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Experimental study on the scattering and absorption coefficients of thermal barrier coatings at elevated temperatures

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ABSTRACT

The study on the scattering and absorption coefficients of thermal barrier coatings (TBCs) is becoming more and more important as the radiation heat transport through TBCs makes a greater contribution due to the continuous increase in turbine inlet temperature. The spectral reflectance and transmittance of the atmospheric plasma-sprayed 8 wt% yttria-stabilized zirconia (8YSZ) TBCs are measured by the two-substrate method at elevated temperatures from 850 to 1150 °C with the wavelength varying from 1.4 to 2.4 μm. The reflectance decreases with increasing wavelength and temperature, while the transmittance has a reverse rule. The high reflectance and transmittance of the 8YSZ TBCs demonstrate that the 8YSZ TBCs have high scattering and low absorption coefficients. The scattering and absorption coefficients of the 8YSZ TBCs are determined by the four-flux model. The scattering coefficient decreases approximately from 820 to 460 cm^{-1} as the wavelength increases with less temperature dependence. The absorption coefficient is extremely low ($<0.1\ \mathrm{cm}^{-1}$), and it increases as the temperature increases with a little wavelength dependence. The transmittance of the 8YSZ TBCs cannot be simplified as a quasi-Beer's law or an exponential term of the thickness, because the scattering coefficient is too large and the condition that the thickness of 8YSZ TBCs is much larger than the effective attenuation length is not met. Due to the low absorption coefficient, the 8YSZ TBCs can be treated as the pure scattering coatings without the effect of absorption. The zero-absorption two-flux model is a simple and accurate model to predict the scattering coefficient of the 8YSZ TBCs approximately as the pure scattering material.

1. Introduction

Thermal barrier coatings (TBCs) are widely used in combustor liners and turbine vanes and blades to insulate them from the hot gas stream and improve the durability [1–3]. With the continuous increase in turbine inlet temperature in advanced turbine engines, which is driven by the requirement of higher efficiency, radiation heat transport through TBCs within the semitransparent wavelength range makes a greater contribution to the overall heat transfer due to the fourth-power dependence of the thermal radiation on temperature. Therefore, estimating the radiative heat transport through TBCs accurately is becoming more important. In a series of papers, Siegel and Spuckler [3–5] have shown that the scattering and absorption coefficients and the refractive index of the TBC material must be known if one wants to determine the radiative transport through a semitransparent TBC. The scattering and absorption coefficients can also be used to calculate the temperature profiles in TBC systems consisting of energy equation that has conduction and radiation terms, and boundary relations with convection, conduction and radiation [3–7]. Furthermore, these coefficients are useful in calculating the emissivity and/or reflectance of freestanding TBCs of any given thickness and TBCs on a substrate of any given reflectivity. The calculated reflectance spectra can be used to evaluate the subsurface damage in TBCs [8]. Another application of the scattering and absorption coefficients is to provide guidance for performing pyrometer-based temperature measurements on TBC-coated specimens.

In the relevant studies, the hemispherical transmittance and reflectance of various transparent materials were measured to determine the scattering and absorption coefficients [8–15]. While these efforts have improved the progress of determination of the radiative parameters, most of them were based on room-temperature transmittance and reflectance measurements. There are differences between the scattering and absorption coefficients at room temperature and elevated temperatures to some extent. In order to investigate the scattering and absorption coefficients at

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Nomenclature

a	absorption coefficient
A	coefficient
B	coefficient
C_1, C_2, C_3, C_4	integration constants
D	thickness-independent prefactor
E	emissivity
I	radiative intensity (in positive direction)
J	radiative intensity in negative direction
l	attenuation length
L	thickness of coating
n	refractive index
R	reflectance
RF	response function
s	scattering coefficient
S	spectrometer output
SRS	sum of residuals squared
T	temperature
Tr	transmittance
z	coordinate across the coating

Greek symbols

β	coefficient
θ	zenith angle
λ	wavelength
μ	attenuation coefficient
ρ	reflectivity of interface
σ	extinction coefficient
τ	optical thickness
ϕ	azimuth angle
ω	single scattering albedo

Subscripts

0	sum of surrounding and spectrometer
1, 2	index of variables
b	blackbody
c	collimated
calc	calculated
d	diffuse
e	real surface
eff	effective
meas	measured
s	sample
sub	substrate
sur	surrounding

Superscripts

0	incident
ext	external
$*$	total or apparent

high temperatures, some researchers deduced the characteristics of the scattering and absorption coefficients at elevated temperatures using the calculated scattering and absorption coefficients at room temperature and the measured normal emissivity at high temperatures [16,17]. The temperature dependence of the absorption coefficient for nonscattering bulk yttria-stabilized zirconia (YSZ) has been reported [18–20], and Makino et al. [21] determined both the scattering and absorption coefficients for bulk YSZ specimens, but only up to 426 °C. Eldridge and Spuckler [22] determined the scattering and absorption coefficient for the plasma-sprayed 8 wt% YSZ (8YSZ) TBCs at high temperatures by the benchtop emissometer [23,24] in which the experimental devices were difficult to machine, and the temperature of specimens was hard to be controlled.

The objective of this paper is to measure the reflectance and transmittance of the freestanding atmospheric plasma-sprayed 8YSZ TBCs at elevated temperatures (from 850 to 1150 °C) conveniently by a modified experimental apparatus used for the measurement of the emissivity of opaque materials and determine the scattering and absorption coefficients of the 8YSZ TBCs at elevated temperatures by applying four-flux model based on the measured reflectance and transmittance. It is important to note that the scattering and absorption coefficients reported here are only valid for the TBCs with the same microstructure. Obtaining the scattering and absorption coefficients for the TBCs deposited under different spraying conditions can be performed using the same methodology reported here.

2. Experiment

2.1. Sample preparation and characterization

Five freestanding atmospheric plasma-sprayed 8YSZ coatings with different thicknesses are prepared for determining the scattering and absorption coefficients. The 8 wt% YSZ powders with particle size of about 20–75 μm are sprayed onto the sacrificial carbon disks (30 mm diameter × 3.5 mm thick) that are initially sandblasted with 60 grit alumina. Atmospheric plasma spraying is performed using a Praxair Surface Technologies (Indianapolis, IN) 7700 AP UPC plasma spray system under standard spraying conditions. The primary gas is argon and the secondary gas is hydrogen with the ratio of 4:1. The torch is mounted on a six-axis robot while maintaining a standoff distance of 95 mm. These spraying conditions produce the 8YSZ coatings with a porosity of 20% determined by the mercury intrusion porosimetry. The 8YSZ-coated carbon disks are heat treated in air for 8 h at 1000 °C to burn off the carbon substrate. Coating thickness is determined indirectly by weighing the freestanding coating and dividing the coating mass by the product of the coating area (7.09 cm^2) and density (4.88 g/cm^3). The density is calculated through the theoretical density of the 8YSZ (6.10 g/cm^3) and the porosity. Five coatings are produced with thickness of 60, 97, 209, 416 and 891 μm. All coatings are produced in the same deposition run to avoid run-to-run variations in porosity. The coatings have a specific morphology with a lot of cracks parallel to the substrate as well as orthogonal cracks to the top coating surface, as shown in Fig. 1.

2.2. Experimental principle

As known to all, the maximum possible thermal radiative intensity at a given temperature T is emitted by the blackbody, and the emissivity is defined by [25]:

$$E_{\lambda,\theta}(\lambda,T,\theta,\phi) \equiv \frac{I_{\lambda,e}(\lambda,T,\theta,\phi)}{I_{\lambda,b}(\lambda,T)} \tag{1}$$

where $I_{\lambda,e}$ and $I_{\lambda,b}$ are the radiative intensity coming from a real surface and the perfect blackbody at the same temperature T and wavelength λ, respectively. θ and ϕ are the emitting zenith angle and azimuth angle, respectively.

The sample spectral intensity $I_{\lambda,meas}(\lambda,T)$ measured by a Fourier transform infrared (FTIR) spectrometer can be express simply as:

$$I_{\lambda,meas}(\lambda,T) \cong I_{\lambda,e}(\lambda,T) + I_{\lambda,sur} = E_\lambda I_{\lambda,b}(\lambda,T) + I_{\lambda,sur} \tag{2}$$