Luminescence-Based Diagnostics of Thermal Barrier Coating Health and Performance

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Motivation

• Address need to test & monitor performance & health of TBCs.
  – Lab environment assessment tool
  – Engine environment validation tool
• Essential for safely increasing engine operating temperatures.

Approach: Luminescence-Based Monitoring of TBC Performance

• Multifunctional TBCs with integrated diagnostic capabilities
• Erosion monitoring
• Delamination progression monitoring
• Temperature sensing
  – Above & below TBC
  – Engine environment implementation
  – 2D temperature mapping
TBC Translucency Provides Window for Optical Diagnostics

Light Transmission Through YSZ

1 mm thick
13.5 YSZ single crystal (transparent)

135 μm thick
Plasma-sprayed 8Y SZ (translucent)

Backlit by overhead projector.
Erosion Detection Using Erosion-Indicating TBCs

Coating Design

Erosion monitoring by luminescence detected from exposed YSZ:Eu and YSZ:Tb sublayers
Luminescence reveals location and depth of coating erosion.

*EB-PVD TBCs produced at Penn State, D.E. Wolfe.*
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.
**EB-PVD TBCs**

*EB-PVD TBCs produced at Penn State, D.E. Wolfe.*

**SEI**

20 kV 550X 50 µm

**BEI**

20 kV 3kX 10 µm

Undoped YSZ

YSZ:Er,Yb

130 µm

6 µm

YSZ

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

NiPtAl

Rene N5
Upconversion Luminescence Images During Interrupted Furnace Cycling for EB-PVD TBC with YSZ:Er(1%),Yb(3%) Base Layer

1 furnace cycle = 45min @ 1163°C + 15 min cooling

Batch 1

7.5 sec acquisition

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<th>1 cycle</th>
<th>10 cycles</th>
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130 µm

YSZ

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

NiPtAl

Rene N5

1 cm
Change in Upconversion Luminescence Intensity with Furnace Cycling to TBC Failure

- #1 fails at 620 cycles
- #2 fails at 500 cycles
- #3 fails at 745 cycles

early indication of TBC life
Failure Progression
EB-PVD TBC with YSZ:Er(1%),Yb(3%) Base Layer

**Microdelamination + TGO growth**

**400 cycles**
- Bright spots produced by large-separation micro-delaminations between TBC & TGO produced by bond coat instabilities (rumpling).

**200 cycles**
- Small microcracks between TBC & TGO increase intensity but may not be resolved individually.

**Luminescence Image**
- Delamination increases luminescence intensity.
- TGO growth decreases luminescence intensity.

**TGO growth during furnace cycling**

- 0 cycles
- 30 cycles
- 200 cycles
- 700 cycles
Monitoring TBC Delamination Around Cooling Holes

- **Problem:** Cooling holes in turbine blades and vanes can act as stress-concentrating failure initiation sites for surrounding TBC. Potential severity of these effects are unknown.

- **Objective:** Determine the severity of the effect of cooling holes on the lifetime of surrounding TBC using upconversion luminescence imaging.

- **Approach:** Performed luminescence imaging during interrupted furnace cycling of TBC-coated specimens with arrays of 0.020” diameter laser-drilled cooling holes.
Monitoring Delamination Around Laser-Drilled Cooling Holes by Upconversion Luminescence Imaging During Furnace Cycling

1 furnace cycle = 45min @ 1163°C + 15 min cooling

1 cm

130 μm
12 μm
YSZ
YSZ:Er(1%),Yb(3%)
NiPtAl
Rene N5

7.5 sec acquisition
Effect of Cooling Holes on TBC Life

• Luminescence imaging easily detects delamination around cooling holes.
• Local delamination does initiate around cooling holes but exhibits very limited, stable growth.
• The unstable delamination propagation that leads to TBC failure actually AVOIDS vicinity of cooling holes.
• **Significance:** Cooling holes in turbine blades and vanes do not shorten TBC life and their behavior as debond initiation sites can be tolerated safely.
Luminescence-Based Remote Temperature Monitoring Using Temperature-Indicating TBCs

Surface Eu-doped YSZ layer, Eu$^{3+}$ luminescence decay

Buried Eu-doped YSZ layer, Eu$^{3+}$ luminescence decay

Decay Time vs. Temperature Calibration

606 nm Eu$^{3+}$ emission (with temperature-dependent decay)

Pulsed 532 nm illumination

Buried Eu-doped YSZ, Eu$^{3+}$ luminescence image

Undoped YSZ (118 µm)

YSZ:Eu (36 µm)

PtAl bond coat

Rene N5 superalloy substrate
AFRL Versatile Affordable Advanced Turbine Engines (VAATE) Project
Gas Turbine Engine Sensor and Instrumentation Development

NASA GRC High-Heat-Flux Laser Facility
•Proof-of-concept with easy optical access, no radiative background, no probe heating issues.
Demonstrated to 1360°C. ✓

Williams International Combustor Burner Rig
•Address probe/TP survivability & ability to “see” through flame.
Demonstrated to >1400°C. ✓

AEDC J85-GE-5
•Probe/translate through afterburner flame.
•Opportunity to test excitation/collection integrated probe.
Demonstrated to >1300°C. ✓

Goal: Demonstrate thermographic phosphor based temperature measurements to 1300°C on TBC-coated HPT stator on Honeywell TECH7000 demonstrator engine.
Temperature Line Scan Across Hot Spot During Williams Combustor Burner Heating

Traversing **High-Flame** Hot-Spot
Luminescence from YAG:Dy Coating

![Graph showing PMT signal vs. distance from edge and decay time vs. temperature](image)

substrate melting!

Luminescence emission observed through 456 nm bandpass filter

**High-Flame Temperature Line Scan**
Implementation of Ultra-Bright High-Temperature Phosphor

• Breakthrough discovery* of exceptional high temperature retention of ultra-bright luminescence by Cr-doped GdAlO$_3$ with orthorhombic perovskite crystal structure: Cr-doped gadolinium aluminum perovskite (Cr:GAP).
  - High crystal field in GAP suppresses thermal quenching of luminescence.
  - Novel utilization of broadband spin-allowed emission extends luminescence to shorter wavelengths where thermal radiation background is reduced.

• Enables luminescence-based temperature measurements in highly radiant environments to 1250ºC.
  - Huge advance over state-of-the-art ultra-bright luminescence upper limit of 600ºC.

*J.I. Eldridge & M.D. Chambers
Demonstrating Temperature Measurement Capability
Time-Averaged Luminescence Emission from Cr(0.2%):GAP Puck
Temperature Dependence
Superb signal-to-noise from thin 25 µm thick coating confirms retention of ultra-bright luminescence at high temperatures.
Demonstrating Temperature Measurement Capability

Calibration of Decay Time vs. Temperature for GAP:Cr Coating

Two distinct regions
200ºC < T < 750ºC: less temperature sensitive
T > 750ºC: more temperature sensitive

Fit to $\tau = \tau_2^R \frac{1 + 3e^{-\Delta E/kT}}{1 + \alpha e^{-\Delta E/kT} + \beta e^{-(\Delta E_q + \Delta E)/kT}}$
2D Temperature Mapping of Effect of Air Cooling Jets

Air Jet Fixture for Laser Heat Flux Testing

GAP:Cr Decay Time vs. Temperature Calibration

Temperature determined from decay time at each pixel.

Sequence of gated images (Tim Bencic, NASA GRC)

Temperature insensitive to surface emissivity & reflected radiation!

Courtesy of Dongming Zhu, NASA GRC
Summary

• Luminescence-based sensing successfully monitors TBC health & performance.
  - Erosion indication by self-indicating TBCs
  - Delamination progression monitoring by upconversion luminescence imaging
    • Predictive for remaining TBC life
    • Cooling hole debond initiation sites safely tolerated.
  - Temperature sensing by luminescence decay time behavior
    • Surface & depth-penetrating measurements
    • Ultra-bright high-temperature GAP:Cr phosphor enables 2D temperature mapping.

• Nearing engine-test-ready status.