PROCESSING AND MECHANICAL / ELECTRICAL CHARACTERIZATION OF CARBON NANOTUBE – BASED COMPOSITES FOR MULTIFUNCTIONAL APPLICATIONS

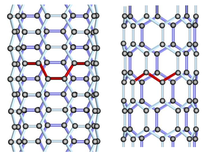
John J. Gangloff Jr., Limin Gao, Pierre C. Yao-Koffi, Thomas Mintel, Erik T. Thostenson

University of Delaware • Department of Mechanical Engineering and Center for Composite Materials

INTRODUCTION AND MOTIVATION

- With the emergence of carbon nanotubes (CNT), researchers from around the world have sought to exploit the CNT's high performing physical and mechanical properties. Unique properties as high specific stiffness, strength and conductivity, coupled with the CNT's exceptionally large aspect ratio (length / diameter) have accelerated research in CNT-based composite materials.

Single-Walled CNT Atomic Structures[1]

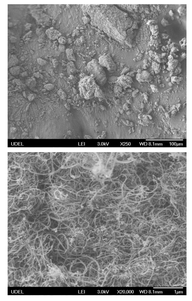


Armchair *Zig-Zag*

- Some critical issues that CNT-based composite applications face are CNT dispersion (effective aspect ratio), wetting and adhesion (interface), and scalability of the manufacturing processes (applications development / cost).
- Recent research[2-4] has established new processing techniques that are scalable for engineering applications aimed at improve overall material properties and cost efficiency.
- Electrical percolation behavior created from the addition of CNTs at extremely low concentrations to electrically insulating plastics epoxy, vinyl ester, has opened-up new applications for nanocomposites, such as electromagnetic interference (EMI) shielding and electrostatic discharge (ESD), and also lead to discoveries for *in situ* sensing of microcracking and delamination in advanced fiber composites.[5]

Essential to the development of new engineering applications for carbon nanotube composites is understanding the influence of processing on their mechanical and electrical properties.

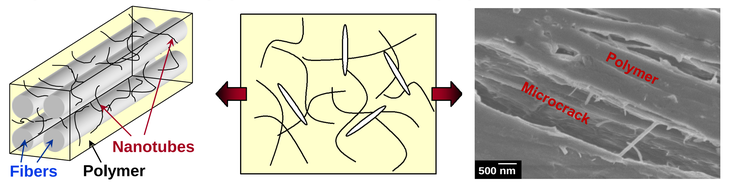
THEORY



- At the microscale, agglomerations of CNTs can be observed.
- CNT agglomerations are due to a high degree of entanglement or a "spaghetti" structure.
- Entanglement leads to poor dispersion, wetting and adhesion and uncontrolled structure.
- Reducing agglomeration of CNTs can lead to higher performing composites.

NANOTUBE / FIBER HYBRIDS[3-6]

- CNTs diameters are three orders of magnitude smaller than advanced fibers (5-20 nm as compared to 5-20 μm).
- CNTs can be added to conventional composite matrix / reinforcement systems to improve physical and mechanical properties.

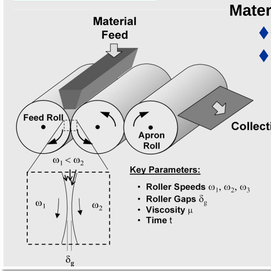


Severing of CNT "nano-wires" cuts electrical junctions leading to increased resistance

- CNTs can penetrate regions surrounding fibers and create an electrically percolating network (i.e. nano-wires) and enables creation of multi-functional *in situ* sensing for strain and damage.[5]

RESEARCH METHODOLOGY

CNT Dispersion



Materials:
- CVD-grown Single or Multi-Walled CNTs
- Epoxy and Vinyl Ester Resins

Key Parameters:
- Roller Speeds $\omega_1, \omega_2, \omega_3$
- Roller Gaps δ_g
- Viscosity μ
- Time t

Decreasing Calendaring Gap → Decreasing CNT Agglomerates → Improved Dispersion, Wetting and Adhesion → Improved Composite Performance

Nanocomposite and CNT/Fiber Hybrid Composite Processing

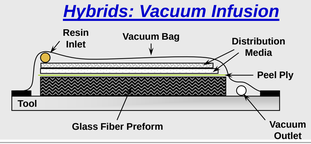
Curing Agent Addition and Degassing

Curing: Elevated or Ambient Temperature

Nanocomposites

Molding and Machining of ASTM-Sized Test Specimens

Hybrids: Vacuum Infusion



Characterization

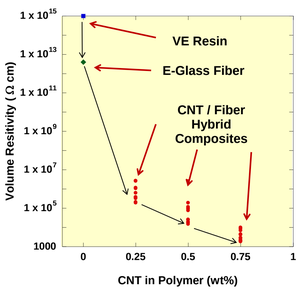
Testing & Data Acquisition: Electrical Conductivity, Load, Displacement, Strain

Data Analysis

Multifunctional Applications Development

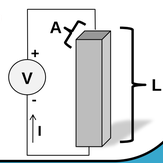
CNT / GLASS FIBER / VINYL ESTER COMPOSITE ELECTRICAL PROPERTIES

- CNT / E-Glass / Vinyl Ester hybrid composites were tested to determine their electrical properties.
- Large volume resistivity decreases with the addition of CNTs correspond to formation of an electrically conductive CNT network.
- Nerve-like CNT networks at small CNT concentration can serve as deformation and damage sensors with minimal intrusion.



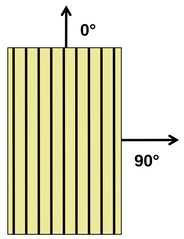
Volume Resistivity for a Rectangular Specimen

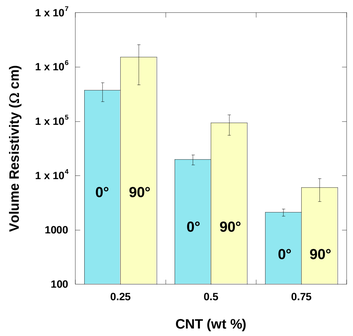
$$\rho_V = \frac{VA}{IL} = \frac{(\text{Voltage})(\text{Cross} - \text{Sectional Area})}{(\text{Current})(\text{Specimen Length})}$$



PRELIMINARY RESULTS: INFLUENCE OF FIBER ORIENTATION

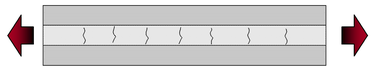
Fiber Orientation

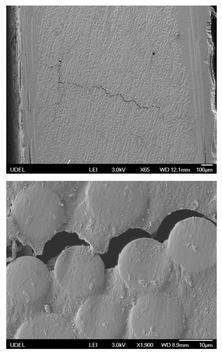




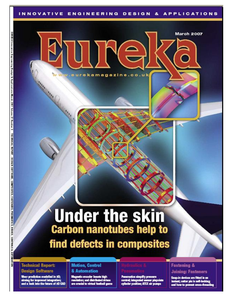
- Fiber orientation strongly influences mechanical properties, but understanding of orientation effects on electrical properties in CNT/fiber hybrid composites is limited.
- Initial electrical resistivity measurements show fiber orientation plays a strong role on volume resistivity, affecting results by approximately one order of magnitude in each direction.

FUTURE APPLICATION: SENSING OF STRAIN AND CRACKS





Electron micrographs courtesy of Limin Gao and Erik Thostenson



*** March 2007 cover of *Eureka Magazine* with the lead article highlighting Profs. Thostenson and Chou findings on CNT sensing**

CONCLUSIONS

- Electrical percolation has been achieved in CNT/fiber composites at CNT concentrations in the polymer of 0.25 wt% (approximately 0.08 volume % in the fiber composite).
- The electrical properties as influenced by fiber orientation has been studied. Preliminary results indicate the specimens are electrically anisotropic.
- Overall, the study of advanced CNT-based composite material processing techniques and application (i.e. *in situ* sensing) will lead to a greater understanding of the CNT's utility within modern engineering applications.

KEY REFERENCES

1. E. T. Thostenson, C. Y. Li and T-W. Chou, "Nanocomposites in Context," ***Composites Science and Technology***, 65(3-4) 491-516 (2005).
2. E. T. Thostenson and T-W. Chou, "Processing-Structure-Multi-Functional Property Relationship in Carbon Nanotube/Epoxy Composites," ***Carbon***, 44(14) 2869-3148 (2006).
3. E. Bekyarova, E. T. Thostenson, A. Yu, H. Kim, J. Gao, J. Tang, H. T. Hahn, T-W. Chou, M. E. Itkis, R. C. Haddon, "Multiscale Carbon Nanotube-Carbon Fiber Reinforcement for Advanced Epoxy Composites," ***Langmuir***, 23(7) 3970-3974 (2007).
4. E. Bekyarova, E. T. Thostenson, A. Yu, M. E. Itkis, D. Fakhrutdinov, T-W. Chou, R. C. Haddon, "Functionalized Single-Walled Carbon Nanotubes for Carbon Fiber-Epoxy Composites," ***Journal of Physical Chemistry C***, 111(48) 17865-17871 (2007).
5. E. T. Thostenson and T-W. Chou, "Carbon Nanotube Networks: Sensing of Distributed Strain and Damage for Life Prediction and Self-Healing," ***Advanced Materials***, 18(22) 2837-2841 (2006).
6. E. T. Thostenson, W. Z. Li, D. Z. Wang, Z. F. Ren and T-W. Chou, "Carbon Nanotube/Carbon Fiber Hybrid Multiscale Composites," ***Journal of Applied Physics***, 91(9) 6034-6037 (2002).

This research is funded by the Air Force Office of Scientific Research (Grant FA9550-06-1-0489) and the Office of Naval Research (Grants N00014-07-1-0345 and N00014-07-1-0621).