Multifunctional Polymers and Composites for Aerospace Applications

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Typical System Needs and Challenges in Aeronautics and Space

- **System Challenges in Aeronautics**
  - Efficiency (power, cost)
  - Mass, noise, emissions reduction

- **Needs**
  - Lightweight composites with higher strength and stiffness
  - High-temperature, toughened composites
  - Thermal management
  - Multi-functionality
    - Morphing structures
    - Electrically conductive composites

- **System Challenges in Space**
  - Efficiency (mass and volume reduction)
  - Degradation in harsh space environments

- **Needs**
  - Lightweight materials and structures
  - Materials and structures that can perform reliably in extreme environments
  - Multi-functionality
    - Radiation protection
    - Impact resistance
    - Smart materials
Novel Electrical Insulation
Polymeric Materials for High Power Density Electric Motors

• **Benefits:**
  - Fuel Savings
  - Noise Reduction
  - Carbon and NOx Reduction

• **System challenges**
  - Higher operating voltages, temperatures, and frequencies
  - Pre-mature electrical insulation failure due to excessive heating and corona discharge

• **Electrical Insulation Development**
  - **System need:** Better thermal management for MW class, high power density (>13 kW/kg) electric machines
  - Thermally conductive electrical insulation necessary to optimize engine performance in hybrid electric motors
  - Thermal conductivity of most electrical insulators: ~0.1 – 0.2 W/mK
  - Goal: ~1 W/mK thermal conductivity
Thermally Conductive Electrical Insulation

- Thermally Conductive, Electrical Insulation Needed
  - Copper wire
  - Slot liner
  - Potting material

- Incorporate conductive fillers to increase thermal conductivity of polymer insulation

- Adding dissimilar materials typically negatively impact insulation performance
  - Lower dielectric strength
  - Higher chances of charge build up
  - Decreased flexibility
  - More interfacial polarization
    - Grains and grain boundaries

Breakdown voltage decreased by as much as 61% after large volume of additives were mixed with polymer
Thermally Conductive Electrical Insulation

PPSU-BN composite ribbon extrusion

High-bend radius

Effect of BN loading on thermal conductivity

Effect of BN loading on dielectric strength

Composite insulation showed 5x’s increase in thermal conductivity and 16% improvement in dielectric strength relative to the neat polymer.
Characterizing High Voltage Electrical Insulation Candidates

• **Dielectric Analysis (DEA):** Correlates chemical structure with end-use performance
  – Thermal analysis tool traditionally used in manufacturing to optimize curing profiles and reduce scrap
  – Provides temperature- and frequency-dependent information about dipole orientation, molecular relaxations, magnitude of conductivity, and magnitude of energy loss

• Electrical properties + molecular activity ➔ Understand how insulation candidates respond in electrical field to help design insulation materials suitable for the anticipated environment

**Information pertinent to insulation:**

• Frequency and temperature-dependent changes
• Changes in electrical properties due to environmental exposure (thermal breakdown, defects, moisture)
• $\varepsilon'$ (relative permittivity)
• $\varepsilon''$ (dielectric loss or loss factor)
• $\tan \delta$
• Ionic conductivity
• $\varepsilon^*$ (complex permittivity)

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**Graphs and Equations:**

- Graph showing the change in loss factor with time for polyimide.
- Equation for capacitance: $C = \frac{I_{\text{measured}}}{V_{\text{applied}}} \sin \theta \frac{2\pi f}{V_{\text{applied}}}$
- Equation for conductance: $\frac{1}{R} = \frac{I_{\text{measured}}}{V_{\text{applied}}} \cos \theta$

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Williams, T. (2019) Application of Dielectric Thermal Analysis to Screen Electrical Insulation Candidates, Manuscript in Preparation
DEA: Effects of filler on dielectric properties

Addition of hBN nanosheets to PI appeared to keep ionic conductivity stable over a broad temperature range at the anticipated operating frequency.

* hBN: Hexagonal boron nitride nanosheets

Synthesized polyimide with BNNS
Textiles and Nano-reinforcement
Structural Nanocomposites: Lightweight Structures

- PMCs have potential to significantly reduce mass of aerospace structures
- **Objective:** Determine if nanocomposites are a viable alternative to CFRP for composite overwrap pressure vessels (COPVs)
- Challenges with nanocomposites:
  - Synthesis
  - Processing \(\rightarrow\) properties
- **Goals:**
  - Develop carbon nanotube (CNT) reinforced composites with 1.5 to 2x’s specific strength of conventional carbon fiber composites
  - Improve strength of bulk CNT reinforcement through processing and post-processing methods
  - Validate materials by design, fabrication, ground and flight testing of nanocomposite overwrap pressure vessel

**Flight-test preparation:**
Nanocomposite overwrap scale-up and burst-testing

*Williams, T., et al, ACS Appl. Mater. Interfaces 2016, 8, 9327-9334*
NanoCOPV Manufacturing: CNT Overwrap Development via Prepreg Filament Winding

**SUCCESSES**
- Developed **scalable** processes to impregnate, filament wind, and cure CNT composites
- Over 2 km of prepreg processed and filament wound during materials development stage
- After 2017 flight test, nano-COPV effort led to Phase III SBIR with Nanocomp to further improve CNT yarn and tape to reduce mass in aerospace structures

![CNT Yarn Prepregger](image)

- Autoclave-cured CNT overwrap
- Rings of CNT prepreg on mandrel
- Four axis CNC controlled Filament Winder
- Spool of CNT yarn prepreg
Tailorable Textiles: Hybrid Reinforcement with Increased Toughness

PMCs are limited in their ability to provide adequate toughness for some aerospace applications

- Resin modifiers and additives
- Nanostructures grown on reinforcement
- Ply Stitching

Challenges

- Toughened resins: $$\text{viscous}$$ and $$\text{viscous}$$
- Lack of controlled nanoparticle synthesis methods
- Ply stitching damages carbon fibers

Goal

High strength carbon fibers + ductile CNT yarns \(\rightarrow\) Toughened hybrid reinforcement

Tensile Tow Failure

Brittle failure observed in tows that did not contain CNT yarns

Fiber Tow Properties

Carbon Fiber/ Epoxy Control

CNT Yarn – Carbon Fiber/Epoxy Hybrid

Strategic placement of more ductile fibers in reinforcement could minimize areas of high axial strains

2D Circular Braider

Carbon fiber – CNT Yarn Hybrid Triaxial Braided Tube
Tailorable Textiles: Durable Electrically Conductive Textiles (E-textiles)

- **Potential applications for e-textiles in aerospace**
  - Spacesuits
  - Sensors
  - Inflatables
  - Blankets
  - Health monitors

- **Common production methods**
  - Screen printing with conductive polymers
  - Embroidery and stitching
    - Stainless steel fibers (breaks easily)
    - Metallic coating on non-conductive fibers (fuzziness and fraying)
  - Fabrics

- **Challenges with e-textiles and wires**
  - Flexibility
  - Durability
  - Reliability
  - Manufacturing challenges
  - Reparability

**Approach:** Use CNT yarns to develop lightweight, flexible, and durable e-textiles
Tailorable Textiles: Shear Thickening Fluid (STF)—Enhanced Fabrics for Impact Energy Dissipation

**Goal:** Develop lightweight, flexible, impact-resistant textiles for inflatable habitat shells to provide protection against micro-meteoroid orbital debris → fewer redundant layers → mass reduction

- STFs are dilatant, colloidal suspensions that behave like a solid above a critical shear rate
- Hydrodynamic interactions between nanoparticles lead to stiffness increase
- STF-treated fabrics have been used as effective, puncture-resistant textiles for flexible body armor (*Army Research Lab/Univ. of Delaware*)
- Can STFs provide protection against micro-meteor impacts in space?
- MMOD hypervelocity impacts > 1 km/sec

Cubic nanoparticles create stronger hydrodynamic interactions than spherical nanoparticles

*Cwalina, C. et al, Soft Matter 2016, 12, 4654-4665*
Summary

• Polymers play an important role in multifunctional materials development → many projects are ongoing

• Mature polymer and composites processing and characterization methods are still viable to develop multi-functional materials
  – Extrusion
  – Filament winding/ prepreg development
  – Braiding
  – DEA

• Preliminary findings show that 1 – 2 W/mK thermal conductivity was achieved in extruded composite insulation. Dielectric strength was not negatively impacted with BN addition.

• Interfaces (or pre-existing defects) between fillers and host polymer must be improved to reduce electrical treeing or cracking and improve breakdown voltage
  – Processing technique
  – Filler size, geometry

• Multi-functional characteristics integrated through textiles offer advantages of tailorability and mass savings
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