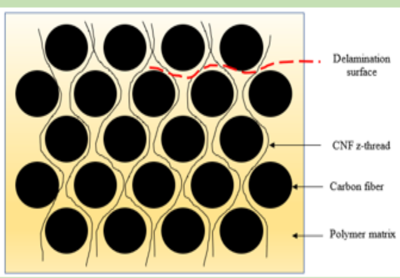
Nano Z-threading Strategy Enhanced Multifunctional Carbon Fiber Composites

Kuang-Ting Hsiao*

Department of Mechanical Engineering, University of South Alabama, Mobile, AL 36688, USA

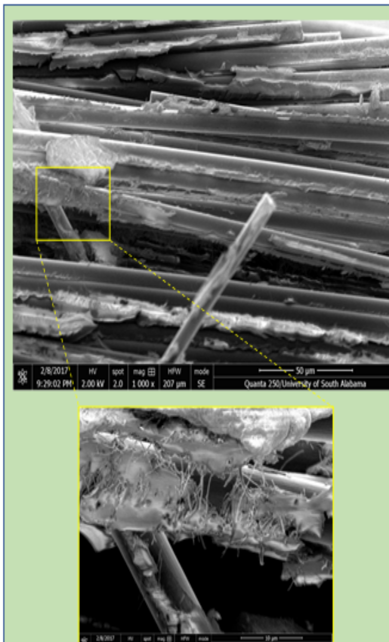
*Corresponding author: Email: kthsiao@southalabama.edu

Graphical Abstract



(a) Schematic of Z-Threading Strategy

(b) Optical microscope analysis of a delaminated ZT-CFRP laminate specimen revealed the CNFs z-threading between carbon fibers.



(c) Scanning electron microscope picture of1wt% ZT-CFRP delamination surface (oblique view) showed the CNF z-threads effectively penetrated the intralaminar region as well and wrapped around the carbon fibers.

Laminate Properties	Conventional CFRP	ZT-CFRP	Enhancement by ZT-CFRP
Mode-I Delamination[1,3] [1]	305.33 J/m^2	393.67 J/m^2	+29%
Interlaminar shear strength (ILSS)[2,3] by short beam shear [2]	64.89 MPa	75.92 MPa	+17%
Compressive Strength (along carbon fiber direction, i.e., longitudinal)[2,3] [3]	673.85 MPa	773.76 MPa	+15%
Z-direction (through thickness) DC Electrical conductivity[2,4] [4]	0.16 S/m	16.24 S/m	+9986%
Z-direction (thick) thermal conductivity[2,3] [5]	1.31 W/m-K	9.85 W/m-K	+653%

Note: [1] Toray T-300 carbon fiber fabric (plainweave); [2]. Hexcel AS-4C carbon fiber fabric (unidirectional); [3] E-field alignement; [4]. Convergning flow induced CNFs alignment

Data Sources:

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(d) Multifunctional Properties Enhancement Examples

Abstract

Carbon fiber reinforced polymer (CFRP) composites have been increasingly used to replace metal parts in many industries such as aerospace, marine, automotive, and sporting goods. The CFRP parts compared with their metallic counter parts have the advantages of lightweight, significantly higher tensile strength, stiffer, and corrosion resistant. On the other hand, compared with many metal parts, the CFRP parts have many well-known disadvantages including the lower toughness, lower through-thickness tensile and shear strengths, lower thermal conductivity, lower electrical conductivity, and lower operating temperature. These disadvantages have made the conversion from metal parts into CFRP parts challenging and costly to design, manufacture, and maintain.

The use of nanoparticles in polymer has been studied in the recent two decades. Carbon nanotubes (CNTs) and carbon nanofibers (CNFs) have been dispersed in various thermoset and thermoplastic polymers and improved the mechanical, electrical, and thermal properties; however, the properties were not comparable to CFRP. Later, researchers tried to infuse CNTs or CNFs into either carbon fiber preforms [**1**] or glass fiber preforms [**2**] for improving the mechanical properties. But the results were marginal and with great uncertainty due to the challenges of nanoparticle dispersion, filtering, and alignment while being infused through the fiber preform. The glass fiber preform experiments ended with relatively more consistent improvement than the carbon fiber preform experiments since that the glass fiber preform has significantly larger pores than the carbon fiber preform' s. The small pore size presented a great challenge for infusing millions of unaligned long CNTs or CNFs through the carbon fiber preform without being filtered.

To infuse long CNFs or CNTs through the carbon fiber preform and achieve reliable improvements, especially for 55% or higher carbon fiber volume fraction with increasingly tighter pores, an innovative plan for the processing and nano-reinforcing strategy is necessary. The z-threading strategy [**3,4,5**] has been reported to have consistent experimental successes in achieving the statistically meaningful improvement in multifunctional properties. The manufacturing steps of the CNF z-threaded CFRP (ZT-CFRP) are: (1) disperse the CNFs in a resin, (2) use a strong electrical field to align the CNFs in either the B-stage epoxy film or a CNF/resin impregnated sponge layer, whereas the CNFs are aligned in the through-thickness direction of the film or sponge layer. (3) place the resin film or sponge layer on a preheated dry carbon fiber fabric and press the resin film into the hot carbon fabric and allow the resin flow to carry the well-aligned CNFs to thread through the pores in the carbon fabric. (4) cool down the resin saturated and CNF z-threaded carbon fiber fabric to obtain the ZT-CFRP prepreg. (5) use the ZT-CFRP prepreg to make the ZT-CFRP laminate. Compared with the traditional CFRP, the ZT-CFRP laminates were reported of having improvement in the Mode-I delamination toughness, interlaminar shear strength, longitudinal compressive strength, through-thickness electrical conductivity, through-thickness thermal conductivity, and can reach the carbon fiber volume fraction of 55-80%. It is an effective approach to achieve a multifunctional CFRP for potentially expanding CFRP's applications.

Keywords

CFRP; multifunctional; Z-threading; carbon nanofiber; carbon nanotube.

Acknowledgements

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Biography of Presenting Author

Dr. K.T. Hsiao is a tenured full professor of mechanical engineering at the University of South Alabama. He received his Ph.D. degree from the University of Delaware in 2000 and has been conducting research in the areas of RTM, VARTM, nanocomposites, carbon fiber reinforced polymer composites, and nanoparticle-enhanced phase change materials. His current interests are in the manufacturing, characterization, and micro-mechanics modeling of nano-enhanced multifunctional carbon fiber composites, the integration of new composite materials with new additive manufacturing techniques, and the design of additive manufacturing process. Prof. Hsiao has published 1 book, 6 book chapters, 31 journal papers, 66 conference papers, and holds 12 patents and 5 pending patent applications. Being an expert in nanomaterials and composites, Prof. Hsiao's research has been funded by NSF, NASA, DOD, DOE, Alabama Commission on Higher Education, Alabama Department of Commerce, and Industries.