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

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

*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
6 µm YSZ:Er(1%),Yb(3%)

NiPtAl

Rene N5

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

Furnace Cycles

Luminescence Intensity Ratio

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

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

Small microcracks between TBC & TGO increase intensity but may not be resolved individually.

- 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 = 45min @ 1163°C + 15 min cooling

7.5 sec acquisition

1 cm

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

White light image
Upconversion luminescence image
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 I$_{Emission}$ vs. Time ($\mu$sec) graphs:
  - 606 nm Eu$^{3+}$ emission (with temperature-dependent decay)
  - Pulsed 532 nm illumination

- Decay Time vs. Temperature graph

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

- Rene N5 superalloy substrate

- PtAl bond coat

- 50 µm
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.

Honeywell TECH 7000

Goal: Demonstrate thermographic phosphor based temperature measurements to 1300°C on TBC-coated HPT stator on Honeywell TECH 7000 demonstrator engine.
Temperature Line Scan Across Hot Spot During Williams Combustor Burner Heating

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

Luminescence emission observed through 456 nm bandpass filter

Substrate melting!

High-Flame Temperature Line Scan

**Range of confidence**

Distance from edge (mm)

Temperature (ºC)

Decay Time (µs)

Decay Time (usec)

Temperature C

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 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

![Graph showing temperature dependence of Cr(0.2%):GAP Puck luminescence emission.](image-url)
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
200°C < T < 750°C: less temperature sensitive
T > 750°C: more temperature sensitive

Fit to \[ \tau = \tau_{2E}^{R} \frac{1 + 3e^{-\Delta E / kT}}{1 + e^{-\Delta E / kT} + e^{-(\Delta E + \Delta E) / kT}} \]
2D Temperature Mapping of Effect of Air Cooling Jets

Air Jet Fixture for Laser Heat Flux Testing

Temperature determined from decay time at each pixel.

GAP: Cr Decay Time vs. Temperature Calibration

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.