Vibration damping/dynamic properties of CNT-reinforced composite structures

M. Kireitseu

[*]University of Sheffield, Dept. of Mechanical Engineering, RR-UTC
Mappin Street, Sheffield S1 3JD, the United Kingdom, indmash@yandex.ru
[**]Institute of mechanics and machine reliability NAS of Belarus, Dynamics laboratory

ABSTRACT

Engineering applications of nanotechnology and nanoparticle-based vibration damping concept may help to achieve the current and future objectives of manufacturing in areas of transportation that are 30-40% enhanced strength, weight and other performance capabilities. In contrast to electronics where nanotechnology dominates as a basis of manufacturing, aerospace engineering is very premature and require consolidated environment for income of nanoideas. This paper will highlight some advanced research work that are being carried out and shows the effect that molecule-level mechanism can have on the damping of structures. Carbon nanotube-reinforced polyamide-6 composite material can enhance both strength and dynamics of many engineering structures. At 5-10 vol.% nanotube concentrations storage and loss modules of the material are in a very narrow region between 105-106 Pa at higher temperatures and an advanced damping behaviour. Energy dissipation mechanisms and finite element approach are discussed. It is particularly worth noting that carbon nanotubes can act as a simple nanoscale damping spring. The mechanisms involved in such materials need to be understood and the relevance to damping identified for a sake of competence. The focus in ongoing research is directed however toward to the development of the current nanotechnology-based damping systems and the next generation of fan blades, providing a road map to manufacturing technology and design solutions.

Keywords: nanoparticle, damping, dynamics, mechanics

1 INTRODUCTION

Energy dissipation (damping) in structures/materials is important as it reduces resonant amplitudes/noise levels giving enhanced integrity and life cycle behavior. If we then go to the nanoscale, the damping levels/dynamics of materials are mostly unknown and require extensive investigations. By invoking the properties of nano-auxetics/nanostructures it may be possible to control the wave propagation in the material and thus enhance the energy dissipation [1].

Polymer-based composite materials can significantly enhance both tensile strength and dynamics/damping performance of engineering structures by an order of magnitude. Reinforcement by carbon nanotubes as little as 2 vol.% can offer a further progress [2, 3] and nanoparticle/tube/fibre-reinforced composite materials are novel vibration damping solutions entailing placement of numerous nanoscale particles inside a vibrating material structure. A novel concept of nanoparticle-based vibration damping [4] shows the effect that molecule-level mechanism can have on the damping and carbon nanotubes nanoparticle/fibre/tubes-reinforced materials can provide enhanced strength, dynamics and vibration damping properties over broader frequency and temperature ranges. Carbon nanotubes can be treated as a simple nanoscale spring or combinations of damping springs due to C-C bonding [5, 6] with some advanced energy dissipation mechanisms, and thus giving a possibility to multiply a damping performance by billions of nanotube dampers for the next generation engineering materials that are light-weight, shock and noise resistant. Understanding the rheological properties of polymeric nanocomposites is crucial to gain a fundamental understanding of machining and structure-property relations for these materials.

2 EXPERIMENTAL DETAILS

2.1 Materials

Thermoplastic polyamide-6 granular particle powder (3T RPD Ltd, UK) was mixed by an ultrasonic agitation procedure with multi-walled carbon nanotube (MWNT) particles produced by Dynamic Enterprises, UK. Polymeric powder has granules size of 40-70 µm and purity of 95%. Reported density of nanotubes was approximately 1.9 g/cm^3, a surface area of 250-300 m^2/g was determined by the BET method [1]. Nanotubes were 10-15 nm in diameter and 5-9 nm in length, have 3±2 graphitic layers wrapped around a hollow 5 nm core and 70-80 vol% purity. They were added in concentrations of 2, 5 and 10% by weight (including impurities) along with a surfactant (polyoxyethylene8laurylether) to aid in dispersion and glue some CNTs to almost each polymeric particle. The materials were dried for a minimum of 10h at 100°C in a vacuum oven. One-kilogram mixtures of polyamide-6 were extruded to obtain concentrations of 2, 5 and 10% nanotubes in the material at a temperature of 210°C (melting point ASTM D 789), a screw speed of 300 rpm, and a feed rate of 800 g/h. The composite material was prepared using an extrusion procedure at injection moulding at 250°C and subjected to a vacuum for 25 min and curing. The compounds were molded into 50x20x5 mm bars and then cut into 3 parts for experimental measurements. Scanning electron microscope (SEM) is

used to evaluate the nanotube dispersion and orientation in the polymeric matrix. CNT orientation was controlled by pressure rates at extrusion.

2.2 Characterization

A detailed study of microstructure of razor blade-cut fractured regions of the specimen was carried out by conventional TEM using selected area diffraction (SAD) performed on a 200 kV microscope (model 2000, Pentax, Japan) with a point resolution of less than 0.5 nm equipped with an EDS (Model 6506, Micronix, UK) at room temperature which caused fracture (fig. 1a). Young modulus was calculated from measurements by an indentation which resulted to E_p=1.2-1.4 GPa for polyamide (ISO 178) and E_c=3.2-3.5 GPa for CNT-reinforced material that is in agreement [7].

Dynamic rheological measurements were performed using an advanced rheometric expansion system (Dynalyser) rheometer from Rheologica Instruments AB (Sweden). Experimental investigations were performed in an oscillatory shear mode using parallel plate geometry (20 mm diameter) at 300°C that is shown in fig. 2, 3. Frequency sweeps between 10 and 200 rad/s were done at strains (0.2±10%) which are to be within the linear elastic range for the polymer. Specimens were placed between the preheated plates and were allowed to equilibrate for approximately 10 min prior to each frequency sweep run.

Damping characterization was carried out by by laser vibrometry at standard vibration shaker tests. A test rig consisted of the clamped sample fixer device, the electro-dynamic exciter and laser vibrometry. The clamping block is fixed so that friction losses and extraneous damping is minimized. The data acquisition and control of the electro-dynamic system is based on the Computer Measurement System [8]. The resonance frequency is determined from peaks on a frequency response curve for each of the experimental methods. The vibrometry procedure yields not only the resonance frequency, but also the mode shape. A true mode will provide a recognizable shape.

The loss factor is used in the frequency domain and is defined as an imaginary part of complex modulus to its real part. For harmonic motion, it is defined as the ratio of energy dissipated per radian to the peak stored energy. Thus the full energy dissipation, energy dissipation and loss factor for one loading cycle can be found respectively as follows:

$$U_{diss} = \int_V (\sigma_{ij}\varepsilon_{ij}/2)dV$$
with i,j=1,2,3; (1)
$$\Delta U = 2\tau^{max}(2\pi r_n l_n^2)\cdot(\varepsilon_z^m - \varepsilon_z^{max}); \qquad \eta = \arcsin\left(\frac{\Delta U}{2\pi U_{diss}}\right)$$

where indexes are related to m – matrix material, max – maximum displacement, n – nanoparticle, diss – dissipation energy, ε – strain, τ - shear stress.

In the Modal Strain Energy analysis [3] to improve the estimate of impedance by using the magnitude of the complex stiffness matrix rather than the real part in the eigenvalue equation, the complex stiffness matrix is replaced by its real part to yield the sample

$$\left(\mathbf{K_c} + \alpha\mathbf{K_v} - \hat{\omega}_R^2\mathbf{M}\right)\hat{x}_R = 0, \qquad \alpha = \sqrt{1+\eta_v^2} \qquad (2)$$

where K_v and K_c are the real stiffness matrices for the viscoelastic nanoparticle-reinforced elements and the rest of the structure respectively, M is the mass matrix, ωR the natural frequencies and xR the real mode shapes. The modified eigenvectors operating on the original stiffness matrix give the mean strain energy dissipated per radian,

$$U_{diss} = \eta_v \sum_{i=1}^{V} \tfrac{1}{2}\hat{x}_R^T \mathbf{K_v}\hat{x}_R = \eta_v \frac{\hat{U}_v}{\alpha} \qquad (3)$$

The total strain energy stored is,

$$U = \sum_{i=1}^{N-V} \tfrac{1}{2}\hat{x}_R^T\mathbf{K_c}\hat{x}_R + \sum_{i=1}^{V} \tfrac{1}{2}\hat{x}_R^T\mathbf{K_v}\hat{x}_R = \hat{U}_c + \frac{\hat{U}_v}{\alpha} \qquad (4)$$

3 RESULTS AND DISCUSSION

The viscous-elastic properties of the composite depend on nanotube concentration and frequency (fig. 2). Polyamide-6 and 2-5 vol.% reinforced composites reach a Newtonian plateau at low frequencies. Above 5 vol.% nanotubes, the damping curves exhibit a much greater decrease with frequency and exhibit non-Newtonian behavior at lower frequencies. Therefore, about 5 wt% may be regarded as a starting composition for damping. The damping increase is accompanied by an increase in the viscous-elastic properties, represented by the storage modulus G// and the loss modulus G/ (fig. 2) at higher temperatures.

CNT nanoscale damping spring

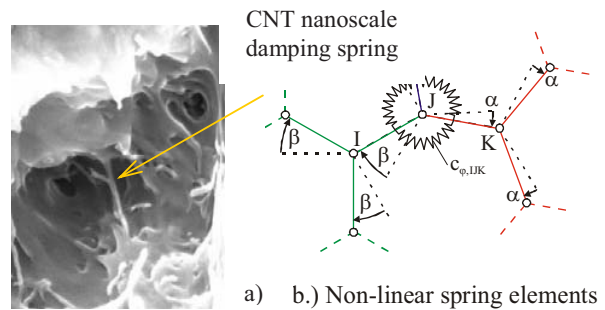a) b.) Non-linear spring elements

Figure 1: Microstructure of CNT-reinforced polyamide-6 composite (a) and FEM representative models of damping behavior of the composite (b).

The CNT-reinforced composite material damping phenomenon is complex because of the variety of other energy dissipation/fracture mechanisms involved that are affecting damping/dynamics. Particularly advanced energy dissipation phenomena of CNT-reinforced polymeric materials can be explained by considerable interfacial fracture mechanics and bonging energy between CNT and polymeric molecular chains. It was found that interfacial shear strength between MWNT and polymeric matrix (polyethylene–butane) at AFM pulling out or some test procedures [8, 9] are ranged between 50-80 G/Jm^2 due to high bond fracture energy. In comparison with other nanoparticle reinforcements a recent study [9] has presented a range of interfacial fracture energy values for glass fibres pulled from a variety of polymers such as polyamide 6 (44–93 G/Jm^2) and polyamide 6.6 (52–61 G/Jm^2) that may be used in prediction methodology. Advanced strength may be associated with chemical modification of the materials to induce strong bonding between the matrix and reinforcement. Thus further possibilities to enhance damping capabilities and operational performance of the CNT-reinforced polymeric composites is to attach high molecular weight ordered polymeric chains.

We proposed [4] that the potential energy and energy dissipation because of the carbon-based materials (fig. 1 b) can be calculated with the force field method and finite element modeling which leads to torsional and nonlinear spring constants to estimate a damping/dynamics of CNT-reinforced composite

$$c_A = \frac{d^2 E_A}{d\theta_{IJK}^2} = C_{IJK}\left[\cos\theta_J^0 \cos\theta_{IJK} - \cos\left(2\theta_{IJK}\right)\right]$$

$$c_B = \frac{d^2 E_B}{dR^2} = 4D_e\left(\alpha n\right)^2\left[e^{-2\alpha n(R-R_e)} - \tfrac{1}{2}e^{-\alpha n(R-R_e)}\right]$$

$$c_T = \frac{d^2 E_T}{d\varphi^2} = \tfrac{1}{2}V_{JK}n_{JK}^2 \cos\left[n_{JK}\left(\varphi - \varphi_{JK}^0\right)\right]$$

(4)

with θ_{j0}=120° and K_{IJK}=100 kcal/(mol rad²). The equilibrium angle is θ_{jk0}=180°, the periodicity n_{JK}=2 and the torsional energy V_{JK}=25 kcal/(mol rad²). Our calculations (Eqs. 1-4) give a result that interfacial shear strength between carbon nanotube and polyamide 6 matrix might be in the range of 75–120 G/Jm^2 depending on the assigned intramolecular energies that affect total dissipation energy criteria of the material.

On the other hand, the strongest interface between CNT and polymeric chains may not be an advantage for enhanced damping and require optimization. During vibration, nanoparticles interact with the material matrix and one another and, thus, dissipate energy through momentum transfer and friction. Friction and "slip-stick" motion (slippage) between CNT and polymeric matrix is regarded as an important mechanism of vibration damping [7, 10] and depends on bonding force that may vary from

0.2-0.8 MPa and is still a poorly understood issue at this scale length. In addition, fracture mechanism of multi-walled carbon nanotubes at tensile loading may has also telescopic-like transformation mechanism [11, 12], acting as a sword-in-sheath where the outer nanotube fractures followed by pullout of the interior walls. Thus the sword-in-sheath mechanism should contribute to another "slip-stick" motion between walls of MWCNT; however, such a friction is noted to be very low [12].
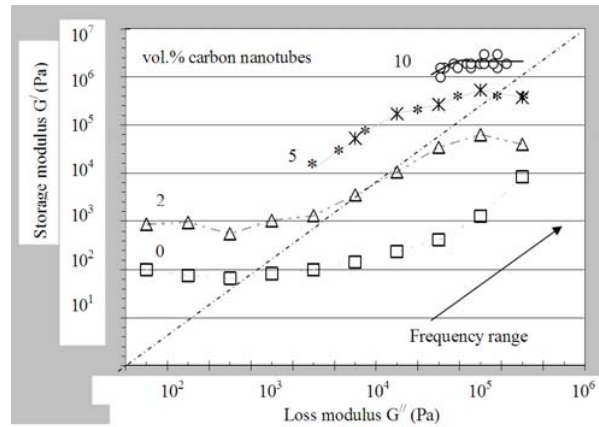

Figure 2: CNT-reinforced polyamide-6 composite at 250^{0}C.

Total damping of the material system may increases with a number of walls as every embedded graphene cylinder sheet of MWCNT may bear applied load and dissipate it via friction and elastic return (stress relaxation phenomenon) [13]. Inter-tube friction between adjacent CNT is also possible when it is close packed as CVD deposited thin film.
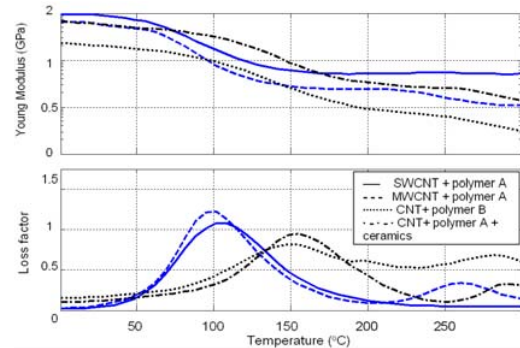

Figure 3: Mechanical and damping and Properties at 10 Hz: 5wt% CNT-reinforced polyamide-6 composite.

Nanotube diameter/length from 1 to 100 nm affects the interfacial fracture energy and therefore damping/dynamic performance. Carbon nanotubes may create stronger interfaces with a polymer matrix [14] via structural defects and shaping geometry (waviness), but is likely not so

sensitive for aerospace engineering structures at this atomic length scale. We suggest that CNT may be used as a simple nanoscale damper and vibration/noise trapping units in polyamide-6 materials. Variation of the damping signal indicates that additional energy losses are mostly due to high adhesion between nanotube and matrix.

The peak damping occurs around 100°C for CNT-reinforced polymer composite (fig. 3) and 150°C for CNT-reinforced polymer and ceramics. It is worth noting that multi-walled CNT slightly contribute to the lower modulus of the material that benefit for the higher damping in comparison with single-walled CNT. The phenomenon may be associated with the greater number of possible energy dissipation mechanisms of MWCNT among that are telescopic-like transformation, buckling and kinking.

The mixes based on thermoset polymer B show lower peak levels of damping due to the higher volume fill of materials; however, it is less sensitive to temperature. The presence of CNT-reinforced polymeric damping material clearly reduces the modulus and also introduces a second transition around 250°C that coincides with the softening point of the polymeric material. Young modulus values in the range 0.2 to 2 GPa can give the highest core strain energy. The presence of high levels of polymeric B composite reduces the modulus below the desirable range. CNT-reinforced composites on the other hand, maintain Young's modulus levels thereby improving the overall damping achieved.

Carbon nanotubes could be particularly promising cost-decreasing reinforcement material for polymeric materials and sandwich-like structural composites in both foamy and bulk state. Results of the research work provide a platform for the development of nanoparticle-reinforced damping materials that are light-weight, vibration and shock resistant. The outcome of the research work is expected to have wide-ranging technical benefits with direct relevance to industry in areas of transportation (aerospace, automotive, rail) and civil infrastructure development. However, the goal is aerospace applications and next generation of turbine engine fan blades with CNT-based ceramics and metal damping technology.

4 CONCLUSION

The presence of CNT-reinforced polymeric damping material clearly enhances the Young, Storage and Loss modules and also introduces a second transition around 250°C that coincides with the softening point of the polymeric material. Young modulus values in the range 0.2 to 2 GPa can increase the highest core strain energy. The presence of high levels of polymeric B composite reduces the modulus below the desirable range. CNT-reinforced polymers on the other hand, maintain stable Storage and Loss modules in a narrow range thereby improving the overall damping achieved.

Nanoparticle/tube/fibre-reinforced composite material is a relatively new vibration damping technology entailing placement of numerous nanoparticles inside vibrating material structure that has wide applications in areas of transportation (aerospace, auto, rail, maritime) and electronics. Carbon nanotubes are particularly cost-decreasing material for large scale industrial applications and there is the gap between engineering applications/structures and nanotechnology leading to the next generation engineering.

REFERENCES

[1] Ru, "Encyclopedia of nanotechnology," American Scientific Publishing, 410-670, 2003.

[2] Harris, "Carbon Nanotubes and Structures," Cambridge Univ. Press, 120-250, 1999.

[3] Talay, "Systems Analysis of Nanotube Technology," NASA, Washington D.C., 95-240, 2000.

[4] Kireitseu, M.V.; Kompiš, V.; Altenbach, H.; Bochkareva, L., Hui, D.; Eremeev, S., *Fullerenes, Nanotubes and Carbon Nanostructures, 13(4),* 312-329, 2005.

[5] Rivera, J.L.; McCabe, C.; Cummings, P.T., *Nanoletters*, *3(8)*, 1001-1005, 2003

[6] Li, Ch.; Chou, T.-W., *Physical review* B, *68*, 1073-1080, 2003.

[7] Zhou, X.; Shin E., Wang K.W., Bakis C.E., *Compos. Sci. Technol., 71*, 1825–1831, 2004.

[8] Barber, A.H.; Cohen S.R.; Kenig, Sh.; Wagner, H.D., *Compos. Sci. Technol.*, *74*, 1931–1937, 2004.

[9] Cooper, C.A.; Cohen, S.R.; Barber, A.; Wagner, H.D., *Appl. Phys. Lett., 81(20)*, 3873-3878, 2002.

[10] Koratkar, N.; Wei, B.; Ajayan, P.M., *Compos. Sci. Technol., 63*, 1525–1531, 2003.

[11] Lau, K.; Shi, S.Q., *Carbon, 40*, 2965–2968, 2002.

[12] Yu, M.; Lourie, O.; Dyer, M.J.; Moloni, K.; Kelly, T.F.; Ruoff, R.S., *Science, 287,* 637–640, 2000.

[13] Ding, H.-Q.; N. Karasawa, and W.A. Goddard III. J. Chem. Phys., 97(6): 4309-4315, 1992.

[14] Barber, A.H.; Cohen, S.R.; Wagner, H.D., *Appl. Phys. Lett., 82(23)*, 4140-4147, 2003.

[15] PoEtschke, P.; Fornes, T.D.; Paul, D.R., *Polymer*, *43,* 3247-3255, 2002.