Materials Research Driven by Key Aerospace Challenges

Higher temperature and harsh environment for aerospace propulsion and planetary entry

Lightweight requirements for large structures

Low carbon and low emission aircraft

Lightweight and durable mechanical system/mechanisms

Structural health management
Outline

• Nanomaterials

• Smart materials

• Sensor materials

• Multifunctional and hybrid structures/materials

• Additive manufacturing of composite materials

• Material Informatics
Replacing Carbon Fiber with Carbon Nanotube (CNT) in Polymer Composites Offer Significant Weight Reduction

**Graph:**
- **Specific Modulus (GPa/g/cc):**
  - 500
  - 50
  - 5
  - 0.5
- **Specific Strength (GPa/(g/cc)):**
  - 1000
  - 100
  - 10
  - 1

- **Materials:**
  - IM7 Carbon Fiber
  - Aluminum
  - Unmodified CNT Yarn
  - Unmodified CNT Sheet
  - Nanocomp CNT Yarn/Tape
  - Nanocomp CNT Sheets
  - Theoretical SWCNT

- **Legend:**
  - ▲ Theoretical SWCNT
  - ▲ Aluminum
  - □ IM7 Carbon Fiber
  - □ Unmodified CNT Yarn
  - □ Unmodified CNT Sheet
  - □ Nanocomp CNT Yarn/Tape
  - □ Nanocomp CNT Sheets
  - ● Project Goal

- **Continuous carbon fiber reinforced polymer composite**
Benign Purification Method Developed for CNT Sheets

TEM Images of CNT Sheets Before (left) and After (right) Purification

<table>
<thead>
<tr>
<th>Condition</th>
<th>Specific Strength, MPa/(g/cc)</th>
</tr>
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<tbody>
<tr>
<td>As Received</td>
<td>110</td>
</tr>
<tr>
<td>Oxidized</td>
<td>280</td>
</tr>
<tr>
<td>Oxidized and Chelated</td>
<td>320</td>
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E-Beam Irradiation Improves CNT Yarn Properties

![Graph showing the effect of E-Beam Irradiation on the ultimate tensile strength of CNT yarns over time.](image-url)
Engineered Properties of Fiber Reinforced Polymer Composites Through Incorporation of Nanotube and Nanofabric

Polymer nanocomposite for structural and thermal management

Incorporation of nanofabric in composite

Toughening of composites

Normal PMC

Nanotoughened PMC

Glenn Research Center at Lewis Field
Nanoclay Polymer Composite

TEM of Thermoplastic Polyimide/Clay Nanocomposite

60% Reduction in H₂ Permeability

2X Increase in Notched Izod Toughness

Five-fold lower leak rate in propellant storage tank
Application of Nanoclay Composites in Food Packaging Industry

Oxygen sensitive products

Carbon dioxide sensitive products

Source: Nanocor presentation
Carbon Nanotube Reinforced Copper Composite

- **Powder Metallurgy**
  - Ball mill MWCNT and Cu alloy powder
  - Consolidate by Field Assisted Sintering Technology (FAST) or extrusion

- **Vapor Infiltration**
  - Start with highly oriented MWCNT nanoforests
  - CVD or otherwise infiltrate with carbide forming element to form carbide monolayer
  - Infiltrate with copper by CVD or cast with molten copper

5 v/o multiwalled carbon nanotube (MWCNT)/Cu Nanoforest Composite

CNT reinforced Cu holds promise for increasing thermal conductivity of Cu, but significant manufacturing challenges remain
Electrically Conductive CNT Yarns/Fibers Offer Potential for Significant Current Carrying Capability Than Cu

- **Commercial CNT Resistance vs. Copper**
  - Two years ago: 460x
  - Today: 200x
  - 2 years: 20x
  - 5 years: 3-5x
  - Copper

- **Iodine-doped CNT from Rice University (2011)**

- Initial application of CNT in data cables, with future application in power cables with improvement in electrical conductivity

Experimental CNT fibers can carry more current than Cu on a mass basis.
CNT/Glass Fiber Composite

Carbon Multiwall Nanotubes Projecting from a fiber Fracture Surface

CNT/glass fiber composite offers potential for economical fiber with same strength as carbon fiber
Boron Nitride Nanotube (BNNT)

- Excellent mechanical properties, strength and modulus similar to carbon nanotube
- Oxidation resistant
- Consistent electrical properties
- Intrinsically polar – B-N bond – potential piezoelectric applications
- High thermal conductivity, electrical insulator

Offers many potential propulsion and power applications
Thermal Conductivity Enhancement of Polymer Composites with BNNT and BNNS Additions

Polymers with electrical insulation and high thermal conductivity required for
- Packaging materials in high speed electronics
- Electrical machines

Wang et.al. (Nanoexpress, 2012)
Mechanically Strong Aerogel Thermal Insulation

Highly porous solid, 10-40 nm pore size

Aerogel insulation on cryotank

High temperature ceramic aerogel

Polyimide aerogel

...but are extremely fragile and moisture sensitive

NASA developed strong silica aerogel

Sandwich Structure Incorporating Aerogels
Advances in Permanent Magnets

Theoretical \((BH)_{\text{max}}\) for \(\text{Nd}_2\text{Fe}_{14}\text{B}\) is 64 MGOe

\((BH)_{\text{max}} = \) maximum energy product
Promise of Nanocomposite Magnets

Theoretical $(BH)_{\text{max}}$, MGOe

- Sm-Co
- Nd2Fe14B
- SmCo5/Fe65Co35
- Sm2Co17/Fe
- FePt/Fe
- Nd2Fe14B/Fe
- Sm2Fe17N3/Fe
- Sm2Fe17N3/Fe65Co35

Maximum $(BH)_{\text{max}}$ for commercial magnets

Only 2 wt. % Samarium (rare earth element)

Significant manufacturing challenges to achieve theoretical $(BH)_{\text{max}}$ in nanocomposites
Nanotechnology in Consumer Products

www.nanotechproject.org/consumerproducts
Outline

- Nanomaterials
- **Smart materials**
- Sensor materials
- Multifunctional and hybrid structures/materials
- Additive manufacturing of composite materials
- Material Informatics
Piezoelectric Materials

PIEZO MATERIALS ARE ACTUATORS AND SENSORS

In piezoelectric materials, mechanical stress causes crystals to electrically polarize and vice versa. Hit them with electric current and they deform (actuator); deform them and they generate electricity (sensor).
Piezoceramic for Control of Vibration in Gas Turbine Engine Fan Blade

Applicable to vibration control in machining processes enabling precision machining
Aerospace Application of Piezoceramic Materials

Smart helicopter blade for noise and vibration control

James Webb Telescope, electrostrictive ceramic actuator to control the shape of mirrors
Development of High Temperature Piezoceramic Materials for Aerospace Applications

Operating Temperature typically half of curie temperature

New complex ceramic chemistries and fabrication process being developed to increase use temperature of piezoceramic materials
Aerospace Application of High Temperature Piezoceramic Materials

Active combustion control through fuel flow modulation

Ultrasonic drilling on Venus surface

Damage sensing for engine components
Actuation Based on Shape Memory Alloys

A special type of metallic alloy that when deformed at low temperatures is capable of “remembering” and recovering its original shape upon heating.
Shape Memory Alloy Applications

**Space**

- **SMA Bellows**
  - Dynamic sealing
  - Fluid handling
  - Flexibility (structure alignment)

- **SMA Spring Tire**
  - Superelastic technology
  - Lunar rovers
  - Terrestrial tires

- **SMA Docking Coupling**
  - Cryogenic transfer coupling
  - Orbital propellant depots
  - Propellant handling/protection

- **SMA Thermal Switch**
  - Thermal management
  - Clean & spark-free operation
  - Passive or active control

- **SMA Bearings**
  - Corrosion resistant
  - Non-galling properties
  - High yield
Shape Memory Alloy Applications

**Aero**

**Adaptive Fan Blade**
- Embedded SMA actuators
- Aerodynamic efficiency
- Specific fuel consumption reduction

**Variable Geometry Chevron**
- SMA actuators morph the chevron
- Noise reduction at takeoff
- Shock cell noise reduction at cruise

**Variable Area Nozzle**
- High bypass turbofan
- SMA torque tubes provide flap rotation
- Engine noise reduction

**SMA Cellular Structures**
- Airframe and engine components
- Morphing airfoils
- Light weight trusses

**Smart Fastening Systems**
- Latches
- Oxygen masks
- Seat configurations
Shape Memory Alloy Applications
Non-Aerospace Potential

Oil and Gas Industry
- SmartRAM™ actuators (LMP)
- SMA couplings (Aerofit Inc)
- Deep-water valves/shut off valves
- Self-torquing fasteners

Medical Industry
- Surgical tools
- Stents and implants
- Glasses frames

Automotive Industry
- Louvers
- Quiet actuators
- Door handle

Other Applications
- Home appliances
- Electronics
- Transportation
- Air conditioners
Development of High Temperature Shape Memory Alloys

High temperature shape memory alloys will enable new aerospace and automotive applications.
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High Temperature Thin Film Ceramic Sensors

SiC Pressure Sensor

Cr-doped GdAlO$_3$ Coating for Temperature Measurement

Multifunctional TaN-Based Sensors

Ceramic Sheath for 2400°C – Capable Temperature Probe
Chemical Sensors

Oxygen Sensor

SiC Hydrocarbon Sensor

H2 Sensor

Nanocrystalline Tin Oxide NOx and CO Sensor
Carbon Nanotube (CNT)-Based Strain, Damage, and Chemical Sensors

- Capacitance Based Strain Sensor on Teflon (left) and CFRP (right)
- CNT Strain Sensor
- Graphene Strain Sensor
- CNT Gas/Chemical Sensor
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Multifunctional Structures

Cessna smart skin - STAR-C2, which stands for “smoothing, thermal, absorbing, reflective, conductive, cosmetic

Multifunctional structure with energy storage capability

BAE smart skin – sense own health like human skin, thousands of microsensors
Increasing Use of Hybrid Materials

Hybrid Composite Gear

Fiber Reinforced Foam Core (FRF)Structure

Hybrid Disk

C-C Composite/Foam/Titanium tube assembly bonded with CuSil-ABA braze paste
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Trend Toward Non-Metallic Gas Turbine Engine

Extensive use of ceramic matrix composite (CMC) in gas turbine engines

- Combustor liners
- Vanes
- Shrouds
- Blades
- Turbine Frame Flowpath
- Flaps & Seals

Enables high OPR with 200 - 700°F temperature advantage over metals, weight = 1/3 of metals

Extensive use of polymer matrix composite (PMC) in gas turbine engines cold section with increase in PMC temperature capability

- Increasingly non-metallic gas turbine engine
- Economical composite manufacturing process will be required
- Additive manufacturing potential solution
Additive Manufacturing of Polymer Matrix Composites

Melts polymer filament and deposits it layer-by-layer following CAD files

Fabrication of high temperature PMC was enable by:
- Chopped-fiber reinforcement
- Moisture reduction in FDM filament
- Versatile printing pattern design

Benefits:
- Quick turn around time for complex parts
- Shorter component production and testing cycle
- Reduced cost of low production volume components
Additive Manufacturing of Polymer Matrix Composite Components

- Ultem 1000 ($T_g = 423^\circ F$) with chopped carbon fiber
- First Polyetherimide composite fabricated

400$^\circ$F operating temperature
Additive Manufacturing of Ceramic Matrix Composite (CMC)

Binder jet printing allows for powder bed processing with tailored binders and chopped fiber reinforcements for fabricating advanced ceramics.
Additive Manufacturing of Ceramic Matrix Composites

- SiC/SiC CMC components with 20% chopped fiber
- First stage nozzle segments
- High pressure turbine nozzle segments
- Cooled doublet nozzle sections
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• **Material Informatics**
Material Informatics – Data Driven Materials Science

Data + Correlations + Theory = Knowledge Discovery

- Combinatorial experimentation
- Digital libraries & data bases

- Data mining
- Dimensionality reduction

- Atomistic based calculations
- Continuum based theories

- Materials discovery
- Structure-property-processing relationships
- Hidden data trends
Concluding Thoughts

Future will be integration of

- Computational material design and big data analytics
- Nanomaterials as building blocks
- Sensors and actuators for adaptability and self healing
- Additive manufacturing
- Multifunctionality

...to create materials with engineered and tailored properties...