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Prediction of the crack bifurcation in layered ceramics with high residual stresses

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ABSTRACT

A computational tool, aiming to predict the crack propagation (i.e. straight propagation, single deflection or bifurcation) in layered ceramics designed with internal residual stresses, is here developed. The laminate consists of ceramic layers of two different materials, alternated in a multilayer structure. The internal stresses developed during sintering are associated with the thermal expansion mismatch between adjacent layers and volume ratio between both materials. The computational model is based on Finite Fracture Mechanics theory, especially focused on cracks terminating at the interface between two different material layers. The method utilises a matched asymptotic procedure to derive the change of potential energy associated with the fracture process. Crack follows the path which maximises the energy released during crack propagation. A combined loading (thermal and mechanical) is taken into consideration to clarify the influence of the residual stresses on the crack path during fracture. The competition between single crack propagation and crack bifurcation (simultaneous propagation in two directions) can be described using the model. The results predicted by the proposed fracture criterion are in a good agreement with the experimental observations on laminate samples.

1. Introduction

The interest for the mechanical behaviour of ceramic materials has been always motivated by the in-service demands made on structural components and machine parts which often require the use of brittle materials, particularly ceramics and glasses, due to certain outstanding properties such as high-temperature stability, oxidation and corrosion resistance, dimensional stability, hardness and wear resistance, as well as other special ones such as thermal, electrical or optical properties. Due to their inherent brittleness, ceramics have been used for many decades as structural elements, but almost always under compressive loading conditions. Nowadays, most of the new engineering design approaches consider the possibility to withstand tensile stresses which imply potential limitations for ceramics due to their low resistance to crack propagation (i.e. low fracture toughness) and the sensitivity of their strength to the presence of defects. It is known that the flaw distribution (size, location, etc.) and size effect in ceramic materials yield a statistical strength distribution (well described by the Weibull theory [1]), which limits the mechanical reliability of ceramic components [2,3].

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Nomenclature

a_p, a_b	finite crack extensions of penetrating and bifurcating crack
a_0	initial notch depth
B, B_S	specimen width
E, E_A, E_B	Young's modulus of the material
$f_{ij}(\theta)$	angular distribution of the stress field
$F_i(\varepsilon)$	coefficients of the inner asymptotic expansion
F, F_{fr}	loading force, fracture force
G, G_c	energy release rate, fracture toughness
H_i	Generalized Stress Intensity Factor (GSIF)
K_1, K_1', K_2, K_2'	coefficients of the perturbed solution for the deflected crack
K_I, K_{Ic}	stress intensity factors for mode I, fracture toughness of the material
l_0	crack ligament in front of interface
L, L_S	specimen length
M1, M2	material 1 and material 2
n_A, n_B	number of layers of material A and B
n_l	vector of the normal
r	polar coordinate
R	radius of the integration path
S	T-stress
S_i, S_o	distances between inner and outer supports
t_A, t_B	thickness of the layer A and B
$\mathbf{u}_i(\theta)$	angular distribution of the displacement field
$\mathbf{u}_{-i}(\theta)$	angular distribution of the auxiliary displacement field
$\mathbf{U}$, $\mathbf{V}$	displacement field
U_i, U_{-1i}	displacement field (vector), auxiliary (dual) displacement field
$\mathcal{U}_i$	basis functions of the outer expansion
V_A, V_B	volume content of material A and B
$\mathcal{V}_{iy_j'}(y'), \mathcal{V}_{iy_j'}(y')$	displacements of the crack increment faces in appropriate coordinates
$\mathcal{V}_i$	basis functions of the inner expansion
W, W_S	height of the specimen (characteristic size of the specimen)
Π^0, Π^ε	potential energies of unperturbed and perturbed state
x, y	Cartesian coordinates
x^ε, y^ε	scaled up Cartesian coordinates
$x^{\varepsilon'}$, $y^{\varepsilon'}$, $x^{\varepsilon''}$, $y^{\varepsilon''}$	rotated scaled up Cartesian coordinates
α	coefficient of the thermal expansion
Γ, Γ_i	integration path
δ, δ_i	characteristic eigenvalue of the singularity
$\delta\Pi$	change of the potential energy
Δa	crack extension behind interface
ΔT	change of the temperature
ΔW	additional energy
ε	characteristic size of the perturbation
ε_{ij}	components of the strain tensor
θ	polar coordinate
φ_p	direction angle of the crack extension
ν	Poisson's ratio
ρ	zoomed variable r with factor ε
σ_f	critical stress – strength of material
σ, σ_{ij}	components of the stress tensor
σ_{res}	residual stress
Ω	unperturbed domain
Ω^{in}, Ω^{o}	inner domain, outer domain
FFM	finite fracture mechanics
ERR	energy release rate

Layered ceramics have become an alternative choice for the design of structural ceramics with improved fracture toughness and mechanical reliability. The brittle fracture of monolithic ceramics has been overcome by introducing layered architectures of different kind, i.e. geometry, composition of layers, residual stresses, weak interfaces, etc. The main goal of such layered ceramics has been to increase the fracture energy of the system. Among the various laminate designs reported in