HEALTH MONITORING OF THERMAL BARRIER COATINGS BY MID-INFRARED REFLECTANCE

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ABSTRACT
Mid-infrared (MIR) reflectance is shown to be a powerful tool for monitoring the integrity of 8wt% yttria-stabilized zirconia (YSZ) thermal barrier coatings (TBCs). Because of the translucent nature of plasma-sprayed YSZ TBCs, particularly at MIR wavelengths (3 to 5 µm), measured reflectance does not only originate from the TBC surface, but contains strong contributions from internal scattering within the coating as well as reflectance from the underlying TBC/substrate interface. Therefore, changes in MIR reflectance measurements can be used to monitor the progression of TBC delamination. In particular, MIR reflectance is shown to reproducibly track the progression of TBC delamination produced by repeated thermal cycling (to 1163°C) of plasma-sprayed YSZ TBCs on René N5 superalloy substrates. To understand the changes in MIR reflectance with the progression of a delamination crack network, a four-flux scattering model is used to predict the increase in MIR reflectance produced by the introduction of these cracks.

INTRODUCTION
While thermal barrier coatings (TBCs) provide thermal protection for turbine engine components, the risk of TBC spallation severely restricts the use of TBCs by either forcing extreme safety margins to guide TBC replacement or by limiting TBC application to engine temperatures at which an unprotected component can still survive. This situation has produced a growing need for a reliable and routine method for nondestructive TBC health monitoring. Because TBC failure results from crack/flaw propagation near the TBC/bond coat interface, any useful health monitoring tool must be able to monitor damage evolution beneath the overlying TBC. One approach is to take advantage of the TBC translucency, as demonstrated by the successful application of piezospectroscopy (Cr³⁺ luminescence) to monitor the stress state of the thermally grown oxide (TGO) that forms beneath the TBC. Unfortunately, the TGO stress state does not provide a good indication of remaining TBC life because the indication of impending TBC failure by TGO stress relaxation tends to occur immediately preceding failure and therefore does not present sufficient warning. In this paper, we present a new approach employing mid-infrared (MIR) reflectance as a diagnostic tool for evaluating the fraction of TBC lifetime remaining by correlating the MIR reflectance with the progress of the buried TBC delamination crack network that ultimately produces TBC failure. This approach offers the advantage of working at wavelengths where the TBC has much greater transmittance than for visible light, and therefore can be applied to highly attenuating (compared to EB-PVD) plasma-sprayed TBCs that are difficult to probe by piezospectroscopy. A hemispherical transmittance measurement (Fig. 1) for a freestanding plasma-sprayed 8wt% yttria-stabilized zirconia (YSZ) TBC clearly shows that
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Motivation

- Risk of TBC failure restricts application of TBCs
  - Requires extreme safety margins for TBC replacement or
  - Limited to temperatures at which unprotected component can survive
- Reliable TBC health monitoring will overcome these restrictions.
Background

- Any TBC health monitoring tool (optical, electrical, acoustic) must be able to monitor *buried* damage evolution.
  - Optical techniques most amenable to non-contact monitoring.
- Piezospectroscopy ($\text{Cr}^3+$ luminescence) has been demonstrated to monitor stress state in thermally grown oxide (TGO) beneath TBC. (U. California—Santa Barbara, U. Connecticut)
  - Very difficult to obtain luminescence signal through highly attenuating plasma-sprayed TBCs.
  - Measured TGO stress relaxation occurs immediately preceding or simultaneous with TBC failure; therefore does not provide early warning.
- Mid-infrared (MIR) reflectance examined for advantages as TBC health monitoring tool.
  - Uses wavelengths where TBC has maximum transmittance.
  - Potentially more sensitive to earlier stages of TBC failure.
Maximum Transmittance at MIR Wavelengths

Freestanding 172 μm plasma-sprayed 8YSZ

Transmittance (%)

Wavelength (μm)
Experimental Approach

- Two types of TBC specimens:
  - with bond coat (4)
    - 200 µm atmospheric plasma-sprayed 8YSZ
    - 120 µm low-pressure plasma-sprayed NiCrAlY bond coat
    - René N5 superalloy substrate
  - no bond coat (3)
    - 200 µm atmospheric plasma-sprayed 8YSZ
    - René N5 superalloy substrate

- Monitor changes in MIR hemispherical reflectance with interrupted furnace cycling.
  - 1 cycle = 45 min @ 1163°C + 15 min cooling to 120°C in air
  - Measure MIR reflectance after 1st cycle & every 10th cycle.
  - Inspect for TBC failure (>20% delamination)
Directional Hemispherical Reflectance Measurements

integrating sphere accessory inside FTIR spectrometer
Effect of Furnace Cycling on Hemispherical Reflectance

![Graph showing the effect of furnace cycling on hemispherical reflectance. The graph plots reflectance (%) against wavelength (μm). Different lines represent different cycle counts: 1 cycle, 40 cycles, 80 cycles, 120 cycles, 160 cycles, and 200 cycles. The graph indicates that the reflectance decreases with increasing cycle counts, and a TBC with bond coat failed after 210 cycles.](image-url)
Effect of Furnace Cycling on Hemispherical Reflectance (expanded scale)

- 1 cycle
- 40 cycles
- 80 cycles
- 120 cycles
- 160 cycles
- 200 cycles
OH Absorption Peak Interference

- before heat treatment
- after heat treatment

no effect of OH
decreasing effect of OH

Freestanding 87 μm plasma-sprayed 8YSZ

Reflectance (%)

Wavelength (μm)
Hemispherical Reflectance ($\lambda = 3.8 \, \mu m$) Monitors Progress of TBC Delamination

- Solid: with bond coat
- Dashed: no bond coat

200 $\mu m$ thick plasma-sprayed 8YSZ

Reflectance (%) vs. Number of cycles
Delamination crack network formed after 150 cycles
Gradual progression allows effective health monitoring
4-Flux (Zero Absorption) Model for Normal Hemispherical Reflectance
TBC with underlying crack

\[ q_{\text{reflected}} = \rho_c^o q_c^o + (1 - \rho_c^i) q_c^-(0) + (1 - \rho_d^i) q_d^-(0) \]

Crack introduces high internal reflection due to index of refraction change across TBC/crack interface.
Predicted Effect of Crack on Hemispherical Reflectance
(based on zero-absorption four-flux model)
Competing Influences on Hemispherical Reflectance

- OH content in TBC
- TBC thickness variation
- TBC sintering
- Thermally grown oxide (TGO) growth
Hemispherical Reflectance Increases with TBC Thickness

Reflectance (%)

Wavelength (microns)

Freestanding plasma-sprayed 8YSZ
Sintering Decreases Hemispherical Reflectance
160-μm-thick freestanding plasma-sprayed 8YSZ

- Reflectance decreases with sintering (especially at short λ's)
- Not much change here

-as-sprayed
- 7 days @1315 C

Wavelength (μm)
Effect of Thermally Grown Oxide (TGO) on Hemispherical Reflectance

- TGO growth on bare substrate decreases reflectance.
- TGO growth beneath TBC requires further investigation.
Summary of Influences on MIR Hemispherical Reflectance

- Increases Reflectance
  - Progression of delamination crack network
  - Decrease in OH content (can select wavelengths where effect is minimized)

- Decreases Reflectance
  - Erosion (decrease in TBC thickness)
  - Sintering (preferentially affects shorter wavelengths)

- Requires Further Investigation
  - Effect of buried TGO growth (change in substrate reflectance)

- Sintering & erosion are nonfactors & OH effect is minimized in this study, but need to be considered under less controlled conditions.
  - Competing influences have distinguishing spectral effect "signatures"
MIR Reflectance Imaging Provides Practical Inspection Capability
(provided by Rich Martin, Cleveland State University)

- These are unoptimized, quick & dim images.
- Imaging provides localized flaw detection capability.
- Visual inspection by MIR reflectance imaging extends technique from lab to practical health-monitoring tool.

Furnace cycles to 1163°C

135 cycles - 45 cycles
Conclusions

- MIR reflectance provides promising approach for TBC health monitoring.
  - MIR wavelengths successfully probe through highly attenuating plasma-sprayed TBCs.
  - MIR reflectance is sensitive to early stages of TBC failure.
  - Gradual progression of delamination crack network allows early warning.
  - Competing influences on MIR reflectance have distinguishing spectral effects.
  - Visual inspection by MIR reflectance imaging will extend technique from lab to practical health monitoring tool.
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