Detecting Thermal Barrier Coating Delamination Using Visible and Near-Infrared Luminescence from Erbium-Doped Sublayers,
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Nondestructive diagnostic tools are needed to monitor early stages of delamination progression in thermal barrier coatings (TBCs) because the risk of delamination-induced coating failure will compromise engine performance and safety. Previous work has demonstrated that for TBCs composed of yttria-stabilized zirconia (YSZ), luminescence from a buried europium-doped sublayer can be utilized to identify the location of TBC delamination from the substantially higher luminescence intensity observed from the delaminated regions of the TBC. Luminescence measurements from buried europium-doped layers depend on sufficient transmittance of the 532 nm excitation and 606 nm emission wavelengths through the attenuating undoped YSZ overlayer to produce easily detected luminescence. In the present work, improved delamination indication is demonstrated using erbium-doped YSZ sublayers. For visible-wavelength luminescence, the erbium-doped sublayer offers the advantage of a very strong excitation peak at 517 nm that can be conveniently excited a 514 nm Ar ion laser. More importantly, the erbium-doped sublayer also produces near-infrared luminescence at 1550 nm that is effectively excited by a 980 nm laser diode. Both the 980 nm excitation and the 1550 nm emission are transmitted through the TBC with much less attenuation than visible wavelengths and therefore show great promise for delamination monitoring through thicker or more highly scattering TBCs. The application of this approach for both electron-beam physical vapor deposited (EB-PVD) and plasma-sprayed TBCs is discussed.
Detecting Thermal Barrier Coating Delamination Using Visible and Near-Infrared Luminescence from Er-Doped Sublayers

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Background

- Practical & reliable nondestructive diagnostic tools needed for informed assessment of TBC delamination progression & remaining life.
- Two recent approaches have shown promise for monitoring TBC delamination progression:
  - Mid-infrared (MIR) reflectance imaging
  - Luminescence from Eu-doped sublayer.
- Thicker plasma-sprayed TBCs remain difficult.
Motivation for erbium doping

- Produces strong NIR luminescence at wavelength where TBC is much more transparent.
- Produces strong upconversion luminescence with near-zero background.
Er$^{3+}$ Energy Level Diagram
Visible Luminescence

Excitation by laser or LED

Emission

Er$^{3+}$ $^{4}I_{15/2}$

$^{4}I_{13/2}$

$^{4}I_{11/2}$

$^{4}I_{9/2}$

$^{4}F_{9/2}$

$^{4}S_{3/2}$

$^{2}H_{11/2}$

$^{4}F_{7/2}$

450 470 490 510 530 550 570 590

Wavelength (nm)

Emission Intensity

514 nm

488 nm

517 nm

525 nm

545 nm

562 nm

Ar$^{+}$ laser

Er$^{3+}$
Er\(^{3+}\) Energy Level Diagram
NIR Luminescence

Excitation by laser diode

Energy transfer

Emission
Er$^{3+}$ Energy Level Diagram

Upconversion Luminescence

- Excitation by laser diode
- Energy transfer
- Emission

Levels:
- $4F_{7/2}$
- $2H_{11/2}$
- $4S_{3/2}$
- $4I_{15/2}$
- $4I_{13/2}$
- $4I_{11/2}$
- $4I_{9/2}$
- $4F_{9/2}$

Transition Wavelengths:
- 980 nm
- 562 nm
- 662 nm
- 086 nm
Effect of Wavelength on Luminescence Attenuation
172 μm plasma-sprayed TBC

% Transmittance

Wavelength (nm)

4000 nm, T = 35.3%
1550 nm, T = 23.5%
980 nm, T = 18.8%
562 nm, T = 5.4%
514 nm, T = 1.8%
NIR and Upconversion Luminescence Imaging

- 980 nm laser diode
- Fiber optic
- Collimating lens
- InGaAs NIR camera
- 1550 nm bandpass filter
- TBC-coated specimen
- CCD camera
- 562 nm bandpass filter
- Upconversion luminescence image
- NIR luminescence image
Er\textsuperscript{3+} Luminescence Imaging of Scratch-Induced Delamination for EB-PVD TBC with YSZ:Er(1%),Yb(3%) Base Layer

White light image

Luminescence images

YSZ

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

PtAl

Rene N5

Line Scans across Delaminated EB-PVD TBC Region

Normalized Intensity

514 nm excitation
563 nm emission
1 sec

980 nm excitation
1550 nm emission
16 msec

980 nm excitation
560 nm emission
6 sec

125 \mu m

12 \mu m

[Diagram with line scans and intensity graph]
Plasma-Sprayed TBCs
Partitioned Multilayer Coating Design

Top View

White light image

PS-8YSZ

YSZ:Eu

NiCr

UV illumination

PS-YSZ

YSZ:Er,Yb

10 μm

5 μm

NiCr

10 μm

5 μm

50 μm
### Er$^{3+}$ Luminescence Image of Freestanding Plasma-Sprayed YSZ Coating with Partitioned Backside YSZ:Er,Yb & NiCr Coatings

<table>
<thead>
<tr>
<th>White light</th>
<th>MIR Reflectance</th>
<th>Visible</th>
<th>NIR</th>
<th>Upconversion</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image" alt="White light" /></td>
<td><img src="image" alt="MIR Reflectance" /></td>
<td><img src="image" alt="Visible" /></td>
<td><img src="image" alt="NIR" /></td>
<td><img src="image" alt="Upconversion" /></td>
</tr>
</tbody>
</table>

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

**Details:**
- **White light**
  - 4.0 μm incident
  - 4.0 μm reflected

**MIR Reflectance**
- 33 msec
- 4 min

**Visible**
- 514 nm excitation
- 562 nm emission

**NIR**
- 980 nm excitation
- 1550 nm emission

**Upconversion**
- 980 nm excitation
- 562 nm emission

- **YSZ:Er,Yb** below 10 μm
- **PS-8YSZ** below 145 μm
- **YSZ:Er,Yb** below 435 μm
- **NiCr** below 10 μm
Line Scans Traversing Border between “Attached” & “Delaminated” Sections of Plasma-Sprayed TBC

- MIR reflectance: NIR 1550 nm, upconversion 562 nm
- YSZ:Er,Yb
- PS-YSZ

Y (mm)

Normalized Intensity

40 35 30 25 20 15 10 5 0

~25x

~2x

~1.25x 15

145 μm

10 μm

5 μm

NiCr
# TBC Delamination Detection Score Card

<table>
<thead>
<tr>
<th>Method</th>
<th>Modified TBC required</th>
<th>Delamination sensitivity</th>
<th>Fast</th>
<th>Thick PS-TBCs</th>
<th>Expensive camera needed</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>EB-PVD</td>
<td>PS</td>
<td></td>
</tr>
<tr>
<td>Visual inspection</td>
<td>No</td>
<td>✓</td>
<td>X</td>
<td>✓ ✓ ✓</td>
<td>X ✓</td>
</tr>
<tr>
<td>MIR reflectance</td>
<td>No</td>
<td>--</td>
<td>✓</td>
<td>✓ ✓ ✓</td>
<td>X ✓ ✓ ✓</td>
</tr>
<tr>
<td>Luminescence</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Visible excitation &amp; emission</td>
<td>✓ ✓ ✓ ✓ ✓</td>
<td>✓ ✓ ✓ ✓ ✓ ✓</td>
<td>✓ ✓ ✓ ✓</td>
<td>X ✓ ✓ ✓ ✓ ✓</td>
<td>X ✓ ✓ ✓ ✓ ✓ ✓</td>
</tr>
<tr>
<td>NIR excitation &amp; emission</td>
<td>✓ ✓ ✓ ✓ ✓</td>
<td>✓ ✓ ✓ ✓ ✓ ✓</td>
<td>✓ ✓ ✓ ✓</td>
<td>✓ ✓ ✓ ✓ ✓ ✓</td>
<td>✓ ✓ ✓ ✓ ✓ ✓</td>
</tr>
<tr>
<td>Upconversion NIR excitation visible emission</td>
<td>✓ ✓ ✓ ✓ ✓</td>
<td>✓ ✓ ✓ ✓ ✓ ✓</td>
<td>✓ ✓ ✓ ✓</td>
<td>X ✓ ✓ ✓ ✓</td>
<td>X ✓ ✓ ✓ ✓</td>
</tr>
</tbody>
</table>

- **EB-PVD**: Effective for delamination detection
- **PS**: Poor for delamination detection
- **Fast**: Fast detection method
- **Thick PS-TBCs**: Suitable for thick PS-TBCs
- **Expensive camera needed**: Requires an expensive camera.
Advantages of Er + Yb Co-Doping for TBC Delamination Detection

- Produces NIR and upconversion luminescence offering *exceptional* thickness probing and delamination contrast.
- Yb-assisted excitation “turns on” luminescence in co-doped sublayer *without* “turning on” interfering luminescence from Er impurities in undoped overlayer.
Acknowledgments

• Dennis Fox (plasma spraying)
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