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Modeling and simulation of thermal fatigue crack in EB-PVD TBCs under non-uniform temperature

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ABSTRACT

Demand for enhanced jet engine efficiencies has led to a significant increase in the combustion temperature. Thus protecting components against the combustion products is necessary and is possible by using thermal barrier coatings (TBCs). In this research, thermal fatigue and creep interaction are studied via analytical and numerical finite element methods. Thermal stress and crack propagation analyses in the ceramic top coat are carried out based on plane stress condition and under inhomogeneous temperature distribution across the layers. The crack is assumed as a penny-shaped crack in both vertical and inclined growth directions. The study proposed that the creep-plasticity results in thermal stress alleviation and the tensile stress transforms into a compressive stress of − 200 MPa in forwarding cycles that will induce crack closure. In addition, the results confirmed that vertical cracks grow much faster than oblique ones due to single mode crack propagation and about 0.14 MPa√m greater values in stress intensity factor. The modeling and simulation results match together, and the obtained crack behavior is in compliance with other researcher's output.

1. Introduction

Hot gas path components in modern gas turbine engines suffer severe service conditions in high temperature. Although enormous efforts like introducing single crystal superalloys have been done, the tendency to improve the thermal efficiency of engines and thus increasing turbine inlet temperature (TIT) result in protection of the components by thermal barrier coating (TBC) [1,2]. TBC consists of three layers of ceramic top coat (TC), thermally grown oxide (TGO), and metal bond coat (BC). There are two main methods to deposit the TC layer consist of atmospheric plasma spray (APS) and electron beam physical vapor deposition (EB-PVD) which are different in microstructure [3]. A common feature of plasma sprayed TCs is their lamellar grain structure, micropores, and thus low heat conduction capacity. In contrast, TBCs deposited by EB-PVD have a columnar microstructure, finer porosity, better toughness, and higher heat conduction [4,5].

The TBC system is subjected to various degradation mechanisms during service life: surface cracking, spallation, delamination and chemical mechanisms such as sintering, aging, oxidation, corrosion, calcium – magnesium – alumina – silicate (CMAS) attack. Successive temperature change due to engine's start/stop is a crucial mechanical factor in TBC failure due to the difference in coefficient of thermal expansion (CTE) of the layers (thermal fatigue) [6–11].

Recently, various experimental and simulation methods have been developed to evaluate the fracture behavior and crack growth rate (CGR) of the cracks in TBCs with different propagation paths. Liu et al. [12] carried out the finite element simulation and experimental evaluation of thermal shock tests on as-sprayed and pre-oxidized TBC specimens under different burner flame conditions. They indicated that the initiation of delaminating cracks in the ceramic top coat at the peak of the interface asperity together with surface cracking are the main reasons for coating failure.

Numerical simulation of the fatigue crack evolution in TBCs subjected to an accelerated test condition was carried out by Hernandez et al. [13]. The cracks of interest evolved in the bond coat parallel and near the interface with the TGO during thermo-mechanical fatigue testing. The cracks led to partial spallation of the TBC in the final stages of growth. Moreover, simulations showed that the inelastic response of the bond coat and the oxidation rate of the TGO govern the crack surface separation. Chen et al. [14] analyzed the effect of a transient thermal load on a crack embedded coating which is bonded to a square substrate using finite element method (FEM). Crack delamination instances including different crack positions between ceramic coating and bond coating were analyzed, and it is found that under the thermal shock the crack tip fields are shear-dominant (Mode II of fracture).

According to the Kumar and Balasubramanian review article [9], the delamination cracks in APS TBCs form within the TGO layer and

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Nomenclature

A	Norton creep law coefficient
a	Crack length
b	BC layer
C	Paris law coefficient
c	Ceramic top coat
E	Young's modulus
F	Radial force
K	Stress intensity factor
K_I	Mode I stress intensity factor
K_{II}	Mode II stress intensity factor
m	Norton creep law exponent
o	TGO layer
P	Paris law exponent
S	Circumferential area
s	Substrate
t	Time
α	Coefficient of thermal expansion
β	Rotation angle in the crack plane
ΔT	Temperature change
ε'	Creep-fatigue interacted strain
ε_{cr}	Creep strain
ε_r	Radial strain
θ	Crack propagation angle
ν	Poisson's ratio
σ'	Creep-fatigue interacted stress
σ_n	Stress component normal to crack plane
σ_r	Radial stress
σ_θ	Hoop stress
τ	Stress component tangent to crack plane

above the BC, change the growth direction into the BC because of the presence of high axial stresses. In addition, for EB-PVD (Pt–Al) coatings, spall life rises by four times with a decrease in the temperature of the cycle from 1151 °C to 1100 °C. Also, they have researched the creep effect in TBC stress redistribution and declared that the fast TGO and BC creep will greatly lessen stress level and delay the crack formation. Therefore, materials of low creep strength correspond to higher lifetime. Rösler et al. and Wang et al. [15,16] mentioned that reducing TGO creep strength will lower the stress when dwell time is terminated. In Dong et al. [17] research, the cracking behavior of APS TBCs during thermal gradient cycles was investigated via finite element and experimental methods. It was found that before 85% of the thermal cyclic lifetime, the crack size increases linearly and at the later stages of the lifetime, the crack propagation accelerates and is attributed to coalescence of numerous cracks.

Zhu et al. [18] investigated the interaction of surface cracking and interfacial delamination in TBCs under tension via a cohesive zone FEM. It is concluded that the surface crack density has a significant effect on the initiation and propagation of interfacial delamination and the delamination length decreases with the increase of the surface crack density. It is shown that the saturated crack densities reduce with higher ceramic coating thickness and also, an increase in the interfacial adhesion energy leads to decrease the delamination length and the critical surface crack density.

Shahid and Musharraf [19] experimentally investigated the effects of BC oxidation under cycling conditions on the failure mechanism of the EB-PVD TBCs. Based on the reported results almost linear increase of crack length with the number of cycles is observed. Besides, microcracks propagate through the ceramic TC perpendicular to the layer.

In this study, thermal fatigue and creep interaction in EB-PVD TCs is studied as a main failure factor of TBCs via analytical and numerical methods. Besides, thermal stress and crack propagation analyses in the ceramic top coat are carried out based on plane stress condition and under inhomogeneous temperature distribution across the layer.

2. Model definition

2.1. Analytical model

Due to low thickness of TBC and substrate layers, thermal stress can be defined by plane stress formulation in a four-layered solid disk including TBC and substrate layers (Fig. 1). By implementing polar coordinate, radial strain can be expressed by Hook's law as:

$$\varepsilon_r = \frac{1}{E}(\sigma_r - \nu\sigma_\theta) + \alpha\Delta T \tag{1}$$

where ε_r, E, σ_r, ν, σ_θ, α, and ΔT are the radial strain, module of elasticity, radial stress, Poisson's ratio, hoop stress, CTE and temperature change, respectively. Due to the axisymmetric disk, radial and hoop components of stress and strain are equal [20,21]. So by considering simultaneous thermal and creep load, the radial stress of each layer can be written as (dropping subscripts) [22]:

$$\sigma = \frac{\mathrm{E}}{1-\upsilon}[\varepsilon - \alpha\Delta T + \varepsilon_{\mathrm{cr}}] \tag{2}$$

where ε_{cr} is creep strain and is expressed by Norton power law as:

$$\varepsilon_{cr} = A\sigma^m t \tag{3}$$

where A and m are material dependent constants and t denotes time. Norton law is used in both analytical modeling and FEM simulation. The ε parameter is calculated by solving equilibrium force equation of four layers in the radial direction, as [20]:

$$\sum_{\mathrm{i}=c,o,b,s} \mathrm{F} = \sigma_i S_i \tag{4}$$

where S represents the circumferential area and the subscripts c, o, b, and s stand for the TC, TGO, BC and substrate layers, respectively. By substituting Eq. (2) into Eq. (4) and solving for ε, the following equation is yielded:

$$\varepsilon = \varepsilon' = \frac{\left[\sum_{\mathrm{i=c,o,b,s}}\left(\frac{\mathrm{E^i}}{1-\nu^{\mathrm{i}}}\alpha^{\mathrm{i}}\mathrm{A^i}\right)\right]\Delta T - \frac{\mathrm{E^i}}{1-\nu^{\mathrm{i}}}\varepsilon_{\mathrm{i}}^{\mathrm{cr}}}{\sum_{\mathrm{i=c,o,b,s}}\left(\frac{\mathrm{E^i}}{1-\nu^{\mathrm{i}}}\mathrm{A^i}\right)} \tag{5}$$

Creep strain is dependent on stress and so, the strain must be defined in advance to calculate the stress. Due to a small time

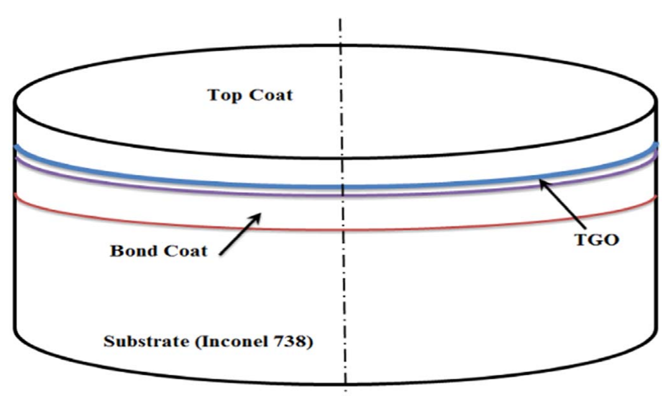

Fig. 1. Four-layered axisymmetric disk containing the TBC and substrate layers.