Mechanical characterization and impact damage assessment of multiscale nanocomposites with multiwalled carbon nanotubes

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Abstract

In this article, the mechanical properties and dynamic response of hybrid filler-modified epoxy/carbon fiber multiscale composites were investigated. The hybrid fillers composed of multiwalled carbon nanotubes and boron nitride nanoplates were dispersed in epoxy resin and used as matrix material. The multiscale hybrid laminated composites were stacked symmetrically consisting of 10 plies of woven carbon fibers and fabricated by vacuum infusion technique. The mechanical properties of the hybrid composites were investigated by tensile tests. Impact response and energy absorption capacity were investigated by using weight drop test method and the tests were performed according to ASTM-D-7136 standard with impact energies of 5, 10, and 15 J. The impact force and displacement versus interaction time were measured. The impulsive force, energy absorption capability, and damage formation were also investigated. It is observed that when the resin is modified by nanoparticles, both strength and the % strain at fracture increase considerably. However, it is shown in the subject manuscript that the enhancement of mechanical has not fully transferred to dynamic response and energy absorption capacities of nanocomposites.

Keywords

Nanostructures, particle reinforcement, impact behavior, damage mechanics, vacuum assisted resin infusion method

1. Introduction

Due to their excellent in-plane stiffness and strength/weight ratio, carbon fiber reinforced polymer composites (CFRP) are very desirable for a variety of applications.[1-2] Despite their superior in-plane mechanical properties, most traditional CFRP laminates have limitations due to relatively poor out-of-plane performance.[3]Particularly, the composite structures are prone to high strain rate loadings when subjected to impact or blast events. In this regard, improving the impact resistance which is mainly related with out-of-plane properties of fiber reinforced plastics (FRP) becomes an important issue considering the critical applications of FRPs. Polymers are generally ductile at low strain rates which result in low stiffness. However, at high strain rates the stiffness and strength of material increase.[4]Viscoelastic behavior of matrix materials and friction between reinforcement/matrix interfaces provide damping and result in impact energy dissipation.[5]It is also reported that delamination between successive plies is also able to absorb considerable amount of impact energy.[6-9]The delamination is controlled by the interlaminar shear strength which is matrix dominant property.[10-11]So, the improvement of mechanical behavior of matrix can result in improved energy absorption capacity. Hence, several strategies are applied to strengthen out-of-plane properties of FRPs such as stitching,[8]fiber surface treatment,[12]and interweaving with toughened polymers.[13]In addition to these approaches, utilization of nano-scale reinforcements in FRPs to produce multiscale composites affords multifunctional approaches in materials science. The selective modification of polymer matrix with nano-scale reinforcement deals with improving matrix depended properties in FRPs. For instance, nano-scale reinforcements in a polymer matrix play important role in toughening of multiscale composites by stopping or deflecting cracks.[14-17]

It is showed that enhancement of mechanical properties of epoxy resin by multiwalled carbon nanotube (MWCNT) and/or boron nitride nanoplate (BNNP) is possible. However, it is not found a study which MWCNT and BNNP used together for enhancing static toughness and impact toughness of CFRP as of this writing. The main goal of this paper is to investigate the effect of MWCNTs and boron nitride nanoparticles on impact properties of CF/epoxy multiscale composites based on their promising applications in regarding areas. The multiscale composites have been manufactured by vacuum-assisted resin infusion method (VARIM). The impact response and energy absorption of nanocomposites were investigated by using drop weight tests. After drop weight test, damage formation was examined by scanning electron microscopy (SEM).

2. Experimental

The multiwalled CNTs were supplied from TimesNano Company and have 30 nm diameter and 10–30 μm length. BNNPs were supplied from Bortek Company and have approximately 350 nm × 225 nm × 65 nm dimensions. The plain woven high strength carbon fabrics (PWCF) with 800 tex and 1–2 μm diameters were used in this study. The diameters of the carbon fibers are 7 μm. The epoxy resin used was diglycidyl ether of bisphenol-A epoxy (Momentive-Hexion L285) with aliphatic amine curing agent (Momentive-Hexion H285). This epoxy system was preferred due to its low viscosity which makes it suitable for VARIM processing. All the chemicals were of analytical grade and used as received without further purification.[18]

The dispersion of nanoparticles within epoxy resin is of great importance. Inhomogeneity can result in agglomeration of nano reinforcements which can act as stress raisers and worsen mechanical properties. In order to assure homogeneous dispersion, the following procedure was applied. After the production the modified epoxy resins have been examined in SEM and no evidence of agglomeration has been found. So, it was concluded that the nanoparticles were dispersed satisfactorily homogenous (Figure 1).

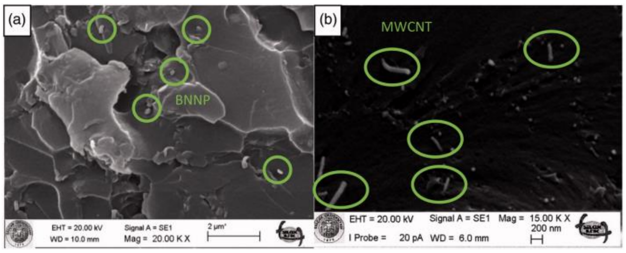

Figure 1. SEM image of epoxy with different nano reinforcement. (a) BNNP–epoxy mixtures, (b) MWCNT–epoxy mixtures.

3. Results And Discussion

Figure 2(a) shows the tensile test results for prepared epoxy resin mixtures differing in nano-scale reinforcement. This figure shows the general trends of three repeats. For all groups of samples, the stress–strain curve shows an initial linear region followed by nonlinear portion. The modification of epoxy resin increased tensile modulus, strength, and the % strain at fracture for all cases with respect to neat epoxy resin. The calculated increase of toughness values for the multiscale composite laminates with respect to control samples are reported in our previous study.Figure 2(b) represents the tensile test results for prepared multiscale composite laminates with different nanoparticle reinforcements. It is expected that the modification of epoxy matrix with MWCNTs and/or BNNPs will mainly influence the matrix-dominated properties of the multiscale composite due to the in-plane mechanical properties are typically dominated by fiber reinforcement.

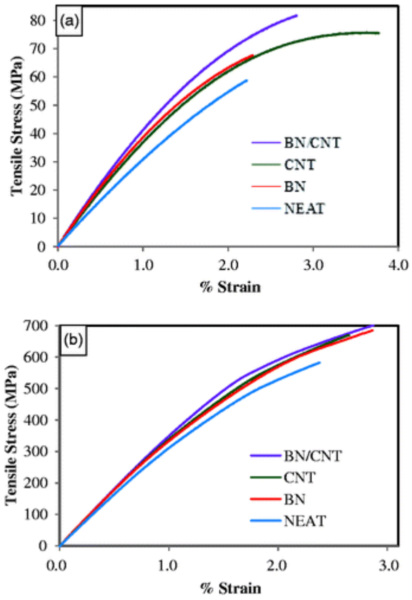

Figure 2. (a) Tensile behaviors of neat epoxy, BNNP/epoxy, BNNP–MWCNT/epoxy, and MWCNT/epoxy nanocomposites (obtained from Ulus et al.[18]). (b) Tensile test results for different nanoparticle reinforced carbon/epoxy plates.

Figures 3 and 4 show the general trends of three repeats. However, in order to trace the force–time and force–displacement variations, only one set of experimental results is presented. Figure 3 shows the variation of impact force versus time for the prepared multiscale composites subjected to different impact energies. This figure shows the general trends of three repeats. The impact forces–time variation shows an initial linear portion and the force reaches its maximum after some time. It is also seen that as the impact energy increased the contact force increased with nanostructure modification of matrix. The slope of force–time curve is designated as contact stiffness. It is observed that the contact stiffness for different samples has similar regardless of type of modification. Furthermore, the interaction between impactor and materials is about 0.015 s and the duration of interaction is generally not affected by impactor energy and matrix modification.

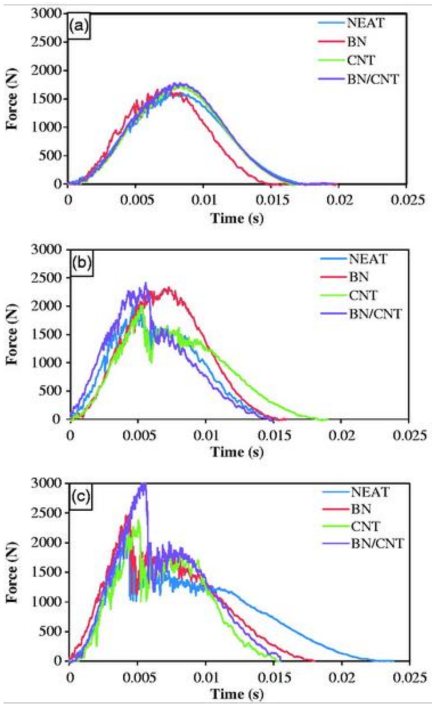

Figure 3. Variation of contact force versus time for different strike velocities: (a) 5 J, (b) 10 J, (c) 15 J.

As seen in Figure 3 the contact forces increased with increasing impact energy. However, large force drops are observed. This situation is an indication of severe damage formation as delamination and/or fiber breakage. Nanoparticle modification has resulted in increase in contact forces. Generally, the highest contact forces are obtained for BNNP/MWCNT-modified specimens.

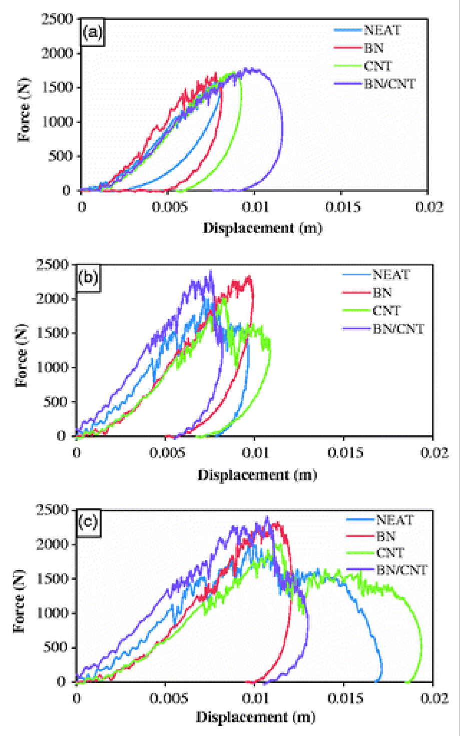

Figure 4. Variation of contact force versus vertical displacement for different strike velocities: (a) 5 J, (b) 10 J, (c) 15 J.

Figure 4 shows the impact force–displacement behavior for composite laminates subjected to different impact energies. At the loading phase, force increases linearly with displacement and reaches to its maximum value. After this point the unloading phase starts with representing nonlinear behavior.

Figure 5 shows the variation of peak load values of composite specimens during impact loading. As seen in this figure, the peak loads obtained for different impact energy levels show gradual increase. On the other hand, it is seen that when the matrix materials modified by nanoparticles the peak loads increase. The highest peak loads were obtained at BNNP/MWCNT-modified matrix/carbon fiber composites while the lowest peak loads were obtained for neat epoxy matrix composites. This result shows that the materials’ resistance to impact load increases by the modification of nanoparticles. It is also observed that the highest resistance to impact loading is obtained for BNNP/MWCNT-modified matrix/carbon fiber composites.

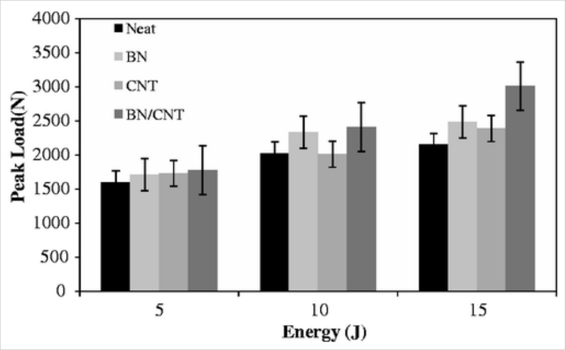

Figure 5. Variation of peak loads for specimens tested under different impact energies.

Figures 6 to 9 show the optical microscopy images of composite materials. The images have been taken from cross sections of test specimens. As seen in these figures, since impact energy levels are relative, the dominant damage modes for tested specimens are matrix cracking and delamination. However, fiber breakage can take place at specimens tested at impact energy of 15 J.

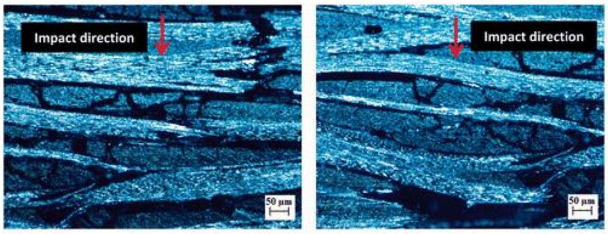

Figure 6. Optical microscopy image of neat epoxy/carbon fiber composite (x50, impact energy = 15 J, the position of arrows approximately corresponds to impact point).

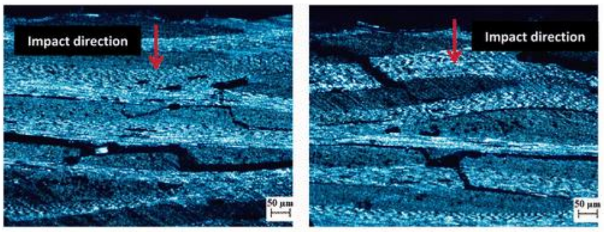

Figure 7. Optical microscopy image of MWCNT-modified epoxy/carbon fiber composite (x50, impact energy = 15 J, the position of arrows approximately corresponds to impact point).

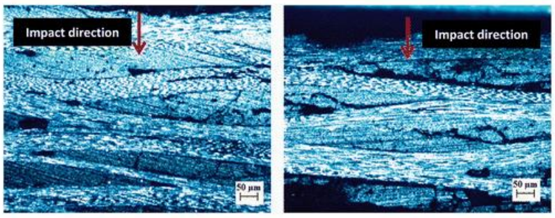

Figure 8. Optical microscopy image of BNNP-modified epoxy/carbon fiber composite (x50, impact energy = 15 J, the position of arrows approximately corresponds to impact point).

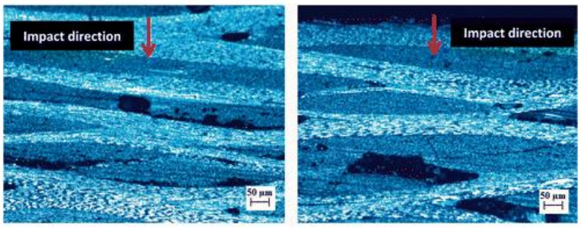

Figure 9. Optical microscopy image of BNNP/MWCNT-modified epoxy/carbon fiber composite (x50, impact energy = 15 J, the position of arrows approximately corresponds to impact point).

Figure 10 shows the SEM images of composite plates tested impact loading. The images have been taken from cross section of the plates where impactor hits. In order to expose the impacted zones to view, the specimens were cut down from impacted zone by using circular saw. The specimens were clamped in order to avoid damage progression. The impact force direction is from top to bottom.

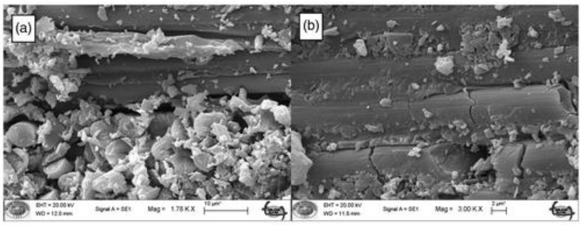

Figure 10. (a) SEM image of carbon fiber-BNNP/CNT-modified epoxy composite (1.78 kX, impact energy 15 J). (b) SEM image of carbon fiber-BNNP/MWCNT-modified epoxy composite (3 kX, impact energy 15 J).

4. Conclution

The improvement in matrix-controlled damage mechanisms such as matrix cracking and delamination are indications for success of nanoparticle modification. It is observed that BNNP- and BNNP/MWCNT-modified specimens showed lower matrix cracking and delamination. On the other hand, the maximum impact forces for BNNP- and BNNP/MWCNT-modified specimens are higher than that obtained for neat and MWCNT-modified epoxy resin. This result also indicates that especially BNNP/MWCNT-modified matrix showed higher resistance to impact force.

Acknowledgements

This work is supported by the National Natural Science Foundation of China（No. 11602066）and the National Science Foundation of Heilongjiang Province of China (QC2015058 and 42400621-1-15047), the Fundamental Research Funds for the Central Universities.

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