The effect of interfacial bonding on the damping behavior of nanocomposites

Literature review

The rapid and continuous growth in aerospace, automotive, and military applications requires special materials that have high performance characteristics to build structures that can achieve and exceed target properties. One of the important material characteristic needed for some of these applications is the ability to absorb vibrations, typically referred to as the damping capacity. Damping capacity is the dissipation of vibration by converting the mechanical energy introduced by vibration into heat. One of the materials that showed promise in this aspect is fibrous composites. The ability to tailor the interface strength between the fibers and matrix enhances the ability to design for a specific damping capacity. It was observed that a low interfacial shear strength between the fibers and the matrix and a high interfacial area, lead to an increase in damping capacity [1]. Such damping capacity can be further increased if discontinuous fibers were used rather than continuous fibers to reinforce the matrix [1, 2]. Following the same logic, nanocomposites with a nano-scale reinforcement and a larger interfacial contact area between the nanotubes and the surrounding material will be able to provide an increased damping capacity [3, 4].

The remarkable mechanical properties of carbon nanotubes and their large specific surface area attracted the attention of many researchers. Theoretical investigation of SWCNT showed that their Young’s modulus scattered between 0.5-5.5 TPa [5], while experimental investigation showed a range of 2.8 to 3.6 TPa [6]. Tensile strength of SWCNT was also investigated theoretically and found to be around 130 GPa [7]. Compared to graphite fibers with 300-800 GPa Young’s modulus and about 5 GPa tensile strength, the superiority of SWCNTs is clear. Such superiority is evident when SWCNTs are used to reinforce polymers. For example, it was reported that using 0.5 wt% of SWCNT increased Young’s modulus of epoxies up to 200% and the tensile strength up to 140% [8, 9]. The elastic properties of SWCNT nanocomposites have been extensively studied, modeled and understood. Much less attention was paid to their damping capacity and response. In order to exploit the potential of this material for an increased damping capacity it is necessary to understand the underlying mechanisms for their performance.

<u>Damping behavior of fibrous composites</u>: Archived literature is rich with research work on the damping behavior of fibrous composites showing a performance similar in some of its aspects to that of nanocomposites. Sun et al used finite element analysis to calculate the damping ratio of randomly oriented short-fiber-reinforced polymer matrix composites [10, 11]. They showed the existence of an optimum aspect ratio and an optimum fiber orientation for a maximum damping capacity, with the predicted optimum aspect ratio in the range of the actual aspect ratio of whiskers. Suarez et al. showed analytically and experimentally that the use of fibers with low aspect ratios (<20) will increase the damping capacity [12]; this argument was further proven by Hwang and Gibson using a finite element model [13]. This could be, possibly, caused by the

shear stress concentration at the fiber ends and its transfer mechanism to the surrounding matrix. It has to be noted that using fibers with a low aspect ratio, while increasing the level of damping, has a detrimental effect on the composite overall stiffness [14, 15]. Chen and Gowayed investigated the effect of the frequency and temperature on the damping of a composite laminate showing experimentally an increase in tan δ with the increase in temperature and a decrease in tan δ with the increase in frequency [16]. They also showed analytically a decrease in tan δ with the increase in aging time.

Damping behavior of nanocomposites: It is typically assumed that the frictional energy dissipation at the interfaces between constituent phases in a nanocomposite is the dominant factor that affects its damping capacity. The large aspect ratio (length/diameter) and the high elastic modulus of carbon nanotubes allow for the design of such nanocomposites with a large difference in strain between its constituents further enhancing the interfacial energy dissipation. In addition, researchers have reported low adhesion between carbon nanotubes and most polymeric materials, an observation based on results of pull-out tests of carbon nanotubes from polymer matrices [17]. This typical behavior allows the nanotubes to have a relative motion with the surrounding matrix. All of these factors, combined with an extremely large specific area and a length scale that is comparable to polymer chains, open a new possibility for a further increase in damping capacity in nanocomposites [4, 18, 19].

Rajoria and Jalili hypothesized using a stick-slip model that the enhancement in the damping capacity can be due to the poor adhesion between the nanotubes and the polymer matrix and they predicted an enhancement in the damping capacity if well alignment and well dispersion are achieved [19]. Their results showed that the impact of adding nanotubes on the loss modulus of the matrix was much higher than that on the storage modulus. An increase in the loss modulus as the volume fraction increases, with a maximum value for SWCNT and MWCNT at 5% wt, was observed. The addition of MWCNT to an epoxy matrix was reported to cause an increase in the damping ratio (tan δ) by nearly 200% [20] while using SWCNT increased tan δ by 140% [21]. The authors argued that sliding of the concentric carbon nanotubes in MWCNT allowed for the higher tan δ. Auad et al. [22] reported a 2.5-times increase in the loss modulus at room temperature for an epoxy elastomer containing 1 wt % SWCNT-COOH and a 90-times increase for the same material at 140°C. From their results, the authors inferred that the matrix–nanotubes interfacial slip process and the presence of nanotube-nanotube sliding mechanism contributed significantly to the increase of loss modulus of the material.

Models of damping behavior of nanocomposites: Zhou et al. investigated the structural damping of SWCNT reinforced polymer matrix composites using micromechanics [4]. The composite was divided into four phases (resin, voids, and bonded and de-bonded nanotubes) and a stick-slip frictional motion was used to model damping while a Weibull distribution function was utilized to describe the evolution of interfacial debonding between the constituent phases. The value for the critical interfacial shear stress was evaluated by fitting the model results to the experimental data.

The stick-slip frictional motion was also observed in a study of the interfacial friction between carbon nanotubes and a graphite surface using an Atomic Force Microscope. Holscher et al. noticed that nanotubes move in a stick-slip fashion indicating a jump in the value of the potential energy of the system from one minimal to the next [23]. Buldum and Lu also studied the interfacial sliding and the rolling motion of carbon nanotubes on a graphite surface using molecular dynamics. They observed that nanotube sticks and then slips suddenly under a sufficient load exerted on it and that the barrier of the potential energy for the sliding motion is higher than that of a perfect rolling motion. This was explained by the combined spinning and sliding motion at the atomic scale when the carbon nanotube is pushed [24].

Analytical models to evaluate stresses at the interface of nanotubes: An understanding of the damping response can be developed based on an evaluation of interfacial bonding between the nanotube and the surrounding matrix and the stress distribution at the interface. The effect of changing the aspect ratio of the nanotube on the stresses at the nanotube interface and the load transfer between the composite constituents were reported in literature. Li and Chou developed a continuum model to characterize the interfacial shear stress transfer from the polymer matrix to the nanotubes utilizing a molecular structural mechanics approach and used Finite Element Analysis to model the polymer matrix [25, 26]. Jiang et al. modified Cauchy-Born rule to establish a constitutive model to study the effect of the radius of nanotubes on the mechanical behavior [27]. They integrated the standard cylindrical force equilibrium equation over the thickness of the nanotube to obtain the equilibrium equation for a SWCNT showing that the change in radius has a minor effect on the mechanical behavior. Few attempts were conducted to evaluate the interfacial shear strength between the nanotube and the matrix using molecular mechanics (MM) and molecular dynamics. Gou et al. performed MM simulations of a pull-out test of SWCNT from a cured epoxy resin. A simulation cell was constructed based on the molecular weights of the cured resin molecules, the nanotube fragment used in the simulation and the density of the resulting nanocomposites. The interfacial bonding energy was calculated for the nanotube and the surrounding matrix system as well as for each individual constituent separately (i.e., nanotube and matrix). The interaction and the pull-out energies were calculated as the difference between the total energy of the system and the sum of energies of the individual constituents [28]. Similar work was also carried out by Al-Ostaz et al. [29].

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