In-situ Optical Monitoring of Operating Gas Turbine Blade Coatings Under Extreme Environments

2020 Sensors and Controls Project Review Meeting
Quentin Fouliard, Post-doctoral Fellow
Co-PI: Ranajay Ghosh
PI: Seetha Raghavan

https://aerostructures.cecs.ucf.edu/

Aug 26, 2020
Overall goals

- Develop and demonstrate at the laboratory scale an advanced optical suite of instrumentation technologies for enhanced monitoring of gas turbine thermal barrier coatings (TBCs).

- Specific goals are to improve the accuracy and effectiveness of temperature and strain measurements made on high temperature gas turbine blades.

Project Objectives

- Achieve intelligent sensing that leverages intrinsic properties of coatings and dopants through optical emission and absorption characteristics while ensuring coating integrity and durability goals are concurrently met.

- Achieve accurate diagnostics of turbine blade coatings under operating environments.

- Achieve advances in benchmarked optical measurement technologies in existing laboratory replicated environments.

Project Tasks

**Task 1:** Project Management & Planning
**Task 2:** Define and manufacture sensor configuration
**Task 3:** Establish Sensing Properties and Characterize Coating Response for Luminescence Based Sensor
**Task 4:** Perform Non-Intrusive Benchmarking Measurements of Surface Temperature and Strain
**Task 5:** Develop and Test Laboratory Scale Sensor Instrumentation Package
Overview of project advancement and results

- **Background, Motivations & Objectives**
  - Thermal Barrier Coatings and their benefits
  - Need for **higher accuracy of temperature measurements**
  - Need for **improved method for coating damage monitoring**

- **Phosphor Thermometry experimentation**
  - Phosphor Thermometry system setup
  - Decay and intensity results on an innovative co-doped YSZ:Er,Eu coating
  - Modeling results and measurements in the presence of a thermal gradient

- **Coating damage monitoring**
  - Coating delamination monitoring concept
  - Modeling results
  - Experimental results
  - Luminescence trade-offs and coating optimization

- **Conclusions and perspectives**
Background, Motivations & Objectives
Thermal barrier coatings (TBCs) used in combination with air cooling to protect metal substrates from extreme temperatures in the high-pressure turbine (1300 - 1600°C)

- Air film cooling: $\Delta T = -100$ to $-400$°C

- TBC: $\Delta T = -150$ to $-200$°C [3,4,5,6]

- Major applications:
  - Aeroengines
  - Power generation engines

---

Background / Motivations / Obj.
Phosphor Thermometry meas.
Coating damage monitoring
Conclusions / Perspectives
## Review of TBC materials properties

<table>
<thead>
<tr>
<th>TBC layer</th>
<th>Top coat</th>
<th>TGO</th>
<th>Bond coat</th>
</tr>
</thead>
<tbody>
<tr>
<td>Typical composition</td>
<td>7-8wt.% YSZ</td>
<td>Al₂O₃</td>
<td>NiCrAlY / PtAl</td>
</tr>
<tr>
<td>Thermal conductivity $\lambda$ at 1100°C (W/(m·K))</td>
<td>1-3 [1,2,4,5]</td>
<td>5-6 [4,6]</td>
<td>34 [5]</td>
</tr>
<tr>
<td>Coefficient of thermal expansion $\alpha$ ($\times 10^{-6}$ K⁻¹)</td>
<td>11-13 [3,4,7,8]</td>
<td>7-10 [3,7,8,9]</td>
<td>13-16 [3,7,8,9]</td>
</tr>
<tr>
<td>Toughness $K$ (MPa·√m)</td>
<td>0.7-2.2 [7,10]</td>
<td>2.8-3.2 [7,11]</td>
<td>&gt;20 [7]</td>
</tr>
<tr>
<td>Poisson’s ratio $\nu$</td>
<td>0.2 [8]</td>
<td>0.2-0.25 [8,9]</td>
<td>0.3-0.33 [8,9]</td>
</tr>
<tr>
<td>Oxygen diffusivity at 1000°C (m²/s)</td>
<td>$10^{-11}$ [4]</td>
<td>$10^{-19}$-$10^{-21}$ [4,6]</td>
<td>-</td>
</tr>
<tr>
<td>Crystal microstructure (phase)</td>
<td>Stable up to</td>
<td>$t'$</td>
<td>$\alpha$</td>
</tr>
<tr>
<td></td>
<td>1200°C [12]</td>
<td>1750°C</td>
<td>1050°C</td>
</tr>
</tbody>
</table>

TGO formation in TBCs
Importance of controlling the operating temperature

- Logarithmic growth limited by the low oxygen diffusivity through the TGO:

\[ 3\beta\text{NiAl} + \frac{3}{2} O_2 \rightarrow \gamma'\text{Ni}_3\text{Al} + \alpha\text{Al}_2\text{O}_3 \]


Temperature drives oxide growth in TBCs and is a key factor in coating failure


Jackson, R, PhD dissertation *University of Birmingham* (2009)

Phase stability in Thermal Barrier Coatings (TBCs)

Importance of controlling the operating temperature

- **Standard top coat material**: 7-8 wt.% (4-4.5 mol.%) YSZ optimal for resistance to spallation and thermal stability [Patnaik, P. et al, National Research Council Of Canada Ottawa, Ontario (2006)]

- Y³⁺ introduces oxygen vacancies that stabilizes t’
  - High temperature sintering of t’-YSZ:
    - Crack forming
  - t’ phase stable up to 1200°C:
    - t’ → t + c → m + c
      - 1200°C
      - 600°C
    - \( \Delta V = +4\% \)

**Accurate control of TBC operating temperature is needed to control degradation of coatings.**

Significance of TBC temperature measurements

- State-of-the-art TBCs are not being used to their highest potential because of uncertainties in temperature measurements at high-temperature.
  - Safety margins as high as 200°C are used.

- Ideal Brayton cycle efficiency: $\eta = 1 - \frac{T_c}{T_t}$
  $\eta$: cycle efficiency, $T_c/T_t$: temperature ratio compressor exit / turbine inlet.

- 1% efficiency improvement can save $20m in fuel over the combined-cycle plant life.

- A 130°C increase leads to a 4% increase in engine efficiency.

- Failure mechanisms are driven by temperature conditions in the depth of the TBC.

**Problem statement:**
Accurate determination of thermal gradients in Thermal Barrier Coatings (TBCs) is critical for the safe and efficient operation of gas turbine engines. Failure mechanisms are thermally activated during engine operation, uncertainty in temperature measurements contribute significantly to lifetime uncertainty.


Background / Motivations / Obj. | Phosphor Thermometry meas. | Coating damage monitoring | Conclusions / Perspectives
Measurement techniques for *in-situ* temperature evaluation of TBCs

<table>
<thead>
<tr>
<th></th>
<th>Thermocouples</th>
<th>Infrared Thermometry</th>
<th>Phosphor Thermometry</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Temperature range (°C)</strong></td>
<td>-250 – 2320</td>
<td>-50 – 2000</td>
<td>-250 – 1700</td>
</tr>
</tbody>
</table>

**Advantages**
- Inexpensive
- Wide temperature range
- Wide temperature range
- Non contact method
- Fast response time
- Non contact method
- High sensitivity at high temperatures
- Fast response time
- Usable on rotating parts
- Low sensitivity to turbine environment (aging and contamination)

**Drawbacks**
- Intrusive probe
- Disrupts flow patterns
- Not chemically stable in all environments
- Low accuracy
- Unusable on rotating surfaces
- Optical access required
- Sensitive to stray light (flames)
- Sensitive to emissivity variations
- Optical access required
- Signal weakening at high temperatures

---

**Gas turbine efficiency**

**Components lifetime**

---

**Background / Motivations / Obj.**
- Phosphor Thermometry meas.
- Coating damage monitoring
- Conclusions / Perspectives
Other critical failure mechanisms: Foreign object damage / Erosion
Importance of controlling coating health

- Unpredictability of the impact damage/erosion
- Amount of degradation
  → **Importance of improving methods for detection and quantification of delamination**

---


Direct damage monitoring methods

- Thermal/optical imaging techniques;
  - Infrared thermography in mid-wave or long-wave infrared, post-exposition to an intense heat source (generally a flash of light).
  - Tomography
  - Laser scattering
  - Luminescence-based mapping (in-situ or ex-situ monitoring), under excitation at specific wavelength.

Luminescence imaging provides:

- Finer spatial resolution
- Richer information through spectral features
Proposed solutions & key objectives

• Better temperature control in gas turbine engines is needed to improve efficiency and reduce maintenance costs
  → Implementation of phosphor thermometry instrumentation with accuracy/precision improvement vs. current state-of-the-art
  → Determination of precise sub-surface location of phosphor thermometry measurement point

• Intense operation of TBC systems result in coating failure that impacts engine availability
  → Development of a novel approach for delamination monitoring using luminescent coatings (compatible with phosphor thermometry coatings)
Phosphor Thermometry measurements

*Part of tasks 2, 3, 4 & 5*
Thermal quenching accelerates decay due to higher probability of vibrational deexcitation. Knappe, C. PhD dissertation Lund University (2013)

Higher sensitivity of the decay method in comparison with the intensity ratio method but often limited to a reduced temperature range. Heeg, et al. AIP Conference Proceedings, Vol. 1552, (2013)
Instrumentation developed for synchronized luminescence decay collection

Parameters:
Nd:YAG 532 nm
0.5 mJ pulse
10 Hz
20 ns pulse duration

Sample:
Air Plasma Spray (UCF team @ FIT, Melbourne, FL, USA)
YSZ:Er,Eu [1.5% Er, 3% Eu]
(Phosphor Technology, UK)
Annealed 2h @ 800°C

Fouliard et al., Measurement Science & Technology, 2020

Background / Motivations / Obj.  Phosphor Thermometry meas.  Coating damage monitoring  Conclusions / Perspectives
Extension of temperature range vs. state-of-the-art

- Luminescence of Europium is quenched rapidly past 500°C, for high sensitivity measurements up to 850°C where reaching detector response limit.
- Temperature range extended by collecting the ratio of the normalized intensity variation Erbium/Europium.

Fouliard et al., *Measurement Science & Technology*, 2020

Simultaneous acquisition at 500°C
Instrumentation developed for sub-surface temperature measurements

**Parameters:**
- Nd:YAG 532 nm
- 0.5 mJ pulse
- 10 Hz
- 20 ns pulse duration

**Sample:**
- Air Plasma Spray (UCF team @ FIT, Melbourne, FL, USA)
- YSZ:Er [1.5% Er] (Phosphor Technology, UK)
- Annealed 2h @ 800°C

**Equation:**
\[ R_{thermal} = R_{topcoat} + R_{bondcoat} + R_{substrate} \]

**Graph:**
- YSZ:Er spectrum
- 560 nm bandpass

**Background / Motivations / Obj.:**
- Phosphor Thermometry meas.
- Coating damage monitoring

**Conclusions / Perspectives:**
- "AIAA Scitech Forum 2020"
Determination of reference decays: isothermal case

- Calibration of the sensor response is achieved using a furnace that includes through holes for thermocouple and luminescence measurements.
- Fit: Temperature-dependent multi-phonon relaxation model for the $^4S_{3/2} \rightarrow ^4I_{15/2}$ transition combined with a model to account for the other thermally populated levels.

Inside view

Outside view

YSZ:Er (562 nm)
New method proposed for Phosphor Thermometry for sub-surface measurements
Sub-surface temperature point was successfully measured

Model sub-surface location prediction for the temperature measurement:

\[ T_{\text{measured}} \]

150 µm

\[ P_{eq} = 38 \mu m \]

YSZ:Er

Doped top coat
Bond coat
Substrate

Erbium luminescence decays

High temperature gas plume

Laser

Thermocouple

Lifetime decay (µs)

Surface temperature (°C)

565°C sub-surface

0 2 4 6 8 10

Fouliard, Raghavan et al., AIAA Scitech Forum 2020

Background / Motivations / Obj. Phosphor Thermometry meas. Coating damage monitoring Conclusions / Perspectives
Coating damage monitoring

Part of tasks 3 & 4
Modeling delamination

Diffuse external reflectivity
\[
\rho_0(n) = \frac{1}{2} + \frac{(3n + 1) \cdot (n - 1)}{6 \cdot (n + 1)^2} + \frac{n^2 \cdot (n^2 - 1)^2 \cdot \ln(n - 1)}{(n^2 + 1)^3} + \frac{2n^3 \cdot (n^2 + 2n - 1)}{(n^2 + 1) \cdot (n^4 - 1)} + \frac{8n^4 \cdot (n^4 + 1)}{(n^2 + 1) \cdot (n^4 - 1)^2} \cdot \ln(n)
\]

Max diffuse internal reflectivity
\[
\rho_{i,max}(n) = (1 - \frac{1}{n^2}) + \frac{\rho_0(n)}{n^2}
\]

Frustrated angle-averaged reflectivity
\[
\overline{R}_f(d) = \frac{\int_0^{2\pi} \int_0^{\frac{\pi}{2}} \cos \theta \cdot \sin \theta \cos \varphi \cdot \sin \alpha \cdot \sinh^2(\beta \cdot d) \cdot \frac{1}{1 + \alpha \cdot \sin^2(\beta \cdot d)} \, d\theta \, d\varphi}{\int_0^{2\pi} \int_0^{\frac{\pi}{2}} \cos \theta \cdot \sin \theta \cos \varphi \, d\theta \, d\varphi}
\]

\[
\alpha_\perp = \frac{(n^2 - 1)^2}{4n^2 \cdot \cos^2 \theta \cdot (n^2 \sin^2 \theta - 1)}
\]

\[
\alpha_\parallel = \alpha_\perp \cdot \frac{(n^2 \sin^2 \theta \cdot (n^2 + 1) - 1)}{n^2 \sin^2 \theta - 1}
\]

\[
\overline{R}_{f,unp} = \frac{\overline{R}_{f,\perp} + \overline{R}_{f,\parallel}}{2}
\]

\[
\beta = \frac{2\pi}{\lambda_0} \sqrt{n^2 \cdot \sin^2 \theta - 1}
\]

\[
\rho_i(d) = \overline{R}_{f,unp}(d) \cdot \left(1 - \frac{1}{n^2}\right) + \frac{\rho_0(n)}{n^2}
\]

---


<table>
<thead>
<tr>
<th>Layer</th>
<th>n</th>
<th>(\rho_{i,max})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air</td>
<td>1</td>
<td>84%</td>
</tr>
<tr>
<td>Top coat</td>
<td>2.17</td>
<td>39%</td>
</tr>
<tr>
<td>TGO</td>
<td>1.76</td>
<td>4%</td>
</tr>
<tr>
<td>Top coat - Bond coat</td>
<td>4%</td>
<td></td>
</tr>
</tbody>
</table>

![Diagram](image-url)
Model prediction of delamination-induced luminescence contrast

\[ Y_{\lambda}(x) = [I_{t,\lambda}(x), J_{t,\lambda}(x), I_{m,\lambda}(x), J_{m,\lambda}(x), I_{b,\lambda}(x), J_{b,\lambda}(x)]^T \]

\[ A_{z,\lambda} = \begin{pmatrix}
-(K_{z,\lambda} + S_{z,\lambda}) & S_{z,\lambda} \\
S_{z,\lambda} & K_{z,\lambda} + S_{z,\lambda}
\end{pmatrix}
\]

\[ Q_{\lambda} = \frac{1}{2} \left( -q_{z} K_{z,\ell} - q_{z} K_{z,\ell} \right) \]

\[ \frac{dY_{\ell}(x)}{dx} = \begin{pmatrix} A_{t,\ell} & 0 & 0 \\
0 & A_{m,\ell} & 0 \\
0 & 0 & A_{b,\ell}
\end{pmatrix} \cdot Y_{\ell}(x) \]

\[ \frac{dY_{\ell}(x)}{dx} = \begin{pmatrix} A_{t,\ell} & 0 & 0 \\
0 & A_{m,\ell} & 0 \\
0 & 0 & A_{b,\ell}
\end{pmatrix} \cdot Y_{\ell}(x) + \begin{pmatrix} Q_{t} & 0 & 0 \\
0 & Q_{m} & 0 \\
0 & 0 & Q_{b}
\end{pmatrix} \cdot Y_{\ell}(x) \]


Delamination monitoring: Comparison experiment vs. model

Delamination monitoring: Luminescence trade-off for delamination detection

## Conclusions & Perspectives

<table>
<thead>
<tr>
<th>Background / Motivations / Obj.</th>
<th>Phosphor Thermometry meas.</th>
<th>Coating damage monitoring</th>
<th>Conclusions / Perspectives</th>
</tr>
</thead>
</table>
Conclusions

- Precise determination of temperatures in TBCs can result in large benefits in terms of fuel savings, reduction of emission, as well as better monitoring of TBC lifetime.

- Enabled the extension of the range of measurable temperatures using Phosphor Thermometry with higher sensitivity by capturing simultaneously luminescence decays and intensities out of a co-doped YSZ:Er,Eu top layer.

- Improved sub-surface temperature measurements using TBC in the presence of a thermal gradient.

- Enabled accurate determination of delamination in coatings through a novel modeling approach, validated with experiments.
  - For the first time, a configuration with a thin sensing layer placed at the top surface was able to track an underlying delamination area (located below a thick YSZ intermediate layer) with high luminescence intensity for fast acquisition.
  - Sensor TBC configuration can be optimized for erosion and delamination tracking using the results of the model.
Future work

• Additional synchrotron experiments for rare-earth doped EB-PVD TBC strain measurements to further establish the effects of rare-earth dopant addition to coating strains (collaboration: GE Research, Argonne National Lab).

• Model adaptation and experimentation using high-emissivity paints for improved temperature measurements on painted TBCs (collaborator: GE Aviation).

Provided acceptance of extension proposal

• Adaptation of the instrumentation to operate on a combustor / turbine section (the current project successfully demonstrated lab-scale functionality as planned – the existing built-up could now be adapted to rapidly increase its technology readiness level).
Publications

• Quentin Fouliard, Ranajay Ghosh, Seetha Raghavan, “Quantifying thermal barrier coating delamination through luminescence modeling”, Surface and Coatings Technology, 126153, 2020

• Quentin Fouliard, Johnathan Hernandez, Bauke Heeg, Ranajay Ghosh, Seetha Raghavan, “Phosphor Thermometry Instrumentation for Synchronized Acquisition of Luminescence Lifetime Decay on Thermal Barrier Coatings”, Measurement Science and Technology 31(5), 054007, 2020

• Quentin Fouliard, Sandip Haldar, Ranajay Ghosh, and Seetha Raghavan. “Modeling luminescence behavior for phosphor thermometry applied to doped thermal barrier coating configurations.” Applied Optics 58(13), D68-D75, 2019


Patents


Acknowledgments

This material is based upon work supported by the U.S. Department of Energy, National Energy Technology Laboratory, University Turbine Systems Research (UTSR) under Award Number: DE-FE0031282.
THANK YOU FOR YOUR ATTENTION

CONTACT EMAILS AND WEBSITE
seetha.raghavan@ucf.edu
quentin@knights.ucf.edu

https://aerostructures.cecs.ucf.edu/
Modeling Luminescence Intensity

Four-flux Kubelka-Munk model to account for scattering and absorption of light

\[
Y_{\text{laser}}(x) = \begin{pmatrix} I_{\text{laser}}(x) \\ J_{\text{laser}}(x) \end{pmatrix} \quad Y_{\text{lum}}(x) = \begin{pmatrix} I_{\text{lum}}(x) \\ J_{\text{lum}}(x) \end{pmatrix}
\]

\[
\frac{dY_{\text{laser}}(x)}{dx} = AY_{\text{laser}}(x) \quad \frac{dY_{\text{lum}}(x)}{dx} = AY_{\text{lum}}(x) + QY_{\text{laser}}(x)
\]

\[
A_{\text{laser}} = \begin{pmatrix} -(K_{\text{laser}} + S_{\text{laser}}) & S_{\text{laser}} \\ -S_{\text{laser}} & K_{\text{laser}} + S_{\text{laser}} \end{pmatrix}
\]

\[
A_{\text{lum}} = \begin{pmatrix} -(K_{\text{lum}} + S_{\text{lum}}) & S_{\text{lum}} \\ -S_{\text{lum}} & K_{\text{lum}} + S_{\text{lum}} \end{pmatrix}
\]

\[
Q = \begin{pmatrix} \frac{qK_{\text{laser}}}{2} & \frac{qK_{\text{laser}}}{2} \\ -\frac{qK_{\text{laser}}}{2} & -\frac{qK_{\text{laser}}}{2} \end{pmatrix}
\]

\[
S \equiv 2s \quad K \equiv 2k.
\]

\[
\lambda \quad (\text{nm}) \quad s \quad (\text{m}^{-1}) \quad k \quad (\text{m}^{-1})
\]

<table>
<thead>
<tr>
<th>(\lambda) (nm)</th>
<th>(s) (m(^{-1}))</th>
<th>(k) (m(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>355 (exc. Dy)</td>
<td>50866</td>
<td>511</td>
</tr>
<tr>
<td>532 (exc. Er, Sm)</td>
<td>33026</td>
<td>111</td>
</tr>
<tr>
<td>545 (em. Er)</td>
<td>32113</td>
<td>107</td>
</tr>
<tr>
<td>590 (em. Dy)</td>
<td>29585</td>
<td>95</td>
</tr>
<tr>
<td>619 (em. Sm)</td>
<td>28685</td>
<td>90</td>
</tr>
</tbody>
</table>

Scattering and absorption coefficients / Excitation and emissions wavelengths used for the modeling study
Modeling Luminescence Intensities – Results of Kubelka-Munk model


<table>
<thead>
<tr>
<th>Configuration</th>
<th>Description</th>
<th>Intensity (AU)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1</td>
<td>Fully doped coating</td>
<td>4.3</td>
</tr>
<tr>
<td>C2</td>
<td>Embedded layer of doped YSZ</td>
<td>1.0</td>
</tr>
</tbody>
</table>

(C1): 250 μm thick doped layer

(C2): 50 μm thick doped layer buried at 50 μm

<table>
<thead>
<tr>
<th>Collectable luminescence intensity</th>
<th>J_{lum}(0)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(C1)</td>
<td>4.3</td>
</tr>
<tr>
<td>(C2)</td>
<td>1.0</td>
</tr>
</tbody>
</table>
Luminescence decay behavior in doped TBC configurations

Modified Kubelka-Munk model

- Phosphor Thermometry based on the decay method is more sensitive to temperature variation than intensity-based methods.
- Classical Kubelka-Munk model provides only luminescence intensity distributions.
- Modeling decay is therefore important to understand the effect of TBC configurations.
- I developed a modified Kubelka-Munk model to predict decay behavior of the luminescence:

\[
\phi = e^{-t/\tau(x)}
\]

\[
\frac{dY_{lum}(x, t)}{dx} = A_{lum}Y_{lum}(x, t) + \phi QY_{laser}(x)
\]

- A gradient of temperature exists in real operating conditions.
- The emerging luminescence is a convoluted signal coming from all the locations in the doped layer.

Luminescence decay behavior in doped TBC configurations

Modified Kubelka-Munk model

\[
\phi = e^{-t/\tau(x)}
\]

\[
\frac{dY_{lum}(x, t)}{dx} = A_{lum}Y_{lum}(x, t) + \phi QY_{laser}(x)
\]

- The gradient of temperature can be calculated using thermal conductivities of the materials.

- The function \( \tau(x) \) is determined from the temperature distribution across the coating, \( T(x) \)

- The objective of the modified model is to predict the equivalent position – indicating at which depth the Phosphor Thermometry system is making its measurement.

Luminescence decay behavior in doped TBC configurations

Extension of Kubelka-Munk model - Results

- The decay constant fitted for any configuration can be associated with a particular position of the top coating.

- The decay constant is found to match with that of the luminescence generated at 37 μm in-depth for (C1).

- In case of TBC with a doped layer (C2) of thickness 50 μm and positioned at 50 μm, the decay constant is the same as the luminescence from a position of depth 69 μm.

Results for YSZ:Dy for 325 doped TBC configurations (resolution 10 μm)

Luminescence decay behavior in doped TBC configurations

Extension of Kubelka-Munk model - Results

Results for YSZ:Er for 325 doped TBC configurations (resolution 10 μm)

Results for YSZ:Sm for 325 doped TBC configurations (resolution 10 μm)