Monitoring Delamination of Thermal Barrier Coatings During Interrupted High-Heat-Flux Laser Testing Using Luminescence Imaging

This presentation showed progress made in extending luminescence-base delamination monitoring to TBCs exposed to high heat fluxes, which is an environment that much better simulates actual turbine engine conditions. This was done by performing upconversion luminescence imaging during interruptions in laser testing, where a high-power CO2 laser was employed to create the desired heat flux. Upconversion luminescence refers to luminescence where the emission is at a higher energy (shorter wavelength) than the excitation. Since there will be negligible background emission at higher energies than the excitation, this method produces superb contrast. Delamination contrast is produced because both the excitation and emission wavelengths are reflected at delamination cracks so that substantially higher luminescence intensity is observed in regions containing delamination cracks. Erbium was selected as the dopant for luminescence specifically because it exhibits upconversion luminescence. The high power CO2 10.6 micron wavelength laser facility at NASA GRC was used to produce the heat flux in combination with forced air backside cooling. Testing was performed at a lower (95 W/cm²) and higher (125 W/cm²) heat flux as well as furnace cycling at 1163°C for comparison. The lower heat flux showed the same general behavior as furnace cycling, a gradual, “spotty” increase in luminescence associated with debond progression; however, a significant difference was a pronounced incubation period followed by acceleration delamination progression. These results indicate that extrapolating behavior from furnace cycling measurements will grossly overestimate remaining life under high heat flux conditions. The higher heat flux results were not only accelerated, but much different in character. Extreme bond coat rumpling occurred, and delamination propagation extended over much larger areas before precipitating macroscopic TBC failure. This indicates that under the higher heat flux (and surface & interface temperatures), the TBC was more tolerant of damage. The main conclusions were that high heat flux conditions can not only accelerate TBC debond progression but can also grossly alter the pathway of delamination.
Monitoring Delamination of Thermal Barrier Coatings During Interrupted High-Heat-Flux Laser Testing Using Luminescence Imaging

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Objective

• Extend luminescence-based delamination monitoring to TBCs subjected to high heat flux.
  – Previous delamination monitoring by upconversion luminescence imaging limited to furnace cycling.
  – Furnace cycling does not adequately simulate engine conditions.
  – Thermal gradients present in high-heat-flux engine environment contribute additional driving forces for TBC delamination and may alter delamination progression pathway.
  – Valid diagnostics for predicting TBC remaining life must be based on measurements of TBCs exposed to engine-like high-heat-flux conditions.

Approach

• Perform upconversion luminescence imaging during interrupted high-heat-flux laser testing.
TBC Temperature Profile Progression
Furnace vs. High-Heat-Flux Laser Heating

Furnace (isothermal)
- TBC
- Metal Substrate
- Bond coat

Laser Testing (high heat flux)
- TBC
- Metal Substrate
- Bond coat

Heat in → crack → Heat out

$t = 0$

Aging does not affect thermal profile.

Aging produces evolving thermal profile.

$t = t_{\text{final}}$
Detecting TBC Delamination by Reflectance-Enhanced Upconversion Luminescence

- Two-photon excitation of Er\(^{3+}\) produces upconversion luminescence at 562 nm with near-zero background for strong delamination contrast.
- Yb\(^{3+}\) absorbs 980 nm excitation and excites luminescence in Er\(^{3+}\) by energy transfer.
- Delamination contrast achieved because of increased reflection of excitation & emission at TBC/crack interface.
Upconversion Luminescence Imaging

980 nm laser diode

fiber optic

collimating lens

upconversion luminescence image

CCD camera

562 nm bandpass filter

TBC-coated specimen
High Heat-Flux Laser Testing

- High power CO₂ laser high-heat-flux rig

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

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

- CO₂ laser heating
High-Heat-Flux Laser Testing Conditions

Furnace Cycling
• \( q = 0 \text{ W/cm}^2 \)
• \( T_{surface} \approx 1163^\circ \text{C} \)
• \( T_{interface} \approx 1163^\circ \text{C} \)
• \( \Delta T \approx 0^\circ \text{C} \)

Heat Flux Test #1
• \( q = 95 \text{ W/cm}^2 \)
• \( T_{surface} \approx 1290^\circ \text{C} \)
• \( T_{interface} \approx 1140^\circ \text{C} \)
• \( \Delta T \approx 150^\circ \text{C} \)

Heat Flux Test #2
• \( q = 125 \text{ W/cm}^2 \)
• \( T_{surface} \approx 1345^\circ \text{C} \)
• \( T_{interface} \approx 1175^\circ \text{C} \)
• \( \Delta T \approx 170^\circ \text{C} \)

1 cycle = 60 min laser on + 3 min laser off

YSZ:Er(1%), Yb(3%)

NiPtAl

Rene N5

\( \Delta T \)
Upconversion Luminescence Images During Interrupted Laser Cycling Heat Flux Test #1, $q = 95 \text{ W/cm}^2$

1 laser furnace cycle = 60 min laser on + 3 min laser off

0 cycles  20 cycles  35 cycles  55 cycles  75 cycles  95 cycles  115 cycles  135 cycles  155 cycles  195 cycles  215 cycles  235 cycles  255 cycles  275 cycles  315 cycles  335 cycles

1 cm

white light image

YSZ:Er(1%),Yb(3%) 11\,\mu m  
YSZ:Er(1%),Yb(3%) 135\,\mu m  
NiPtAl  1140\degree C
Rene N5  1290\degree C
Comparison of Upconversion Luminescence Intensity During Interrupted Furnace vs. Laser Cycling

First indication of early stage of TBC delamination
Comparison of Upconversion Luminescence Intensity During Interrupted Furnace vs. Laser Cycling

Laser cycling exhibits an initial incubation stage followed by accelerated delamination progression.
Temperature Sequence During High-Heat Flux Laser Testing

\[ q_{thru} = 125 \text{ W/cm}^2 \]
Upconversion Luminescence Images During Interrupted Laser Cycling Heat Flux Test #2, $q = 125 \text{ W/cm}^2$

1 laser furnace cycle = 60 min laser on + 3 min laser off

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Localized Sub-millimeter Delamination Observed

- glancing white light image
- upconversion luminescence image

TBC surface undulations*

Not observed for furnace cycled or lower heat flux test!

*Tolpygo & Clarke

NiPtAl

YSZ:Er(1%),Yb(3%)

YSZ

Rene N5

1345°C

1175°C

5 mm overlay 150 cycles 135 µm 11 µm
Comparison of Upconversion Luminescence Intensity During Interrupted Furnace vs. Laser Cycling

Out-of-family, accommodates greater damage before TBC failure.
TBC Failure Occurs When Delamination Driving Force Exceeds Delamination Resistance

- Coating delamination resistance decreases with time
  - Ceramic through-thickness/interfacial cracking and damage accumulation
  - Interfacial oxidation
  - Materials property degradation due to phase instability
  - Interface morphological variation
  - Less resistance to bond coat rumpling

- Coating delamination driving (energy release rate) increases
  - Stress state change and increased stress
  - Ceramic modulus increase due to sintering shrinkage
  - Visco-elastic behavior and reduced modulus

- Shorter life

- Differential elastic expansion/contraction
- Differential sintering shrinkage
- Large transient thermal stresses at start of heating/cooling
- Interface temperature increases as TBC thermal conductivity decreases
- △T across crack produces energy release
Summary

- Upconversion luminescence imaging successfully monitors delamination progression for TBCs exposed to high heat flux conditions.
- High-heat-flux conditions produce TBC debond progression that accelerates (relative to isothermal conditions).
- High-heat-flux conditions change path of TBC debond propagation (allowing bond coat rumpling).
- Diagnostic life prediction based on damage evolution occurring during isothermal exposures will grossly overestimate TBC remaining life under high heat flux conditions (even with same starting interface temperature).

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