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

Min, J., Williams, T. et al, AIAA 2016-1501
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

**Effect of BN loading on thermal conductivity**

- PPSU-BN composite ribbon extrusion
- High-bend radius

**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.

- Electrical treeing in composite insulation at breakdown site.

PPSU- polyphenylsulfone
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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![Diagram](image-url)
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*
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 → 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

**Split D-ring Mechanical Testing**

**COPV tank with nanocomposite overwrap**

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
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: $$$$ and viscous
- Lack of controlled nanoparticle synthesis methods
- Ply stitching damages carbon fibers

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

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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