CARBON NANOTUBE FIBERS: CHALLENGES AND OPPORTUNITIES

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Keywords: *carbon nanotubes; fibers; nanocomposites; mechanical properties*

The superb mechanical and physical properties of individual carbon nanotubes (CNTs) provide the impetus for researchers in developing high-performance continuous fibers based upon CNTs [1]. The highest specific strength and stiffness reported for CNT fibers are, respectively, 5.3 times that of the strongest commercial fiber (T1000), and 4.3 times that of the stiffest commercial fiber (M70J) [2]. These findings demonstrate the potential for CNT fibers to be used as reinforcements in multifunctional composites. In this paper, we assess the recent advances in CNT-based continuous fibers. The review is conducted in terms of their fabrication methods as well as characterization and modeling of mechanical and physical properties. The challenges and opportunities in CNT fiber research will be evaluated.

1. Fabrication

Unlike in the case of carbon fibers, the processing of CNT fibers does not require the cross-linking step of the precursor structures. The following major techniques for the fabrication of CNT fibers will be reviewed [1,3,4]:

(1) spinning fibers from a lyotropic liquid crystalline suspension of nanotubes, in a wet-spinning process similar to that used for polymeric fibers such as aramids [5];

(2) spinning fibers from multi-walled CNTs previously grown on a substrate as ‘‘semi-aligned” carpets [2,6], and

(3) spinning fibers directly from an aerogel of single-walled CNTs and multi-walled CNTs as they are formed in a chemical vapor deposition reactor [7].

2. Characterization

The combination of unique mechanical, electrical and thermal properties of CNT fibers enables their application in multifunctional composites. The characterization of CNT fiber performance requires an understanding of the contributing factors over various length scales, ranging from nanoscale to microscale to macroscale. At the nanoscale, the relevant individual CNT structural parameters include tube diameter, wall thickness, tube length, tube waviness, defect contents and collapsing of tube walls. At the microscale, factors such as tube arrangement, tube entanglement, intertube load transfer, etc [8] need to be examined. Finally, at the macroscale, the major contributing factors may include fiber twist angle, fiber diameter, and their processability for textile preforms, such as woven fabrics and braids.

3. Analysis and Modeling

The characterization of CNT fibers as well as their constituent CNTs has motivated some analytical work for modeling their properties. Existing research work has focused on, for example, the statistical fiber strength [9,10], and the entanglement[11] and radial deformation[12] of CNTs in the fiber.

4. Challenges and Opportunities

Laboratory scale CNT fibers, which often possess small fiber size and exhibit high modulus and strength, as well as superb thermal and electrical conductivities, have high potential as reinforcements in multifunctional composites.

Despite the significant improvements in recent years toward developing high performance CNT fibers, there still exists some major challenges. For example, their mechanical and physical properties remain significantly lower than those of individual CNTs due to the low load transfer efficiency among the CNTs [8]. Another challenge is to scale-up current processes to produce continuous fibers suitable for textile processing.

Lastly, challenges and opportunities also exist in integrating the knowledge base developed in fabrication and characterization of CNT fibers. Such an effect will greatly facilitate the development of modeling methodologies, which are indispensible for the application of CNT fibers in advanced composites.

Acknowledgments

This work is funded by the Army Research Office (Dr. Bruce LaMattina, Program Director) and the Korea Foundation for International Cooperation of Science and Technology through a grant provided by the Korean Ministry of Education, Science and Technology.

References

[1] T.W. Chou, L.M. Gao, E.T. Thostenson, Z.G. Zhang, and J.H. Byun 'An assessment of the science and technology of carbon nanotube-based fibers and composites', Composites Science and Technology 70, pp 1-19, 2010.

[2] X.F. Zhang, Q.W. Li, T.G. Holesinger, P.N. Arendt, J.Y. Huang, P.D. Kirven, T.G. Clapp, R.F. DePaula, X.Z. Liao, Y.H. Zhao, L.X. Zheng, D.E. Peterson, and Y.T. Zhou 'Ultrostong, stiff and lightweight carbon-nanotube fibers', Advanced Materials 19, pp 4198-4201, 2007.

[3] K. Koziol, J. Vilatela, A. Moisala, M. Motta, P. Cunniff, M. Sennett, and A. Windle "High-performance carbon nanotube fiber". Science 318, pp 1892-1895, 2007.

[4] M. Naraghi, T. Filleter, A. Moravshy, M. Locascio, R.O. Loutfy, and H.D. Espinosa 'A multiscale study of high performance double-walled nanotube-polymer fibers', ASC Nano 4, pp 6463-6476, 2010.

[5] B. Vigolo, A. Penicaud, C. Coulon, C. Sauder, R. Pailler, C. Journet, P. Bernier, and P. Poulin 'Macroscopic fibers and ribbons of oriented carbon nanotubes', Science 290, pp 1331-1334, 2000.

[6] K. Liu, Y.H. Sun, R.F. Zhou, H.Y. Zhu, J.P. Wang, L. Liu, S.S Fan, and K.L. Jiang 'Carbon nanotube yarns with high tensile strength made by a twisting and shrinking method', Nanotechnology 21, pp 045708(7pp), 2010.

[7] X.H. Zhong, Y.L. Li, Y.K. Liu, X.H. Qiao, Y. Feng, J. Liang, J. Jin, L. Zhu, F. Hou, and J.Y. Li 'Continuous multilayered carbon nanotube yarns', Advanced Materials 22, pp 692-696, 2010.

[8] J.J. Jia, J.N. Zhao, G. Xu, J.T. Di, Z.Z. Yong, Y.Y. Tao, C. Fang, Z.G. Zhang, X.H. Zhang, L.X. Zheng, and Q.W. Li 'A comparison of the mechanical properties of fibers spun from different carbon nanotubes', Carbon doi:10.1016/j.carbon. 2010. 11.054, 2010.

[9] F. Deng, W.B. Lu, H.B. Zhao, Y.T. Zhou, B.S. Kim, and T.W. Chou 'The properties of dry-spun carbon nanotube fibers and their interfacial shear strength in an epoxy composite', Carbon doi: 10.1016/ j.carbon.2010.12.061, 2010

[10] I.J. Beyerlein, P.K. Porwal, Y.T. Zhu, and X.F. Xu 'Scale and twist effects on the strength of nanostructured yarns and reinforced composites', Nanotechnology 20, pp 485702, 2009.

[11] W.B. Lu and T.W. Chou 'Analysis of the entanglements in carbon nanotube fibers using a self-folded nanotube model', Journal of Mechanics and Physics of Solids doi:10.1016/j.jmps.2011.01.004, 2011.

[12] W.B Lu, T.W. Chou, and S.B. Kim 'The radial deformation and its related energy variation of single-walled carbon nanotubes', submitted, 2011.