The Lattice and Thermal Radiation Conductivity of Thermal Barrier Coatings

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The lattice and radiation conductivity of thermal barrier coatings was evaluated using a laser heat flux approach. A diffusion model has been established to correlate the apparent thermal conductivity of the coating to the lattice and radiation conductivity. The radiation conductivity component can be expressed as a function of temperature and the scattering and absorption properties of the coating material. High temperature scattering and absorption of the coating systems can also be derived based on the testing results using the modeling approach. The model prediction is found to have good agreement with experimental observations.
The Lattice and Thermal Radiation Conductivity of Thermal Barrier Coatings

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This work was supported by NASA Fundamental Aeronautics Program

The 32nd International Conference on Advanced Ceramics and Composites
Daytona Beach, Florida, January 27-February 1, 2008
Motivation

— Thermal and environmental barrier coatings help increase gas turbine operating temperatures, reduce cooling requirements, improve engine fuel efficiency and reliability
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
Revolutionary Ceramic Coatings Impact Gas Turbine Engine Technology - Continued

Temperature Capability

- 2800°F combustor TBC
- 2500°F Turbine TBC
- 3000°F+ (1650°C+)
- 2700°F (1482°C)

Increase in ∆T across T/EBC

- Single Crystal Superalloy
- Ceramic Matrix Composite
- SiC/SiC CMC coatings

Step increase in temperature capability

2700°F SiC/SiC CMC and Si₃N₄ coatings

Year

Gen I
Gen II – Current commercial
Gen III
Gen IV
Objectives

- Evaluate thermal conductivity and thermal radiation resistance of ceramic coatings at high temperatures (2700-3200°F), under realistically thermal gradient conditions

- Facilitate the development of advanced thermal and environmental barrier coatings

- Improve understanding of the coating thermal radiation performance

\[\text{Laser heat flux} \quad \downarrow \quad \downarrow \quad \downarrow \quad \text{Ceramic coating} \quad (a) \text{Internal radiation} \]

\[\text{Laser heat flux} \quad \downarrow \quad \downarrow \quad \downarrow \quad \text{High emissivity layer} \quad \text{Ceramic coating} \quad (b) \text{Combined internal & external radiation} \]

\[\text{Laser heat flux} \quad \downarrow \quad \downarrow \quad \downarrow \quad \text{Radiation emitter} \quad \text{Ceramic coating} \quad (c) \text{External radiation} \]
NASA Steady-State Laser Heat-Flux Approach for Ceramic Coating Thermal Conductivity Measurements

- A uniform laser (wavelength 10.6 $\mu$m) power distribution achieved using integrating lens combined with lens/specimen rotation
- The ceramic surface and substrate temperatures measured by 8 micron and two-color pyrometers and/or by an embedded miniature thermocouple
- Thermal conductivity measured at 5 second intervals in real time and thermal cycling incorporated
Ceramic Coating Thermal Conductivity Measurement Approach by the Laser High-Heat-Flux Testing

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

\[
q_{\text{thru}} = q_{\text{delivered}} - q_{\text{reflected}} - q_{\text{radiated}} \quad \text{and} \quad \Delta T_{\text{ceramic}}(t) = T_{\text{ceramic-surface}} - T_{\text{metal-back}} - \int_{0}^{l_{\text{bond}}} \frac{q_{\text{thru}} \cdot dl}{k_{\text{bond}}(T)} - \int_{0}^{l_{\text{substrate}}} \frac{q_{\text{thru}} \cdot dl}{k_{\text{substrate}}(T)}
\]

Where

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

![Diagram showing thermal conductivity of different oxide coatings](image)

La$_2$Zr$_2$O$_7$ sol-gel hot-press

Hot-pressed specimens

ZrO$_2$-8wt%Y$_2$O$_3$ plasma-sprayed porous coating

Free-standing coating
Thermal Conductivity of Fully Dense Oxides

(continued)

![Graph showing thermal conductivity versus surface temperature for different oxides](image)

- \( \text{La}_2\text{Zr}_2\text{O}_7 \)
- \( (\text{La,Gd})_2\text{Zr}_2\text{O}_7 \)
- \( (\text{La,Yb})_2\text{Zr}_2\text{O}_7 \)
- \( (\text{La,Gd,Yb})_2\text{Zr}_2\text{O}_7 \)
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 5-15% total heat transfer at 1650°C

![Graph showing thermal conductivity and temperature over time](image-url)
Radiative Diffusion Models

- The diffusion conduction equations

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

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

- \( q_{total} \) = Total heat flux
- \( k_{cond} \) = Intrinsic lattice conductive thermal conductivity
- \( k_{rad} \) = Radiation thermal conductivity
- \( k_{effective} \) = Effective thermal conductivity
- \( \sigma \) = Stefan-Boltzmann constant \( 5.6704 \times 10^{-8} \) W/(m\(^2\)-K\(^4\))
- \( n \) = Refractive index, 2.2
- \( a \) = Absorption coefficient, cm\(^{-1}\)
- \( \sigma_s \) = Scattering coefficient, cm\(^{-1}\)
- \( \bar{T} \) = Average temperature of the material, K

<table>
<thead>
<tr>
<th>( q_{r1} )</th>
<th>( q_{r2} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>opaque</td>
<td>Radiative diffusion approximation</td>
</tr>
<tr>
<td>transparent</td>
<td>transparent</td>
</tr>
</tbody>
</table>

Regions of optical thickness

\( T_{g1} \)
\( T_{g2} \)
\( T_{s1} \)
\( D \)
**Evaluation of Lattice and Radiation Thermal Conductivity of 3000F Coating Systems**

- Freestanding coatings and gray layer radiative diffusion assumption models

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

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

Thermal radiation evaluation of advanced coating materials
Scattering Component of Plasma-Sprayed Coating Systems

Blackbody radiation penetration $I/I_0$ vs. Coating thickness, microns

- Baselines
- Advanced coatings
- Scattering: baseline coatings
- Scattering: advanced coatings
- Absorption
Radiation Component of Ceramic Materials

- **Dense materials-1100C**
- **Dense materials-1200C**
- **Dense materials-1300C**
- **Dense materials-1400C**
- **Coatings-1550C**
- **Coatings-1600C**
- **Coatings-1650C**
- **Coatings-1700C**

**Legend**
- Radiation component, \((ka - kl)/kl\)
- Thermal gradient, K/mm

The graph shows the variation of radiation component with thermal gradient for different materials at various average temperatures.
Preliminary results showed doped HfO₂ 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
- Scattering and absorption determined for coatings under realistic thermal gradients at high temperatures
- Advanced coatings promising in reducing radiation conductivity