DEVELOPMENT OF NDE METHODS FOR CERAMIC COATINGS

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Outline

• Background on TBC degradation and NDE
• Objectives of this project
• NDE developments for TBC systems
  – Method development/validation
  – NDE for industrial components
• NDE for TBC life prediction
• Summary
• Planned future efforts
Background

- Thermal barrier coatings (TBCs) are required for high-temperature metallic components in advanced gas turbines to be operated at higher efficiency and low emission
  - TBCs may reduce metal surface temperature by >100°C

- TBCs have become “prime reliant” material → their condition monitoring and lifetime prediction by NDE is important

Temperature drop schematics

Uncoated and TBC-coated blades

From Feuerstein et al, 2008
TBC Materials and Structures

- Standard TBC material is 7-8wt% yttria stabilized zirconia (7-8YSZ)
  - Multi-ceramic-layer TBCs are being developed
- TBC is usually applied by air plasma spraying (APS) or electron-beam – physical vapor deposition (EB-PVD)
  - Both thermal conductivity and thickness are important TBC parameters
- Because TBC is applied on component surface, its inspect over entire surface (by imaging NDE methods) is necessary
TBC Property/Structural Change in Life

- Two characteristic changes:
  - (1) TBC continuously sinters with conductivity increase
  - (2) Cracks and delaminations develop near interface

- Quantitative NDEs are required to detect both changes for life prediction
  - To measure material property changes
  - To determine property – structure relationship (for entire TBC life)
NDE Applications for TBCs

• Many NDE technologies have been studied/used for TBCs: thermal imaging, optical (reflection/scatter, emission, spectroscopy, etc), electrochemical, electromagnetic, ultrasonic, x-ray, etc
  – Most are not quantitative
  – Most are not suitable for field application

• NDE for TBC health monitoring and life prediction:
  – A practical NDE method/model has not been established

• NDE for detection of coating flaws (eg, delaminations, FOD):
  – Many NDE methods can detect large flaws; those flaws usually appear near end of TBC life so their detection is of less value
  – Small and deep flaws are difficult to detect but more important

• NDE for quality control of fabricated TBC components:
  – Only single-point thickness measurement is used by manufacturer
  – Current NDE methods are not suitable for TBC property/quality measurement especially for entire TBC-coated component surface
Objectives of This Project

• Develop and evaluate advanced NDE methods for (1) TBC life prediction and (2) high-resolution detection of coating flaws
  – (1) For life prediction (quantitative NDE):
    • thermal multilayer analysis (MLA) method
  – (2) For high-resolution flaw detection
    • thermal tomography (TT) method

• Develop NDE methods for functional materials (gas-separation membrane, fuel cell, etc)
  – Synchrotron x-ray CT, thermal tomography
Recent NDE Developments

• Continued development of two thermal imaging methods
  – Thermal multilayer analysis (MLA) for TBC life prediction
    • Validation of MLA measurement accuracy for TBCs
    • Surface treatment (black paint) material evaluation
    • Development of theoretical models for (1) translucent TBCs and (2) double-layer TBCs
    • Evaluation for testing industrial components
  – Thermal tomography method (3D TT imaging)
    • Continued development of new algorithm for high-resolution imaging

• Continued evaluation of thermal imaging NDE methods for TBC life prediction
  – Collaborations with Siemens and Stony Brook Univ.
Presentation Topics

• Development and application of multilayer analysis MLA method
  – Validation of MLA measurement accuracy
  – Effect of surface paint on TBC property measurement
  – Theoretical development for translucent TBCs
  – Theoretical development for double-layer TBCs
  – Application for a turbine blade

• NDE for TBC life prediction
Thermal Imaging Multilayer Analysis (MLA) Method

- MLA method developed at ANL can measure TBC thermal properties:
  - Two TBC properties: thermal conductivity and heat capacity (or thickness)
  - The only method suitable for field applications (and fully automated)
  - The only method for imaging entire component surface
  - Paper accepted by JHT

One-sided experimental setup

Thermal conductivity imaging

- 0.5 W/m-K
- 1.4 W/m-K
MLA Measurement Accuracy

- MLA measurement results were demonstrated to be consistent with other measurement methods.
- However, all other methods don’t have adequate accuracy (5% or poorer) and there is no TBC “standard”.
- What is absolute accuracy for MLA?
  - A long-standing problem for MLA and all other NDE methods.

![TBC Thermal Conductivity Data (2010)](chart.png)
MLA Absolute Accuracy - Demonstrated

- MLA accuracy was demonstrated from thermal effusivity $e = (k \rho c)^{1/2}$ measurements for various standard bulk materials
- A tape was bonded on bulk material to form a two-layer system
  - Measured bulk material effusivity $e$ is within 2% of nominal value
  - This is best demonstrated accuracy among all methods
    - Suitable for TBC life prediction because TBC property change is small (10%)

**Predicted and nominal thermal effusivity $e$ values for various standard materials**

![Graph showing predicted and nominal thermal effusivity values for various materials](image)
Effect of TBC Surface Treatment

- Current thermal-imaging model is for opaque coatings (eg, metallic)
- TBC is translucent, needs surface treatment to make it opaque
  - Common method: apply a thin graphite-based paint on TBC surface (which can be easily burn off at a low temperature)

- In collaboration with Dr. Cernuschi and Dr. Bison of Italy, effect of surface treatment on TBC property measurement was evaluated
  - Three different graphite paints
  - Three type TBCs: APS, EB-PVD, PS-PVD
  - Graphite layer did not affect measured TBC thermal diffusivity
  - A paper was submitted to a journal
Thermal Imaging for Translucent TBCs

• A method for translucent TBC property measurement is needed
  – Because it is usually not desirable to paint a TBC part black

• Difficulty: large optical property changes over thermal imaging wavelength bands

• No theoretical model for flash thermal imaging at present
  – Exp. data for “opaque” and translucent TBC are significantly different

From: Wahiduzzaman & Morel, ORNL Report, 1992

![](image_url)

TBC optical properties

Thermal imaging data for “opaque” and translucent TBC
Theoretical Modeling for Translucent TBCs

- Theoretical model for translucent TBCs include both conductive and radiative heat transfer within the coating layer

\[
\rho c \frac{\partial T(z,t)}{\partial t} = k \frac{\partial^2 T(z,t)}{\partial z^2} - \frac{\partial q_r(z,t)}{\partial z}
\]

- Radiative transport is modeled by a two-flux formulation:

\[
q_r = \int_0^\infty q_{r\lambda} d\lambda = \int_0^\infty (q_{r\lambda}^+ - q_{r\lambda}^-) d\lambda
\]

- IR camera reading:

\[
E(t) = N(1 - \rho^i) \int_3^5 [q_{r\lambda}^-(0,t) - q_{r\lambda}^-(0,0)] d\lambda
\]

- A complete solution was derived
Preliminary Results for A Translucent TBC

Predicted thermal conductivity $k$ and heat capacity $\rho c$ images for a TBC sample at translucent and "opaque" conditions

- Predicted properties for translucent TBC are consistent with those of "opaque" TBC (for the same TBC sample)
- A paper is being prepared
**Multilayer (>=2) TBCs**

- Multilayer TBCs are being developed to extend functionality (e.g., erosion) or higher-temperature capabilities of current TBCs.
- A collaboration has been established with Dr. Sampath at Stony Brook Univ. for NDE study of multilayer TBCs.
  - Dr. Sampath’s group is developing multilayer TBCs under a DOE FE project.

From: Dwivedi, Viswanathan, and Sampath (2013)
Thermal Imaging for Double-Layer TBCs

- Many double-layer TBCs or coatings are of interests.
- Initial effort was on measuring 2-layer-averaged TBC property.
- Current effort is on measuring coating properties for each layer:
  - MLA method was extended to 2-layer coating systems.
  - Preliminary tests were conducted – data need verification.

Four types of double-layer coating configurations:

<table>
<thead>
<tr>
<th>TBC + bond coat</th>
<th>LZO + 7YSZ</th>
<th>CMAS + 7YSZ</th>
<th>TBC + delamination</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ceramic top coat (7YSZ)</td>
<td>$\text{La}_2\text{Zr}_2\text{O}_7$</td>
<td>CMAS</td>
<td>Ceramic top coat (7YSZ)</td>
</tr>
<tr>
<td>Bond coat</td>
<td>7YSZ</td>
<td>7YSZ</td>
<td></td>
</tr>
<tr>
<td>Metallic substrate</td>
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<td>Metallic substrate</td>
<td>Metallic substrate</td>
</tr>
</tbody>
</table>
Prediction of Double-Layer TBC Properties

Double-layer TBC

- La$_2$Zr$_2$O$_7$
- 7YSZ
- Metallic substrate

Predicted layer effusivity
- e: 1$^{st}$ layer (LZO)

Predicted thickness profiles
- LZO
- YSZ
- Substrate
- 700µm

Single-layer TBC

- 7YSZ
- Metallic substrate

Predicted layer effusivity
- e: (YSZ)

Predicted thickness profiles
- YSZ
- Substrate
- 300µm

Thermal effusivity of YSZ in double-layer TBC is much lower than that in single-layer TBC?
TBC Property Measurement for a Turbine Blade

TBC: ~0.25mm thick

Thermal effusivity image

1000 2000 W-s\(^{1/2}\)/m\(^2\)-K
TBC Thickness Predictions

Thickness image

TBC thickness profiles

TBC

Substrate

0.1mm 0.3mm

400µm

Thermal effusivity

Low  High
Metallic coating property/thickness prediction

Coating thickness profile

Coating

Substrate

Low  High

Thermal effusivity
Presentation Topics

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  – Theoretical development for double-layer TBCs
  – Application for a turbine blade

• NDE for TBC life prediction
  – Crack/delamination progression
Tests for APS TBC Sample (SB Univ.)

Exposed at 1100ºC

Measured thermal conductivity images

Delamination (low conductivity dark regions) development at edge and internal
Thermal Tomography Images

@0mm (surface)

@0.15mm (mid TBC depth)

@0.3mm (interface)

Dark regions are delaminations
Summary

• Thermal imaging multilayer analysis (MLA) method development:
  – Absolute accuracy of 2% was demonstrated – MLA is ready for TBC studies
  – Developments for translucent and double-layer TBCs are successful
  – Successfully applied for testing of industrial components

• NDE for TBC life prediction:
  – Thermal tomography is successful for detect delamination growth
Planned Future Efforts

• Continued evaluation of NDEs for TBC lifetime prediction
  – Collaborations with Siemens and Stony Brook Univ.

• Thermal NDE method development for complex TBC systems:
  – For complex coatings: translucency, multilayer
  – Evaluation of measurement accuracy for TBC thermal conductivity, thickness, density/porosity
  – Improving crack/delamination resolution

• Tech transfer to industry