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

- Undoped YSZ
- YSZ:Eu
- YSZ:Tb
- PtAl bond coat
- Rene N5 superalloy substrate

Erosion monitoring by luminescence detected from exposed YSZ:Eu and YSZ:Tb sublayers
Erosion Depth Indication Using Eu- and Tb-Doped YSZ

coating surface, white light illumination

coating surface, UV illumination

Luminescence reveals location and depth of coating erosion.

165 µm sublayer-doped 7YSZ/PtAl/Rene N5

*EB-PVD TBCs produced at Penn State, D.E. Wolfe.
Detecting TBC Delamination by Reflectance-Enhanced Upconversion Luminescence

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

SEI

BEI

20 kV  550X  50 µm

20 kV  3kX  10 µm

130 µm

6 µm

YSZ:

YSZ:Er,Yb

Undoped YSZ

NiPtAl

Rene N5

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

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

0 cycles  1 cycle  10 cycles  20 cycles  30 cycles  40 cycles  60 cycles  80 cycles  100 cycles  120 cycles

140 cycles  160 cycles  180 cycles  200 cycles  220 cycles  240 cycles  260 cycles  280 cycles  300 cycles  320 cycles

340 cycles  360 cycles  380 cycles  400 cycles  420 cycles  440 cycles  460 cycles  480 cycles  500 cycles  520 cycles

540 cycles  560 cycles  580 cycles  600 cycles  620 cycles  640 cycles  660 cycles  680 cycles  700 cycles  720 cycles

740 cycles  745 cycles

130 µm  6 µm

YSZ

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

NiPtAl

Rene N5

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

Luminescence Intensity Ratio

Furnace Cycles

early indication of TBC life

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

0 cycles

30 cycles

200 cycles

700 cycles

TGO growth during furnace cycling

• Delamination increases luminescence intensity.
• TGO growth decreases luminescence intensity.
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 = 45 min @ 1163°C + 15 min cooling

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

<table>
<thead>
<tr>
<th>Surface Eu-doped YSZ layer, Eu$^{3+}$ luminescence decay</th>
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<tr>
<td>Buried Eu-doped YSZ layer, Eu$^{3+}$ luminescence decay</td>
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- Pulsed 532 nm illumination
- 606 nm Eu$^{3+}$ emission (with temperature-dependent decay)

- Undoped YSZ
- Eu-doped YSZ
- PtAl bond coat
- Rene N5 superalloy substrate

Decay Time vs. Temperature Calibration

- Decayed Exponential Function
- Luminescence Decay

Buried Eu-doped YSZ, Eu$^{3+}$ luminescence image
- Undoped YSZ (118 µm)
- YSZ:Eu (36 µm)
- PtAl (50 µm)
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.

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

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 decay time vs distance from edge](image)

**High-Flame Temperature Line Scan**

Luminescence emission observed through 456 nm bandpass filter
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
200°C < T < 750°C: less temperature sensitive
T > 750°C: 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

Sequence of gated images (Tim Bencic, NASA GRC)

Temperature determined from decay time at each pixel.

1.7 μs

courtesy of Dongming Zhu, NASA GRC

Insensitive to surface emissivity & reflected radiation!
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.