Next Generation Composite Materials for Flywheel Development

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Abstract

Flywheels are "mechanical battery" storage systems that have fast response times, long lifetimes and lower maintenance costs; when coupled with high-temperature superconducting (HTS) bearings, flywheels can exhibit extremely low rotational losses resulting in high efficiency. For energy storage purposes, materials with higher strengths, and lower densities that would allow the flywheel to spin faster are desirable. We have recently begun a project to develop new composite materials for flywheel rotors for energy storage. We are examining the use of:

1.) Nanoscale "fillers" (NFs) within the epoxy polymer matrix, and

2.) The use of electro-spun carbon nanoscale fibers (CNFs) as potential replacements for the currently used micron-sized carbon fibers (CFs).

Introduction

Flywheels are rotating mechanical devices that store rotational energy. The amount of energy stored is proportional to the square of its rotational speed.

$$E_k = (I \times \omega^2)/2$$

where ω = angular velocity, I = moment of inertia

For a thick walled empty cylinder $I = m(r_{external}^2 + r_{internal}^2)/2$
Where r = radius, m = mass

The amount of energy (E_k) able to be stored depends upon the point at which the rotor will warp or shatter. The hoop stress (σ_t) on the rotor is:

$$\sigma_t = \rho \times r^2 \times \omega^2$$

Hence, E_k is proportional to: $(\sigma_t/\rho) \times m$
Where (σ_t/ρ) can be considered specific tensile strength
where ρ = density

Developing composite materials with higher specific tensile strengths will lead to stronger rotors and increased energy storage capacity for flywheels.

Goals

Develop new composite materials with improved mechanical properties that will allow for faster angular velocities leading to increased energy. Understand and improve chemical/mechanical interface between components (polymer (EPON), CFs, nanoscale filler, etc.) in the composite materials.

Specifically, here we aim to:

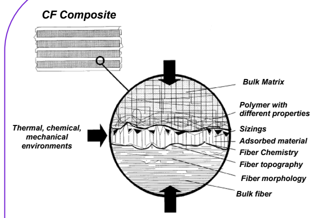
- Prepare EPON and CF/EPON and test (baseline)
- Demonstrate improvement w/ EPON w/ NFs
- Demonstrate improvement w/ CF/EPON w/NFs
- Prepare electrospun CNFs as CF alternative
- Demonstrate improvement w/ CNF/EPON composite
- Demonstrate improvement w/ CNF/EPON w/ NFs

Acknowledgments

We gratefully acknowledge support from Dr. Imre Gyuk and the Office of Electricity, Delivery and Energy Reliability.

Sandia is a multi-program laboratory operated by Sandia Corporation, a Lockheed-Martin Company, for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Carbon-Polymer Composites



Schematic adapted from L. T. Drzal *et al.* "comparison of methods for the measurement of fibre/matrix adhesion in composites" *Composites* **1992** *23 (1)* , 2-26.

Tensile Strength of some carbon-based materials

Material	Ultimate Strength (MPa)
Carbon Fibers (CFs) (Toray T1000G)	6370
Carbon Nanotube (CNT)	11,000-63,000
Carbon Nanotube composites	1200
Graphene	130,000

There are numerous opportunities for optimizing materials and interfacial boundaries in order to improve CF composites as they are applied to flywheels for energy storage.

We have chosen to first examine:

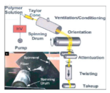
1. Modifying the bulk matrix with the incorporation of "Nanofillers" (NFs). For this project we have been focusing on the use of carbon-based Nanofillers.
2. Examining nanoscale replacements for CF. As a first step we are examining carbon nanofibers (CNFs) prepared from an electrospinning/carbonization procedure utilizing poly(acrylonitrile) (PAN) precursor polymers.

Composite materials are then fabricated into test coupons and their mechanical properties examined using dynamic mechanical analysis (DMA) methods.

Carbon Nanofibers (CNFs)

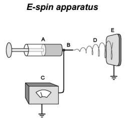
Synthesis of CNFs

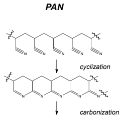
An electrospinning apparatus was used to electrospin poly(acrylonitrile) (PAN) onto a nickel foil collection plate. The fibers were removed from the nickel foil, and heated at 280 °C under tension to induce cyclization. The fibers were then heated in a reducing atmosphere to carbonize them.



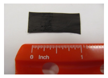
Collection of espun PAN fibers for continuous processing is feasible

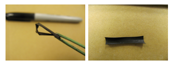
Schematic adapted from F. Ko *et al.* "Electrospinning of Continuous Carbon Nanotube-Filled Nanofiber Yarns" *Adv. Mater* **2003** *15 (14)*, 1161-1165.





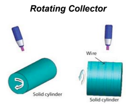
A high speed rotating collection wheel was built in order to collect "aligned" electrospun PAN fibers.

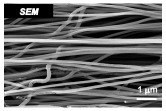




Aligned fiber mats are flexible while the random orientation fibers are very brittle

Mechanical Testing of CNFs





Three point bend and tensile measurements are being conducted on CNFs. These tests will allow for optimum CNFs to be prepared prior to their incorporation into polymer composites.

Nanoscale Filler/EPON Composites

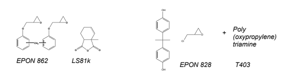
Preparation of EPON/Carbon Fiber (CF) Composites

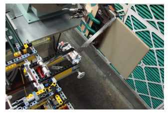
We have chosen the following EPON resin systems and CFs for our test platform:

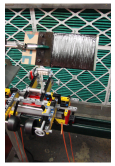
1. EPON 862 resin / LS81k curing agent
2. EPON 828 resin / T403 curing agent

CF (diameter, tensile strength and modulus)

1. *Toray T700S (7 µm, 4900 MPa, 230 GPa)*
2. *Toray T800S (5 µm, 5880 MPa, 294 GPa)*
3. *Toray M40J (5 µm, 4410 MPa, 377 GPa)*

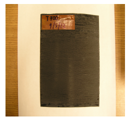






After winding, samples were cured in a vacuum laminating press at 14psi , 80 °C, 24 h

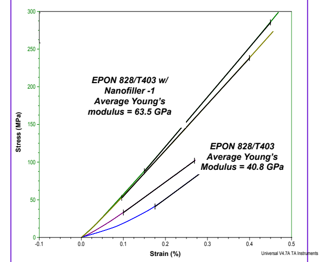
Photo of ~ 5" x 6.5" EPON 828/T-700 Test Coupon



Mechanical Testing of Composites

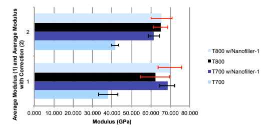
Initial studies were performed with three point bend measurements to determine the Young's modulus for EPON 8282/T403 T700 CF w/ and w/out a NanoFiller.

EPON 828/T403/T-700 w/ and w/out Nanofiller-1



Initial Nanofiller results are promising with ~ 55% increase in Young's modulus achieved; however, better process control is needed in order to ensure equal resin weights between samples. A vacuum bag and oven will be used for future cures.

T700 and T800 Comparison of Moduli



Conclusions & Future Work

EPON 828/T403/T700s and EPON 828/T403/T800s composites were fabricated with a winding/vaccum laminating press protocol. The addition of a carbon-based nanofiller into the EPON mixture was readily achieved. Initial mechanical testing focused on bend tests to extract the Young's modulus. In general an increase in the Young's modulus was obtained with the use of nanofiller. These preliminary results are encouraging but the process control for our EPON/CF manufacturing needs to be improved. Hence, we will re-fabricate the parts using a slightly different method and conduct more exhaustive mechanical testing. We also want to develop methods to alter the interfacial interactions between the carbon fiber and the EPON polymer – "sizing" the CF with EPON/NF mixtures is one approach.

A high speed mandrel was developed in order to collect aligned electrospun PAN fibers which were subsequently oxidized and then fired in a reducing atmosphere. Optimization and mechanical testing is ongoing.