The Lattice and Thermal Radiation Conductivity of Thermal Barrier Coatings: Models and Experiments

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Abstract

The lattice and radiation conductivity of ZrO$_2$-Y$_2$O$_3$ thermal barrier coatings was evaluated using a laser heat flux approach. A diffusion model has been established to correlate the coating apparent thermal conductivity to the lattice and radiation conductivity. The radiation conductivity component can be expressed as a function of temperature, coating material scattering, and absorption properties. High temperature scattering and absorption of the coating systems can be also derived based on the testing results using the modeling approach. A comparison has been made for the gray and nongray coating models in the plasma-sprayed thermal barrier coatings. The model prediction is found to have a good agreement with experimental observations.
Revolutionary Ceramic Coatings Greatly Impact Gas Turbine Engine Technology

— Ceramic thermal and environmental barrier coating system development goals
- Meet engine temperature and performance requirements
- Ensure long-term durability
- Improve technology readiness
- Develop design tools and lifing methodologies

— Crucial for envisioned supersonic vehicles: reduced engine emission, improved efficiency and long-term supersonic cruise durability

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Step increase in temperature capability

<table>
<thead>
<tr>
<th>Year</th>
<th>Temperature Capability</th>
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<tr>
<td>Gen I</td>
<td>2000 °F (1093 °C)</td>
</tr>
<tr>
<td>Gen II</td>
<td>2500 °F (1316 °C)</td>
</tr>
<tr>
<td>Gen III</td>
<td>2400 °F (1316 °C)</td>
</tr>
<tr>
<td>Gen IV</td>
<td>2000 °F (1093 °C)</td>
</tr>
</tbody>
</table>

Increase in AT across T/EBC

- 3100 °F (1650 °C+)
- 2700 °F (1482 °C)
- 2700 °F (1482 °C) + Si$_3$N$_4$ coatings
- 2700 °F (1482 °C) + CMC coatings
Objectives

- Evaluate thermal conductivity and thermal radiation resistance of ceramic coatings at high temperatures (2700 to 3200 °F), under realistically thermal gradient conditions
- Facilitate the development advanced thermal and environmental barrier coatings
- Improve understanding of the coating thermal radiation performance

Laser heat flux

(a) Internal radiation
(b) Combined internal & external radiation
(c) External radiation

NASA Steady-State Laser Heat-Flux Approach for Ceramic Coating Thermal Conductivity Measurements

- A uniform laser (wavelength 10.6 µm) power distribution achieved using integrating lens combined with lens/specimen rotation
- The ceramic surface and substrate temperatures measured by 8 µm and two-color pyrometers and/or by an embedded miniature thermocouple
- Thermal conductivity measured at 5 sec intervals in real time

National Aeronautics and Space Administration

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- The ceramic surface and substrate temperatures measured by 8 µm and two-color pyrometers and/or by an embedded miniature thermocouple
- Thermal conductivity measured at 5 sec intervals in real time

Diagram showing the experimental setup with labeled components and conditions.
Ceramic Coating Thermal Conductivity Measurement Approach by the Laser High-Heat-Flux Testing

\[ k_{\text{ceramic}}(t) = \frac{q_{\text{thru}}}{\Delta T_{\text{ceramic}}(t)} \]

Where

\[ q_{\text{thru}} = q_{\text{delivered}} - q_{\text{reflected}} - q_{\text{radiated}} \]

\[ \Delta T_{\text{ceramic}}(t) = T_{\text{ceramic-surface}} - T_{\text{metal-back}} \]

8 μm pyrometer for \( T_{\text{ceramic-surface}} \)

Two-color and 8 μm pyrometers for \( T_{\text{substrate-back}} \)

Optional miniature thermocouple for additional heat-flux calibration

Thermal Conductivity of Fully Dense Oxides

- The radiation conductivity component evaluated
- Significant conductivity increase due to increased radiation at high temperatures especially under thermal gradients

Laser heat flux

Ceramic coating

(a) Internal radiation
(b) Combined internal & external radiation
(c) External radiation

Laser heat flux

Radiation emitter

Internal radiation

Combining internal & external radiation

External radiation

La₂Zr₂O₇

Hot-pressed specimens

Increasing porosity

ZrO₂-8wt%Y₂O₃ plasma-sprayed porous coating

Free-standing coating

Hot-pressed specimens

Increasing porosity

Free-standing coating
Evaluation of Lattice and Radiation Thermal Conductivity of TEBC Systems at High Temperatures

- ZrO$_2$-8wt%Y$_2$O$_3$/BSAS/mullite+20wt%BSAS/Si coating on SiC/SiC CMC substrate
- Conductivity determined by a steady-state laser heat-flux technique
- Coating surface radiation can contribute 5 to 15% total heat transfer at 1650 °C
Radiative Diffusion Models

- The diffusion conduction equations

\[ q_{\text{total}} = k_{\text{cond}} \frac{dT}{dx} + \frac{16\sigma \cdot n^2 \cdot T_m^3}{3(a + \sigma_s)} \frac{dT}{dx} = k_{\text{cond}} + \frac{16\sigma \cdot n^2 \cdot T_m^3}{3(a + \sigma_s)} \frac{dT}{dx} \]

\[ k_{\text{effective}} = k_{\text{cond}} + \frac{16\sigma \cdot n^2 \cdot T_m^3}{3(a + \sigma_s)} = k_{\text{cond}} + k_{\text{rad}} \]

\[ q_{\text{total}} = \text{Total heat flux} \]

\[ k_{\text{cond}} = \text{Intrinsic lattice conductive thermal conductivity} \]

\[ k_{\text{rad}} = \text{Radiation thermal conductivity} \]

\[ k_{\text{effective}} = \text{Effective thermal conductivity} \]

\[ \sigma = \text{Stefan-Boltzmann constant} \times 5.6704 \times 10^{-8} \text{ W/(m}^2\text{K}^4) \]

\[ n = \text{Refractive index, 2.2} \]

\[ a = \text{Absorption coefficient, cm}^{-1} \]

\[ \sigma_s = \text{Scattering coefficient, cm}^{-1} \]

\[ T = \text{Average temperature of the material, K} \]

\[ q_{r_1} \]

\[ T_{g_1} \]

\[ T_{g_2} \]

\[ q_{r_2} \]

\[ T_{g_1} \]

\[ T_{g_2} \]

\[ D \]

Regions of optical thickness

Radiative Diffusion Models for Nongray Materials

- The diffusion conduction models established for nongray coating materials

Gray model

\[ q_{\text{total}} = k_{\text{cond}} \frac{dT}{dx} + \frac{16\sigma \cdot n^2 \cdot T_m^3}{3(a + \sigma_s)} \frac{dT}{dx} = k_{\text{cond}} + \frac{16\sigma \cdot n^2 \cdot T_m^3}{3(a + \sigma_s)} \frac{dT}{dx} \]

Non-gray model

\[ q_{\text{total}} = \frac{k + 16\sigma \cdot n^2 \cdot T_m^3}{3} \left[ T_0 - T(d) \right] \]

\[ d \]

\[ k_{\text{effective}} = k_{\text{cond}} + \frac{16\sigma \cdot n^2 \cdot T_m^3}{3(a + \sigma_s)} = k_{\text{cond}} + k_{\text{rad}} \]

\[ q_{\text{total}} = \text{Total heat flux} \]

\[ k_{\text{cond}} = \text{Intrinsic lattice conductive thermal conductivity} \]

\[ k_{\text{rad}} = \text{Radiation thermal conductivity} \]

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\[ T = \text{Average temperature of the material, K} \]

\[ q_{r_1} \]

\[ T_{g_1} \]

\[ q_{r_2} \]

\[ T_{g_2} \]

\[ D \]

Regions of optical thickness
Evaluation of Lattice and Radiation Thermal Conductivity of 3000 °F Coating Systems

- Freestanding coatings and gray layer radiative diffusion assumption models

\[ q_{\text{rad}} = k_{\text{rad}} \frac{dT}{dx} \]

\[ q_{\text{cond}} = k_{\text{cond}} \frac{dT}{dx} \]

\[ q_{\text{total}} = q_{\text{rad}} + q_{\text{cond}} \]

**Thermal radiation evaluation of advanced coating materials**

Scattering Component of Plasma-Sprayed Coating Systems

**Blackbody radiation penetration**

Absorption

Scattering:
- Baseline coatings
- Advanced coatings

Coating thickness, microns
Radiation Conductivity Component of Ceramic Materials

Evaluation of Radiation Flux Resistance of Oxide Coating Systems

Preliminary results showed doped HfO$_2$ coatings had better radiation resistance.
Concluding Remarks

- Laser heat-flux approach established for radiation thermal conductivity measurements and advanced coating development
- Lattice and radiation conductivity determined for dense materials and coatings
- The diffusion conduction models established for gray and nongray coating materials
- Scattering and absorption determined for coatings under realistic thermal gradients at high temperatures
- Advanced coatings promising in reducing radiation conductivity
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