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A failure scenario of ceramic laminates with strong interfaces

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ABSTRACT

Over the last years many researchers have put a lot of effort into designing layered structures combining different materials in order to improve low fracture toughness and mechanical reliability of ceramics. It has been proven that an effective way is to create layered ceramics with strongly bonded interfaces. Significant internal residual stresses are developed within the composite layers after the cooling process from the sintering temperature, due to the different coefficients of thermal expansion of individual composite constituents. Residual stresses can significantly change the crack behaviour. Suitable choice of material of layers and ratio between layer thicknesses can lead to higher value of the so-called apparent fracture toughness, i.e. higher resistance of the ceramic laminate to the crack propagation.

The paper deals with a description of the specific crack behaviour in the layered alumina–zirconia ceramics. Attention is devoted to the differences in the stress field description in the vicinity of the crack front. Two-dimensional and three-dimensional numerical models are developed for this purpose. The main aim is to clarify crack behaviour in the compressive layer and provide computational tools for estimation of crack behaviour in the field of strong residual stresses. The crack propagation is investigated on the basis of linear elastic fracture mechanics. Fracture parameters are computed numerically and by routines of authors. The sharp change of the crack propagation direction is estimated using the Sih's criterion based on the strain energy density factor, and conditions for crack bifurcation are determined. Estimated crack behaviour is qualitatively in a good agreement with experimental observations.

1. Introduction

1.1. Layered ceramics

Ceramic materials are widely used in many engineering applications for their temperature stability, hardness, mechanical strength or chemical inertness. However, ceramics are very brittle materials; therefore they are mainly utilized under compression loading. Over the last years many researchers have been working on improving of mechanical properties of ceramics by fabricating ceramic composites materials. It was shown that material interfaces play an important role in mechanical behaviour and material properties of composite, which can cause improving of fracture toughness of the ceramic

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Nomenclature

a	crack depth
a'	crack depth under first ATZ/AMZ interface where the crack is sharply deflected in relation to the original crack propagation direction
a''	main crack tip length
a_0	depth of initial crack modelled in the middle of 3D specimen
a_{11}, a_{12}, a_{22}	functions of elastic material properties and polar coordinates with origin at the crack tip (Eqs. (4a)–(4c))
dW/dV	*strain energy density*
E	Young's modulus
E_{AMZ}	Young's modulus of alumina with monoclinic zirconia
E_{ATZ}	Young's modulus of alumina with tetragonal zirconia
E'_{AMZ}	modified Young's modulus of alumina with monoclinic zirconia
E'_{ATZ}	modified Young's modulus of alumina with tetragonal zirconia
k	correction function dependent on plane strain or plane stress condition
$K_{apt}(a)$	apparent fracture toughness
K_I	stress intensity factor corresponding to mode I
K_{II}	stress intensity factor corresponding to mode II
K_{IC}	fracture toughness
N	number of layers of laminate
P	mechanical loading force
P_{max}	maximum value of mechanical loading force required for crack deflection in the second layer
r	polar coordinate with origin at the crack tip
S	strain energy density factor
S_{CR}	critical value of the strain energy density factor
t_{AMZ}	thickness of the AMZ layer
t_{ATZ}	thickness of the ATZ layer
T_0	room temperature
T_{sf}	stress free temperature
w	strain energy density
α_t	coefficient of thermal expansion
α_{AMZ}	coefficient of thermal expansion of alumina with monoclinic zirconia
α_{ATZ}	coefficient of thermal expansion of alumina with tetragonal zirconia
Δa	crack increment
θ	polar coordinate with origin at the crack tip
θ_0	angle of crack propagation direction in next step of numerical simulation
μ	shear modulus
ν	Poisson's ratio
ν_{AMZ}	Poisson's ratio of alumina with monoclinic zirconia
ν_{ATZ}	Poisson's ratio of alumina with tetragonal zirconia
ρ	thickness layer ratio
σ_f	strength of material
$\sigma_{res,AMZ}$	residual stress in AMZ layers
$\sigma_{res,ATZ}$	residual stress in ATZ layers

Abbreviations

4PB	four-point-bending
AMZ	alumina with monoclinic zirconia
ATZ	alumina with tetragonal zirconia
FE	finite element (method)
APDL	ANSYS Parametric Design Language

laminate. The presence of multiple constituents influences the stress distribution in the composite. Therefore, the influence of different materials and geometry combination and weak and strong material interfaces on the resulting material behaviour were studied both experimentally and theoretically, see e.g. [1–9] for details.

Improvement of resistance against crack propagation through a ceramic composite body can be caused by several factors; (a) presence of residual stresses developed during the fabrication of ceramics due to different coefficients of thermal expansion of constituents and cooling down from high temperatures; (b) material interfaces; (c) consuming of more fracture energy during crack deflection or/and bifurcation [10–15], see Fig. 1. Mentioned mechanisms were proved experimentally