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

Multi-functional structure with energy storage capability

Shape Changing SMA - PMC Fan Blade
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

- PPSU- polyphenylsulfone

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

Arcing event at dielectric failure

PPSU-BN composite ribbon extrusion
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)
• ε’ (relative permittivity)
• ε” (dielectric loss or loss factor)
• tan δ
• Ionic conductivity
• ε* (complex permittivity)

Williams, T. (2019) Application of Dielectric Thermal Analysis to Screen Electrical Insulation Candidates, Manuscript in Preparation
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 → Toughened hybrid reinforcement

Tensile Tow Failure
Carbon Fiber/ Epoxy Control
CNT Yarn – Carbon Fiber/Epoxy Hybrid
Brittle failure observed in tows that did not contain CNT yarns

Fiber Tow Properties

2D Circular Braider
28” long
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

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

Approach: Use CNT yarns to develop lightweight, flexible, and durable e-textiles

- 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

IR thermal image of preliminary heating pad construction: Heat distribution dependency on CNT stitch spacing
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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