Journal of Materials Science & Technology xxx (2017) xxx–xxx

Contents lists available at ScienceDirect

Journal of Materials Science & Technology

journal homepage: www.jmst.org

# Bimodal TBCs with low thermal conductivity deposited by a powder-suspension co-spray process

Wei-Wei Zhang [a,b,c], Guang-Rong Li [a], Qiang Zhang [a,d], Guan-Jun Yang [a,*], Guo-Wang Zhang [a], Hong-Min Mu [a]

[a] State Key Laboratory for Mechanical Behavior of Materials, School of Materials Science and Engineering, Xi'an Jiaotong University, Xi'an 710049, China
[b] School of Materials Science and Engineering, Chang'an University, Xi'an 710064, China
[c] Institute of Publication Science, Chang'an University, Xi'an 710064, China
[d] AECC Beijing Institute of Aeronautical Material, Beijing 100095, China

ARTICLE INFO

*Article history:*
Received 16 September 2017
Received in revised form
19 November 2017
Accepted 21 November 2017
Available online xxx

*Keywords:*
Thermal barrier coatings
Aspect ratio
Bimodal microstructure
Thermal conductivity
Co-spray process

ABSTRACT

Advanced thermal barrier coatings (TBCs) with better thermal barrier performance are required by both advanced gas turbine and air engine. In this work, novel bimodal TBCs with low thermal conductivity were deposited and characterized by a novel co-spray approach with both solid powder and suspension. Experimental and finite element analyses were used to optimize the process parameters to prepare the specific morphology nanostructure features. With a comprehensive understanding on the influence of spraying parameters on the morphology of nano-particles, homogeneous nano-particle heaps with a large aspect ratio were introduced to conventional layered coatings by plasma co-spraying with suspension and solid powder. Co-sprayed bimodal microstructure composite coatings resulted from both wet suspension droplets and molten particle droplets exhibited low thermal conductivity. The thermal conductivity of the composite coating was 1/5 lower than that of the counterpart coatings by conventional plasma spraying with solid powder. This study sheds light to the structural tailoring towards the advanced TBCs with low thermal conductivity.



## 1. Introduction

Thermal barrier coatings (TBCs) are widely applied on the hot sections of gas turbines. As to turbine components with suitable internal cooling, temperature drops may be up to 200 K with a thickness of TBCs between 200 μm and 500 μm [1]. A typical TBCs system often exhibits a multi-layer structure. An oxidation-resistant metallic layer (bond-coat) is deposited on superalloy component prior to an insulating ceramic layer (top-coat) [2,3]. The enhanced efficiency is attributed to the thermal insulation introduced by the top-coat with low thermal conductivity. The state of the art of top-coat is represented by yttria stabilized zirconia (YSZ) deposited onto the components either by air plasma spray (APS) or by electron beam physical vapor deposition (EB-PVD) [4]. In particular, owing to the deposition process, APS coatings exhibit a lamellar structure resulted from multi-layer stacking. There are spherical pores, intersplat and intrasplat cracks running vertically along the splat thickness. EB-PVD coatings have a typical columnar structure oriented parallel to the heat flux. As a result of the existence of defects (the defects are filled with air, of which the thermal conductivity is 0.025 $W\,m^{-1}\,K^{-1}$ [5]), thermal conductivities of APS and EB-PVD YSZ top-coat decrease from 2.5 $W\,m^{-1}\,K^{-1}$ (bulk YSZ) to 0.8–1.2 $W\,m^{-1}\,K^{-1}$ [6] and 1.5–1.8 $W\,m^{-1}\,K^{-1}$ [7], respectively.

It is widely believed that pore volume fraction (porosity) plays a very important role in reducing of thermal conductivity [8–10]. Furthermore, spatial and geometrical characteristics of the pores inside TBCs are significant factors of XXXX owing to their thermal insulation behavior [11–18]. Our previous research [19] reveals that thermal conductivity presented a significant dependence on pore morphology and pattern. The large aspect ratio pores with in-plane direction dominantly affect the heat transfer in the top-coat. However, the intrinsic pores have not been effectively utilized in conventional TBCs [19]. There are only 25% of the pores play a powerful role in reducing thermal conductivity of coatings [20]. And intersplat pores in conventional coatings may disappear during thermal exposure [21]. Furthermore, most aspect ratios of conventional TBCs are located in a range of 10–50 [19,20,22,23] (The aspect ratio is defined as the ratio between width and thickness

* Corresponding author.
*E-mail address:* ygj@mail.xjtu.edu.cn (G.-J. Yang).

https://doi.org/10.1016/j.jmst.2017.11.052

of a pore). These TBCs fail to maximize their thermal insulation, as thermal conductivity is highly dependent on the disk-like pores with a high aspect ratio. Therefore, it might be very important to introduce some in-plane pores with higher aspect ratios, so as to form a multi-scale structure with low thermal conductivity.

There are lots of methods to introduce large-scale pores during deposition or post-deposition treatment. Replica, sacrificial template, and direct foaming technique are widely used [17,24]. The sacrificial template method [25] is to introduce some sorts of pore former or sacrificial material to act as a place holder. Pore formers, such as starch [26], graphite [27,28] and polyester [29,30], will disappear during a post-production thermal cycle, resulting in the formation of large scale pores [31–34]. To sum up, the existing approaches are restrained by the following limitations. On one hand, materials of the introduced heterogeneous pore formers should be clear away. In reality, it is difficult to remove them completely. On the other hand, the removal of heterogeneous materials requires additional preparation steps, which increases the process difficulty and would introduced risk of errors in process.

In this work, a structural model was developed to correlate effective thermal conductivity with structure. A new structure design with nano-particle heaps and micro-scale pores was proposed. Homogeneous nano-particle heaps with a high aspect ratio were introduced to conventional layered coatings to enhance the thermal properties of YSZ coatings. To begin with, the plasma parameters for single-solution step were analyzed. In addition, a structure model was developed to determine optimal spraying parameters. Subsequently, YSZ coatings, with an ultra-low thermal conductivity, composed of nano-particles stacking layers and splats were deposited using plasma co-spraying with suspension and solid powder, resulting from wet suspension droplets and molten particle droplets.

## 2. Model developments

### 2.1. Structural tailoring toward lower thermal conductivity

Based on our previous research [19], it would be very important to introduce some in-plane pores with higher aspect ratios, so as to form a multi-scale structure with lower thermal conductivity. However, it is difficult to remove the introduced heterogeneous pore formers completely for the existing approaches. Can the homogeneous materials be introduced?

Nanoscience and technology offer the potential for significant advances in the performance of new and established materials based on improvements in physical and mechanical properties [35,41], owing to the fact that the grain size reduces by factors from 100 to 1000 times when compared to current engineering materials [36]. Hence, the surface-to-bulk ratios of nano materials are much higher than those of coarse particle (e.g., micrometer-sized) materials and, in turn, the interface density between such features is much higher. For conventional materials, the grain boundary contributing to thermal conduction is thought to be small [37]. However, in fact, grain boundaries can have a significant effect on XXXX, particularly when the grain size is of the same order as the mean free path for phonon scattering [38]. It has been found that thermal conductivity is drastically reduced for fine grained materials, particularly when grain size reaches nanometer dimensions [39]. Based on the above considerations, nano-particle heaps can be embedded in lamellar coatings to replace large pores to avoid the removal of troubled heterogeneous materials. Hence, the specific morphology nano-particle heaps can be used as homogeneous materials to reduce the thermal conductivity of coatings. Morphology and pattern (including the orientation and aspect ratio) of the nano-particle heaps, similar to pores in thermal barrier coatings (TBCs), may have a significant effect on their thermal insulation performance.

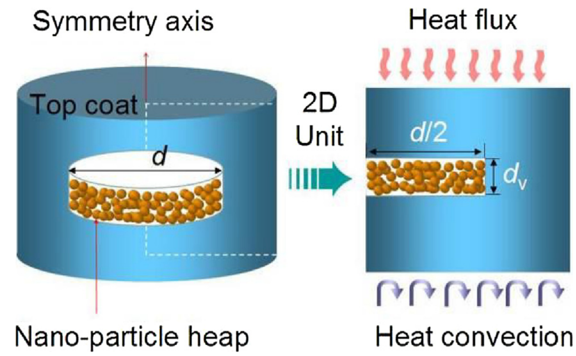


**Fig. 1.** Developed model used in finite element simulation.

**Table 1**
Parameters of the developed model with nano-particle heaps used in simulation.

| Parameters | Value |
|---|---|
| Model height ($h$), μm | 30 |
| Model width ($w$), μm | 120 |
| Nano-particle heaps porosity, % | 1 |
| Nano-particle heaps thickness ($d_v$), μm | 0.3–6 |
| Nano-particle heaps diameter ($d$), μm | 6–120 |
| Nano-particle heaps aspect ratio ($d/d_v$) | 1–400 |
| Thermal conductivity of the matrix (in-depth), W m$^{-1}$ K$^{-1}$ | 1.0 |
| Thermal conductivity of the matrix (in-plane), W m$^{-1}$ K$^{-1}$ | 1.5 |
| Thermal conductivity of the nano-particle heaps, W m$^{-1}$ K$^{-1}$ | 0.04 |

### 2.2. Simulation method and procedure

In order to investigate the effect of nano-particle heaps morphologies on thermal insulation, finite element analysis (FEA) was used to simulate thermal conduction. A 3D cylinder plate like axial symmetry model was developed with a uniform heat flow from top to bottom (Fig. 1). Therefore, a 2D analytical model unit was used to simulate heat transfer. In detail, a rectangular plate with a disk-shaped nano-particle heaps was obtained from the cross-section of the 3D model. The disk-shaped nano-particle heaps have a same volume ratio of 1% to that of XXX but different aspect ratios. Aspect ratio is defined as the ratio between width and thickness along cross-section. Parameters of the disk-shaped nano-particle heaps morphology can be found in Table 1.

In this study, thermal analysis was conducted with the commercially available ANSYS software (afflicted with ANSYS finite element code-APDL). Planes of 55 elements (four nodes element, axisymmetric) were used in the model. Top surface temperature of the top-coat was set as 1273 K, whereas the environmental temperature was 298 K. The thermal convection coefficient at the bottom of the model was set as 1000 W m$^{-2}$ K$^{-1}$. Adiabatic boundary conditions were applied to left and right sides of the 2D model. The simulation results were extracted from ANSYS visualization. The effective thermal conductivity of the model can be calculated as follows [19]:

$$k_e = \frac{(T_D - T_S)hH}{\Delta T} \quad (1)$$

where $T_D$ is the top surface temperature of the top-coat, $T_S$ is the environmental temperature, $h$ is the thermal convection coefficient, $H$ is the height of model, $\Delta T$ is the temperature difference between the top and the bottom surface.

Please cite this article in press as: W.-W. Zhang, et al., J. Mater. Sci. Technol. (2017), https://doi.org/10.1016/j.jmst.2017.11.052