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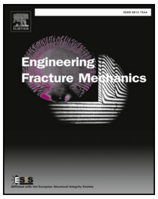

Numerical analyses of the residual stress and top coat cracking behavior in thermal barrier coatings under cyclic thermal loading

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ABSTRACT

Acting as one of the original cracks for interfacial delamination, the horizontal roughness-induced top coat crack plays an important role in the premature failure of the air plasma sprayed thermal barrier coating system. Thus, the residual stress and top coat cracking behavior in thermal barrier coatings under cyclic thermal loading were numerically investigated. The effects of thermally grown oxide swelling, creep, and interfacial roughness were taken into account. The arbitrary top coat cracking was modeled using the extended finite element method. In addition, the effect of the interfacial cracking on top coat cracking and their mutual interaction were investigated using the cohesive zone model. The results showed that the top coat crack initiated before thermal cycling due to large residual stress, the combination of the thermally grown oxide swelling and creep relaxation promoted crack propagation during the early periods, and the crack continued to grow with the thermally grown oxide thickening during the later periods. The initiation and propagation of the interfacial crack between the thermally grown oxide and bond coat accelerated the top coat cracking, and their mutual interaction led to premature interfacial delamination.

1. Introduction

As a key technology in thermal protection, thermal barrier coatings (TBCs) are being applied to turbine engine components such as turbine blades and combustors [1]. However, the premature failure of TBC systems dramatically shortens their service lifetime [2]. Interfacial delamination is one of the main failure modes in air plasma sprayed (APS) TBCs, which occurs due to the coalescence of micro-cracks around the interface between the ceramic top coat (TC) and the metallic bond coat (BC) upon thermal cycling [2,3]. Fig. 1 [4] shows various kinds of micro-cracks that appear near the rough interface before linking, such as interfacial cracks, thermally grown oxide (TGO) cracks, and top coat cracks. Horizontal top coat cracks are found in the off-peak of the interface, and are different from the preexisting cracks within top coat that occur due to the porous microstructure of the top coat such as the parallel inter-splats and micro-voids [5–7]. The initiation and propagation of this roughness-induced top coat cracks play important roles in the coalescence of micro-cracks during thermal cycling. Thus, to further understand the interfacial failure mechanism of TBCs, a

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Nomenclature

a_S, b_S^α	enriched DOFs
B	pre-factor of creep function
D	damage variable
$F_\alpha(\mathrm{x})$	an asymptotic crack tip enrichment function
G	strain energy release rate
G_c	fracture toughness
G_n^c, G_s^c	mode I/II fracture toughness
K	initial stiffness
k_p	parabolic creep rate constant
n	creep exponent
N_H	nodes of the elements cut by a crack
$N_i(\mathrm{x})$	conventional modal shape function
N_{tip}	nodes of the element where the crack tip lies
$\mathrm{sgn}(\mathrm{x})$	a Heaviside function
u_s	DOF for non-enriched nodes
u_{XFEM}	displacement in XFEM
δ	displacement
δ_0, γ_0	critical opening displacement for mode I/II traction-separation response
δ_f, γ_f	fracture displacement for mode I/II traction-separation response
$\dot{\varepsilon}_{cr}$	creep strain rate
σ	stress
σ_0, τ_0	fracture strength for mode I/II traction-separation response
σ_{max}^0	maximum critical principal stress
BC	bond coat
CZM	cohesive zone model
TBC	thermal barrier coating
TC	top coat
TGO	thermally grown oxide
TSL	traction-separation law
XFEM	extended finite element method

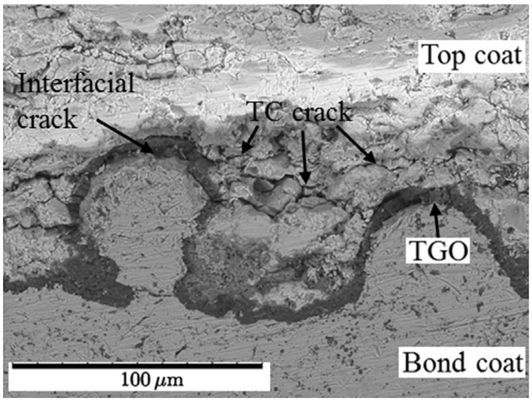

Fig. 1. The failure pattern in APS TBCs: the interfacial crack and horizontal TC crack [4].

detailed investigation on the roughness-induced top coat cracking is necessary.

The complex interfacial morphologies commonly exist in both the as-sprayed and oxidized APS TBCs [1–3]. Weeks et al. [8] found that there existed an optimal interfacial morphology for a longer lifetime when the positive effect of interfacial roughness on the top coat compliance and toughness near the interface overcame the detrimental effect of local stress concentration. In the case with proper interfacial roughness, micro-cracks may be easy to initiate at the peak or off-peak driven by local tensile stress but hard to propagate due to the compressive stress state near the valley, which delays the final spallation of TBCs [9]. The initiation and propagation of micro-cracks around the interface are the first concern in building the relation between interfacial delamination and the lifetime of TBCs. TC/TGO/BC interfacial cracking [4,10–13] and top coat cracking with pre-existing horizontal cracks [5–7] were widely investigated by numerical and experimental methods. For roughness-induced top coat cracks, the crack initiation was explained by assessing the residual stress determined by thermal mismatch, oxidation, and other mechanisms [10,14–17]. However, crack propagation was difficult to predict. Not only the critical fracture strength and toughness but also the crack length and crack orientation should be taken into account to model the arbitrary crack growth within the top coat [5,7]. Furthermore, the different kinds of original micro-cracks may have interactive effects on each other before the final linking, which has seldom been studied. From the perspective of stress evolution, once the interfacial crack initiates, the local stress will be relaxed and the stress field around the crack surface will change greatly, which may increase the possibility of the top coat crack initiation, and vice versa. Białas [10] predicted possible top coat cracking when modeling TGO/BC interfacial cracks, but detailed crack initiation and propagation in top coat could not be described, and the mutual effect of the interfacial crack and top coat crack was not researched.

In this work, the horizontal top coat cracking in APS TBCs is numerically studied. The stress evolution during thermal cycling is firstly conducted as a precondition for crack initiation and propagation. Influential factors such as creep, oxidation rate, and roughness are taken into account. Then, horizontal top coat cracking and TGO/BC interfacial cracking are simulated based on the extended finite element method (XFEM) and cohesive zone model (CZM), respectively. The interaction between the two cracking mechanisms is discussed.