Advanced Ceramic Materials for Future Aerospace Applications

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Presented at 39th International Conference and Exposition on Advanced Ceramics and Composites, Jan 25 – 30, Daytona Beach, Florida
Widespread Use of Ceramics in Multiple Aerospace Systems
Ceramic Materials in Gas Turbine Engines

CMC Combustor
Ni-base disk
Thermal Barrier Coatings

CMC Turbine Blade

CMC Turbine Vane
Thermal Barrier Coatings

Future challenges:
• Increased temperature capability
• Low thermal conductivity
• Erosion resistance
• Resistance to molten sand/glass deposit
CMCs for Gas Turbine Engine Hot Section

Environmental Barrier Coatings Required for CMCs

SiC/SiC CMC preferred

EBC
Bondcoat
CMC

BSAS
Mullite + BSAS

AS-800 Si$_3$N$_4$

Ox-Ox CMC

SOA SiC/SiC CMC

Under Development

~Best Superalloy

Rupture Strength $S_x$, MPa

Stress-Rupture Temperature, °C
Challenges for Increasing Temperature Capability of SiC/SiC CMCs for Gas Turbine Engines

2400°F Today 2700°F + Future

Advanced SiC Fiber

Durable Environmental Barrier Coatings with 2700°F+ Capability

Dense, Si-free Matrix

- Three-layer coating
  - Hf-RE oxide with dopant variation (Directed EB-PVD)
  - HfO₂-Si bond coat (Directed EB-PVD)

Graph showing recession rate in mg/cm²-hr:
- BSAS
- HPBR 1350°C (2462°F), 6 atm, 30 m/s
- Yb silicate
- HfResilicate
Increasing Use of CMCs in Aircraft

Boeing – CMC Exhaust Nozzle

NASA Environmentally Responsible Aviation Project – CMC Nozzle Demonstration

GE Passport Engine Exhaust Nozzle
Ceramic Matrix Composites for Hypersonic Vehicles

3000 F + temperature capability required

Benefit: Reduced weight

Ceramic Matrix Composites

Hypersonic Control Surfaces

Leading Edges

Exhaust-Washed Structure

Reentry TPS

Leading Edges

Acreage TPS

Actively Cooled CMC Combustor

Control Surfaces
Cooled Ceramic Matrix Composite Structures in Hypersonic and Rocket Propulsion
High Temperature Materials for Planetary Entry, Descent, and landing (EDL)

Thermal Barrier Seals

Woven SiC Fiber

Outer Fabric

Aerogel Insulation

Gas Barrier

High Temperature Ceramic Aerogel
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
Ion and Hall Thrusters for In-Space Propulsion

- Provides higher exhaust velocity than chemical rockets – reduces propellant mass and reduction in launch mass

Life Limiting Mechanisms:
- Ion sputter erosion of electrodes and ceramics
- Erosion and depletion of cathode materials

Material Needs:
- High temperature sputter resistant electrodes and ceramics
- Long-life, low work function cathode (LaB$_6$ – ZrB$_2$ eutectic promising)
Superconducting Ceramics in Electric Propulsion

Variable Specific Impulse Magnetoplasma Rocket (VASIMR)

Superconducting magnet for VASIMR

MgB$_2$ round wire
- Small diameter to reduce ac loss

MgB$_2$ round wire
BSocco or YBCO tape

STATOR COILS
(MUST BE NON-PLANAR TO CLEAR ROTOR)

ROTOR COILS
(CAN BE PLANAR)

Turboelectric Propulsion for Aircraft

High Power Density Superconducting Motor

Glenn Research Center at Lewis Field
Mars Oxygen ISRU Experiment (MOXIE)

- Extract oxygen from the horrible Martian atmosphere by breaking down carbon dioxide.
- Enable a manned Mars mission to have oxygen ready and waiting when they arrived by sending remote oxygen generators to the surface ahead of time.
Glass Windows in Space Systems

- Rendezvous / Docking Windows (2) Silica/Silica/Acrylic
- Side Windows (2) Silica/Silica/Acrylic
- Hatch Window Silica/Silica/Silica
- Docking Hatch Window Silica/Silica/Acrylic
- Hatch Window Silica/Silica/Acrylic

Crew Vehicles

Ascent vehicles

Habitats

Rovers

Laboratories

Visors

ISS
Advanced Window Glass Materials for Space Systems

Damage of Glass Windows due to Micrometeoroid Impact

Damaged Space Shuttle window

Damaged ISS window

Damage of Glass Windows due to Micrometeoroid Impact

![STS-84 Atlantis](Image)

![Damaged Space Shuttle window](Image)

![Damaged ISS window](Image)

![Graph showing window life and mass](Image)
Application of Piezoceramic Materials

**AIRFRAME**
Piezoresistive Devices
- Embedded pressure sensors
- Embedded strain sensors

Piezoelectric Devices
- Energy harvesting
- Cabin noise suppression
- Active flow control
- Variable control surfaces

**ENGINES**
Piezoelectric Devices
- Energy harvesting
- Power amplification
- Vibration suppression
- Noise suppression

Challenges:
- High temperature capability (>> 300°C)
- Large displacement
- Integration with structure and durability of integrated structure
- Multifunctionality
Piezoceramic Patches for Controlling Vibration of PMC Fan Blades

**GE Blade Vibration Control**

- **No Control**
- **Control**

**Blade Response (microstrain/excitation G)**

**Excitation Frequency (Hz)**

- 168
- 170
- 172
- 174
- 176
- 178
- 180
- 182
- 184

**Fan Blade with Piezo patches**

**Fan Blade with Piezo Patch in Test Rig**
Demonstration of Smart Rotor for Helicopters Using Piezoceramic Materials

- Smart rotor incorporates cutting edge changes to MD900 baseline rotor
  - Trailing edge control flap
  - Piezo-electric “smart” material actuators
- Effectiveness of flap for noise and vibration control demonstrated
- Closed-loop feedback control applied for first time to full-scale active rotor
- Initial demonstration of blade displacement technique
Power Conversion and Energy Storage System

Hybrid Electric Aircraft

Long-Duration EVA

Landers, Rovers, Habitats

High Energy Density Batteries

- Need 2 – 4X increase in energy density of batteries
- Need > 5X increase in power density of fuel cell for electric aircraft

High Power Density Solid Oxide Fuel Cell

- All oxide ceramic components
- Multifunctional systems with structural load bearing capability

Ceramic electrolyte for solid state batteries

Ceramic cathode

SiC Power Electronics for High Power Density and Radiation Tolerant Power Processing System
Ceramics in Satellite Communication

- Ceramic dielectric materials with engineered properties for microwave, millimeter wave communication system
- Dielectric ceramics as resonators, filters, oscillators
- Miniaturization continuing trend

Piezoceramic materials”
- Change in shape of reflector to improve signal quality
- Vibration control
- Positioning control
Use of Ceramics in Space Telescope Mirror

Future requirements: Lower cost and increase in aerial density
Concluding Remarks

- Will see increasing use of CMCs in aircraft – challenge to increase temperature capability to > 2700°F; cost reduction required
- Goal of Durable 3000°F CMC system for hypersonics and rocket propulsion still remains a major challenge
- Increasing use of piezoceramic and dielectric type of materials
  - Multifunctional structures will be future
  - Integration with components without adversely impacting component performance is challenging
  - Miniaturization will be the trend
- For high power density and high energy density systems, engineered porous materials through advanced manufacturing processes will be required
  - Additive manufacturing likely to play a role
  - Increasing use of nanomaterials
- Significant potential for improving ceramic materials for in-space propulsion