehyde reduction to chiral hydrobenzoin on the CNT surface under near-UV light irradiation, *Green Chemistry*, 18, 6, 1482–7, **2016**.

[108] **López-Lorente, Á. I. and Valcárcel, M.**: The third way in analytical nanoscience and nanotechnology: Involvement of nanotools and nanoanalytes in the same analytical process, *TrAC Trends in Analytical Chemistry*, 75, 1–9, **2016**.

[109] **Kazemi-Beydokhti, A., Heris, S. Z. and Jaafari, M. R.**: Investigation of different methods for cisplatin loading using single-walled carbon nanotube, *Chemical Engineering Research and Design*, 112, 56–63, **2016**.

[110] **Hajibadi, H. and, Nowroozi, A.**: Study on the interaction of metallocene catalysts with the surface of carbon nanotubes and its influence on the catalytic properties. 1. Investigation of possible complex structures and the influence on structural and electronic properties, *Journal of Organometallic Chemistry*, **2016**.

[111] **Li, J. and Lee, E. C.**: Functionalized multi-wall carbon nanotubes as an efficient additive for electrochemical DNA sensor, *Sensors and Actuators B: Chemical*, 239, 652–9, **2017**.

[112] **Bal, S. and Samal, S. S.**: Carbon nanotube reinforced polymer composites – a state of the art, *Bulletin of Materials Science*, 30, 4, 379–86, **2007**.

[113] **Chen, Y., Zhang, H. B., Yang, Y., Wang, M., Cao, A. and Yu, Z. Z.**: High-Performance Epoxy Nanocomposites Reinforced with Three-Dimensional Carbon Nanotube Sponge for Electromagnetic Interference Shielding, *Advanced Functional Materials*, 26, 3, 447–55, **2016**.

[114] **Fujigaya, T., Saegusa, Y., Momota, S., Uda, N. and Nakashima, N.**: Interfacial engineering of epoxy/carbon nanotubes using reactive glue for effective reinforcement of the composite, *Polymer Journal*, 48, 2, 183–8, **2016**.

[115] **Bakhtiar, N. S., Akil, H. M., Zakaria, M. R., Kudus, M. H. and Othman, M. B.**: New generation of hybrid filler for producing epoxy nanocomposites with improved mechanical properties, *Materials & Design*, 91, 46–52, **2016**.

[116] **Üstün, T., Eskizeybek, V. and Avci, A.**: Enhanced fatigue performances of hybrid nanoreinforced filament wound carbon/epoxy composite pipes, *Composite Structures*, 150, 124–31, **2016**.

[117] **Kleinschmidt, A. C., Almeida, J. H., Donato, R. K., Schrekker, H. S., Marques, V. C., Corat, E. J. and Amico, S.C.**: Functionalized-Carbon Nanotubes with Physisorbed Ionic Liquid as Filler for Epoxy Nanocomposites. *Journal of Nanoscience and Nanotechnology*, 16, 9, 9132–40, **2016**.