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Analytical and numerical investigations of the crack behavior in thermal barrier coatings under the trip thermal load

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ABSTRACT

Increasing the temperature of the combustion products in power plant turbines is one of the easiest way to enhance the efficiency and decrease the fuel costs. Therefore, using thermal barrier coating (TBC) to protect the load carrying components in the hot gas path is inevitable. In this manuscript, the damage caused by trip shutdown in power plants as an emergency thermal shock is investigated based on analytical and finite element (FE) analysis for in-plane stress condition. The used geometry is a thin disk under axisymmetric condition. The results show that as a consequence of a fast and inhomogeneous temperature loss, a thermal strain of more than 1.1% occurs in the TBC top layer. Similar behavior is observed in the stress and thus the stress intensity factor of a preexisting surface crack because it approaches the critical value of the ceramic top layer. This condition has a significant effect on the length and growth rate of the crack in comparison with heating and constant temperature period as the crack length is about one- third of the ceramic layer thickness at the end of a single cycle. In addition, the analytical and the finite element calculation results match together and the determined crack behavior is compatible with the other researcher's output.

1. Introduction

Load carrying components in the modern turbo engines suffer several destructive mechanisms in the high-temperature service conditions. Introducing single crystal superalloys is one of the key efforts that have been carried out [1,2], but the tendency to improve the thermal efficiency of gas turbines with increasing the working fluid temperature, has resulted in protection of the components by thermal barrier coating (TBC) application. The inlet temperature of gas turbines can reach over 1400 °C and TBCs will increase the service life by temperature reduction of about 200 °C on the blade surfaces [3]. Thermal fatigue is a failure mechanism that will form both mechanical and thermal strain in the components. As cooling rate effect is not large enough for operation at low temperature [4], this situation is more intense in thermal shock condition and the resultant damages like crack nucleation are much more destructive [5–7]. The high magnitude shock stresses occur at the TBC interfaces. Under such circumstances, the consequence of voids or crack like defects at the top surface and interfaces are much more accountable for the beginning of debonding and accelerate the oxidation procedure [8]. Thus, running and stopping power plant gas turbines are performed so cautiously and based on start/stop standards for the least damage occurrence in components exposed to the high temperature. However, in emergency conditions which the turbine must be soon shutdown, this fact is unavoidable. This shock that is named trip will induce a great thermal strain and stress in the substrate and coating of the turbine blades [9].

A TBC system includes top coat ceramic layers (TC), thermally grown oxide (TGO), and metallic bond coat (BC) [3]. The TBC system is exposed to several mechanical and chemical deterioration mechanisms during actual service conditions, e.g. erosion, corrosion, wear and cracking [5]. The temperature changes due to engine's starts/stops (thermal fatigue) are a vital mechanical factor in the TBC failure and the main reason is the difference in thermal expansion coefficients (ΔCTE) between the layers [10–15]. Recently, various simulations and experimental methods have been developed to evaluate the fracture behavior and crack growth rate (CGR) of the TBCs. NDT tests like acoustic emissions are also carried out [9,16,17]. Zhou and Hashida [9] evaluated thermal fatigue damage by non-destructive acoustic emissions (AE) and impedance spectroscopy (IS) methods. The observations revealed that TC vertical crack and BC/TC interfacial cracks play role in fatigue failure. Dalkilic and Tantamis [18] investigated the high-temperature low cycle fatigue damages by thermomechanical fatigue tests at 950 °C. The results showed that the cracks nucleate in the TGO/BC interface and grow perpendicular to the loading axes into the substrate. Ahmadian and Jordan [19] studied the effect of high-temperature loading time on the micro cracking and the failure life of the TBCs. The

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Nomenclature

a	Crack length	P	Paris law exponent
b	Bond coat layer	S	Circumferential area
C	Paris law coefficient	s	Substrate
c	Ceramic top coat	t	Time
E	Young's modulus	α	Coefficient of thermal expansion
F	Radial force	ΔT	Temperature change
K	Stress intensity factor	ε_r	Radial strain
o	TGO layer	ν	Poisson's ratio
		σ_r	Radial stress
		σ_θ	Hoop stress

results revealed that the total dwell time to failure is directly related to the cyclic rate. Moreover, the micrographs of scanning electron microscope (SEM) showed that fatigue failure during the experiments was due to cracking within the ceramic top coat and the above TGO interface due to the oxide layer excessive growth and high interfacial roughness (sharp peaks). Microstructure and thermal fatigue behavior of atmospheric plasma sprayed (APS) TBCs with dense segmentation crack were studied by Karger et al. [20]. The specimens revealed promising lifetime in burner rig tests at high temperatures for surface (1350 °C) and BC (up to 1085 °C) while coatings with lower crack densities showed a reduced performance. According to the microstructural and fractographic investigations, the segmentation crack with different densities was stable during the thermal shock tests. They announced that cracks may also penetrate to the oxide layer, but the majority of cracks won't cross the TGO/TC interface. The fact that is also mentioned in other studies [21,22]. Liu et al. [22] carried out numerical finite element simulation and experimental evaluation of the thermal shock tests on as-sprayed and pre-oxidized TBC specimens under different temperature conditions. They indicated that the initiation of delaminating cracks (resulted by growth in TGO thickness) in the ceramic top coat at the peak of the interface asperity and surface cracking, are the key factors for the TBC failure.

In Dong et al. [23] research, the crack resistance of TBCs during thermal gradient cycles was investigated via numerical and experimental techniques. Based on the results, linear increase in crack length until 15% of the final thermal fatigue life is evident and at the remaining fraction of the lifetime, the crack propagation accelerates due to the coalescence of numerous cracks and the propagation direction is along TC/BC interface or in the TC near the interface. As Nusier and Newaz declared [8] this phenomenon is related to the critical strain energy release rate in that area. Fleck et al. [24] examined thermal shock resistance of APS TBCs by calculating the interfacial mode I and II stress intensity factors (SIFs) for the delamination cracks which are compared with the mode-dependent TGO/TC interface fracture toughness. The applied temperature range was 300 to 1600 °C. The solution showed that SIFs are dependent on the temperature and Young's modulus profiles in the TC. The effect of layers interface can be summarized as the growth of TGO layer, CTE incompatibility, and interface roughness which will encourage redistribution of stress along the TC/BC boundary [25].

Although most of the theoretical and practical studies about crack behavior are performed adopting plane strain models [10,18,26,27] regarding micro scale thickness of TBC layers, plane stress formulations can be applied to calculate the in-plane stress in TC. From the interface to the TC free surface, no significant disparity in-plane stress can be observed. High in-plane stress may promote the initiation of vertical cracks near the peak of the asperity and/or surface cracks in the ceramic top coat. TBC spallation is triggered by a combination of delamination and cracking occurred in the interfaces and surface, respectively [22]. Majority of studies are dedicated to interlaminar failure. In this study, besides analytical and numerical stress field calculations, the surface crack behavior and growth rate in the ceramic top coat are investigated.

2. Model definition

2.1. Analytical model

As TBC and substrate layers are of low thickness, thermal stress can be formulated in a four-layered solid disk by adopting plane stress relation. Radial in-plane strain can be expressed by Hook's law in polar coordinate 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, the module of elasticity, radial stress, Poisson's ratio, hoop stress, CTE and temperature change, respectively. Due to the disk axisymmetry, the radial and hoop components of the stress and strain are equal [28,29]. So, radial stress of each layer can be written as (subscripts are dropped) [28]:

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

The parameter ε can be defined by solving equilibrium force equation of four layers in radial direction, as [28]:

$$\sum_{\mathrm{i=c,o,b,s}} \mathrm{F} = \sigma_i S_i \tag{3}$$

where S represents the circumferential area and the subscripts c, o, b, and s respectively stand for the TC, TGO, BC and substrate layers. Introducing Eq. (2) into Eq. (3) and solving for ε, the following equation is yielded:

$$\frac{\left[\sum_{\mathrm{i=c,o,b,s}}\left(\frac{\mathrm{E^i}}{1-\nu^{\mathrm{i}}}\alpha^{\mathrm{i}}\mathrm{S^i}\right)\right]\Delta T}{\sum_{\mathrm{i=c,o,b,s}}\left(\frac{\mathrm{E^i}}{1-\nu^{\mathrm{i}}}\mathrm{A^i}\right)} \tag{4}$$

Because of low temperature during the trip thermal shock and short time, creep effect is neglected in the stress calculation. The TBC model is supposed to be heated up from the stress-free state. TGO roughness is also neglected as a surface crack is under consideration. Due to the little possibility of yielding of the high hardness ceramic top coat under the thermal load, linear elasticity is assumed for this layer [30]. Based on this assumption, mode I of the crack growth rate can be expressed by Paris law as a function of the stress intensity factor (K), the critical stress intensity factor (K_{IC}), and the initial crack length (a) as [24]:

$$\frac{da}{dt} = C\left(K/K_{IC}\right)^p \tag{5}$$

For APS ceramics the constants C, K_{IC}, and p are given as 7.6×10^{-5} m/s, 1 MPa.m$^{1/2}$, and 18, respectively [31]. The initial crack length is assumed 2a = 2.5 μm. Since temperature decrease in the trip process is triggered on the coating surface and the crack nucleation is more probable in this zone [22] and crack propagates normal to the layer [20], a surface semicircular crack is modeled. Therefore, the stress intensity factor of the crack subjected to the plane tensile stress is formulated as [32]: