Monitoring Delamination of Thermal Barrier Coatings by Near-Infrared and Upconversion Luminescence Imaging


Previous work has demonstrated that TBC delamination can be monitored by incorporating a thin luminescent sublayer that produces greatly increased luminescence intensity from delaminated regions of the TBC. Initial efforts utilized visible-wavelength luminescence from either europium or erbium doped sublayers. This approach exhibited good sensitivity to delamination of electron-beam physical-vapor-deposited (EB-PVD) TBCs, but limited sensitivity to delamination of the more highly scattering plasma-sprayed TBCs due to stronger optical scattering and to interference by luminescence from rare-earth impurities. These difficulties have now been overcome by new strategies employing near-infrared (NIR) and upconversion luminescence imaging. NIR luminescence at 1550 nm was produced in an erbium plus ytterbium co-doped yttria-stabilized zirconia (YSZ) luminescent sublayer using 980-nm excitation. Compared to visible-wavelength luminescence, these NIR emission and excitation wavelengths are much more weakly scattered by the TBC and therefore show much improved depth-probing capabilities. In addition, two-photon upconversion luminescence excitation at 980 nm wavelength produces luminescence emission at 562 nm with near-zero fluorescence background and exceptional contrast for delamination indication. The ability to detect TBC delamination produced by Rockwell indentation and by furnace cycling is demonstrated for both EB-PVD and plasma-sprayed TBCs. The relative strengths of the NIR and upconversion luminescence methods for monitoring TBC delamination are discussed.
Monitoring Delamination of Thermal Barrier Coatings by Near-Infrared and Upconversion Luminescence Imaging

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Objectives

• Improved TBC delamination monitoring using near-infrared (NIR) & upconversion luminescence imaging.
  – Greater transmittance using longer wavelengths
  – Co-doping strategy reduces interference from impurity luminescence
  – Luminescent sublayer fully integrated into TBC
• Monitor delamination progression produced by furnace cycling.
• Evaluate delamination progression for both EB-PVD & plasma-sprayed TBCs.
• Show that added dopants do not reduce TBC life.
Detecting TBC Delamination by Reflectance-Enhanced Luminescence
Er + Yb Co-Doped Sublayer

514 nm illumination

562 nm Er\textsuperscript{3+} emission (intensified by high internal reflectivity)

562 nm Er\textsuperscript{3+} emission

Undoped YSZ

Er + Yb-doped YSZ

NiPtAl bond coat

Rene N5 superalloy substrate

delamination
Detecting TBC Delamination by Reflectance-Enhanced Luminescence
Er + Yb Co-Doped Sublayer

Motivation for erbium + ytterbium co-doping
• $\text{Er}^{3+}$ produces strong NIR luminescence at 1550 nm where TBC is much more transparent.
• $\text{Yb}^{3+}$ is a good absorber of 980 nm excitation and produces luminescence in $\text{Er}^{3+}$ by energy transfer. Luminescence from $\text{Er}^{3+}$ impurities in undoped overlayer are not effectively excited without $\text{Yb}^{3+}$ co-dopant.
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Er + Yb Co-Doped Sublayer

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- Er\(^{3+}\) produces upconversion luminescence at 562 nm with near-zero background for strong delamination contrast.
### Table 1: TBC Transmittance in Plasma-Sprayed vs. EB-PVD

<table>
<thead>
<tr>
<th>Type of Luminescence</th>
<th>$\lambda_{\text{excitation}}$ (nm)</th>
<th>$\lambda_{\text{emission}}$ (nm)</th>
<th>$T_{\text{excitation}}$</th>
<th>$T_{\text{emission}}$</th>
<th>$T_{\text{excitation}} \times T_{\text{emission}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Visible</td>
<td>514</td>
<td>562</td>
<td>1.8%</td>
<td>21.4%</td>
<td>0.10%</td>
</tr>
<tr>
<td>NIR</td>
<td>980</td>
<td>1550</td>
<td>18.8%</td>
<td>37.4%</td>
<td>4.42%</td>
</tr>
<tr>
<td>Upconversion</td>
<td>980</td>
<td>562</td>
<td>18.8%</td>
<td>37.4%</td>
<td>1.02%</td>
</tr>
</tbody>
</table>

**Graph:**
- **TBC Transmittance**
- **Plasma-Sprayed vs. EB-PVD**
- **Wavelength (nm):**
- **% Transmittance:**
  - 173 µm EB-PVD TBC
  - 172 µm plasma-sprayed TBC
NIR and Upconversion Luminescence Imaging

980 nm laser diode via fiber optic

InGaAs NIR camera with 1550 nm bandpass filter

TBC-coated specimen

CCD camera with 562 nm bandpass filter

NIR luminescence image

Upconversion luminescence image
EB-PVD TBCs
Er$^{3+}$ Luminescence Imaging of Scratch-Induced Delamination for EB-PVD TBC with YSZ:Er(1%),Yb(3%) Base Layer

White light image

Luminescence images

514 nm excitation
562 nm emission
1 sec

980 nm excitation
1550 nm emission
16 msec

980 nm excitation
562 nm emission
6 sec

Line Scans across Delaminated EB-PVD TBC Region

YSZ

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

NiPtAl

Rene N5

Normalized Intensity

X (mm)
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

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  620 cycles + 1 week  130 μm  6 μm

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

2 sec acquisition
Log 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

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<th>0 cycles</th>
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<th>10 cycles</th>
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<th>80 cycles</th>
<th>100 cycles</th>
<th>120 cycles</th>
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<tr>
<th>140 cycles</th>
<th>160 cycles</th>
<th>180 cycles</th>
<th>200 cycles</th>
<th>220 cycles</th>
<th>240 cycles</th>
<th>260 cycles</th>
<th>280 cycles</th>
<th>300 cycles</th>
<th>320 cycles</th>
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<th>340 cycles</th>
<th>360 cycles</th>
<th>380 cycles</th>
<th>400 cycles</th>
<th>420 cycles</th>
<th>440 cycles</th>
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YSZ
YSZ:Er(1%),Yb(3%)
NiPtAl
Rene N5
Change in Luminescence Intensity with Furnace Cycling

![Graph showing the change in luminescence intensity ratio with furnace cycling. The y-axis represents luminescence intensity ratio, and the x-axis represents furnace cycles. The line graph indicates an increasing trend with cyclical fluctuations.]
Change in Luminescence Intensity with Furnace Cycling

Furnace Cycles

Luminescence Intensity Ratio

Furnace Cycles

- 562 nm upconversion
- 1550 nm NIR
Plasma-Sprayed TBCs
Partitioned Multilayer Coating Design

Top View

PS-YSZ

PS-YSZ

YSZ:Er,Yb

25 µm

PS-YSZ

PS-YSZ

NiCr

YSZ:Er,Yb

25 µm

5 µm

White light image

PS-8YSZ

YSZ:Er,Yb

NiCr

50 µm
NIR & Upconversion Luminescence Imaging of YSZ:Eu,Yb below Metco PS-8YSZ
Shows Tremendous Sensitivity to Attached Substrate

top coat thickness ➔ 145 µm 190 µm 230 µm 430 µm

White light

NIR
980 nm excitation
1550 nm emission
12 msec acquisition

Upconversion
980 nm excitation
562 nm emission
25 sec acquisition
Line Scans Showing NIR & Upconversion Delamination Enhancement

- **NIR 1550 nm**
- **Upconversion 562 nm**

- **PS-YSZ**
- **YSZ:Er,Yb**
- **NiCr**

~2x enhancement

~15x enhancement
NIR Luminescence Imaging Monitors Advancing Delamination Front During Interrupted Furnace Cycling of Plasma-Sprayed TBC with YSZ:Er(1%),Yb(3%) Base Layer

![Image showing images of delamination fronts after different cycles.](image-url)
NIR Luminescence Imaging Monitors Advancing Delamination Front During Interrupted Furnace Cycling of Plasma-Sprayed TBC with YSZ:Er(1%), Yb(3%) Base Layer

Line Scan across Delamination Front

~35% enhancement

0 cycles
10 cycles
20 cycles

~110 µm
~20 µm
NiCrAlY
Rene N5

Intensity

X (mm)
Effect of YSZ:Er,Yb Base Layer Microstructure on Delamination Contrast

Vertical boundaries of columnar microstructure does not impede downward light propagation (wave guide).

No scattering of downward propagating light in base layer. Many boundaries in overlayer to reflect light back into base layer.

Splat microstructure of base layer is highly scattering.

Substantial reduction of luminescence by attached substrate absorption.

Near-complete absorption of luminescence by attached NiCr layer.

Less absorption of luminescence by attached substrate absorption since there is significant scattering within base layer.

Excellent delamination contrast

Superb delamination contrast

Modest delamination contrast
Summary

• NIR & upconversion luminescence imaging offer improved detection of TBC delamination progression.
  – Upconversion luminescence imaging
    • Enhanced contrast for discriminating between finer gradations of TBC delamination progression in EB-PVD TBCs.
  – NIR luminescence imaging
    • Superior penetration for detecting delamination in highly scattering plasma-sprayed TBCs.
    – Er\(^{3+}\) + Yb\(^{3+}\) co-doping strategy minimizes interference from Er\(^{3+}\) impurities above the luminescent sublayer.

• Integration of luminescent sublayer achieved (EB-PVD) without reducing TBC life. (in progress)