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Improved Nanocomposite Materials for Flywheel Energy Storage Applications

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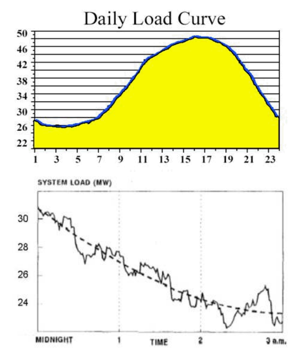
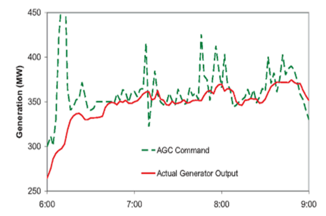
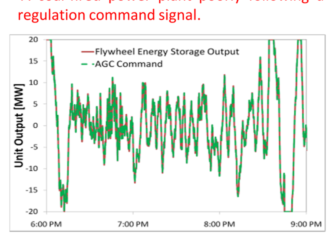
Flywheel Energy Storage Systems



The network of interconnected lines for transmitting and distributing electrical energy in the United States is often referred to as the 'power grid'. Most of the three major grids in the US [Western Interconnection, Eastern Interconnection, and the Electrical Reliability Council of Texas (ERCOT)] employ high-voltage, 3-phase, alternating currents and thus this network is referred to as the AC-grid. In order for a safe and stable AC grid, the supply and demand of electricity must be exactly regulated at 60 Hz. Due to the inconsistent load placed by consumers, significant variations (i.e, surplus and deficits) of electricity occurs.



A coal-fired power plant poorly following a regulation command signal.

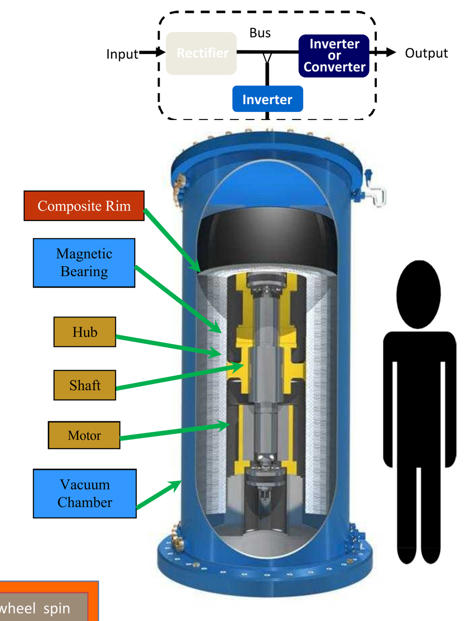


A 20MW flywheel energy storage unit accurately following a signal.

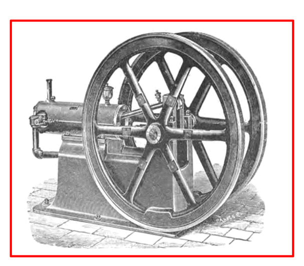
Traditionally, the AC-grid is regulated using gas powered generators, which are inefficient, wasteful, and cause green house emissions, with significant wear and tear on the equipment. Shown to the left (on top) is a graph of the electrical usage over time (green) and the response of a gas powered generator (red). As non-traditional sources of electricity (i.e., wind or solar) become a larger part of the AC-grid, significant issues concerning energy regulation will occur due to the inconsistent energy produced using these 'green' methods. For instance, for wind power gusts due to storms or other weather phenomenon will cause spikes in energy production, while clouds will cause unpredictable times of reduced electrical production for solar energy

As shown (above, bottom), flywheel systems can meet all of these demands. Flywheel energy storage systems are a clean and efficient method that can meet the energy leveling demands. These mechanical batteries have been around for over 100 yrs and were used in early industrial systems to store energy and smooth the output of early power generation systems. Flywheels works by accelerating wheel and storing the resultant energy as rotational energy.

Modern flywheels rotate at much higher speeds (50,000 rpm; Mach 2). The newest designs use magnetic levitation to decrease friction even further. A flywheel is attached to a motor/generator that adds power and energy to the flywheel by speeding it up and taps power from the flywheel by generating electricity when needed which slows the wheel down. Current systems are being commercialized with 20 MW storage capabilities.



Modern composite flywheel (Beacon, Inc.)



1898 illustration of a White and Middleton stationary engine; note the large twin flywheels.

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

16,000 rpm → 25 kWh
20,000 rpm → 39 kWh
of extractable energy

More electricity will need to be stored to handle the 'green energy generators. In order to do this, the flywheels merely need to spin faster. In order to do this, the rim material needs to be stronger. Small changes will have big impact on the final energy stored:

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

$$E_k = ½ \cdot I \cdot \omega^2$$

ω = 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:

$$s_t = \rho \cdot r^2 \cdot \omega^2$$

s_t = tensile stress on the rim, ρ = density, r is the radius, ω is the angular velocity of the cylinder.

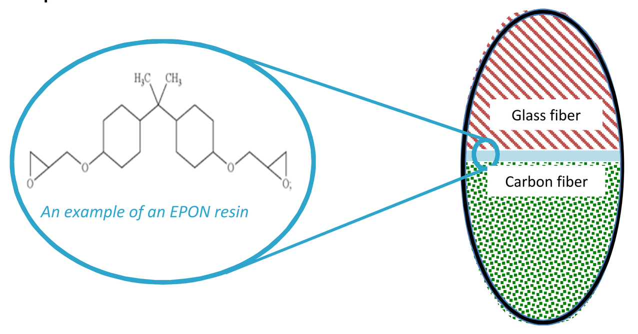
Approach to Improved Flywheel Materials

For this study, the interaction of the materials (carbon fiber, glass fiber, and resin 'glue') for a composite flywheel was investigated. The weakest aspect of this is the resin. For this effort, an EPON resin was used. Often these employ an activator to generate the 'glue'. Since this is the weakest component, our study focused on improving the resin strength.

Fillers are often employed to alter a matrix's properties. Meso-sized fillers are added at >6 % to impact properties. Nanofillers can be added a very low levels (%) due to high surface areas, with dramatic impact. Two were investigated: graphene and titania

Ceramic Nanofillers
- synthesis routes available
- inexpensive
- variety of shapes (wires!)
- reactive surfaces (-OH)
- easily functionalized
  - + carboxylate
  - + silanes
- varied composition

Graphene Nanofillers[6,7]
- High surface area (~ 2600 m^2/g)
- 200X stronger than steel
- 2-12X stronger than CNTs
- Potentially cheaper than CNTs
- Surface Chemistry can be altered (scalability ?)

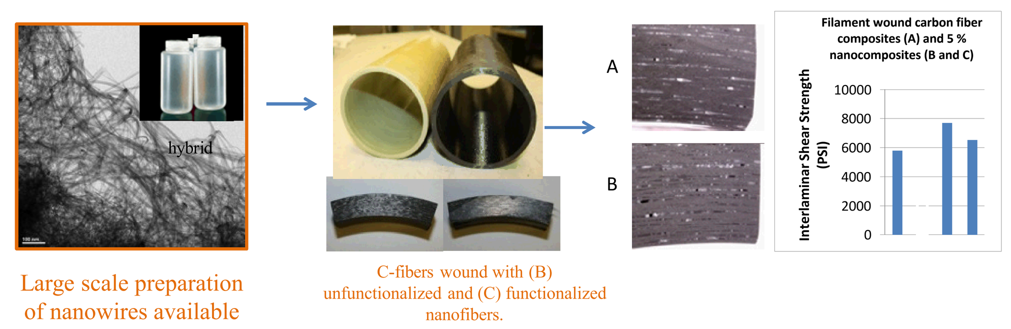


- Fillers are a simple cost-effective method to alter resin properties.
- Meso-sized fillers require high loads (> 60%) due to small surface area.
- Nanomaterials are 2 D fillers with all surface area, added at low levels.
- Nanofillers' surface functionality can interact with the resin.
- Reactivity can be tailored by surfactant on the nanomaterial
- wires and planes have biggest impact at lowest load level.

Previously, 25-30% increase in measured strength demonstrated by using TiO_2 nanofillers

Goal: Improve the overall strength of composite flywheel materials, so the flywheel can spin faster (store more energy).

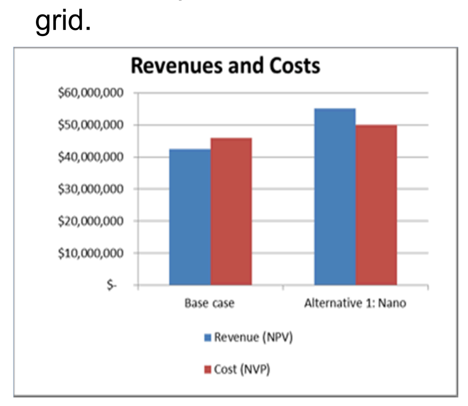
Approach: Explore use of nanomaterials in strengthening composite flywheel rims to improve performance. Low load levels (<5%) have led to dramatic property changes.



Large scale preparation of nanowires available

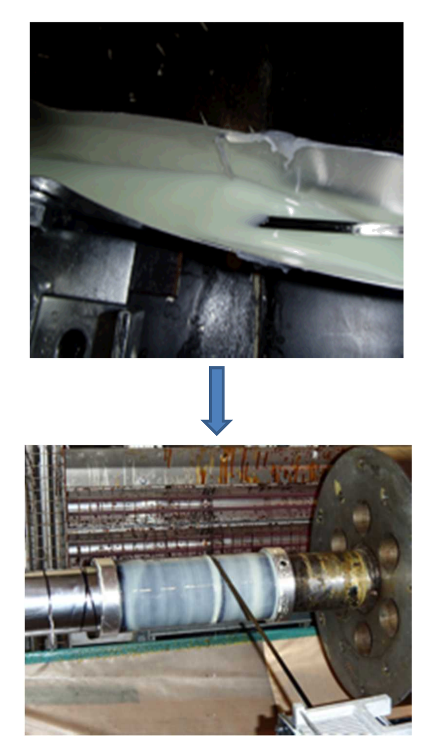
C-fibers wound with (B) unfunctionalized and (C) functionalized nanofibers.

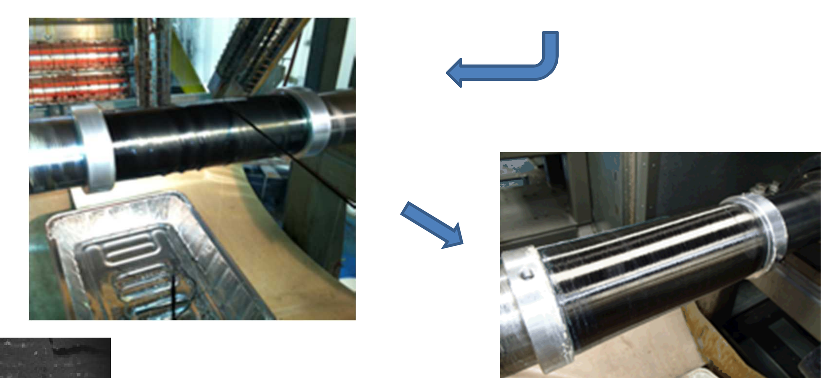
Energy Storage Impact: The economics of flywheel-based energy storage might be improved by a factor of 3 or more. The increased storage/supply will be necessary to meet expected future complications as alternative energies are introduced to the grid.

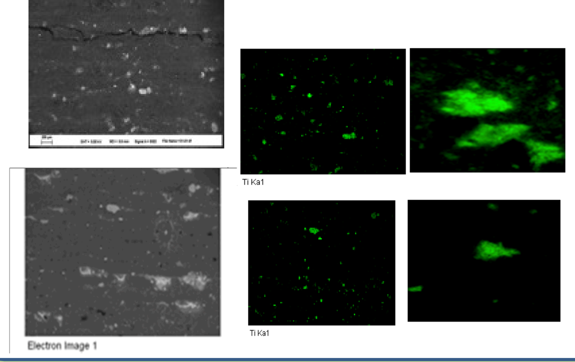


Case Study: 20-MW Beacon Power Facility (NY)

- 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 \$6000/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.

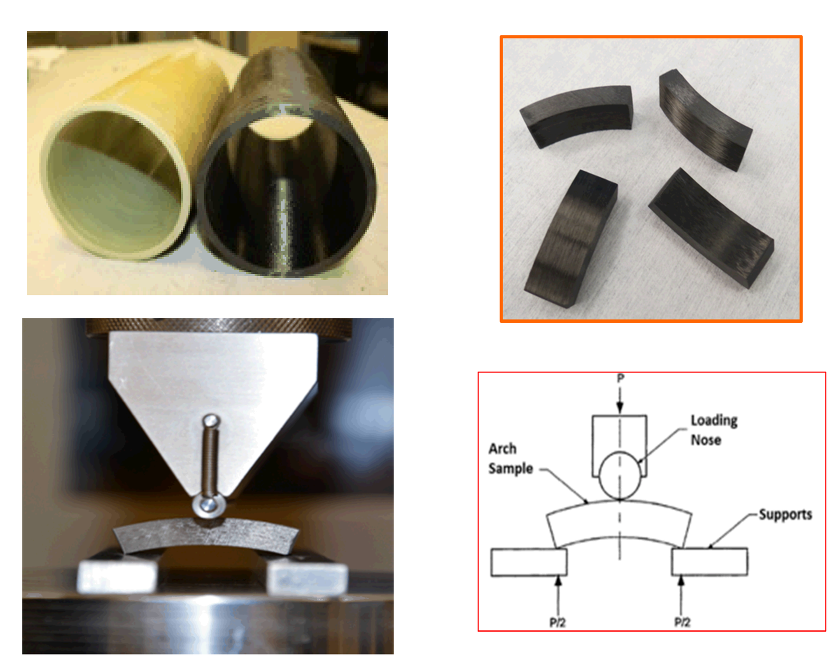




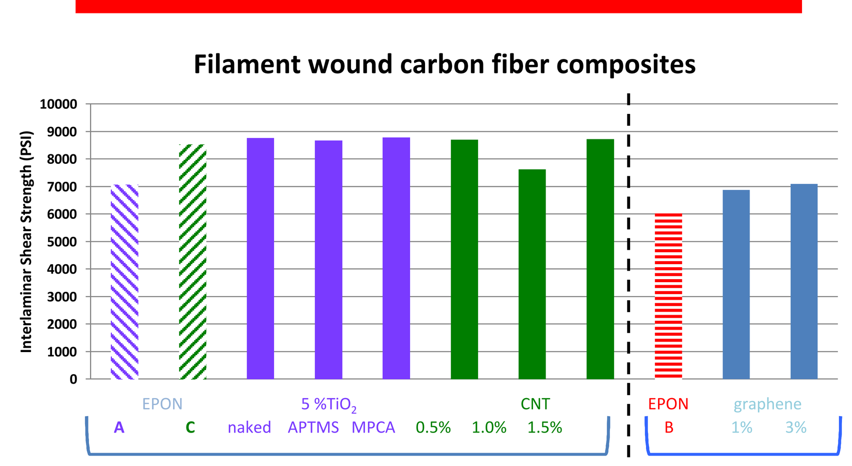


Impact: The nanofillers were found to be clustered. So efforts focused on developing a distributed nanocomposite.

3-point bend test results of modified resin test coupons

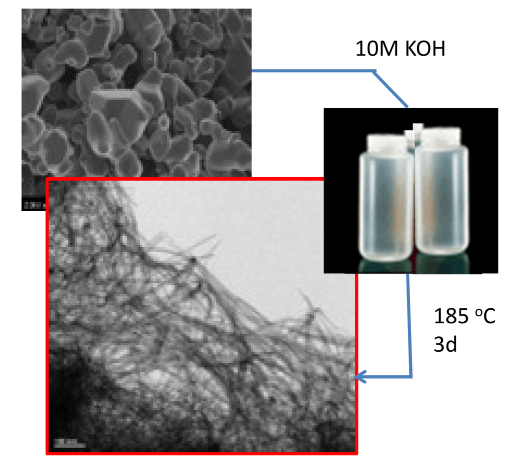


All flywheels have similar issues – the 'need for speed' - kills!

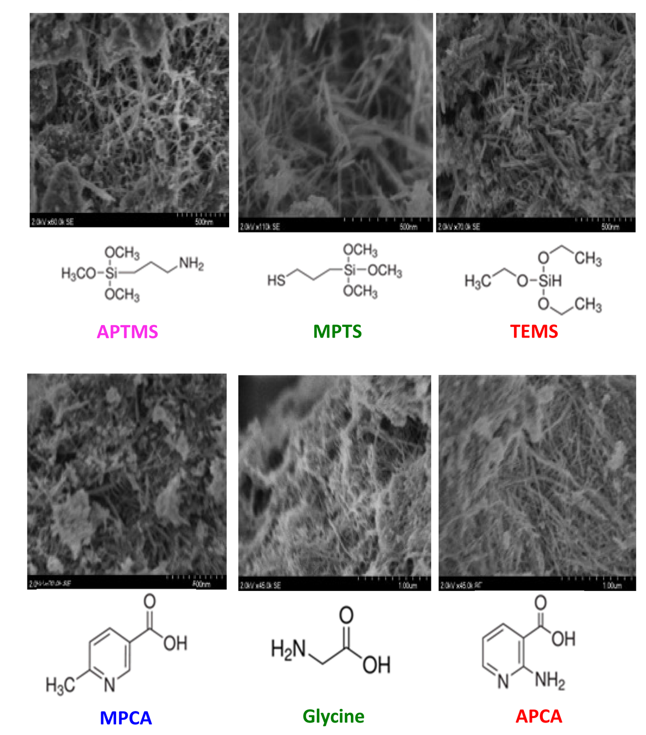


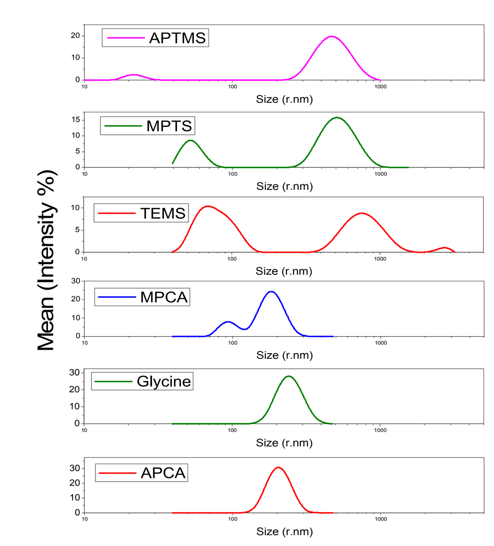
Functionalized Titania Nanowires

Large scale (500 g) of TiO_2 nanowires were synthesized by the hybride (HYBR) route.

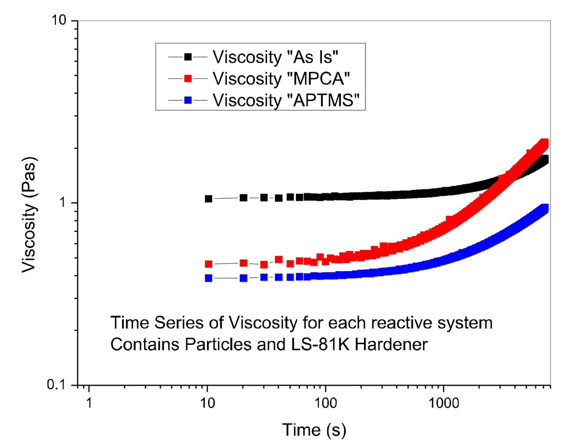


A set of silane and carboxylate surfactants were selected. The TiO_2 NW were heated in a toluene/surfactant mixture. The final materials were isolated as wires. Functionality was confirmed by FTIR.





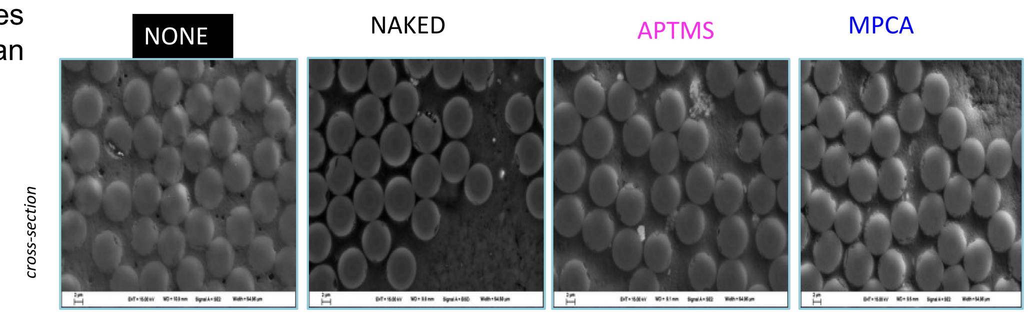
Dynamic light scattering data showed the APTMS and MPCA had the best dispersion in the epoxy for the silane and carboxylate derivatives, respectively. There samples also had viscosities that were lower than the 'naked' (unfunctionalized) TiO_2 NW.



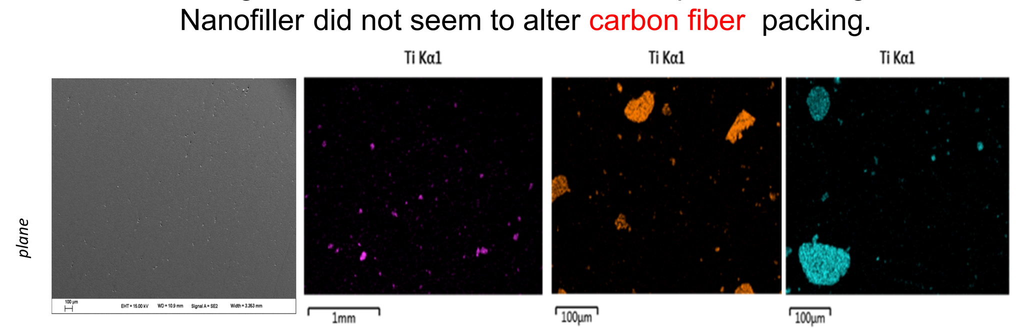
Part Manufacture:
- Single Tow, near hoop wound

Part Dimensions:
- 04.0 I.D. X .25" thick (04.5 O.D.) X 10" long
- Target 60% Fiber Mass Fraction
- Tubes produced with 5 $\%TiO_2$

Test sample tubes were manufactured at Carelton, Inc. with no reported issues or changes required in the processing using the nanofiller filled Epon resin. Once shipped, they were sectioned and analyzed.



SEM images of cross section shows voids present throughout. Nanofiller did not seem to alter carbon fiber packing.

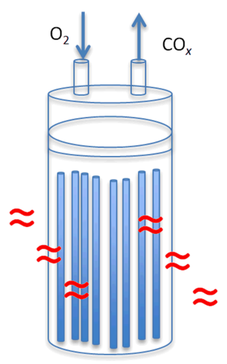


SEM false color imaging clearly shows TiO_2 clustering.

C-fiber resin interaction is the weak link, so C-fiber functionalization was studied

<u>Acid oxidation</u>
the C-fiber is treated with different concentrations of nitric acid to alter the surface features. The growth of ZnO was monitored by SEM.

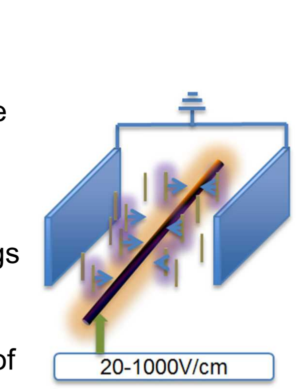
<u>Thermal oxidation</u>
reactive chemistry to induce C=O, O-C=O, C-O functionalities on the surface, that could be used for further grafting or better adhesion with the polar matrix.

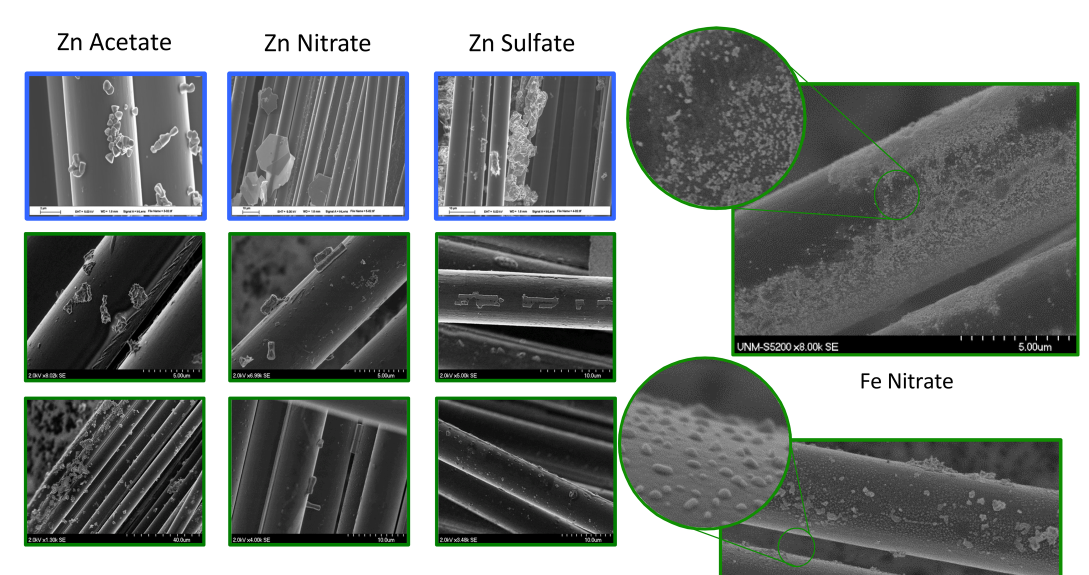


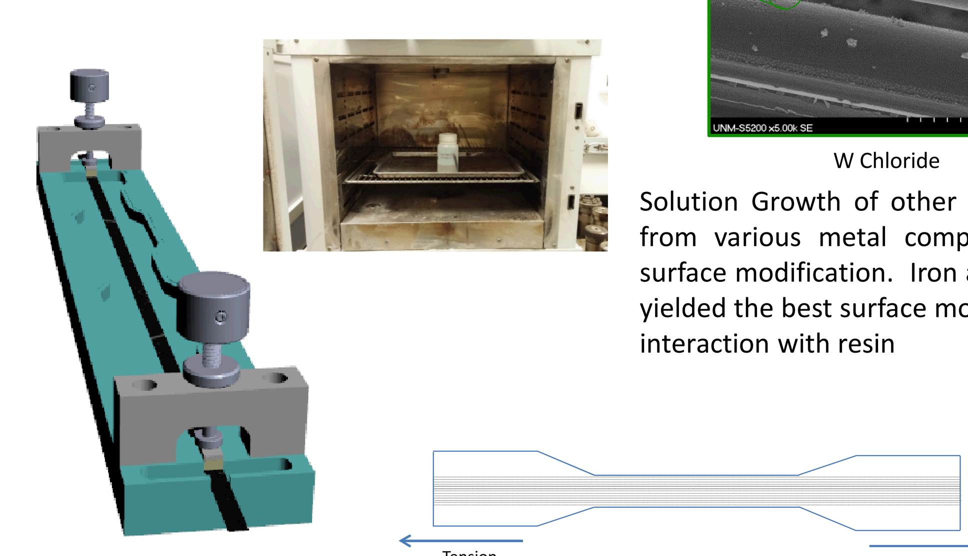
<u>Solution Growth</u>

Solution growth of ZnO from from different Zn^{2+} complexes on carbon fibers (at 70 ºC), led to surface modification.

<u>Electrophoretic Deposition</u>:
Under applied DC voltage, oppositely charged particles are attracted to the C fiber and deposited.
- Scalable, conformal process leading to nanoporous coatings of nanorod materials.
- Process is dependant on surface charge development of TiO_2 nanomaterials.





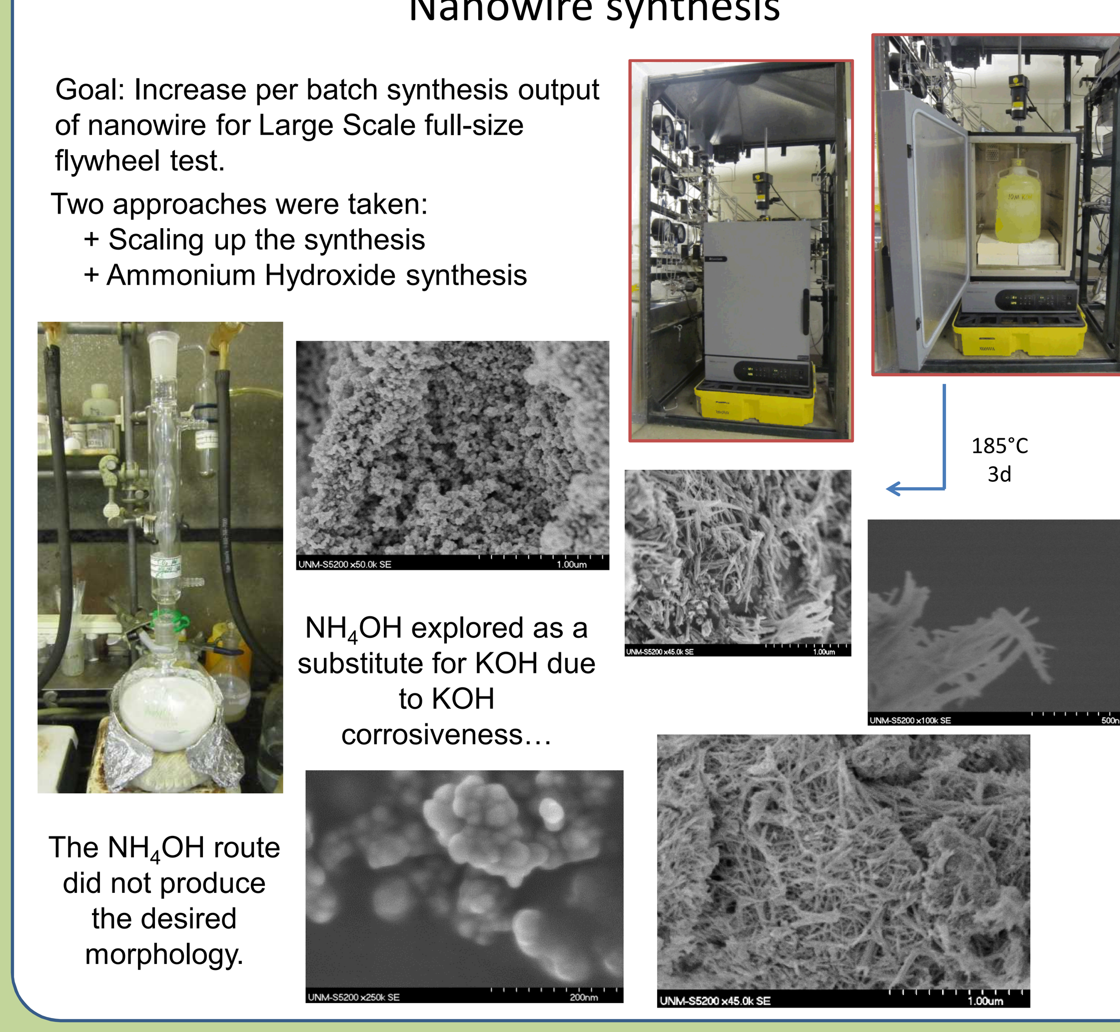


Solution Growth of other metal oxides from various metal complexes led to surface modification. Iron and Tungsten yielded the best surface modification for interaction with resin

Nanowire synthesis

Goal: Increase per batch synthesis output of nanowire for Large Scale full-size flywheel test.

Two approaches were taken:
+ Scaling up the synthesis
+ Ammonium Hydroxide synthesis



NH_4OH explored as a substitute for KOH due to KOH corrosiveness…

The NH_4OH route did not produce the desired morphology.

Summary/Conclusion

Ceramics
+ Synthesized large quantity of TiO_2 nanowires (2000 g)
+ Determined distribution in resin system for various functionalized TiO_2 NW.
+ Selected optimized distributions to minimize viscosity impact
  [naked < carboxylate < silane]
+ Functionalized Carbon Fiber synthesized and characterized via SEM
+ Dogbone cast developed for C-Fiber Resin interaction testing

<u>**Overall**</u>
- Large scale samples successfully prepared, shipped, and successfully wound by Carelton/Cobham (ceramic)
- Characterization of sample parts undertaken.
  + SEM revealed that the functionalized;
    (a) TiO_2 resin dispersion results did *not* translate to comm. processed parts!
  + 3-Point Bend test revealed:
    - 5% TiO_2 nanoceramic materials **None < naked~silane~carboxylate (+ 20-25 %)**