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

Dongming Zhu*, Louis J. Ghosn** and Robert A. Miller*

* Durability and Protective Coatings Branch  
** Mechanics and Life Prediction Branch  
Structures and Materials Division  
NASA John H. Glenn Research Center  
Cleveland, Ohio 44135, USA

Contact: Dr. Dongming Zhu, (216) 433-5422; Dongming.Zhu@nasa.gov

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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

![NASA CO₂ Laser Rig](image_url)
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

Test chamber pressure: 5 atm

- 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

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**Thermal conductivity, W/m-K**

- Initial conductivity reduction
- Steady-state testing: $T_{\text{surface}} = 1316^\circ\text{C}$, $T_{\text{interface}} = 1100^\circ\text{C}$
- Cyclic testing
- ZrO$_2$-8wt%Y$_2$O$_3$ 20min heating/3min cooling

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**Thermal conductivity, W/m-K**

- Interface temperature 1100°C
- Interface temperature 1200°C
- ZrO$_2$-8wt%Y$_2$O$_3$
- Spallation
High Heat-Flux Sintering Induced Cracking and Delamination in Turbine EB-PVD ZrO₂-7wt%Y₂O₃ 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
- Interface temperature 2125°F
- Cycle life, hours
- Testing Type
- K_{effective}, MPa mm^1/2
- Time, sec.

Heat Flux 100 W/cm²:

- 0.254mm
- 0.127mm
- 3.175 mm
The Cyclic Life of Thermal Barrier Coatings - Continued

Surface high heat flux testing

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

![Diagram showing FEA modeling of temperature distributions and thermal conductivity reduction as a function of crack length.](image-url)
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, \((a/\lambda)\)

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

\[ \Delta k, \text{ Mpa} \cdot \text{m}^{1/2} \]

\[ \frac{da}{dN}, \text{ mm/Cycle} \]

- \( \triangle 1100\text{C Int.} \)
- \( \circ 1200\text{C Int.} \)
Coating Failure Modes under Very High Thermal Gradients

0.5 mm
Delamination Driving Forces Correlated to Temperature Gradients and Coating Elastic Modulus

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

As compared to CTE mismatch
\[
G = \sigma^2 h / 2E = \frac{[Eh(1+\nu)/(1-\nu)](\Delta \alpha \Delta T)^2}{2}
\]

Hutchinson, Irsee, Germany 2007;
Evans and Hutchinson, Surface Coating Technology, 2007

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

T_{\text{surface}}=1482^\circ\text{C}
T_{\text{interface}}=1250^\circ\text{C}
Failure Modes of Environmental Barrier Coating Systems

- Mullite
- Mullite+BSAS
- Si
- YSZ
- BSAS+Mullite
- Si
- SiC/SiC
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.
Temperature Capability of Advanced Thermal and Environmental Barrier Coatings

Supersonics project goal

Advanced coatings

Plasma-sprayed coatings (except specified)
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