

# DEVELOPMENT OF NDE METHODS FOR CERAMIC COATINGS

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# Outline

- Background on TBC degradation and NDE
- Objectives
- Recent NDE development for TBC life prediction
  - Optical methods: Laser backscatter and mid-IR reflectance
  - Thermal multilayer analysis method: model and validation
- Summary
- Planned future efforts

# Background

- Thermal barrier coatings (TBCs) are required for high-temperature metallic components in advance turbine systems to be operated with higher efficiency and low emission
- TBCs have become "prime reliant" material  $\rightarrow$  their condition monitoring and lifetime prediction by NDE is important



# **NDE Applications for TBCs**

- Two characteristics of TBC degradation/failure:
  - (1) Ceramic top coat continuously sinters with minimal damage
  - (2) Cracks and delaminations develop and expand near interface
- NDE methods based on detection of cracking & its effect (2<sup>nd</sup> factor)
  - Photo-luminescence piezo-spectroscopy for stress accumulation
    - Detailed stress distribution for thin TBCs in lab tests (not suitable for field use)
  - Electrochemical impedance spectroscopy for cracking and phase transformation
    - Not exactly a NDE method (requires permanent attachment)
  - Laser-backscatter and mid-IR reflectance (MIRR) for crack detection
    - Optical methods have some success for thin coatings (mostly in lab tests)
  - Thermal imaging for crack/delam detection
    - Successful for large cracks and delaminations (for TBCs near end of life)
- NDE methods based on property measurement (1<sup>st</sup> and 2<sup>nd</sup> factors)
  - Thermal imaging for TBC thermal property measurement
    - TBC conductivity evolves with TBC life (in predictable trend?)

# **NDE for TBC Life Prediction**

- Current NDE methods have limited capability for TBC life prediction
  - Spectroscopy methods are not suitable for real component field application
  - Optical methods have some success for thin coatings in lab tests
    - Investigated under this project; may have potential for field application
  - Traditional NDE methods for delamination detection are not quantitative
    - Many NDE methods are usable; thermal imaging is most effective
- Advanced NDE methods are required for TBC characterization
  - Life prediction (based on quantitative TBC property measurement)
  - High-resolution detection of crack initiation and propagation
  - Applicable to new more complex TBC systems (eg, duel-layer)

# **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:
    - laser backscatter, mid-IR reflectance
    - thermal multilayer analysis
  - (2) For high-resolution flaw detection
    - thermal tomography
- Develop NDE methods for functional materials (gas-separation membrane, fuel cell, etc)
  - Synchrotron x-ray CT, thermal tomography

# **Recent NDE Developments under This Project**

- Continued evaluation of optical NDE methods (mid-IR reflectance and laser backscatter) for TBC life prediction
  - New samples from Siemens and Harvard Univ.
- Continued development of two thermal imaging methods
  - Thermal multilayer analysis for TBC life prediction
    - Evaluate TBC life prediction model based on measured TBC thermal properties (thermal conductivity)
    - Continued calibration for TBC property measurement accuracy from collaboration with researchers in Japan and Italy
    - Investigate property measurement for duel-layer TBCs
  - Thermal tomography method (3D imaging)
    - Continued development of new algorithm for high-resolution imaging
    - Applied to a DARPA SBIR project with success

## **Presentation Focus: NDE for TBC Life Prediction**

- Optical methods: Laser backscatter and Mid-IR reflectance (MIRR)
  - Method evaluation
- Thermal imaging methods: multilayer analysis method
  - TBC life prediction model
  - Model evaluation

# Laser Backscatter for TBC Life Prediction

### **Schematics** Detector A with Detector B with Pinhole Aperture Wide Aperture Imaging Lenses λ/4 Plate CCD Camera PBS Cubes Monitor 25 mW 50/50 BS le-Ne Laser Cube Focusind Lens Data Acquisition Stage X•Y•Z•Ø Optical Translation/Rotation PĊ Power Controller Stage & Driver Meter

### **Experimental setup**



### Scatter intensity vs. TBC life



- Technology developed at ANL by Dr. Ellingson
- Detect backscattered laser light from subsurface, not surface reflection
- Backscatter signal may be correlated with TBC degradation (cracking)

# **Mid-IR Reflectance for TBC Life Prediction**

### **Schematics**



### **Experimental setup at ANL**



### **Reflectance vs. TBC life**



- Technology developed by Dr. Eldridge of NASA
- Reflectance increases with TBC cracking
- Mid-IR reflectance developed at ANL
  - Use entire 3-5µm wavelength (narrow band in NASA system)
  - Use weaker IR source (low thermal heating)
  - Test/data processing procedure established

# **Comparison/Discussion of Optical Methods**

- Laser backscatter (visible 633nm wavelength)
  - Sensitive only to internal scatter (from TBC volume and interface)
  - Low penetration depth  $\rightarrow$  lower sensitivity to interface signal
- MIRR (infrared 3-5µm wavelengths)
  - Sensitive to all reflections/scatters (from TBC surface, internal, interface)
  - Deep penetration depth  $\rightarrow$  more sensitive to interface condition

### Advantages

- Non-contact, remote, direct 2D imaging
- Instantaneous (point-and-read), signal can be scaled (quantitative)

### Disadvantages

- Limited detection depth (typically up to 300µm coating thickness)
- Signal intensity is a function of TBC thickness (in addition to flaws)
- Susceptible to surface contaminations

### **TBC Life Prediction Based on TBC's Thermal Property**

- To use thermal property for TBC life prediction, ANL developed a NDE method that can accurately measure TBC thermal properties
  - Multilayer analysis method measures two TBC properties:
    - Thermal conductivity distribution
    - Heat capacity distribution (or thickness distribution)
  - Applicable to all coating systems on engine components

# One-sided experimental setup

### Thermal conductivity imaging



0.5 W/m-K

# Modeling TBC Conductivity Change with Life

- TBC thermal conductivity is affected by two factors:
  - (1) Conductivity increase due to coating material sintering
    - Measured by laser flash on stand-alone coating samples
  - (2) Conductivity decrease due to cracking/delamination at interface
- A TBC conductivity-life model should account for both factors



Effective (measured)  $k_{exp}$  = (intrinsic k) - (cracking reduction  $\Delta k$ )

# Intrinsic Coating Conductivity due to Sintering

 Intrinsic coating conductivity change due to sintering (annealing) is commonly correlated with LMP (Larson-Miller parameter):

```
\ln(k/k_0) = a + b^*LMP,
                                                   1.0
                                                            1200°C annealed
                                                            1150°C annealed
                                                   0.8
                                                            1100°C annealed
LMP = T^*(\ln t + C),
                                                            1050°C annealed
                                              0.6
Ilu (k*)
                                                            Linear fit
k = \text{conductivity (W/m-K)},
                                                  0.4
k_0 = initial conductivity (at t=0),
T = temperature (K),
                                                  0.2
t = time (s),
                                                                           Tan et al. 2009
a,b,C = fitting constants
                                                       40000
                                                               42000
                                                                      44000
                                                                                    48000
                                                                             46000
                                                               Larson-Miller Parameter (LMP)
```

• Note:  $k_0$  and *a* can be combined, because:

 $\ln(k/k_0) = \ln(k) - \ln(k_0) = \ln(k) - \text{constant}$ 

50000

# **TBC Conductivity - Life Prediction Model**

• TBC life may be predicted from conductivity reduction due to cracking:

 $\Delta k = k - k_{exp}$ , (need to determine  $\Delta k$  at 100% life)

*k* is determined from LMP correlation (exposure condition dependent)  $k_{exp}$  is measured by thermal imaging



### **Evaluation of NDE Methods for TBC Life Prediction**

- TBC samples from Dr. Kulkarni of Siemens
- Optical methods: laser backscatter and mid-IR reflectance (MIRR)
- Thermal imaging method

# **Siemens APS TBC Samples**

### **TBCs exposed at a high temperature**



### **TBCs exposed at lower temperatures**



T1 < T2

# **Laser Backscatter Scan Images**

### TBCs exposed at a high temperature



1 day



3 days

8 days



Contamination from

### TBCs exposed at lower temperatures



T1, 6 days

### T1, 22 days

T2, 2 days

T2, 10 days

# Laser Backscatter Intensity vs. Time



- Backscatter intensity reduces with TBC life (?)
- May require operation in IR wavelength to improve correlation

# **Mid-IR Reflectance Images**

### TBCs exposed at a high temperature



Furnace fume contamination not visible, both other contamination presents

### **TBCs** exposed at lower temperatures



# **Mid-IR Reflectance Intensity vs. Time**



- Mid-IR reflectance is correlated with TBC life (small range!)
- Contamination is an issue
- Failure (delamination) level is a function of TBC thickness

### **Thermal Conductivity Images**

### TBCs exposed at a high temperature



### **TBCs** exposed at lower temperatures



T1, 6 days T1, 22 days T2, 2 days T2, 10 days



0

2 W/m-K

### **TBC Life Prediction Based on TBC Conductivity**

### **TBCs** exposed at lower temperatures



- TBC exposed at higher T2 for 10 days has some damage
- This is for illustration only because few samples (4) were used

### **TBC Life Prediction Based on TBC Conductivity**



- No correlation:
  - All TBC have some damage?
  - Coating thickness varies between samples?
  - TBC conductivity is not constant along depth?

# **Thermal Imaging Data for All TBCs**



- TBC samples exposed at a high temperature are different:
  - Data suggesting a high conductivity at surface and low conductivity at interface; this effect was not accounted for by the conductivity measurement algorithm
  - Further study is needed

# **Comparison of NDEs for TBC Life Prediction**



- $\Delta R$  decreases near failure  $\rightarrow$  more difficult to detect
  - Failure R is a function of many parameters
- $\Delta k$  increases near failure  $\rightarrow$  more sensitive (and easier to detect)
  - Failure  $\Delta k$  also relates to some factors, but large data sets exist!

# Summary

- Three NDE imaging methods were evaluated for TBC life prediction
  - Laser backscatter (optical)
    - Not sensitivity to TBC life; may need IR laser to improve sensitivity
  - Mid-IR reflectance (optical)
    - Good correlation to TBC life, although sensitivity is within a small range
    - Contamination, thickness limit, and failure level are remaining issues
  - Thermal multilayer analysis method (thermal)
    - TBC life prediction model is based on conductivity reduction due to interface cracking
    - Preliminary data showed good potential for TBC life prediction
    - Effective conductivity for TBCs with depth-dependent conductivity variation needs to be defined and measured
- Thermal TBC life prediction model could be more sensitive than optical because the "damage parameter" becomes larger in thermal (∆k) while smaller in optical (∆R) when TBC is near failure
- NDE methods for TBC life prediction are well developed; further evaluation for TBCs with various exposure conditions is needed

# **Planned Future Efforts**

- Continued evaluation of NDEs for TBC lifetime prediction
- Development of thermal multilayer analysis method:
  - For complex coatings: dual-layer, conductivity depth gradient
  - Investigate prediction accuracy due to secondary effects
- Development of thermal tomography method
  - Correlate NDE data with destructive examination results
  - Develop new high-resolution algorithm for data processing