Luminescence-Based Diagnostics of Thermal Barrier Coating Health and Performance

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37th International Conference on Advanced Ceramics & Composites
Daytona Beach, FL
January 29, 2013
Acknowledgments

• NASA GRC
  - Dongming Zhu (High heat flux testing)
  - Tim Bencic (2D surface temperature mapping)
  - Joy Buehler (Metallography)

• Penn State
  - Doug Wolfe (EB-PVD)

• U. Connecticut
  - Eric Jordan (SPPS)

• Metrolaser
  - Tom Jenkins (VAATE engine test team)

• Emerging Measurements
  - Steve Allison (VAATE engine test team)

• Funding by NASA Fundamental Aero and Air Force Research Laboratory.
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

UV illumination

543 nm Tb$^{3+}$ emission

606 nm Eu$^{3+}$ emission

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

erosion crater

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 $\text{Er}^{3+}$ 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 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 = 45 min @ 1163°C + 15 min cooling

Batch 1
7.5 sec acquisition

YSZ

NiPtAl

Rene N5

130 µm
6 µm
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

10 µm

30 cycles

10 µm

200 cycles

10 µm

700 cycles

10 µm
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.

20° hole pattern (typical angle for turbine blades)
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

White light image
Upconversion luminescence image

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

5 mil undoped YSZ/1 mil YSZ:Eu hitemp decay

Temperature (°C)

Asymptotic Decay Time (µsec)

ln [Emission Intensity (V)]

Time (µsec)

ln [Emission Intensity (V)]

Time (µsec)

Temperature (°C)

Buried Eu-doped YSZ, Eu\(^{3+}\) luminescence image

undoped YSZ (118 µm)

YSZ:Eu (36 µm)

PtAl bond coat

Rene N5 superalloy substrate

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 TECH7000

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

**High-Flame Temperature Line Scan**

Luminescence emission observed through 456 nm bandpass filter

**Substrate melting!**
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 luminescence emission with intensity on the y-axis and wavelength on the x-axis, with curves for different temperatures and a bandpass indicated.]
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.
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 $\tau = \tau^R_2 \frac{1 + 3e^{-\Delta E/kT}}{1 + \alpha e^{-\Delta E/kT} + \beta e^{-(\Delta E_0 + \Delta E)/kT}}$
2D Temperature Mapping of Effect of Air Cooling Jets

Laser heat flux

Air Jet Fixture for Laser Heat Flux Testing

4 cooling jets

nozzle

970°C
980°C
990°C
1000°C
1010°C
1020°C
1030°C
1040°C
1050°C

Temperature determined from decay time at each pixel.

Sequence of gated images

(Tim Bencic, NASA GRC)

Temperature map (B&W) Temperature map (color)

1 cm

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.