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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Motivation

— Thermal and environmental barrier coatings help increase gas turbine operating temperatures, reduce cooling requirements, improve engine fuel efficiency and reliability.

(a) Current TEBCs   (b) Advanced T/EBCs
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

Step increase in temperature capability

(T/EBC) surface

- 3000°F+ (1650°C+)
- 2700°F (1482°C)

Increase in $\Delta T$ across T/EBC

- Ceramic Matrix Composite
- Single Crystal Superalloy
- 2400°F (1316°C)
- 2000°F (1093°C)

Year

Gen I - Current commercial
Gen II
Gen III
Gen. IV

3100°F SiC/SiC CMC coatings
2700°F SiC/SiC CMC and Si$_3$N$_4$ coatings
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

(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 \(\mu\)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

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

where

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

and

\[ \Delta T_{\text{ceramic}}(t) = T_{\text{ceramic-surface}} - T_{\text{metal-back}} - \int_0^{l_{\text{bond}}} \frac{q_{\text{thru}} \cdot dl}{k_{\text{bond}}(T)} - \int_0^{l_{\text{substrate}}} \frac{q_{\text{thru}} \cdot dl}{k_{\text{substrate}}(T)} \]

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

\[ \text{La}_2\text{Zr}_2\text{O}_7 \]  
**Hot-pressed specimens**

\[ \text{ZrO}_2 - 8\text{wt}\%\text{Y}_2\text{O}_3 \text{ plasma-sprayed porous coating} \]

**Free-standing coating**

- Increasing porosity
- Sintering induced conductivity rise
- Lattice conduction
- Radiation

\[ \text{L}_2\text{Zr}_2\text{O}_7 \text{ sol-gel hot-press} \]

\[ \text{L}_2\text{Zr}_2\text{O}_7 \text{ sol-gel hot-press} \]

\[ \text{L}_2\text{Zr}_2\text{O}_7 \text{ hot-press} \]
Thermal Conductivity of Fully Dense Oxides (continued)

![Graph showing thermal conductivity vs. surface temperature for different oxides.]

- $\text{La}_2\text{Zr}_2\text{O}_7$
- $(\text{La,Gd})_2\text{Zr}_2\text{O}_7$
- $(\text{La,Yb})_2\text{Zr}_2\text{O}_7$
- $(\text{La,Gd,Yb})_2\text{Zr}_2\text{O}_7$
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
Radiative Diffusion Models

- The diffusion conduction equations

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

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

\(q_{\text{total}}\) = Total heat flux
\(k_{\text{cond}}\) = Intrinsic lattice conductive thermal conductivity
\(k_{\text{rad}}\) = radiation thermal conductivity
\(k_{\text{effective}}\) = effective thermal conductivity
\(\sigma\) = Stefan-Boltzmann constant \(5.6704 \times 10^{-8}\) W/(m²-K⁴)
\(n\) = Refractive index, 2.2
\(a\) = Absorption coefficient, cm⁻¹
\(\sigma_s\) = Scattering coefficient, cm⁻¹
\(\overline{T}\) = Average temperature of the material, K

\(q_{r1}\)

\(T_{g1}\)

\(T_{s1}\)

\(D\)

\(q_{r2}\)

\(T_{g2}\)

Regions of optical thickness

| \(0\) | \(\nu_{c1}\) | \(\nu_{c2}\) |
|opaques| Radiative diffusion approximation| transparent|
Evaluation of Lattice and Radiation Thermal Conductivity of 3000F Coating Systems

- Freestanding coatings and gray layer radiative diffusion assumption models

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

\[
k_{\text{effective}} = k_{\text{cond}} + \frac{16\sigma \cdot n^2 \cdot T_{\text{ave}}^3}{3(a + \sigma_s)} = k_{\text{cond}} + k_{\text{rad}}
\]
Scattering Component of Plasma-Sprayed Coating Systems

Blackbody radiation penetration $I/I_0$

Coating thickness, microns

- Baselines
- Advanced coatings

Scattering and absorption components
Radiation Component of Ceramic Materials

Average temperature

0.0 0.2 0.4 0.6 0.8 1.0 1.2

0 200 400 600 800 1000 1200

Radiation heat flux Data

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

Radiation component, (ka-kl)/kl

Thermal gradient, K/mm

Average temperature
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

• Scattering and absorption determined for coatings under realistic thermal gradients at high temperatures

• Advanced coatings promising in reducing radiation conductivity