Thermal barrier coatings are used in gas turbine engines to protect engine hot-section components in the harsh combustion environments and extend component lifetimes. For thermal barrier coatings designed for turbine airfoil applications, further improved erosion and impact resistance are crucial for engine performance and durability. Advanced erosion resistant thermal barrier coatings are being developed, with a current emphasis on the toughness improvements using a combined rare earth- and transition metal-oxide doping approach. The performance of the doped thermal barrier coatings has been evaluated in burner rig and laser heat-flux rig simulated engine erosion and thermal gradient environments. The results have shown that the coating composition optimizations can effectively improve the erosion and impact resistance of the coating systems, while maintaining low thermal conductivity and cyclic durability. The erosion and impact damage mechanisms of the thermal barrier coatings will also be discussed.
The Development of Erosion and Impact Resistant Turbine Airfoil Thermal Barrier Coatings

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Motivation

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**Thermal barrier coating (TBC) system development goals**

- Emphasize high heat-flux cyclic durability
- Improve turbine airfoil thermal barrier coatings up to 3x erosion resistance

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**Temperature Capability**

2850°F (1560°C) combustor TBCs

2500°F (1370°C) Turbine TBCs

3000°F+ (1650°C+)

2700°F (1482°C)

Increase in $\Delta T$ across T/EBC

Ceramic Matrix Composite

Single Crystal Superalloy

2400°F (1260°C)

2000°F (1093°C)

Step increase in temperature capability

Gen I

Gen II – Current commercial

Gen III

Gen IV

Year

3100°F SiC/SiC Turbine CMC coatings

2700°F SiC/SiC CMC and Si$_3$N$_4$ coatings

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Outline

— High-heat-flux erosion test capability
— Low conductivity thermal barrier coating updates
— Advanced erosion resistant low conductivity coating development
— Erosion and impact damage observations
— Summary
High-Heat-Flux Tests Critical to Turbine TBC Development

High-heat-flux laser test approach for thermal barrier coating cyclic durability

- Temperature gradient requirements: up to 200 °C/100 microns
- Heat flux requirements 200-300 W/cm²
- Cooling also an issue in laboratory tests

Current capability up to 315 W/cm²
In-Situ Thermal Conductivity Measurements by a Steady-State Laser High-Heat-Flux Approach

\[ k_{\text{ceramic}}(t) = \frac{q_{\text{thru}} \cdot l_{\text{ceramic}}}{\Delta T_{\text{ceramic}}(t)} \]

\[ q_{\text{thru}} = q_{\text{delivered}} - q_{\text{reflected}} - q_{\text{radiated}} \]

\[ \Delta T_{\text{ceramic}}(t) = T_{\text{ceramic-surface}} - T_{\text{metal-back}} - \int_{0}^{l_{\text{bond}}} \frac{q_{\text{thru}} \cdot dl}{k_{\text{bond}}(T)} - \int_{0}^{l_{\text{substrate}}} \frac{q_{\text{thru}} \cdot dl}{k_{\text{substrate}}(T)} \]

Where

\[ \Delta T_{\text{ceramic}} = \Delta T_{\text{measured}} - \Delta T_{\text{substrate}} - \Delta T_{\text{bond}} \]

8 μm pyrometer for \( T_{\text{ceramic-surface}} \)

8 μm pyrometers for \( T_{\text{substrate-back}} \)

Optional miniature thermocouple for additional heat-flux calibration
Laser High-Heat-Flux Erosion Test Rig

Test cycles of erosion-heat-flux test

- Thermal conductivity, W/m-K
- Temperature, °C
- Time, hours

Erosion jet direction

Erosion jet
Mach 0.3-1.0 High Velocity Burner Erosion Test Rig

High precision particle feeder system
Burner exhaust nozzle
Specimens under testing
Low Conductivity Thermal Barrier Coating Design Requirements

- Low conductivity ("1/2" of the baseline) retained under thermal gradient at 2400°F
- Improved sintering resistance and phase stability (up to 3000°F)
- Excellent durability and mechanical properties
  - Cyclic life
  - Toughness
  - Erosion/impact resistance
  - CMAS and corrosion resistance
  - Compatibility with the substrate/TGO
- Processing capability using existing infrastructure and alternative systems
- Other design considerations
  - Favorable optical properties
  - Potentially suitable for various metal and ceramic components
Low Conductivity Thermal Barrier Coating Design Approaches

- Emphasize ZrO$_2$- or HfO$_2$-based alloy systems – defect cluster approach, for toughness considerations

- Advantages of defect cluster approach
  
  - **Advanced design approach:** design of the defect clustering
  
  - **Better thermal stability:** point defects and clustering are thermodynamically stable
  
  - **Improved sintering resistance:** effective defect concentration reduced and activation energies increased by clustering
  
  - **Easy to fabricate:** plasma-sprayed or EB-PVD processes
Thermal Conductivity of Dense Monolithic Low Conductivity Oxides

— Hot-pressed, fully dense (density ~6.0 g/cm³) low conductivity oxide specimens prepared by Pratt & Whiney
— 15% lower conductivity observed for the specimens with 3mol% higher RE cluster dopants

N1 Composition: ZrO₂-5.5mol%Y₂O₃-2.25mol%Gd₂O₃-2.25mol%Yb₂O₃
N2 Composition: ZrO₂-8.5mol%Y₂O₃-0.75mol%Gd₂O₃-0.75mol%Yb₂O₃

Total dopants 10mol%

Baseline ZrO₂-4.5mol%Y₂O₃
Advanced Low Conductivity Coatings for Combustor Applications

Thermal conductivity, W/m-K

Time, hours

7YSZ: Tsurface 2700°F/Tinterface 2030°F
30 min cyclic after 20 hr steady-state sintering test

Low k 256:Tsurface 2800°F/Tinterface 2030°F
200, 30 min cyclic after 20hr steady-state sintering test
Coated engine components (CFM TAPS, IHPTET, JSF, Propulsion 21 engine flame tubes, combustor liners, adapters and dome plates etc) tested under simulated engine sector rig environments

Low conductivity TBC flame tube and combustor deflector demos in Advanced Subsonic Combustion Rig (ASCR)

Low conductivity TBC combustor liner demonstration in GE Trapped Vortec Combustor rig

Low conductivity TBC Propulsion 21 flame tube and deflector demonstrations
Development of Advanced Defect Cluster Low Conductivity Thermal Barrier Coatings for Turbine Airfoil Applications

- **Multi-component oxide defect clustering approach** (Zhu and Miller, *US Patents No. 6,812,176, No.7,001,859, and 7,186,466; US Patent Application 11/510,574*)

  \[ \text{ZrO}_2\cdot\text{Y}_2\text{O}_3\cdot\text{Nd}_2\text{O}_3(\text{Gd}_2\text{O}_3,\text{Sm}_2\text{O}_3)\cdot\text{Yb}_2\text{O}_3(\text{Sc}_2\text{O}_3) \quad \text{TT(TiO}_2+\text{Ta}_2\text{O}_5) \text{ systems} \]

  \[ \text{Primary stabilizer} \quad \text{Oxide cluster dopants with distinctive ionic sizes} \quad \text{Toughening dopants} \]

- **Defect clustering associated with dopant segregation**

  - Plasma-sprayed \(\text{ZrO}_2\cdot13.5\text{mol}\%(\text{Y, Nd, Yb})\_2\text{O}_3\)
  - EB-PVD \(\text{ZrO}_2\cdot12\text{mol}\%(\text{Y, Nd, Yb})\_2\text{O}_3\)
  - EELS elemental maps of EB-PVD \(\text{ZrO}_2\cdot14\text{mol}\%(\text{Y, Gd, Yb})\_2\text{O}_3\)
Defect Clusters in a Plasma-Sprayed Y$_2$O$_3$, Nd$_2$O$_3$ and Yb$_2$O$_3$ Co-Doped ZrO$_2$-Thermal Barrier Coating

— Yb, Nd rich regions consisting of small clusters with size of 5 to 20 nm

Nd and Yb rich region clusters

Yb and Nd rich region EDS

Overall EDS
The low conductivity turbine airfoil thermal barrier coatings successfully tested under simulated engine thermal gradient cyclic conditions.

**Advanced Low Conductivity Coatings Showed Excellent High Temperature Cyclic Durability**

- T_{surface} = 2480°F (1360°C)
- T_{interface} = 2020°F (1104°C)

6 min heating, 2 min cooling cycles
The cubic-phase ZrO$_2$-based low conductivity TBC durability improved by a thin 8YSZ or low k t$'$-phase interlayer.

The t$'$-phase based low conductivity TBCs had excellent furnace cyclic life.

![Graph showing cycles to failure vs total dopant concentration for different TBC types and with or without interlayer.](graph.png)
Furnace Cyclic Behavior of ZrO$_2$-(Y,Gd,Yb)$_2$O$_3$ TBCs Co-doped with TiO$_2$ and Ta$_2$O$_5$

Effect of temperature on coating cyclic life

- ZrO$_2$-7wt%Y$_2$O$_3$ baseline
- ZrO$_2$-(Y,Gd,Yb,TT)

2125°F (1163°C), 1 hr cycles
2075°F (1135°C), 1 hr cycles
**Furnace Cyclic Behavior of ZrO$_2$-(Y,Gd,Yb)$_2$O$_3$ Co-doped with TiO$_2$ and Ta$_2$O$_5$**

- ZrO$_2$-Y$_2$O$_3$-Gd$_2$O$_3$-Yb$_2$O$_3$ and ZrO$_2$-Y$_2$O$_3$-Gd$_2$O$_3$-Yb$_2$O$_3$-TT coatings designed for improved cyclic and erosion resistance
- Focusing on $t'$ and $t'$-nano clustering (cubic) phase systems
Thermal Conductivity of ZrO\textsubscript{2}-(Y,Gd,Yb)\textsubscript{2}O\textsubscript{3} and ZrO\textsubscript{2}-(Y,Gd,Yb)\textsubscript{2}O\textsubscript{3} + TT(TiO\textsubscript{2}-Ta\textsubscript{2}O\textsubscript{5}) Systems

Thermal conductivity of EB-PVD erosion TBCs
Improved impact/erosion resistance observed for advanced low conductivity six-component coatings.
— Improved erosion resistance demonstrated for advanced low conductivity thermal barrier coatings

![Graph showing erosion resistance](image)
Tetragonality of Multi-Component ZrO₂ being Evaluated and Correlated to Coating Performance

Area detector x-ray diffractometer used for EB-PVD coatings
Toughened structures observed for advanced multi-component coatings

ZrO$_2$-7wt\%Y$_2$O$_3$  Advanced coating
— Surface sintering and impact densification zones observed, with subsequent spallation under the erodent further impacts
— Toughened structures observed

SEM micrographs of advanced thermal barrier coating after impact/erosion damage

Secondary electron image  Backscattered electron image
Multi-level delaminations under combined impact loading and thermal gradients
High Heat Flux Testing for Studying CMAS Effect

— Durability of advanced coatings with CMAS testing
Summary

• High temperature erosion testing developed

• An interlayer coating significantly improved the furnace cyclic life of four-component “cubic” phase low conductivity TBCs

• Six-component with Ta, Ti coating systems improved the coating durability – advanced phase development possible

• Improved erosion/impact resistance observed for the multi-component coating systems

• Other interactions such as CMAS considered for coating composition designs

• Coatings being optimized for cyclic life, thermal conductivity and erosion/impact and CMAS resistance