Surface & Coatings Technology 203 (2009) 1059–1068

Contents lists available at ScienceDirect

Surface & Coatings Technology

journal homepage: www.elsevier.com/locate/surfcoat

# Infrared-optical properties and heat transfer coefficients of semitransparent thermal barrier coatings

J. Manara [a,*], M. Arduini-Schuster [a], H.-J. Rätzer-Scheibe [b], U. Schulz [b]

[a] Bavarian Center for Applied Energy Research (ZAE Bayern), Am Hubland, 97074 Würzburg, Germany
[b] German Aerospace Center (DLR), Institute of Materials Research, Linder Höhe, 51147 Cologne, Germany

ARTICLE INFO

*Article history:*
Received 28 April 2008
Accepted in revised form 29 September 2008
Available online 10 October 2008

*PACS:*
44.05.+e
44.10.+i
44.40.+a
66.30.Xj
78.30.-j
81.40.-z

*Keywords:*
Heat transfer
Thermal radiation
Thermal conductivity
Thermal barrier coating
Electron-beam physical-vapor-deposition
Partially yttria stabilized zirconia

ABSTRACT

Thermal barrier coatings (TBC) which are used in aircraft and land-based gas turbines for thermal insulation of thermally highly loaded components are usually semitransparent in the infrared spectral region at higher temperatures. Thus, at turbine surface conditions the total heat transfer coefficient of TBCs increases above the heat transfer coefficient caused by solid heat conduction alone.

The solid thermal conductivity of electron beam physical vapor deposited (EB-PVD) partially yttria stabilized zirconia (YSZ) coatings derived from laser flash measurements were correlated with the microstructure of the coatings, which was adjusted by defined heat treatments. To obtain the contribution of the radiative transfer on the total heat transfer coefficient, infrared-optical characterizations were carried out at ambient and elevated temperatures.

A theoretical model was developed which can be used to describe the heat transfer through semitransparent, absorbing and scattering media. Finally, the total heat transfer, caused by solid thermal conduction, radiative transfer and an interaction of both is derived for the coatings prepared in this work. Additionally the measurement method BBC (black body boundary conditions) which is suitable to determine spectral transmittance and emittance at elevated temperatures is introduced.



## 1. Introduction

Thermal barrier coatings (TBCs) are important for protecting metal parts in high temperature applications such as combustion liners, turbine vanes and blades for current and advanced turbine engines. Thermal insulation of TBCs is due to the low thermal conductivity but also to improved infrared-optical properties. Partially yttria stabilized zirconia (YSZ) is the currently preferred TBC for gas turbine engine applications as it has, besides these two properties, a relatively high thermal expansion coefficient and a good erosion resistance. However, zirconia is semitransparent to thermal radiation in the infrared spectral region [1,2]. Therefore, in addition to heat conduction by lattice waves (phonons), in TBCs heat is also transferred by a radiative component which becomes increasingly important at elevated temperatures as it is proportional to $T^3$ according to the Rosseland radiative conductivity [3–5]. Thus, the total energy transfer through the coating increases above the heat transfer caused by solid heat conduction alone. This degrades the insulating ability of the coating.

Appropriate techniques for depositing TBCs are either air plasma spraying (APS) or electron beam physical vapor deposition (EB-PVD). In this paper only EB-PVD YSZ TBCs are investigated. The columnar grain structure of EB-PVD coatings aligned perpendicular to the interface maximizes the resistance to strains that arise from differences in thermal expansion coefficients of bond coat and TBC top coat. Other advantages are: aerodynamically favorable smooth surface, better interaction with the substrate, greater thermal cycle tolerance and, hence, greater lifetime if compared with the plasma spray process. Because of these properties, EB-PVD YSZ coatings are particularly appropriate for application as TBCs on gas turbine blades and vanes [6].

In EB-PVD TBCs grain size varies from 1 to 2 µm near the bond coat/TBC interface, while the TBC columnar grain length is often 100–250 µm, depending on the overall coating thickness, with a high degree of crystallographic texture [7]. As the heat flow is mainly parallel to the intercolumnar gaps between the columns, the heat transfer is not effectively reduced. However, the primary columns exhibit a feathery structure with intracolumnar pores, which are inclined to the heat flow, resulting in a moderate reduction in the thermal conductivity [8,9]. Thus the thermal conductivity of EB-PVD YSZ coatings is reduced from the bulk values of 2.2–2.6 W/(m K) to values in the range 1.4–1.6 W/(m K) [10–12]. However, within the first

* Corresponding author. Tel.: +49 931 70564 46; fax: +49 931 70564 60.
*E-mail address:* manara@zae.uni-wuerzburg.de (J. Manara).

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doi:10.1016/j.surfcoat.2008.09.033

**Nomenclature**

| | |
|---|---|
| $\varepsilon$ | emittance |
| $\lambda$ | wavelength m |
| $\Lambda$ | thermal conductivity W m$^{-1}$ K$^{-1}$ |
| $\mu$ | direction cosine |
| $\Pi$ | porosity |
| $\rho$ | density kg m$^{-3}$ |
| $\theta$ | scattering angle ° |
| $\tau$ | optical depth |
| $\tau_0$ | optical thickness |
| $\sigma$ | Stefan–Boltzmann constant W m$^{-2}$ K$^{-4}$ |
| $\omega_0$ | albedo |
| $\Omega$ | solid angle sr |
| $A$ | absorption coefficient m$^{-1}$ |
| $A_\perp$ | area normal to the surface m$^2$ |
| $a$ | weight factor |
| $a_{solid}$ | solid thermal diffusivity m$^2$ s$^{-1}$ |
| $c_p$ | specific heat J kg$^{-1}$ K$^{-1}$ |
| $d$ | thickness m |
| $E$ | extinction coefficient m$^{-1}$ |
| $g$ | anisotropy factor |
| $k$ | heat transfer coefficient W m$^{-2}$ K$^{-1}$ |
| $I$ | intensity W m$^{-3}$ sr$^{-1}$ |
| $p$ | scattering phase function |
| $q$ | heat flux W m$^{-2}$ |
| $Q_{rad}$ | radiant flux W |
| $Q_{sca}$ | relative scattering cross section |
| $R_{dh}$ | directional–hemispherical reflectance |
| $S$ | scattering coefficient m$^{-1}$ |
| $t$ | time s |
| $T$ | temperature K |
| $T_{dh}$ | directional–hemispherical transmittance |
| $x$ | length m |
| *subscripts and superscripts* | |
| b | black body |
| meas | measured |
| rad | radiation |
| solid | solid conduction |
| sp | sample |
| * | effective |

few hours of turbine engine operation, the thermal conductivity of EB-PVD TBCs may increase due to sintering to 1.5–2.1 W/(m K) [12].

Concerning the radiative properties, YSZ is fairly transparent below 5 µm wavelength and nearly 100% opaque above 8 µm wavelength, and it is semitransparent in the range of 5–8 µm wavelength. Because of this transparent property, in high-temperature environments significant heat can be transported through the YSZ to the base material in spite of its low solid thermal conductivity. But, as a white ceramic oxide, zirconia has also a high reflectance of radiation at wavelengths of 1–5 µm, and consequently it will reduce the heat loads onto the first stage of the turbine nearby the combustion chamber significantly which is associated with radiation [13,14].

Further efforts were done to produce modified TBC microstructures that increase both phonon and photon scattering which decreases thermal conductivity and reduces radiative heat transfer by higher reflectance, respectively [4,15]. Especially for increasing the infrared reflectance, TBCs with a multilayer structure of alternate layers of two different materials (7% yttria-stabilized zirconia (7YSZ) and $Al_2O_3$) having different refractive indexes were deposited using EB-PVD.

Concerning emittance of EB-PVD YSZ TBCs, it was investigated in dependence on wavelength, emission angle, temperature, and coating thickness by Manara et al. [14]. A high emittance (which is associated to a low reflectance) is advantageous if the heat transfer onto the TBC is dominated by forced convection which is valid for turbine vanes and blades behind the guide vanes, as discussed below. In contrast to that a low emittance (which is associated to a high reflectance) would be advantageous if the heat transfer mainly occurred via thermal radiation which is the case for the combustion chamber walls, as explained above.

Siegel and Spuckler [16,17] basically analyzed heat transfer properties for zirconia TBCs under the specific conditions of gas turbines. With radiative and convective heating the surface temperature of the hot side of the thermal barrier coating can be near 1200 °C and above. The contribution of radiative and conductive heat transfer from the surrounding onto the surface of the TBCs depends on the coating location within the engine. The combustion chamber walls, first stage vanes, and partially first stage blades, are adjacent to the combustor and it can be assumed that radiation is incident on the coating from blackbody surroundings at the combustion gas temperature in the range of 1400–1700 °C. Hence the radiative transfer dominates the heat transfer onto the coating surface and a low emittance is advantageously to reduce the heat load. Further back in the engine away from the combustor, the turbine blades are surrounded by similar blades so external radiative exchange is negligible and the heat transfer onto the coatings is dominated by forced convection. In this case a high emittance of the coating is desirable to dissipate the assimilated energy via thermal radiation into the surrounding. Beside the heat transfer onto the surface of the TBC the heat transfer through the TBC has to be considered. In both cases regarded above, two internal heat transfer mechanisms are existing: diffuse radiative transfer within the TBC and solid thermal conduction. Internal radiant emission, absorption, and scattering act in combination with solid heat conduction.

Contributions to the total heat transfer due to radiation are often disregarded in calculations for thermal conductivity in TBCs, because of the small effect at low temperatures. However, the effect of radiation on heat transfer can become quite large at elevated temperatures because of the third order dependency on temperature. In the literature, there are only few references dealing with this subject.

The main objective of the present study was to determine the total heat transfer through a standard EB-PVD YSZ TBC (about 280 µm in thickness) caused by solid thermal conduction and radiative heat transfer and to correlate the results with the microstructure of the coatings. For the application of TBCs on vanes and blades in gas turbines it is important to investigate the heat transfer under service conditions simulated by heat treatment at 1100 °C for different durations. The thermal conductivity and the infrared-optical properties of EB-PVD YSZ coatings were determined in the as-coated state and after heat treatment using the laser flash technique, the integrating sphere and the black body boundary conditions method.

## 2. Theory

### 2.1. Heat transfer equation

The heat transfer inside a medium (without heat sources) due to solid conduction can be described by the non-steady state heat transfer equation which is a partial differential equation:

$$\frac{\partial T}{\partial t} = a_{solid} \cdot \nabla^2 T, \quad \text{with} \quad a_{solid} = \frac{\Lambda_{solid}}{\rho \cdot c_p}. \tag{1}$$

The solid thermal diffusivity $a_{solid}$ is correlated with the solid thermal conductivity $\Lambda_{solid}$, the density $\rho$ and the specific heat $c_p$. For the steady state case and one-dimensional heat transfer,

$$\nabla^2 T = \frac{\partial^2 T}{\partial^2 x} = 0 \Rightarrow \frac{dT}{dx} = \text{constant}, \tag{2}$$