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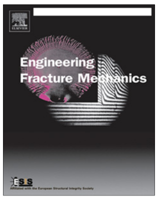

Mechanisms governing the failure modes of dense vertically cracked thermal barrier coatings

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ABSTRACT

The introduction of dense vertical cracks in ceramic top coat has been recognized as an efficient way to improve the strain tolerance and service durability of thermal barrier coatings (TBCs). However, further growth of these pre-existing cracks may cause the delamination of the coatings to form various failure modes. The motivation of this work is to numerically study the mechanisms that govern the formation of failure modes in dense vertically cracked TBCs. The effects of vertical crack density and material properties on the fracture behaviors are discussed. An energy-based criterion is employed to deal with the surface crack deflection/penetration behavior at a bimaterial interface, and an interaction integral method for discontinuous materials is utilized to evaluate the fracture parameters. The failure maps of TBCs are constructed by examining the continuous variations of crack tip driving forces over the whole fracture process. It is verified that the interfacial fracture resistance could be enhanced by introducing high-density vertical cracks. At the same time, these cracks tend to penetrate into the bond coat that results in debonding at bond coat/substrate interface or at both interfaces. In addition to benefit in alleviating the interfacial mismatch stress, it is found that the high-density vertical cracks give toughening increases to the coating system by releasing more energy from multiple paths. Moreover, the effects of mixed-mode interface toughness and initially residual stress on the formations of failure mode are discussed.

1. Introduction

Thermal barrier coatings (TBCs) have been widely used in industrial gas turbines and aircraft engines to protect hot components against high-temperature oxidation and hot corrosion, thereby improving the lifetime of these components and allowing higher operation temperature [1,2]. In general, TBCs are multilayer system which includes an insulating ceramic top coat, a metallic bond coat, and a structural load carrying superalloy substrate [3,4]. Yttria stabilized zirconia (YSZ) is considered as an efficient ceramic top coat material owing to its low thermal conductivity, relatively high coefficient of thermal expansion and favorable environment durability. The metallic bond coat is typically made of MCrAlY (M = Ni, Co or both) to improve the adhesion between top coat and substrate as well as providing oxidation protection to the substrate.

Nevertheless, due to the large temperature gradient and thermal expansion mismatch among different layers, high stresses could be developed in the coatings and at the interfaces during thermal cycling, leading to the cracking and spalling of

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Nomenclature

a_d, a_p	putative interface crack length and penetration crack length in judging surface crack deflection/penetration
a_{di}, a_{pi}	putative interface crack length and penetration crack length in judging crack onset
C_{ijkl}^{tip}	stiffness tensor at crack tip ($i, j, k, l = 1, 2$)
E_i	Young's modulus ($i = 1, 2$)
F, U, K_d, k	nodal force vector, displacement vector, stiffness matrix, and stiffness parameter of discrete fracture element
G_d, G_p	energy release rates of deflection crack and penetration crack
I, J	interaction integral, J-integral
$K_I^{aux}, K_{II}^{aux}, K_I, K_{II}$	auxiliary and actual mode I and II stress intensity factors of continuous material crack
K, K_1, K_2	complex stress intensity factor of interface crack, and the mode 1 and mode 2 components
q	weight function of J-integral
r, θ	local polar coordinates
S_{ijkl}^{tip}, S_{ijkl}	compliance tensors at the crack tip and at a material point ($i, j, k, l = 1, 2$)
T_0, ΔT	initial temperature, and temperature change referred to initial temperature
u_i^{aux}, u_i	displacements in the auxiliary and actual fields ($i = 1, 2$)
α, β	Dundurs' parameters
α_{TC}^{th}, α_{BC}^{th}, α_{sub}^{th}	coefficients of thermal expansion of top coat, bond coat and substrate
Γ_d, Γ_p	fracture toughnesses of deflection crack and penetration crack
δ_{ij}	Kronecker delta ($i, j = 1, 2$)
δ_i	crack flank displacements ($i = 1, 2$)
ε_{ij}^{aux}, ε_{ij}	strains in the auxiliary and actual fields ($i, j = 1, 2$)
ε_{ij}^{t}, ε_{ij}^{m}, ε_{ij}^{th}, ε_{onset}	total strain, mechanical strain, thermal strain, and delamination onset strain
ε^{tip}, κ_{tip}, l	oscillation index, Kolosov constants at crack tip, and characteristic length of interface crack
λ_ψ, ψ	parameter adjusting the contribution of mode mixity, and phase angle
μ_i, μ_{tip}	shear modulus ($i = 1, 2$), and shear modulus of crack tip material
ν_i, ν_{tip}	Poisson's ratio ($i = 1, 2$), and Poisson's ratio of crack tip material
σ_{ij}, σ_{ij}^{aux}	stresses in the actual and auxiliary fields ($i, j = 1,2$)
BC/Sub	bond coat/substrate interface
HH	He and Hutchinson's method
TC/BC	top coat/bond coat interface

the coatings. In particular, the vertical surface cracking may occur in the cooling stage of thermal cycles, in which there exist large temperature gradient and tensile stress across the coating thickness due to transient thermal shock on the outer surface of the top coat. The tensile stresses may drive the surface crack extending towards the interface. When the crack tip touches the interface, it may further penetrate into the next layer or deflect along the interface. Actually, it is the propagation and coalescence of interface cracks that eventually lead to spallation of the coatings. Therefore, the surface cracking and the induced interfacial delamination are recognized as the dominant failure mechanisms in TBCs [5–7]. To improve the service durability, it is desirable to delay the growth of interface cracks.

Fortunately, many experiments have reported the positive effect of surface crack in improving the coating strain tolerance and service durability [8–11]. The thermal shock resistance of TBCs can be significantly improved by introducing a large amount of vertical surface cracks in the top coat [9–12]. These cracks are considered beneficial in reducing the tensile stiffness of the coating, and thus relieving the mismatch stresses. Taylor et al. [9] experimentally found that the thermal cycling life of initially surface cracked coating is superior to initially intact coating. Guo et al. [11] showed that the vertically cracked coatings have an excellent thermal shock resistance. Zhou and Kokini [5,12] observed that the interfacial fracture resistance of the coatings is enhanced with the increase of surface crack density. Moreover, issues of dense vertically cracked TBCs have been extensively studied by numerical methods. Wu et al. [13] analyzed the interfacial stresses in coating-substrate systems considering the periodic surface cracks, and it showed that peak values of the interfacial stresses decrease with the increase of surface crack density. By using fracture mechanics method, Chen et al. [14] found that the energy release rate (ERR) at the interface crack tip decreases with the increase of surface crack density. The similar conclusions have also been obtained in Ref. [15–17]. The failure map for interface crack initiation from the root of surface crack was proposed by Mei et al. [18]. Influence of coating thickness and interfacial adhesion parameters on the interaction between surface cracking and interfacial delamination were discussed by Zhu et al. [19]. Additionally, multiple surface cracking problems incorporating various influence parameters, interface roughness and thermally grown oxide have been systematically investigated by Fan et al. [6,7,20].

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