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Study on thermal resistance performance of 8YSZ thermal barrier coatings

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ABSTRACT

The application of ceramic thermal barrier coatings (TBCs) can significantly increase gas turbine performance. The microstructure of TBCs fabricated by APS and EB-PVD is remarkably different. The thermal and mechanical properties of TBCs with the same material are determined by its microstructures. In order to establish structure-property relationships of TBCs with complex inhomogeneous geometry, in this work, various 3D-microstructures of TBCs were reconstructed using the geometric reconstruction software developed by our team. A three-dimensional model based on Lattice Bolzmann method (LBM) was developed to investigate the heat transfer behaviors in TBCs. The effect of microstructure parameters such as porosity, pore size and pore shape on the effective thermal conductivity of TBCs was studied in detail. The relationship between microstructures and effective thermal conductivity of TBCs was obtained. The calculated values of the effective thermal conductivity of 3D-TBCs agree well with the experimental values, and all relative errors are less than 4%. It can be found that the layered coatings should have larger size pores, and the columnar coatings should have smaller size pores. This can make the internal temperature distribution of TBCs more uniform. The effect of pores size on the thermal conductivity of two types of TBCs is different, but their thermal conductivity increase with the increase of porosity. The effective thermal conductivity of the columnar TBCs with the same porosity decreases with the decrease of pores size, but that of the layered TBCs increases with the decrease of pores size. The pores shape has a great influence on the effective thermal conductivity of the coating, especially for high porosity columnar coating. The effective thermal conductivity of the columnar coatings logarithmically increases with the length of the elongated pores, and it is increased by 21.6% when the porosity is 20%. However, the effective thermal conductivity of the layered structure coatings logarithmically decreases with the length of the elongated pores. The results will provide us a theoretical guide to design TBCs with a high thermal insulation property.

1. Introduction

Thermal barrier coatings (TBCs) are widely used for thermal protection of air-cooled hot sections in modern gas turbine, such as power generation, marine and aero engines [1–3]. The application of ceramic TBCs can significantly increase engine performance by elevating turbine entry temperature, reducing specific fuel consumption and internal cooling, reducing the oxidation rate of metal components, and extending the lifetimes and durability of component. Now, the turbine entry temperature in gas turbine already reach 1500–1700 °C [4]. The efficiency and specific power of gas turbine are constantly increased with the increase of turbine inlet temperature.

TBCs usually consist of a ceramic coating, a thermal grown oxide and a metallic bonding layer (i.e. MCrAlY where M represents a combination of Ni and Co) [5]. Throughout the decade of the 1970's and up to the present, 8 wt% Yttria Stabilized Zirconia (8YSZ) has been the most widely used material for the top coatings because of its low density, low thermal conductivity, phase stability to high temperature, good thermal shock resistance and excellent erosion resistant properties [6–8]. The thermal conductivity of dense YSZ

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varies from 0.6 to 3 $Wm^{-1}K^{-1}$ [9], according to the temperature and grain size. Due to its low thermal conductivity, the ceramic coatings play a key role in the decrease of thermal fluxes under high temperature environments. The top coating is mostly fabricated either by air plasma spraying (APS) and electron-beam physical vapor deposition (EB-PVD). Compared with EB-PVD, APS is low cost, high preparation efficiency, easy to control the composition of coating material, and so on. The microstructures produced by two fabrication methods are remarkably different [10]. The APS top coating has a specific layered morphology with a lot of pores and cracks that are parallel to the coating surface; while EB-PVD ceramic top coating has a unique columnar morphology, the columnar grains grow almost perpendicular to the bond coat surface and extend through the entire ceramic coatings thickness [11–13]. In addition, the surface of EB-PVD TBCs is smoother, making it more attractive for aerodynamic design.

There are many factors that will affect the effective properties of TBCs, such as the intrinsic thermal conductivity of the ceramic layer of TBCs, the microstructure of the TBCs (architecture of the pores and cracks), the dense vertically cracked (DVC) [14,15], and so on. These porous microstructures can be characterized by inter-lamellar and globular pores, intra-splat micro-cracks and splat boundaries. Their porosity ranges between 5% and 20% [16,17]. These porous microstructures greatly influence the effective properties such as thermal conductivity and elastic modulus, and thus influence the coating behavior. Pores are often beneficial to decrease the thermal conductivity of the TBCs. The effective thermal conductivity of TBCs varies in a large range, typically from 1.8 to 2.0 $Wm^{-1}K^{-1}$ for EB-PVD coatings and from 0.9 to 1.4 $Wm^{-1}K^{-1}$ for APS coatings. Some nano-sized pores can play a special role in changing the thermal shift or heat diffusion behavior in the coatings [18]. Cracks also play an important role in changing the thermal conductivity of the TBCs. However, many factors, such as the droplet temperature, the velocity of impact and the temperature of substrate, can make the microstructures of coating highly heterogeneous in the spraying process [19,20]. Also, the multilayer structure and new material coatings was studied in order to further improve the durability and functional performance [14,15,21]. The thermal barrier ability and the service lifetime have played important role in estimating TBCs performance no matter which way is used to fabricate it. The thermal insulation ability of TBCs is not only related to the temperature of the metal parts, but also affected by the thermal cycle lifetime of TBCs. Therefore, quantitative microstructure-property correlations need to be established for predicting the coating properties and conversely for improving the microstructure by optimizing the spray process [22].

The key role of TBCs is to minimize heat transfer and maximize the temperature drop across the coating. The insulation performance of TBCs with the same material is determined by its microstructure. The effect of YSZ particles size, the stabilized materials and other additives which affect the thermal conductivity of coatings on the performance of the coating have been studied in the last years [23–27]. There exist three heat transfer mechanisms in the coatings, i.e., thermal conduction in solids, conduction in gases and radiative transmission [28,29]. Among those three mechanisms, the conductions in solids and gases is one of the most critical issues for the application of the coatings. So far, most studies referring to the heat transfer properties of TBCs mainly focus on the conduction aspect [30–34].

The difference of thermal conductivity and thermal barrier ability in various types of coatings is related to the pore microstructure and porosity of coatings [35]. The influence of microstructures on the thermal conduction has been investigated by several researchers using both experimental and numerical methods [36,37]. In particular, image-based numerical analysis was intensively applied using either real images or artificial coating models during the last 10 years. Since, Deshpande [38] applied image analysis to characterize the porosity in thermal sprayed coatings, several studies [39–41] have taken advantage of this technique in conjunction with the use of finite element based software programs to estimate the effective thermal conductivity of coatings from cross-sectional images. Chi and Sampath [36] investigated the relationship between microstructure and thermal conductivity for three sets of plasma-sprayed YSZ coating systems. Golosnoy [37] developed a numerical and analytical model to investigate the effect of pore shape on thermal conductivity. Wang [35] employed the finite element method to simulate the thermal transfer behavior of TBCs with different spatial and geometrical characteristic of pores. The simulation results indicated that the parameters of pores, such as size, orientation and volume have a close relationship with the thermal conduction of coatings. Wang [42] and A. Kulkarni [43] built an artificial structural model of coatings from the collective microstructural information obtained by multiple small-angle neutron scattering [42–46], and then calculated the thermal conductivity. In addition, the effective thermal conductivity of the gas trapped within the pores is influenced not only by the temperature and pressure, but also by the dimension of the pores at the micro-scale level. This effect depends upon the Knudsen number. Especially for submicron or nano-scaled pores, the decrease in the thermal conductivity of the trapped gas appears obvious [47–49]. The microstructure of TBCs not only affects the thermal conductivity but also has a significant effect on the radiative properties [50,51]. In particular, the large grain boundary and pore architecture (i.e., its size, morphology, and distribution) can strongly affect the spectral reflectance and transmittance of coatings [52,53]. The radiative properties of the TBCs has been investigated and extensively developed by Zhao's group [54,55]. This numerical method has been widely used in the field of micro/nano-scale thermal radiation in recent years [56,57].

All these previous studies provide useful information about fundamental characteristics, heat transfer performance and analysis methodologies in thermal conductivity of porous TBCs. In order to further improving the thermal barrier ability of TBCs and optimizing the spraying technology, it is necessary to study the effects of pore microstructure on the effective thermal conductivity of TBCs. In our previous works, 2-D geometry reconstruction program based on the four-parameter stochastic growth method was developed by our team [58], and the effect of pore microstructures on the effective thermal conductivity of layered and columnar TBCs was investigated using the thermal resistance network method and 2-D geometric model [59]. However, 2-D geometric model cannot represent the real microstructure of TBCs, especially the connection between the pores. The weak flow of gas in the pores cannot be analyzed by the thermal resistance network method, especially the surface of TBCs with high porosity. Therefore, it is necessary to develop the detailed mathematical formulation to investigate how the pore microstructure affect the effective thermal conductivity of TBCs. The objective of this work is to investigate the mechanism of heat transfer inside coatings and provide a fundamental understanding of the correlations between the coating microstructures and heat transfer properties. 3D geometry reconstruction program is developed and various 3D geometric models with different porosities, pore sizes and shapes were reconstructed. Lattice Boltzmann method is applied to investigate the heat transfer properties of TBCs with various microstructural parameters and is validated by the typical series and parallel models of composite materials. The heat transfer analysis software is developed by our team, and the numerical method is optimized to improve computational accuracy and convergence. The parameters of microstructures, such as porosity, pore size and shape, are considered, and their effects on