Ceramic thermal and environmental barrier coatings (TEBCs) will play an increasingly important role in gas turbine engines because of their ability to further raise engine temperatures. However, the issue of coating durability is of major concern under high-heat-flux conditions. In particular, the accelerated coating delamination crack growth under the engine high heat-flux conditions is not well understood. In this paper, a laser heat flux technique is used to investigate the coating delamination crack propagation under realistic temperature-stress gradients and thermal cyclic conditions. The coating delamination mechanisms are investigated under various thermal loading conditions, and are correlated with coating dynamic fatigue, sintering and interfacial adhesion test results. A coating life prediction framework may be realized by examining the crack initiation and propagation driving forces for coating failure under high-heat-flux test conditions.
Failure Mechanisms and Life Prediction of Thermal and Environmental Barrier Coatings under Thermal Gradients

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Objective

— High heat flux testing development
— The coating delamination behavior under thermal gradients
— Finite element analysis of coating delamination driving forces
— Coatings design and life prediction issues
— Summary and Conclusions
High-Heat-Flux Tests Critical to Turbine Component Coating 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 up to 200-300 W/cm²

Current capability up to 315 W/cm²
High-Heat-Flux Tests Critical to Turbine Component Coating Development (continued)

— Atmospheric burner rig heat fluxes characterized using an embedded thermocouple (TC) sensor approach
— Initial heat fluxes 100-200 W/cm² observed
High-Heat-Flux Capability Recently Developed for High Pressure Burner Rig

— Testing pressure up to 12 atm
— Gas velocity up to 400 m/s
— Heat flux up to 200 W/cm²
Generalized Coating Failure Modes for Thermal Barrier Coatings under Thermal Gradients

(a) Low Heat Flux and High Interface Temperature
(b) Medium Heat Flux and Interface Temperature
(c) High Heat Flux and Low Interface Temperature
Generalized Coating Failure Modes for Environmental Barrier Coatings under Thermal Gradients

- Sintering and CTE mismatch induces surface wedge-shape crack propagation
- Surface cracking accelerates coating delamination under mixed mode loading ($K_I$ and $K_{II}$)
- Interfacial pore formation due to the chemical reactions further accelerated coating spallation under thermal gradient conditions

\[
\text{O}_2 + \text{H}_2\text{O(g)}
\]

ZrO$_2$-8wt\%Y$_2$O$_3$
Mullite-BSAS
Si
SiC/SiC CMC
Damage Accumulation of Thermal Barrier Coatings under Laser Heat Flux Testing

— Approximate constant heat flux
— Sintering induced conductivity increase during the steady-state testing
— Sintered coatings tend to have accelerated delamination under subsequent cyclic testing and damage accumulation
High Heat-Flux Sintering Induced Cracking and Delamination in Turbine EB-PVD ZrO$_2$-7wt$\%$Y$_2$O$_3$ Coatings

— High-heat-flux surface sintering cracking and resulting coating delaminations

The Cyclic Life of Thermal Barrier Coatings

Heat Flux 100 W/cm²

- Non conducting crack
- 0.254mm
- 0.127mm
- 3.175 mm

Testing Type

- Interface temperature 2125°F
- FCT
- Laser heat flux
- Burner heat flux

Cycle life, hours

Cycle life, hours vs. Testing Type

K_{effective}, MPa mm$^{1/2}$ vs. Time, sec.

Testing Type

- 4 mm

Non conducting crack
The Cyclic Life of Thermal Barrier Coatings - Continued

Surface high heat flux testing

\[ \ln(\text{Cycle time to failure}) \text{, hours} \]

\[ \frac{1}{T}, \frac{1}{K} \]

- Zr2.5Y0.75Gd0.75Yb (ln)
- Zr2.0Y1.5Gd1.5Yb (ln)
- Zr1.6Y1.2Gd1.2Yb (ln)
- Zr2.5Y0.75Gd0.75Yb (Ln)
- Zr2.0Y1.5Gd1.5Yb (Ln)
- Zr1.6Y1.2Gd1.2Yb (Ln)
- Zr2.5Y0.75Gd0.75Yb (2h) (Ln)
- Zr2.0Y1.5Gd1.5Yb (2h) (Ln)
- Zr1.6Y1.2Gd1.2Yb (2h) (Ln)
- 7YSZ (ln)
- 7YSZ (Ln)
- 7YSZ (2h) (Ln)
- 7YSZ
- 7YSZ Laser heat flux
- 7YSZ burner rig
Thermal Gradient Tested TBC Delamination and Modeled TBC Delamination Induced Conductivity Reduction

Laser tested at $T_{\text{surface}} \approx 1316^\circ \text{C}$ and $T_{\text{interface}} \approx 1100^\circ \text{C}$ under the combined steady state (22 hrs) and 20 min heating/3 min cooling cycles (256 cycles)

FEA modeling of temperature distributions

Thermal conductivity reduction as a function of crack length

Heat Flux, W/cm²
- 95.0
- 85.0
- 45.7

Normalized Crack Length, $(a/\lambda)$

Normalized Thermal Conductivity
- 1.0
- 0.8
- 0.6
- 0.4
- 0.2
- 0.0
Delamination Driving Force Increases with Heat Flux

Effective SIF vs Crack Length

Heat flux, W/cm²
- 95.0
- 85.0
- 45.7

Normalized Crack Length, \( \frac{a}{\lambda} \)

\( K_{\text{eff}}, \text{MPa.m}^{1/2} \)
Crack Propagation Rate Increases with Interface Test Temperature

![Graph showing crack propagation rate with interface test temperature.](image)
Coating Failure Modes under Very High Thermal Gradients
Accelerated Delamination under Vertical Surface Cracks

$\Delta T \approx 500^\circ C$

Temperature, °C

Time, sec

Surface
Interface
Crack Opening Surface

Temperature, °C

1467 °C
1315 °C
1066 °C
Delamination Driving Forces Correlated to Temperature Gradients and Coating Elastic Modulus

Predicted delamination driving force $G$ can be in the range of 20-80 J/m$^2$

$$G = \frac{1}{6} \left( \frac{1 + \nu_1}{1 - \nu_1} \right) E_1 h \left( \alpha_1 \left( T_s - T_0 \right) \right)^2$$

As compared to CTE mismatch

$$G = \sigma^2 h / 2\bar{E}$$

$$= \left[ Eh(1+\nu)/(1-\nu) \right] (\Delta \alpha \Delta T)^2 / 2$$

Hutchinson, Irsee, Germany 2007;
Evans and Hutchinson, Surface Coating Technology, 2007
Delamination Crack Propagation Observed under Heat-Flux Thermal Gradient Cyclic Condition

Crack propagation and coating delamination
ZrO₂-8wt%Y₂O₃

A center penny-shape crack propagation

Thermal conductivity change as a function of cycle number

Crack propagation da/dN-stress intensity amplitude ΔK plot for life prediction
High Temperature Sintering Accelerates Cracking in Thermal and Environmental Barrier Coatings

- Conductivity initially increased due to sintering
- Conductivity later decreased due to coating delamination cracking resulting from the large sintering shrinkage
- Coating delaminates at temperature during the steady-state testing due to sintering

Conductivity reduction due to sintering cracking induced delamination cracking

After 20h testing

Relative Graph:

- Measured thermal conductivity
- Predicted thermal conductivity

Temperature:
- $T_{\text{surface}} = 1482^\circ\text{C}$
- $T_{\text{interface}} = 1250^\circ\text{C}$

Sintering cracks

500 nm
Failure Modes of Environmental Barrier Coating Systems

- Mullite
- Mullite+BSAS
- Si
- BSAS+Mullite
- SiC/SiC
- YSZ
Accelerated Coating Degradation under Thermal Gradient and Water Vapor Environments

— Significant interfacial pore and eutectic phase formation due to water vapor attack and Si diffusion at the interface temperature of 1300°C under the thermal gradient cycling conditions

Coating spallation
**Temperature Capability of Advanced Thermal and Environmental Barrier Coatings**

- **Specific weight change, mg/cm²-h**
  - Temperature, °C
  - 1/T, K⁻¹
  - Supersonics project goal

- **Thermal conductivity, W/m-K**
  - Temperature, °C
  - 1/T x 10⁴, K⁻¹
  - Advanced coatings
  - Plasma-sprayed coatings (except specified)

Legend:
- AS800
- SN282
- SiC/SiC CMC
- La₂Hf₂O₇
- HfO₂ (doped)
- RE Alloyed Mullite
- BSAS
- Rare earth silicates

Graphs showing data points and trends for different materials and coatings.
Conclusions

• The coating failure involved both time-temperature dependent sintering and cycle dependent fatigue processes

• Coating high temperature stability demonstrated critical durability issue

• Increased delamination driving forces and accelerated degradation quantified under heat fluxes and thermal gradients

• Advanced low conductivity, high stability sintering resistant, and compliant coatings demonstrated better long-term durability

• Design databases and life prediction approaches established