Thermal barrier coatings (TBCs) are typically composed of translucent ceramic oxides that provide thermal protection for metallic components exposed to high-temperature environments, such as in jet turbine engines. Taking advantage of the translucent nature of TBCs, optical diagnostics have been developed that can provide an informed assessment of TBC health that will allow mitigating action to be taken before TBC degradation threatens performance or safety. In particular, rare-earth-doped luminescent sublayers have been integrated into the TBC structure to produce luminescence that monitors TBC erosion, delamination, and temperature gradients. Erosion monitoring of TBC-coated specimens is demonstrated by utilizing visible luminescence that is excited from a sublayer that is exposed by erosion. TBC delamination monitoring is achieved in TBCs with a base rare-earth-doped luminescent sublayer by the reflectance-enhanced increase in luminescence produced in regions containing buried delamination cracks. TBC temperature monitoring is demonstrated using the temperature-dependent decay time for luminescence originating from the specific coating depth associated with a rare-earth-doped luminescent sublayer. The design and implementation of these TBCs with integrated luminescent sublayers is discussed, including co-doping strategies to produce more penetrating near-infrared luminescence. It is demonstrated that integration of the rare-earth-doped sublayers is achieved with no reduction in TBC life. In addition, results for multilayer TBCs designed to also perform as radiation barriers are also presented.
Optical Diagnostics for High-Temperature Thermal Barrier Coatings

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Thermal Barrier Coatings (TBCs) Provide Thermal Protection for Gas Turbine Engine Components

— Ceramic oxide TBCs, e.g., yttria-stabilized zirconia, can increase engine temperatures, reduce cooling, lower emission, and improve engine efficiency and reliability

— TBCs provide thermal protection by sustaining a thermal gradient between the TBC surface and underlying metal component.

(a) without TBC  
(b) with current TBC  
(c) with improved TBC
Motivation

• Need to monitor the performance and health of TBCs so that the thermal protection provided by TBCs is not compromised.

Approach

• Develop “diagnostically friendly” thermal barrier coatings (TBCs) by incorporating rare-earth-doped luminescent sublayers without sacrificing TBC performance. Produce multifunctional TBCs that integrate the following functions:
  – Thermal protection
  – Effective radiation barrier
  – Luminescence-based erosion and delamination indication
  – Luminescence-based temperature monitoring.
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 8YSZ (translucent)

Backlit by overhead projector.
TBC Microstructure
Plasma-Spray vs. EB-PVD

Plasma-Spray Microstructure

Electron Beam – Physical Vapor Deposition (EB-PVD) Microstructure

Highly Scattering

Weakly Scattering
Effect of Wavelength on Luminescence Attenuation
EB-PVD vs. Plasma-Sprayed TBC

![Graph showing the effect of wavelength on luminescence attenuation between EB-PVD and Plasma-Sprayed TBC materials. The graph plots % transmittance against wavelength (µm) for two different thicknesses: 173 micron EB-PVD TBC and 172 micron PS TBC.]
TBC Transmittance
Plasma-Sprayed vs. EB-PVD

![Graph showing the comparison between 172 μm plasma-sprayed TBC and 173 μm EB-PVD TBC across different wavelengths.](image-url)
Erosion Detection
Coating Design for 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 Luminescent Sublayers Produced by EB-PVD

coating surface, white light illumination

coating surface, UV illumination

Erosion produced by alumina particle (50 µm) alumina particle jet through 5 mm diameter nozzle

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

Luminescence reveals location and depth of coating erosion.
Cross-Section of Erosion Crater in Erosion-Indicating TBC

Cross-section, white light illumination

Cross-section, UV illumination

Coatings deposited at Penn State
Delamination Monitoring
Detecting TBC Delamination by Reflectance-Enhanced Luminescence
Er + Yb Co-Doped Sublayer

- Er$^{3+}$ produces strong NIR luminescence which is much less strongly scattered by TBC than visible wavelengths ⇒ much better depth probing.
- Yb$^{3+}$ absorbs 980 nm excitation and excites luminescence in Er$^{3+}$ by energy transfer.
- Er$^{3+}$ produces upconversion luminescence at 562 nm with near-zero background for strong delamination contrast.
NIR and Upconversion Luminescence Imaging

- 980 nm laser diode
- Fiber optic
- Collimating lens
- InGaAs NIR camera
- 1550 nm bandpass filter
- TBC-coated specimen
- Upconversion luminescence image
- 562 nm bandpass filter
- CCD camera

NIR luminescence image
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

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

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

early indication of TBC life
Effect of Er + Yb Co-Doped Base Layer on TBC Cyclic Life

Number of Cycles

Conventional Undoped

With Doped Base Layer
Plasma-Sprayed TBCs

Coatings deposited at NASA GRC
NIR Luminescence Time-Lapse Imaging of Unstable Delamination of Plasma-Sprayed TBC

7 hr time lapse

0 cycles

40 cycles

50 cycles

~110 μm
~20 μm

YSZ
YSZ:Er(1%),Yb(3%)
NiCrAlY
Rene N5

1cm
Remote Temperature Monitoring
Coating Design for Temperature-Indicating TBCs

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

Pulsed 532 nm illumination

Emission intensity (V)

Time (µsec)

Undoped YSZ

Eu-doped YSZ

PtAl bond coat

Rene N5 superalloy substrate

700°C

800°C
Buried Eu-doped YSZ exhibits same temperature dependence as surface Eu-doped YSZ, therefore buried Eu-doped YSZ layers still function as effective temperature indicators & can be used to measure temperature gradients & heat fluxes.
Luminescence decay time can be used to indicate temperature at dopant location.
**Radiation Barrier**

Apply concept of constructive multilayer interference of reflected beams

**Single Layer**

Pathlength difference = 2d

Phase difference = \(4\pi d/(\lambda/n)\)

For constructive interference, Phase difference = \(\pi\), so \(d = \lambda/4n\)
Fixed Layer Thickness High Reflectance Coatings

High Reflectance Stack

- Alternating layers of high refractive index material YSZ (n = 2.1) and low refractive index material \( \text{Al}_2\text{O}_3 \) (n = 1.62)
- Al\(_2\)O\(_3\) layer thickness = 100 nm
- YSZ layer thickness = 400 nm
- Total thickness \( \sim 100 \mu\text{m} \)

Design & prediction by Chuck Spuckler

Coatings deposited at Penn State

\( H \) = high index of refraction (2.1 for YSZ)
\( L \) = low index of refraction (1.62 for \( \text{Al}_2\text{O}_3 \) )

Predicted Reflectance

Reflectance (%) vs Wavelength (\( \mu\text{m} \))
Multilayer TBC Increases IR Reflectance

Fixed spacing gives higher reflectance over narrow wavelength range

Standard 5 mil single layer 8YSZ

0.8 µm  2 µm
Variable Layer Thickness High Reflectance Coatings

High Reflectance Stack

Coating Design

262 layers  Alternating layers of high refractive index material YSZ (n = 2.1) and low refractive index material Al₂O₃ (n = 1.62)
First layer next to substrate  n = 2.1  87.86 nm thick
  each succeeding n =2.1 layer increased by 4.88 nm
Second layer from substrate  n = 1.62  115 nm thick
  each succeeding n =1.62 layer increased by 5.0 nm
Second last layer                    n = 2.1            722.38 nm thick
Last layer                               n = 1.62          765  nm thick
Thickness of all n = 2.1 layer 53 µm
Thickness of all n = 1.62 layer 57.6 µm
Total thickness  111 µm

Design & prediction by Chuck Spuckler

Coatings deposited at Penn State
Multilayered TBC Increases IR Reflectance
fixed vs. variable spacing
multilayers 3 hr @1000C

Fixed spacing gives higher reflectance over narrow wavelength range
Variable spacing gives higher reflectance over wider wavelength range

Reflectance (%)

Wavelength (µm)
Increasing TBC Reflectance By Multilayer Design

EB-PVD TBCs

| Variable spacing Al2O3/7YSZ multilayers | Fixed spacing Al2O3/7YSZ multilayers | Standard 7YSZ |

Increased reflectance due to increased scattering, not constructive interference.
Radiation Barrier Lessons Learned

• Multilayer design does increase reflectivity, but much of reflectivity gain is due to increased scattering.

• Non-optical quality multilayers result in underperformance with respect to predicted reflectivity from constructive interference.

• Preferred approach would be to increase reflectivity by engineered porosity.
  – Effects of porosity not sensitive to angle of incidence or coating erosion.
Conclusions

- Multifunctional TBCs incorporating luminescent sublayers can provide:
  - Thermal protection
  - Erosion indication by luminescence from exposed sublayers.
  - Delamination indication by reflectance-enhanced luminescence.
  - Temperature monitoring by luminescence decay time measurements from subsurface layers.

- Multilayer design makes TBC a more effective radiation barrier.
  - A better, more robust approach may be using engineered porosity.

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