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 ≥ 2200°F (1204°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\textsubscript{x} emissions and airport noise through advancements in enabling materials (Refr. 5, 6).

Development of MI (Melt Infiltrated) SiC/SiC for Combustor Liner Application

* CVI—Chemical Vapor Infiltration
CVI and MI SiC/SiC CMC Manufacturing Processes

SiC Fiber

Weave into 2D Fabric or 3D Preform

CVI Interphase (Fiber Coating) Deposition [BN]

Place in Tooling

Stacked 2D Fabric or 3D Preform

CVI SiC Matrix Deposition

Reactor

Dense Slurry Cast Melt Infiltrated (MI) SiC/SiC

Furnace

Slurry Cast SiC Particles Into Porous “Preform”

CVI Preform

CVI Preform

no free silicon in matrix

CVI*—Chemical Vapor Infiltration

*CVI*—Chemical Vapor Infiltration
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
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
- Si
- SiC
- BN Fiber Coating
- CVI SiC
- Surrounding BN Interphase
- Sylramic™ SiC Fibers

* Fabricated by GE Power Systems Composites
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
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\textsubscript{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

Refr. 12
Hybrid (CVI + PIP) SiC/SiC CMC Manufacturing Process

- **SiC Fiber**
  - Weave into 2D Fabric or **Designed** 3D Preform
  - CVI Interphase (Fiber Coating) Deposition [BN]
  - Place in Tooling
- **CVI SiC Matrix Deposition**
  - Reactor
- **PIP – Polymer Infiltration and Pyrolysis SiC Matrix**
  - Refr. 12
  - Furnace
  - Dense Hybrid SiC/SiC For 2700°F Application
  - no free silicon in matrix

**Stacked 2D Fabric or 3D Preform**
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
- MoSi₂ 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 HfO$_2$, ZrO$_2$ and Hf (Zr)-RE silicates
- Strain tolerant oxide-silicate interlayers
- Rare Earth-Silicate and HfO$_2$-Rare Earth-Alumino-Silicate EBC
- HfO$_2$-Si or RE-Si based bond coats
- SiC/SiC Composite

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(Caption for diagram: "Multilayer / Multifunctional EBC."
- Multicomponent low conductivity, high stability Rare Earth (RE) doped HfO$_2$, ZrO$_2$ and Hf (Zr)-RE silicates
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- Rare Earth-Silicate and HfO$_2$-Rare Earth-Alumino-Silicate EBC
- HfO$_2$-Si or RE-Si based bond coats
- SiC/SiC Composite)
**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

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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 ($Yb_2Si_2O_7$)

Aircraft Engines Ingesting Sand on Runway

Residual CMAS Glass

Interaction Region

~13 µm thick

$Y_2Si_2O_7$ Substrate (EBC)

$Y_2Si_2O_7$ Substrate Exposed to CMAS at 1200°C for 20h