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Stress analysis of thermal barrier coating system subjected to out-of-phase thermo-mechanical loadings considering roughness and porosity effect

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ABSTRACT

This paper presents the out-of-phase thermo-mechanical stress analysis of thermal barrier coating (TBC) system in real working conditions used as thermal barrier in diesel engine cylinder heads. The coating system in this research comprises 350 μm zirconium oxide top coat (TC) and 150 μm metallic bond coat (BC). These layers were deposited on the substrate, aluminum A356 alloy, by the aid of air plasma spray (APS) method. Afterwards, the specimen was subjected to thermo-mechanical fatigue (TMF) loadings. Based on the experimental conditions, FE simulations were performed by both time-independent and time-dependent substrate material properties in ABAQUS software. Simulation results related to heat transfer analysis demonstrate only about 10.5% comparative error compared to experimental results. Moreover, defining time-dependent properties, which were obtained from two-layer visco-plastic model, yields results with 15% less comparative error in comparison to the results based on time-independent material properties. In addition, the effects of roughness and porosity in coating layers and substrate were studied on three different models by the aid of a scanning electron microscopy image. Obtained results based on real geometry illustrate that consideration of porosity in TC layer has an effective role in the stress distribution of this layer. However, BC layer stress distribution is much more dependent on interface morphology.

1. Introduction

One of the functions of thermal barrier coatings is their usage in diesel engine combustion chamber. This would cause less heat dissipation and consequently would result in higher working temperature of combustion chamber, which eventually can increase the thermal efficiency [1,2]. This increase in thermal efficiency would finally cause a decrease in specific fuel consumption [2–4]. In addition, higher working temperature would cause a decrease on CO emissions because it has been concluded that CO reactions are dependent on temperature [5]. Moreover, TBC can cause remarkable decrease in substrate temperature. Therefore, due to the less thermal gradient in substrate, considerable increase in fatigue life is anticipated [6].

Thermal barrier coatings used in diesel engine components comprise two main layers, namely top coat which is mostly made of zirconium oxide and a metallic bond coat. In this research, the composition of top coat is ZrO_2 7–8 wt.% Y_2O_3 and that of bond coat is NiCrAlY. Both layers were applied on substrate by the aid of air plasma spray (APS) method. Afterwards, the specimen was subjected to out-of-phase (OP) thermo-mechanical fatigue loadings based on actual cylinder head working conditions.

In this field of research, many researches have been presented by both simulation and experiment. In order to provide a well-organized literature review, three categories could be studied as (a) thermo-mechanical stress analysis, (b) consideration of actual geometry, and (c) influential factors in TBC field of research.

As in the first category (thermo-mechanical stress analysis), Chen et al. [7] investigated the failure behavior of TBC subjected to thermo-mechanical loadings. They concluded that out-of-phase TMF lifetime was less than that of in-phase TMF. Tzimas et al. [8] studied different failure mechanisms of thermal barrier coating system subjected to thermo-mechanical loadings. This was done by the aid of post-mortem microstructural analysis. Tsuyoshi-Takahashi and Sasaki [9] investigated aluminum alloy A356 under thermo-mechanical loadings. They established a relationship between microstructure changes and low cycle thermal fatigue. Ranjbar-Far et al. [10] observed the crack propagation and layer delamination for thermal barrier coating under thermo-mechanical loading. In other work done by Ranjbar-Far [11], the effect of amplitude and wavelength of interface asperity was taken into consideration in order to obtain both accurate thermo-

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mechanical stress analysis and critical thermal grown oxide thickness causing the delamination of TBC layer. Moridi et al. [12] investigated the effect of interface roughness on stress distribution of coating layers subjected to thermo-mechanical loadings. In other work by these researchers [13], more attention was given to the shape of interface asperities. It was concluded that out-of-phase waves in bond coat would result in critical regions which are prone to microcrack nucleation and growth. Azadi et al. [14] studied the failure mechanisms of thermal barrier coating system which was deposited on aluminum alloy A356 and was subjected to thermo-mechanical loading. The fractography of specimen indicated that the delamination of coating layers from substrate was the main cause of TBC system failure.

As an example of the second category (consideration of actual geometry), Wang et al. [15] studied the effect of defect orientation angle on effective thermal conductivity. They used computational micromechanics method in order to simulate the real geometry of coating. Qiao et al. [16] investigated the effect of porosity of top coat layer, which was deposited by air plasma spray technique method, on effective elastic modulus. In addition, they compared the results between 2D and 3D image-based analyses. In their work, serial sectioning technique was used in order to obtain an artificial 3D model from cross-sectional images.

As in the third category (influential factors in TBC field of research), Rezvani Rad et al. [17] studied the two-step residual stress analysis of TBC due to the separate deposition processes of bond coat and top coat layers. They also considered the effects of actual geometry, preheating temperature and cooling rate on residual stress distribution. In a comprehensive series of studies done by Han et al. [18–21] on double-ceramic-layer thermal barrier coating, influential factors such as coating thickness, thermal conductivity, thermal expansion, elastic modulus and buffer effect of the inside ceramic layer have been taken into account. In these analyses, they investigated these key factors from both thermal and structural aspects. They studied the coating thickness and thermal conductivity effects of both top and inside ceramic layers. They concluded that by defining top ceramic thickness, total ceramic thickness, and thermal conductivity in temperature safe region, overheat failure in coating layers could be avoided [18,19]. In another works by the same group of researchers [20,21], they studied the stress safety aspect of TBC system. In these works, three parameters of elastic modulus, thermal expansion, and coating thickness were investigated in order to optimize the stress buffer effect of inside ceramic layer. The optimized values could be obtained within the stress safe regions, which were calculated from stress distribution of different parts of TBC system subjected to the thermo-mechanical loadings. Taking into account all these influential factors, they concluded that 8YSZ, which is widely used as TC in conventional thermal barrier coatings, is the perfect material that can be used as inside ceramic layer in DCL-TBC.

It is obvious that the performance of thermal barrier coating considerably depends on its durability, which is another influential factor in TBC field of study. In this regard, Evans et al. [22] studied a complete review of the TBC failure mechanisms. It was stated that nucleation and propagation of cracks emanating from imperfections near thermal grown oxide interface can lead to large-scale buckling and spalling prior to final failure. In another research, delamination of TBC system subjected to thermal cycling was studied by He et al. [23]. They investigated the effect of number of cycles on normal stresses in TBC between peaks in interface oscillations. They concluded that abrupt failure occurs when the minimum energy release rate due to the presence of cracks exceeds the fracture toughness of TBC.

It is clear that one of the most important factors in finite element simulation of thermal barrier coatings is defining accurate material properties for each layer. In the present work, two different cyclic behaviors for substrate were taken into consideration. It should be mentioned that comprehensive properties based on temperature were also defined for coating layers.

In this work, firstly, the accuracy of temperature distribution was validated with experimental results. Then, stress distribution was simulated based on temperature history of the previous analysis. Afterwards, simulation results were compared with those obtained from the experiment.

Moreover, the effect of considering real geometry, including porosity and interface morphology, is also studied in this work.

According to the literature review, thermo-mechanical stress analysis of thermal barrier coatings based on finite element method, especially for TBC systems intended to be used as thermal insulators on diesel engine components, is quite rare. Accordingly, the novelty of this work is to investigate thermo-mechanical analysis of thermal barrier coating considering real geometry including roughness and porosity, which was obtained by the aid of scanning electron microscopy (SEM). Furthermore, the comparison of force-mechanical strain graph between simulation and experimental results is mentioned for the first time.

2. Materials

In this study, the substrate was an aluminum alloy, entitled the A356.0 alloy, which has been typically used in diesel engine cylinder heads. The element composition of this alloy was measured as 7.06% Si, 0.37% Mg, 0.15% Fe, 0.01% Cu, 0.02% Mn, and 0.13% Ti and Al was the remainder. A typical TBC system, consisted of two layers, was applied on the substrate. These layers included a metallic BC layer (Ni–22%Cr–10%Al–1%Y) and a ceramic TC layer made of Yttria stabilized Zirconia with the composition of ZrO_2–8%Y_2O_3. More details can be found in Ref. [14].

The coating process was performed on aluminum alloy cylindrical specimen by air plasma spraying method. Before deposition of coating layers, the specimen was already blasted with SiC particles. More details about parameters of the coating process can be found in the literature [24,25]. The SEM image of the coated specimen is shown in Fig. 1.

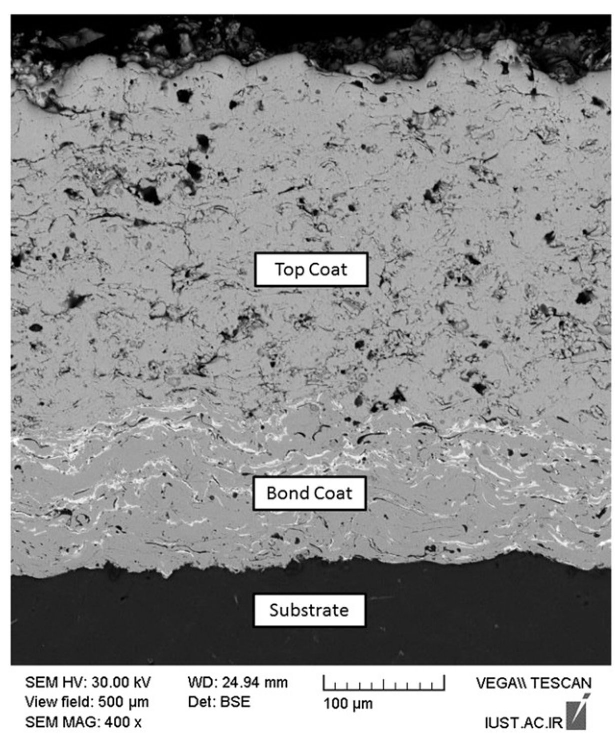

Fig. 1. The SEM image of the coated specimen.