Overview of CMC (Ceramic Matrix Composite) Research at the NASA Glenn Research Center

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John H. Glenn Research Center (GRC) at Lewis Field is one of nine National Aeronautics and Space Administration (NASA) Centers

Originally: NACA (National Advisory Committee on Aeronautics) Engine Research Laboratory (Refr. 1)
NASA Glenn Core Competencies

- **Air-Breathing Propulsion**
- **In-Space Propulsion and Cryogenic Fluids Management**
- **Physical Sciences and Biomedical Technologies in Space**
- **Communications Technology and Development**
- **Power, Energy Storage and Conversion**
- **Materials and Structures for Extreme Environments**
Overview

• SiC/SiC CMCs and EBCs (environmental barrier coatings)
• Background information / Applications
• Current and Future NASA GRC CMC/EBC Research

Acknowledgment
The GRC CMC R&D described in this presentation was performed or is being performed primarily by Materials and Structures researchers and technologists.
SiC/SiC CMCs: Applications and Need for Coatings

- SiC/SiC (SiC fiber reinforced SiC matrix) CMCs are being developed for / utilized in aircraft gas turbine engine hot section component applications ($T \geq 2200^\circ F (1204^\circ C)$) (Refr. 2, 3).

- These CMC components will have an environmental barrier coating (EBC), which is a protective, multilayer oxide surface coating to prevent environmental degradation.
SiC/SiC Components for Gas Turbine Engines: Benefits

• Reduced component weight (1/3 density of superalloys)
• Higher temperature capability/increased thermal margin
• Reduced cooling requirements
• Improved fuel efficiency
• Reduced emissions (NO$_x$ and CO)

Refr. 2, 4
NASA Glenn—
Fiber / CMC / EBC R&D, Leadership, and Teaming
• We have been leaders in the assessment and development of SiC fibers, SiC/SiC CMCs, and EBCs for application in advanced, efficient gas turbine engines for decades.
• We have collaborated with Industry, Academia, and DOD (Department of Defense) Labs for over 25 years.
Early 1990s: The NASA Enabling Propulsion Materials (EPM) Program allowed NASA to work closely with Industry to tackle a broad range of CMC technologies (including EBCs) required to reduce NO$_x$ emissions and airport noise through advancements in enabling materials (Refr. 5, 6).
CVI and MI SiC/SiC CMC Manufacturing Processes

SiC Fiber

Weave into 2D Fabric or 3D Preform

Stacked 2D Fabric or 3D Preform

Place in Tooling

CVD Interphase (Fiber Coating) Deposition [BN]

Dense Slurry Cast Melt Infiltrated (MI) SiC/SiC

Silicon Melt Infiltration

Reactor

CVI SiC Matrix Deposition

CVI* SiC/SiC

no free silicon in matrix

Weave into 2D Fabric or 3D Preform

Slurry Cast SiC Particles Into Porous “Preform”

CVI Preform

* CVI—Chemical Vapor Infiltration

(Refr. 5)
Example of the Microstructure of a 2D SiC/SiC CMC*

As-Fabricated Slurry Cast Melt Infiltrated (MI) SiC/SiC Material
Polished Section—Examined With FESEM

90° SiC Fiber Tow

0° SiC Fiber Tow

MI SiC Matrix

* Fabricated by GE Power Systems Composites

Q-126 6.0kV 11.9mm x250 SE(L) 7/6/2015

200µm
Example of the Microstructure of a 2D SiC/SiC CMC*

As-Fabricated Slurry Cast Melt Infiltrated (MI) SiC/SiC Material
Polished Section—Examined With FESEM

- MI SiC Matrix
- CVI SiC Surrounding BN Interphase
- BN Fiber Coating
- Si
- SiC
- Sylramic™ SiC Fibers

* Fabricated by GE Power Systems Composites

Q-126 6.0kV 11.9mm x1.50k SE(L) 7/6/2015
NASA Glenn—SiC/SiC and EBC Development

- The NASA Ultra-Efficient Engine Technology (UEET) Program continued the advancement of Melt Infiltrated (MI) SiC/SiC CMC and EBC technology for commercial aircraft engines (Refr. 7 - 10).

- GRC has further developed “High Temperature” SiC/SiC (no free silicon in matrix) and EBCs for use above 2600°F (1427°C) in subsequent NASA Programs/Projects including:
  - Next Generation Launch Technology (NGLT) Project
  - Hypersonics Project
  - Supersonics Project
  - Aeronautical Sciences (AS) Project
  - Environmentally Responsible Aviation (ERA) Project
  - Transformational Tools and Technology (TTT) Project

MI CMC Vane w/EBC: NASA UEET Program
Refr. 7, 8

CVI SiC/SiC Vane Test Articles w/EBC: NASA ERA Project
Refr. 11
SiC/SiC Components for Gas Turbine Engines: Benefits

- Reduced component weight (1/3 density of superalloys)
- Higher temperature capability/increased thermal margin
- Reduced cooling requirements
- Improved fuel efficiency  
  further increase with 2700°F CMC components

- Reduced emissions (NO\(_x\) and CO)

Incentive to Increase Engine Operating Temperatures
Current / Future CMC/EBC System Research at NASA GRC

- 2700°F SiC/SiC Development & Characterization
- Durable, High Temperature (3000°F) EBC
- High Temperature (2700°F Capable) SiC Fiber
- SiC/SiC CMC / EBC Durability Modeling & Validation

Goal:
- Overall, ICME (Integrated Computational Materials Engineering) Culture
- All CMC/EBC Research Involving / Influenced by Modeling
Hybrid (CVI + PIP) SiC/SiC CMC Manufacturing Process

1. Weave SiC Fiber into 2D Fabric or Designed 3D Preform.

2. Place in Reactor or Tooling for CVI Interphase Deposition (Fiber Coating) [BN].

3. CVI SiC Matrix Deposition in Reactor.

4. PIP – Polymer Infiltration and Pyrolysis SiC Matrix in Furnace.

5. Dense Hybrid SiC/SiC For 2700°F Application with no free silicon in matrix.

Refer. 12
High Temperature CMC Testing: Tensile Creep and Fatigue

Testing used to validate models for CMC and CMC / EBC samples

Instron Test Rig
- Testing in Air
- Temperatures up to 2800°F (1538°C)
- Creep and Fatigue
- Frequencies up to 1 Hz
- Electromechanical, 50 kN Load Cell
- MoSi\textsubscript{2} Element Furnace
- 1 in. Gage Length, Water-Cooled Extensometer

Example of Rig Used to Test SiC/SiC CMCs

Typically Test 6 in. Long Tensile Specimens
**Importance of Environmental Barrier Coating (EBC)**

- Reaction with water vapor from combustion environment causes rapid **surface recession** of Si-based ceramics, seriously limiting component life

\[
\text{SiO}_2 (s) + 2\text{H}_2\text{O} (g) = \text{Si(OH)}_4 (g)
\]

- An Environmental Barrier Coating (EBC) provides protection from water vapor and enables long life.
Durable, High Temperature EBC for Use With 2700°F SiC/SiC

**Issue:** - Need for EBC systems with *up to* 3000°F (1650°C) capability that exhibit low thermal conductivity and high temperature durability.  
- EBC design (thickness/composition/etc.) is component dependent.

**Addressed By:** EBC (environmental barrier coating) systems designed with:

- High melting point / oxidation resistant systems capable of up to 3000°F
- Advanced environmental barrier and 2700°F+ capable bond coats
- Controlled surface emittance and radiative properties
- High strength and self-healing capabilities, CMAS-resistant
- Low thermal conductivity 0.5-1.2 W/m-K at 2700-3000°F (1482-1650°C)

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**Multilayer / Multifunctional EBC**

- Multicomponent low conductivity, high stability Rare Earth (RE) doped HfO₂, ZrO₂ and Hf (Zr)-RE silicates
- Strain tolerant oxide-silicate interlayers
- Rare Earth-Silicate and HfO₂-Rare Earth-Alumino-Silicate EBC
- HfO₂-Si or RE-Si based bond coats
- SiC/SiC Composite

Refr. 10
High Temperature (2700°F (1482°C)) SiC Fiber Research

**Issue:** SiC/SiC CMCs that will operate at 2700°F will require strong, creep-resistant SiC fibers.

**Addressed By:**

- Determination of key mechanical/structural properties of potential 2700°F SiC fibers to:
  - Understand basic mechanisms and *correlation* with microstructure
  - Develop analytical fiber and CMC models for time-temperature deformation and rupture behavior
  - Identify current limitations and approaches for property improvement

- **GRC fiber processing:** obtain 2700°F SiC fiber with improved microstructure (reduced porosity, specific SiC grain size, etc.) and optimal properties

Example of Increased Amount of Porosity in SiC Fiber Core

Refr. 12
GRC Modeling of CMC/EBC Behavior/Properties/Durability

• Modeling: We have a broad perspective and work with everyone

**Issue:** Need for a wide range of approaches (different scales) for CMC and CMC/EBC system modeling to provide understanding of behavior / performance; - enabling life prediction and guiding of CMC and EBC durability enhancement.

**Addressed By:**

• Large portfolio of internal codes/software
• **Multiscale modeling**
• Computationally-efficient methods/tools
• Account for environmental effect: Air, vacuum, inert, steam, CMAS
• Creep/fatigue interaction with environment
• Unique/creative non-linear modeling capabilities
• Proposed use of a model SiC/SiC material system and mini-composites in some studies
• **Strong collaboration with industry**

• Validation of models (CMC and CMC/EBC system)
• Understand the effects of the constituents/structure
Summary

• NASA’s efforts have helped move SiC/SiC CMC and EBC technology forward to the point where CMC components are being introduced in commercial jet engines.

• Aircraft gas turbine engines will continue to operate at higher temperatures, and there will be a need for higher-temperature (>2500°F/1371°C) SiC/SiC composites and EBCs.

• A 2700°F capable fiber is an enabling constituent for a durable 2700°F CMC/EBC system.

• Analytical modeling of material behavior is needed to help understand CMC/EBC durability issues, and to provide guidance for material development.
References


2) “Ceramic Matrix Composites Improve Engine Efficiency,”


4) “New material for GE Aviation a play for the future,”


References


Appendix—Back-up Slides
Investigation of CMAS Interactions with EBC Materials

- **CMAS: Calcium magnesium aluminosilicate**

**Issue:** Ingested particulates (e.g., sand) can form CMAS glass deposits on EBCs in the engine hot section, with coating degradation occurring due to reaction and infiltration of the coating.

**Addressed By:**
- Characterization of thermal and mechanical properties of CMAS glass provides fundamental knowledge that will help to mitigate damage and improve EBC durability

- Evaluation of interactions between heat treated EBC substrates with CMAS glass pellets. EBC materials evaluated include:
  - Yttrium disilicate ($Y_2Si_2O_7$)
  - Hafnium silicate ($HfSiO_4$)
  - Ytterbium disilicate ($Yb_2Si_2O_7$)