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# Residual stress distribution along interfaces in thermal barrier coating system under thermal cycles

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ABSTRACT

The residual interfacial stress plays an important role in crack initiating and propagating along the interface, which could result in delamination failure of the thermal barrier coatings (TBCs). In this study, the finite element model of air plasma spraying(APS) TBCs was established to assess the level and distribution of residual stress along top coat(TC)/thermally grown oxide (TGO) and bond coat (BC)/TGO interfaces under thermal cycles. Instead of using vertical stress $S_{22}$ in global coordinate system, the normal and tangential components in the local system along the interfaces, transformed from stress components $S_{11}$, $S_{22}$, and $S_{12}$ in the global one, were used to evaluate the way the cracks initiate and propagate along the interfaces. Firstly, the effect of the number of thermal cycles on residual stress was investigated. It was found that, for the TBCs model without TGO growth and crack, the impact of the number of thermal cycles on the stress is very insignificant and could be ignored. So the present study only chose to focus on the first thermal cycle. Then the influence of the TGO thickness and the interface amplitude on the normal and tangential residual stresses for both homogeneous and inhomogeneous temperature fields was explored. The results show that the TGO thickness, interface amplitude and temperature field affect the residual stress level and distribution, leading to different fracture mechanisms along TC/TGO and TGO/BC interfaces. Finally, the difference between the vertical stress in the global coordinate system and the normal stress in the local coordinate system was studied. Compared with vertical stress $S_{22}$, the stress components normal and tangential to the TC/TGO and TGO/BC interfaces are more appropriate to describing the stress distribution along the interfaces and predicting the propensity of crack initiating and propagating along the interfaces.

## 1. Introduction

Thermal barrier coatings(TBCs) are widely used to prolong the life of hot-side components in the aero-engine, gas turbine and so on. The temperature of the turbine blade with thermal barrier coating(TBC) in an aerospace engine can be lowered up to a few hundred degrees since the ceramic layer has a low thermal conductivity [1–4]. A typical air plasma spraying(APS) TBC system comprises four layers: the ceramic top-coat(TC), thermally grown oxide (TGO), metallic bond-coat (BC) and substrate. Each layer has significantly different physical, thermal and mechanical properties, which brings about some difficulties in investigating the failure mechanism of TBCs. Generally speaking, the damage and failure of TBCs is related to the following factors: residual stresses, mismatch of thermal expansion coefficients of all four layers, oxidation of BC, complicated morphology of interfaces, high-temperature sintering of TC layer, and stress redistribution due to creep of each layer, plastic deformation of the adhesive layer [5]. As a matter of fact, the functionality and reliability of plasma sprayed coatings is related to the microstructure, coating porosity [6] and residual stress [7,8]. Residual stress is caused by the misfit of thermal-expansion coefficient and elastic property when TBC is cooled down from preparation or operation temperature to room temperature [9,10]. M.Ranjbar-Far and his team have studied various influence factors of the residual stresses in TBCs [2,4,5,11]. They investigated the residual stresses generated during coat spraying in TBCs and found the residual stresses can induce micro-cracks along the interface after several thermal cycles and can be greatly reduced by substrate preheating [2]. In Ref.[4], they investigated the impact of non-homogenous temperature distribution on the residual stresses in TBCs under thermal cycling load and found the large difference between the maximum values of tensile stress in homogenous and non-homogenous temperature fields, and that higher values in homogenous temperature fields reduce the lifetime of TBCs. The influence of material property and interfacial roughness on residual stress in TBCs during thermal cycles was investigated in detail in Ref. [5]. They also investigated crack propagating along the TC/TGO and TGO/BC interfaces and the results show crack propagation is

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strongly related to the thickness of TGO and the interfacial roughness [11].

Besides, Sfar investigated the residual stress in TBCs with an initial micro-crack in the TC region right at the peak of the TC/TGO interface [12]. Bäker studied the residual stresses in the axisymmetric component coated with TBC [13]. In literatures above, the stress component $S_{22}$ in global coordinate system was always used to predict the crack initiation along the interfaces and the eventual delamination of TBCs. Using this stress component to evaluate the interfacial toughness or to predict the crack initiation may be reasonable not only for ideal flat surfaces but also for specific positions such as the peak and valley of generic curved interfaces. In fact, insufficient attention has been paid to the normal and tangential residual stress distribution along the TC/TGO and TGO/BC interfaces. There is no doubt that the state of an interfacial crack is closely related to the stress normal and tangential to the interface, which can cause the interfaces to slide, separate and open once the stress values exceed the interfacial toughness. So knowing about the normal and tangential stress distribution along the interface helps to predict where the interfacial cracks are likely to initiate and how the initial crack will propagate along the interface. Furthermore, there is a need for investigating the effect of the TGO thickness and the interface amplitude on the normal and tangential residual stress levels and their distribution along the TC/TGO and TGO/BC interfaces in TBCs in homogeneous or inhomogeneous temperature fields.

In this work, the finite element model of air plasma spraying(APS) TBCs was established to assess the normal and tangential residual stresses along TC/TGO and BC/TGO interfaces under thermal cycles. The influence of the TGO thickness and the interface amplitude on residual stresses in both the homogeneous and inhomogeneous temperature fields was investigated. The plastic property of the BC layer, creep behavior of each constituent in TBCs and transient heat conduction in inhomogeneous temperature field were considered.

## 2. Finite element model

### 2.1. The composition and the representative unit of TBCs

The model used in this work consists of APS ceramic TC, TGO derived from BC, MCrAlY BC (where M represents certain kind of metal, such as Ni, Co) and an Inconel 617 substrate. The thickness of TC, BC and substrate is assumed to be 0.25 mm, 0.1 mm, and 1.6 mm, respectively. These composition and dimensional data of the TBCs have been used in previous literatures [4,5,12].

The TC/TGO and BC/TGO interfaces are always uneven as the thermal spraying material can impossibly be uniformly coated on a substrate during thermal spraying, as shown in Fig. 1(a). Admittedly, due to the complexity of TBC system, to acquire the accurate stress experimentally and numerically requires a considerable amount of measuring and calculating. Thus the finite element method(FEM) was usually used to investigate the stress distribution and evolution in TBC system, and the interfaces were often modeled by using ideal simple curve [5,14–16] such as $y(x) = A\cos\frac{2\pi}{\lambda}x$ (where $A$, $\lambda$ are the amplitude and wavelength of the interface, respectively). Here the TC/TGO and TGO/BC interfaces are assumed to be of cosine-type shape and to have the same curvature. In this interface model, the value of wavelength $\lambda$ is selected as 60 μm and the value of the amplitude is defined in the range from 5 to 15 μm. These values are commonly obtained by observing the scanning electron microscope(SEM) image of a cross-section of the TBCs and often set as [2,4,8,11–13]. The representative periodic unit cell of the TBCs is used for calculation and analysis, as illustrated in Fig. 1(b). Two-dimensional mesh was generated on the selected unit cell of TBCs, and the part around the TC/TGO and TGO/BC interfaces was shown in Fig. 2. In order to improve the accuracy and reliability of the results, the mesh was refined at the region right next to the TGO/BC and TC/TGO interfaces. At the same time, for the sake of convenient counting, some brief names are assigned to the corresponding location of the TC/TGO and TGO/BC interfaces. For example, the *peak-off* and *valley-off* refers to the regions in close proximity to the highest and lowest position, respectively. Four-node bilinear plane strain quadrilateral(CPE4) elements were used for the model on which the homogeneous temperature field was imposed, and 4-node coupled temperature-displacement plane strain elements (CPE4T) elements for the inhomogeneous temperature field.

### 2.2. Material parameters

The micro pores and defects in TBCs generally formed during the thermal-spraying process of the BC and TC layers is not taken into consideration in this work, and all the four layers in TBCs are assumed to be homogeneous and isotropic. The TC, TGO and substrate are generally regarded as viscoelastic materials, and the BC is considered elastic and viscoplastic [11]. The coefficients of thermal expansion, Young's modulus and Poisson's ratios of each layer are temperature-dependent and given in Table 1. As to the plasticity of BC layer, the temperature-dependent plastic data is listed in Table 2. For creep behavior of all layers, the following creep model based on time-hardening power law is used,

$$\dot{\bar{\varepsilon}}^{cr} = B\sigma^n t^p \tag{1}$$

where $\dot{\bar{\varepsilon}}^{cr}$ is the uniaxial equivalent creep strain rate, $\sigma$ is Mises equivalent stress when the materials of all four layers are isotropic, and $t$ is the total time. $B$ , $n$ , $p$ are the parameters which are related to material and dependent on temperature. The parameters $B$,$n$ are listed in Table 3, and the parameter $p$ is set up to be zero here. However, for the type of coupled-thermo-mechanic TBCs model in which the transient heat conduction exists, the density ρ, and some thermal parameters such as thermal conductivity k and specific heat C are required. They are also temperature-dependent listed in Table 4.

### 2.3. Boundary conditions

As illustrated in Fig. 1(b), the symmetrical boundary conditions were applied to the model. In order to form the periodic boundary condition, the coupling constraint [7], which has already been implemented in ABAQUS [22], was imposed on the right side of the model to keep the horizontal displacement of each point the same, while the vertical displacements can move freely. Besides the mechanical boundary conditions above, the thermal boundary conditions were also required. It was assumed that both sides of the model were adiabatic, and on the top and bottom surfaces of the model, the temperature boundary conditions illustrated in Fig. 3(a) and (b) were imposed, respectively. Namely, when the temperature on the top surface rises from 25°C to 1100°C, the bottom surface is preheated from 25°C to 400°C. For the TBCs model without heat transferring, the appropriate temperature field must be imposed on it. Here it was thought of as homogeneous, and the temperature variation with time is illustrated in the Fig. 3(a). Firstly, it takes 300 s to raise temperature from 25°C to 1100°C, then the temperature is kept at 1100°C for 2 h, and at last it takes 300 s to decrease the temperature from 1100°C to 25°C. The initial temperature for both homogeneous and un-homogeneous temperature fields is 25°C.

## 3. Results and discussion

It's well known that the level and distribution of the residual stress in TBC system strongly affect the quality and life of the coating. Generally speaking, there are two primary causes for the residual stresses in TBCs: one is the difference between the coefficients of thermal expansion of the four layers, the other is the volume swelling of the TGO layer due to its oxidation at high temperature. In order to