Improved Properties of Nanocomposites for Flywheel Applications

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**Project:** Improved Flywheel Materials

**Problem:** Small changes in the AC grid energy levels necessitates rapid and exact changes in the demand/surplus requirements to ensure energy leveling. Gas powered generators are lacking.

**Approach:** Flywheels are a clean and efficient method that can meet the energy leveling demands. To store more energy, flywheels need to spin faster, which requires stronger rims. Focused on the materials (C-fiber, glass fiber, resin) of composite flywheels. No major changes to basic design, processing parameters, and/or cost can be incurred.

**Stationary Energy Storage Impact:** The economics of flywheel-based energy storage might potentially be improved by a factor of 3 or more. The increased storage/supply will be necessary to meet expected future complications expected as alternative energies (i.e., solar, wind, etc.) are introduced.

The Need for Speed Kills
Goal: to explore nanocomposites as the rim material to produce improved flywheel performance.

Low load levels of nanoparticle fillers have lead to dramatic property changes:

<table>
<thead>
<tr>
<th>Loading (wt %)</th>
<th>Storage, 113% flexural strength, 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 Al$_2$Si$_2$O$_5$(OH)$_4$</td>
<td>23% tensile strength, 2</td>
</tr>
<tr>
<td>3 Al$_2$O$_3$</td>
<td>hardness, 57% impact, 65% flex, 88% tensile strength, 3</td>
</tr>
<tr>
<td>2 SiO$_2$</td>
<td>Youngs Modulus, 14% tensile strength 6%, fracture toughness, 4</td>
</tr>
<tr>
<td>2 ZrP</td>
<td>Youngs Modulus, 55% tensile strength, 5</td>
</tr>
<tr>
<td>0.4% CNT</td>
<td>2% ZrP</td>
</tr>
</tbody>
</table>

Energy is stored in the rotor as kinetic energy, or more specifically, rotational energy:

\[ E_k = \frac{1}{2} \cdot I \cdot \omega^2 \]

\( \omega = \) angular velocity, \( I = \) moment of inertia of the mass about the center of rotation.

The amount of energy that can be stored is dependent on:

\[ S_t = \sigma \cdot r^2 \cdot \omega^2 \]

\( \sigma = \) tensile stress on the rim, \( \rho = \) density, \( r = \) the radius, \( \omega = \) the angular velocity of the cylinder.

Small % changes in the flywheel spin speed leads to magnified energy storage:

16,000 rpm ➞ 20,000 rpm
25 kWh ➞ 39 kWh

25 kWh/100 kW per unit = 21 kg TNT
FY12 Overall Objectives: defining nanoparticle fillers effects on the ‘state-of-the-art’ system

- Flywheel applications are interested in increasing the strength of the resin/C-fiber interaction to allow for faster spin speeds.

Team determined approach and tasks assigned based on expertise:

- Composite System
- Resin/Epoxy System
- Nanomaterials
- Surface Characterization
- Test Specimen (Epoxy)
- Nano/Epoxy Characterization

- Increasing strength is the pressing issue.

- Incorporation of suggested nanomaterials or resins will represent verification of our approach.
Interlaminar strength of composite test specimens for different resin systems indicated that the....

Filament wound glass and carbon fiber composite tubes

Arc 3-point bend specimens

**Resin Systems**
(a) Standard: epoxy anhydride/catalyst
(b) Epoxy anhydride/catalyst
(c) Epoxy anhydride/catalysts/modifier
(d) Epoxy amine

(i) system is good model to ‘real-world materials’ and allows for interpretation of NW additives
(ii) C-fiber/resin interaction needs increased
Nanocomposites show a <30% increase in measured strength of C-fiber wound test specimen!

Large scale preparation of nanowires available

C-fibers wound with unfunctionalized nanoparticles (B)

C-fibers wound with functionalized nanoparticles (C)

Filament wound carbon fiber composites (A) and 5% nanocomposites (B and C)

Increased shear and interlaminar-fracture strength of flywheel carbon fiber-epoxy composite by 30%, may enable 20-30% reduction in flywheel energy storage cost ($/kW-h).

Case Study: 20-MW Beacon Power Facility (NY)
- Technology increases power capacity to 26 MW and energy capacity to 7.5 MW-service hours.
- Decreases average energy storage costs to $1500/kW and $60000/kW-h.
- After accounting for new-technology and additional production costs, return on improved-nanocomposite investment is 4%-6% per year over 20-year service life.

Revenues and Costs
- Bar chart showing revenues ($M) and costs ($M) for base case and Alternative 1: Nano.

Optical image of C-fiber B after mechanical testing.

Optical image of C-fiber C after mechanical testing.

Poor distribution of nanomaterial observed, implies a minimal impact for the load levels used.
C-fiber resin interaction requires improvement, so functionalization of the C-fiber undertaken.
Several approaches to functionalize C-fibers were undertaken:

**Solution Growth**

- 5 wt% PAA solution
- 0.1M Zn(NO$_3$)$_2$ solution

**Rapid Thermal Decomposition**

**Thermal oxidation**

- O$_2$
- CO$_2$
C-fiber modification results promising

**Solution Growth**
- Zinc Nitrate
- Zinc Chlorate
- Zinc Oxalate

**Thermal Oxidation**
- SEM of etched 1770 carbon fiber
- XPS to probe surface oxidation of carbon fiber exposed to 0.6% oxid. at 175°C
- 225°C, 2d, 0.7% oxid.

**Rapid Thermal Decomposition**
- PAA-Zn²⁺ solution
- Pechini formulation
- PAA, TiO₂, and Zn²⁺
- Formation of nanoparticle coatings
- Inorganic bridging between C-fibers
- Surface roughness rapidly developed
Summary/Conclusions

• Test Specimen Model identified:

(i) good indicator of ‘real world’ properties,
   • Introduction of TiO₂ nanowires led to a 30 % increase in tested strength
   • Economically correlates to a 20 % reduction in cost
   • Better properties expected upon better distribution of poorly distributed nanowires in matrix.

(ii) C-fiber/resin interaction needs increased.

C-fiber modification underway:
(a) solution growth,
   • surface modification shown with control indicated by anion
(b) thermal oxidation
   • CO₂ gas observed without substantial decomposition of C-fiber
(c) rapid thermal decomposition.
   • rapid surface modification noted with bonding between fibers.
Future Tasks: Milestones for FY13

- Retest resin at higher load levels consistent with test specimen.
- Functionalize/characterize TiO₂ nanowires for improved distribution.
- Re-evaluate distributed functionalized TiO₂ nanowires in test specimen.
- Optimize surface modification of C-fiber with ceramic nanomaterials.
- Determine interaction strength of C-fiber and ceramic NM.
- Introduction of optimized modified C-fiber into test specimen model system.
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