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
Erosion Depth Indication Using Eu- and Tb-Doped YSZ

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.
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

YSZ

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

6 µm

NiPtAl

Rene N5

1cm
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

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.

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![Diagram of 20º hole pattern (typical angle for turbine blades) and TBC-coated specimen with 0.020” diam laser-drilled cooling holes at 20º.](image-url)
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

1 cm

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

In [Emission Intensity (V)]

Temperature (ºC)

Asymptotic Decay Time (µsec)

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

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

Goal: Demonstrate thermographic phosphor based temperature measurements to 1300°C on TBC-coated HPT stator on Honeywell TECH7000 demonstrator engine.

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.

Honeywell TECH7000
Temperature Line Scan Across Hot Spot During Williams Combustor Burner Heating

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

**High-Flame Temperature Line Scan**

- **PMT Signal (V)** vs **Time (µs)**
  - Multiple curves for different distances from edge: 2.5 mm, 6.9 mm, 11.2 mm, 15.7 mm, 20 mm, 24.4 mm, 28.8 mm, 33.1 mm

- **Temperature (ºC)** vs **Decay Time (µs)**
  - Range of confidence indicated

- **Temperature Line Scan Across Hot Spot**
  - Luminescence observed through 456 nm bandpass filter

- **Substrate melting** indicated

- **Distance from edge (mm)** vs **Temperature C**

- **Decay Time (usec)** vs **Distance from edge (mm)**
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 1250° C.
  – Huge advance over state-of-the-art ultra-bright luminescence upper limit of 600° C.

*J.I. Eldridge & M.D. Chambers
Demonstrating Temperature Measurement Capability

Time-Averaged Luminescence Emission from Cr(0.2%):GAP Puck Temperature Dependence

![Graph showing temperature dependence of luminescence emission from Cr(0.2%):GAP Puck. The graph displays intensity as a function of wavelength for various temperatures ranging from 20°C to 977°C. The intensity is measured on a logarithmic scale, and the graph includes a bandpass filter.]
Coatings for 2D Temperature Mapping
Luminescence Decay Curves from 25 µm Thick EB-PVD Cr:GAP Coating

Superb signal-to-noise from thin 25 µm thick coating confirms retention of ultra-bright luminescence at high temperatures.

Fit to $I = I_1 e^{-t/\tau_1} + I_2 e^{-t/\tau_2}$
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 $\tau = \tau^R_2 \frac{1 + 3e^{-\Delta E/kT}}{1 + \alpha e^{-\Delta E/kT} + \beta e^{-(\Delta E + \Delta E)/kT}}$
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.

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.