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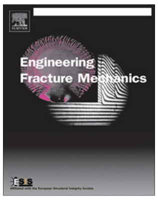

Modelling of edge crack formation and propagation in ceramic laminates using the stress–energy coupled criterion

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ABSTRACT

The high compressive stresses in ceramic laminates utilized to enhance their fracture resistance may lead to the formation of edge cracks at the surface of the compressive layers. In this work, a 2D parametric numerical model is developed to assess the effect of residual stress and thickness of the compressive layers on the edge crack formation, by using a coupled stress–energy criterion. The results predict the existence of a lower bound, below which no edge crack occurs (i.e. obtaining crack-free laminates), and an upper bound, beyond which onset of the edge crack would lead to the complete delamination of the compressive layer.

1. Introduction

Ceramics have been used for many decades as structural components but, due to their inherent brittleness, they have mainly been utilized under compressive loading conditions. Nowadays, most of the new engineering designs need to withstand tensile stresses which imply potential limitations for ceramics due to their low fracture toughness and the sensitivity of ceramic material strength to the presence of defects [1–3]. The brittle fracture of glasses and ceramics is a consequence of the material defects located either within the bulk or at the surface, resulting from the processing and/or machining procedures [4,5]. Under external applied stress, the stress concentration associated with such defects is the common source of failure of ceramic components. If each defect is considered as a crack or a potential source for crack initiation, then the size and type of these defects obviously determine the mechanical strength of the material [6].

The distribution of defects of different sizes within a ceramic component yields a statistically variable strength which can be described by the Weibull theory [7,8]. As a consequence of such a behaviour, there remains a (small) probability of failure even at very small applied loads (i.e., no lower threshold for strength). Since flaws are intrinsic to processing and in most cases unavoidable, the mechanical reliability of ceramic components is associated with such a flaw distribution. In order to reduce both the defect population and the defect size, many studies have been devoted in the past to improve ceramic processing [9]. Another approach to increase strength has been to introduce compressive residual stresses at the surface.

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Nomenclature

a	edge crack length (depth)
B	specimen width
C	fitting constant
E	Young's modulus
G	energy release rate
G_c	critical energy release rate, fracture energy
$G(a)$	energy release rate as a function of edge crack length
$G_{inc}(a)$	incremental energy release rate as a function of edge crack length
H	height of the specimen (characteristic size of the specimen)
K_{Ic}	fracture toughness
L	specimen length
t_1, $t^{(ATZ)}$	thickness of the tensile layer
t_2, $t^{(AMZ)}$	thickness of the compressive layer
T_A	sum of component A thicknesses
T_B	sum of component B thicknesses
V_A	volume of component A
V_B	volume of component B
$W(0)$	potential energy of the body without a crack
$W(a)$	potential energy of the body as a function of edge crack length
x, y, z	Cartesian coordinates
α	coefficient of thermal expansion
ΔT	change of the temperature
ν	Poisson's ratio
σ_c	critical stress – strength of material
σ_{res}	residual stress
σ_{yy}	normal stress along the prospective crack path
AMZ	alumina with 30% monoclinic zirconia
ATZ	alumina with 5% tetragonal zirconia
CC	coupled criterion
ERR	energy release rate
FE	finite element
FFM	finite fracture mechanics

A successful example can be found in strengthened glass [10] and more recently Gorilla® glass [11]. However, a significant reduction of strength variability cannot be achieved with these approaches. In an attempt to reduce the level of uncertainty in mechanical strength and to overcome the lack of toughness of structural and functional ceramics, newer approaches have been developed in which knowledge about the energy release mechanisms has resulted in the creation of "flaw tolerant" materials (i.e. reducing strength variability), with improved fracture toughness [9,10,12–27].

Layered ceramic materials (also referred to as "ceramic laminates") are becoming one of the most promising areas of materials technology. They have been proposed as an alternative for the design of structural ceramics with improved fracture toughness, strength and mechanical reliability. Among all, laminates designed with strong interfaces and compressive residual stresses have led to an increase in fracture energy, thermal shock resistance and, in some cases, a decrease in the sensitivity of the material strength to the different size of defects. The utilization of tailored compressive residual stresses acting as physical barriers to crack propagation has succeeded in many ceramic systems [17,23,25,28–31].

However, a limiting factor in the design of these multilayer systems is the fact that the beneficial compressive stresses in one type of layers have to be balanced by (potentially critical) tensile stresses in the counterpart layers. Therefore, the use of relatively high residual stresses to enhance the mechanical behaviour can lead to the onset of initial cracks in the layers, which may later propagate in service under external applied stresses, leading to failure of the component. Fig. 1 illustrates typical surface cracks associated with residual stresses in planar ceramic–ceramic multilayer systems [32]. Tunnelling cracks may appear at the free surface of the layers with tensile stresses, and are oriented perpendicular to the layer plane [33,34]. Another type of cracks are the so-called "edge cracks", which initiate from pre-existing flaws at the free surface of compressive layers, oriented parallel to the layer plane [35,36]. The third type is delamination, mainly occurring at the corner interface between adjacent layers.

Experimental observations have shown that edge cracking may be associated not only with the magnitude of internal compressive stresses but also with the thickness of the compressive layer [26]. Some authors have speculated that this phenomenon may be related to crack bifurcation observed in some laminates with relatively high compressive residual stresses [37,38]. In a recent work, the present authors have applied a stress–energy criterion to set the conditions for edge cracking

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