C. R. Mecanique 343 (2015) 192–198

Contents lists available at ScienceDirect

Comptes Rendus Mecanique

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Edge cracking due to a compressive residual stress in ceramic laminates

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ARTICLE INFO

Article history:
Received 23 July 2014
Accepted 6 November 2014
Available online 24 November 2014

Keywords:
Ceramic laminates
Residual stresses
Fracture mechanics
Coupled criterion

ABSTRACT

The onset of an edge crack in compressive layers of a ceramic laminate undergoing residual stresses is predicted using the stress–energy coupled criterion based on the data of the tensile strength and the toughness of the material under consideration. The proposed criterion does not contain any adjustable parameter, which is its indisputable advantage. The results of predictions of the edge crack nucleation are in a very good agreement with the experimental observations of this phenomenon. They allow us to recover and even to improve slightly an approximate formula to estimate the critical layer thickness as a function of the compressive residual stress that was proposed some years ago.

1. Introduction

Ceramics are brittle materials and several attempts to improve their apparent toughness have been made [1]. The most common approach is to fabricate laminates to promote crack deflection in order to delay the final ruin of the structure. This can be achieved by using weak interfaces including layers of pyrocarbon, for instance [2–4]. Another approach consists in adding thin interphases of a porous ceramic between the dense layers [5–7]. More recently, the idea was to create strong compressive residual stresses in some intermediate layers in order to trap the growing cracks in the compressive layers [8–11]. This latter method seems most effective, but the onset of an edge crack is observed, under some conditions, in the layers undergoing a strong compressive residual stress [8–12].

To predict the onset of such an edge crack, the coupled criterion [13,14] allows getting rid of any assumption on the existence of flaws able to trigger cracking [12]. There is no adjustable parameter in the coupled criterion, whereas in the other case the flaw size is selected so as to fit with the experimental measures. This choice is somewhat arbitrary, because it does not rely on micrographic observations. Moreover, the flaw approach analyzes the early stage of the edge cracking and assumes a further crack growth in depth and along the specimen faces (channeling) to reach the observable state, while with the coupled criterion we make the assumption that the crack appears almost simultaneously all around the specimen and then grows in depth.

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http://dx.doi.org/10.1016/j.crme.2014.11.001

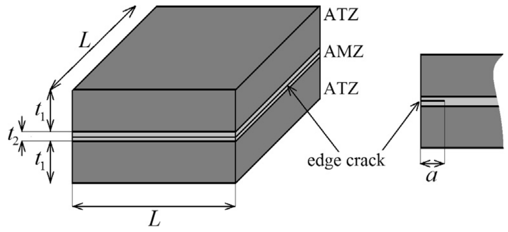

Fig. 1. The simplified 3-layer laminate and a schematic view of the edge crack with depth a in a cross section of the sample.

Table 1
Material data. E: Young's modulus, ν: Poisson's ratio, α: coefficient of thermal expansion, σ_c: tensile strength, K_{Ic}: material toughness.

Material	E (GPa)	ν	$\alpha \times 10^6$ (K^{-1})	σ_c (MPa)	K_{Ic} (MPa mm$^{1/2}$)
ATZ (1)	390	0.22	9.8	422	101.2
AMZ (2)	280	0.22	8.0	90	82.2

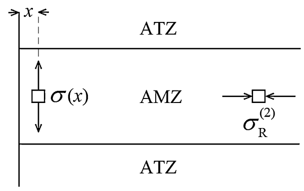

Fig. 2. The compressive residual in-plane stress $\sigma_R^{(2)}$ far from the free surface and the out-of-plane tension $\sigma(x)$ near the free surface in the AMZ layer.

2. The model

We consider a simplified symmetric ceramic laminate made of two outer layers of ATZ (thickness t_1) and one inner layer of AMZ (thickness t_2) with an edge crack of depth a running all around the specimen in the middle of the AMZ layer (Fig. 1). ATZ and AMZ are two different kinds of alumina-toughened zirconia, their elastic and fracture parameters are those given in [15] (Table 1).

The specimen length and width are $L = 4$ mm, the total thickness is $2t_1 + t_2$. The thicknesses t_1 and t_2 vary respectively from 0.4 mm to 1.5 mm and from 0.04 mm to 0.15 mm, so that the ratio $2t_1/t_2$ remains constant and equal to 20. As a consequence, for a given change of temperature $\Delta\theta$ during cooling, the layers are subjected to an in-plane bi-axial state of stress that remains unchanged for the various thicknesses [10,15], with:

$$\begin{cases} \sigma_R^{(1)} = E^{(1)*} \dfrac{(\alpha^{(2)} - \alpha^{(1)})\Delta\theta}{\frac{E^{(1)*}}{E^{(2)*}} \frac{2t_1}{t_2} + 1} \\ \sigma_R^{(2)} = -E^{(2)*} \dfrac{(\alpha^{(2)} - \alpha^{(1)})\Delta\theta}{\frac{E^{(2)*}}{E^{(1)*}} \frac{t_2}{2t_1} + 1} \quad \text{with } E^{(i)*} = \dfrac{E^{(i)}}{1 - \nu^{(i)}} \text{ for } i = 1, 2 \end{cases} \tag{1}$$

For $\Delta\theta = -1000$ K, this gives $\sigma_R^{(1)} = 31.2$ MPa and $\sigma_R^{(2)} = -624$ MPa, where the upper index denotes the material: (1) for ATZ and (2) for AMZ as in Table 1.

Due to its small thickness, the AMZ layer undergoes a high compressive residual stress. Near the free edge, the stress distribution is perturbed and exhibits a strongly localized out-of-plane tensile component (Fig. 2), of the same order of magnitude as $|\sigma_R^{(2)}|$ [12], which can trigger cracking.

FE calculations are carried out in a quarter of the cross section (because of symmetries) under the assumption of plane strain. For this geometry, it is a reasonable assumption compared to full 3D calculations [16]. For each pair of thicknesses, the crack length a is varied from 0 to 0.5 mm by unbuttoning nodes. The change in potential energy $\delta W^P(a)$ between the cracked and uncracked states is computed as a function of the crack length a as well as the out-of-plane tensile stress $\sigma(x)$ along the presupposed crack path (i.e. for $0 \le x \le a$, x is the distance to the free surface, Fig. 2) prior to fracture.

3. The coupled criterion

The coupled criterion states that crack onset occurs if two conditions are fulfilled simultaneously; the first one specifies that there is enough available energy to create a crack and the second that the tensile stress is greater than the tensile strength all along the presupposed new crack path: