Numerical Estimation of Crack Behaviour and Apparent Fracture Toughness of Layered Composites with Strong Interfaces

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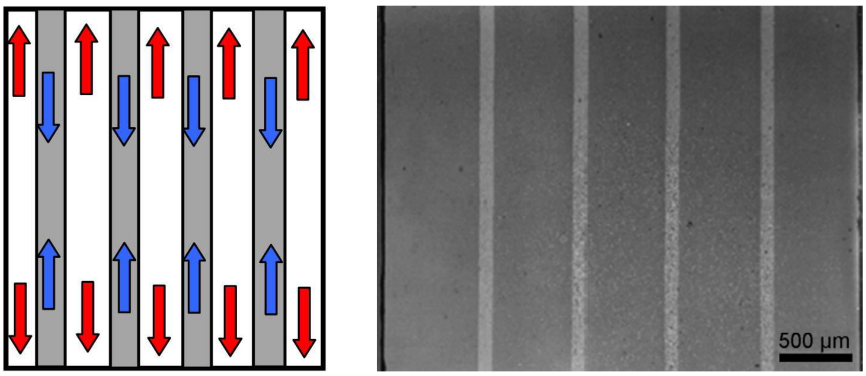
1 Introduction

During the last few decades, remarkable advances have been achieved in improving the mechanical behaviour of ceramic materials. Recently, new strategies have emerged aiming to achieve “flaw tolerant” materials by designing special microstructures that improve the toughness of ceramics. One of the very promising approaches for fabrication of flaw tolerant ceramics is the lamination of different kinds of ceramics.

Laminates on the base of alumina and zirconia can be mentioned as an example of flaw tolerant ceramics. The higher fracture toughness of ceramics laminates is reached by strong residual stresses developed during the sintering process in individual layers. The typical design of such laminates is shown in Fig. 1. The value of the apparent fracture toughness of laminates can be 2-3 times higher than the fracture toughness of materials of individual layers, see e.g. [1].



A) B)

Fig. 1. A) Typical design of layered ceramics – alternating layers with compressive (blue arrows) and tensile residual stresses; B) ceramics laminate on the base of alumina and zirconia (by courtesy of R. Bermejo [1])

In papers [1,2] procedures for an estimation of apparent fracture toughness can be found: in the work [1] on the base of weight functions, in the paper [2] on the base of a generalized strain energy density factor. A common comparison of resulting values obtained was made in [2] and good agreement was found. However, a question about crack propagation through layers during experimental testing occurred.

The aim of the paper presented is to estimate crack behaviour during the loading of ceramics laminate and explain the stepwise crack propagation observed during experimental investigation of the fracture toughness of laminates to which we have referred.

2 Materials characteristics

Materials characteristics and the geometry of the composite body considered were taken from references [1,3] to provide a comparison with published data. The composite studied was composed from nine layers of Al_2O_3/5vol.%t-ZrO_2 (alumina with tetragonal zirconia, noted as ATZ) and Al_2O_3/30vol.%m-ZrO_2 (alumina with monoclinic zirconia, noted as AMZ), see Fig. 2. The particle size of individual material components was about 0.3 μm [3].

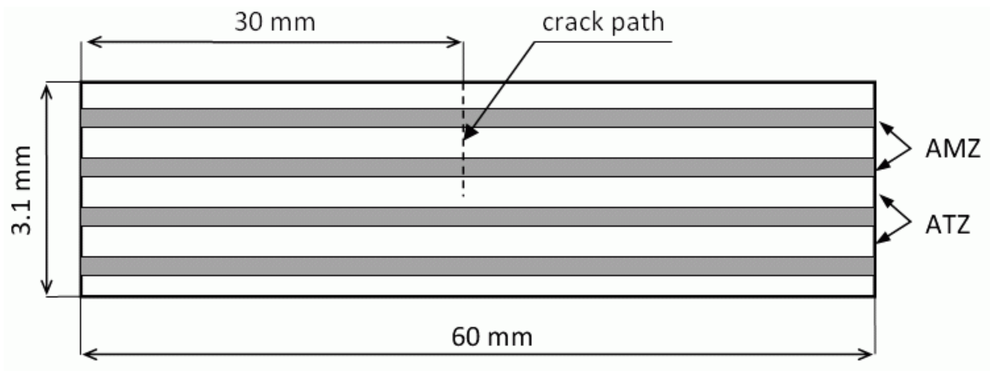


Fig. 2. Considered ceramics laminate on the base of alumina and zirconia

The thickness of ATZ layers was considered as t_{ATZ} = 0.52 mm and the thickness of AMZ t_{AMZ} = 0.1 mm. All material properties used for simulations are summarized in Table 1.

Table 1. Material properties of alumina-zirconia laminate [1,3]

Property	Units	ATZ	AMZ
Young's modulus E	GPa	390	280
Poisson's ratio ν	-	0.22	0.22
Coefficient of thermal expansion α_t	$10^{-6}\cdot K^{-1}$	9.82	8.02
Fracture toughness K_{IC}	$MPa\sqrt{m}$	3.2	2.6
Layer thickness t	mm	0.52	0.1

3 Residual stresses

The studied type of laminate is prepared by sintering and mainly due to different coefficients of thermal expansion of used materials, the layers contain rather high compressive and tensile residual stresses, which significantly influence the fracture behaviour of the laminate body. Residual stresses that develop during the sintering process were determined by numerical calculations in the author's work [2]. The sintering temperature 1250°C was considered a residual stress free temperature. The composite specimen was then subjected to cooling to room temperature (20°C). The resulting values of residual stresses for the laminate considered are shown in Fig. 3. Residual stresses were obtained by FEM for individual layers of the composite. Strong compressive stresses, more than 700 MPa, cause higher resistance against crack propagation through a composite body.

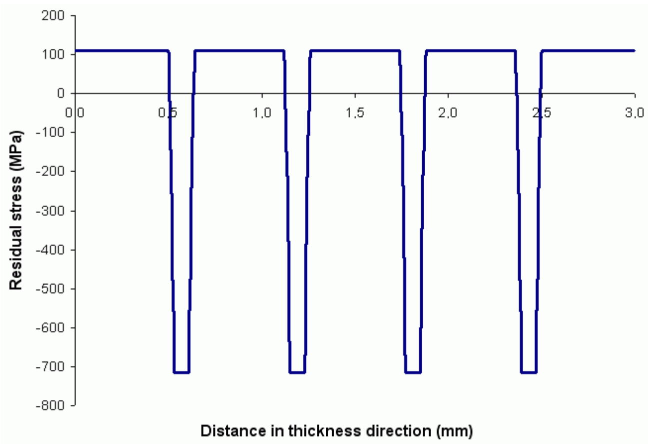


Fig. 3. Resultant values of residual stresses through the thickness of laminate

4 Apparent fracture toughness

Table 2 shows values of apparent fracture toughness estimated by the procedure based on the generalized strain energy density factor in the author's work [2] and values obtained from the analytical solution based on weight functions published in [1].

Table 2. Calculated apparent fracture toughness values on first four interfaces

Crack length *a* (mm)	${}^{1}K_{apt,c}^{\text{interface}}\ \left(\mathrm{MPa}\sqrt{\mathrm{m}}\right)$	${}^{2}K_{apt,c}^{\text{interface}}\ \left(\mathrm{MPa}\sqrt{\mathrm{m}}\right)$
0.52 (ATZ/AMZ interface)	0.12	-
0.62 (AMZ/ATZ)	7.98	7.1
1.14 (ATZ/AMZ)	0.38	-
1.24 (AMZ/ATZ)	8.28	8.1

[1] Values estimated by generalized strain energy density factor [2]; [1] Values published in reference [1]

The crack propagation in mode I was assumed, i.e. perpendicular to the material interface and residual stresses in layers. This assumption results from observation of very similar alumina-zirconia laminate. Fig. 4 shows the perpendicular crack propagation through material interfaces. The crack started from a V-notch made by micro indentation and propagates under mode I perpendicular to the interface and loading of layers without regard to the direction of residual stresses. The existence of residual stresses influences only the value of the stress intensity factor, but does not influence the crack propagation direction.

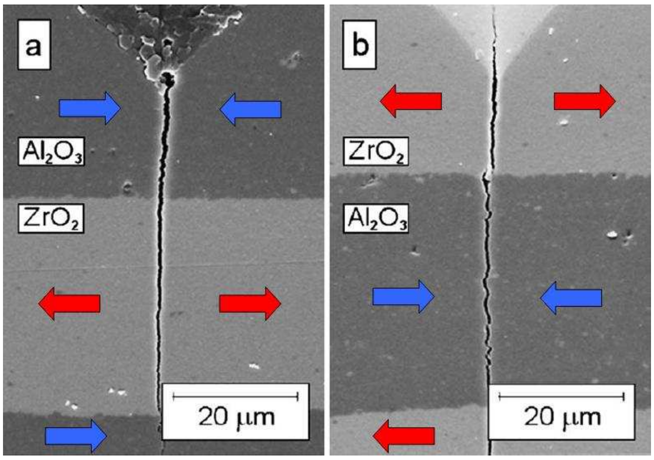


Fig. 4. Crack propagation from the corner of initial footprint made by micro indentation. Crack propagates perpendicularly to the interface under mode I of loading (by courtesy of H. Hadraba [4])

The observation referred to is different from the crack behaviour published in [5,6]. There, stepwise crack propagation was observed, see Fig. 5. In this case, four point bending test was used for fracture toughness measurements and the cracks propagated from an initial flaw on the surface through the thickness of the laminate. Strong crack deflection or bifurcation on the interface between layers with tensile and compressive stresses was observed, see Fig. 6. In the case of crack propagation from the layer with compressive stress to the layer with tensile stress no deflection or bifurcation was observed and the crack returned to the original propagation direction perpendicular to the interface between layers.

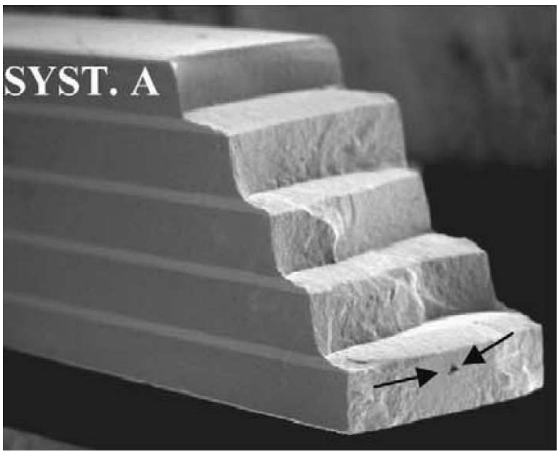


Fig. 5. Stepped crack propagation (by courtesy of R. Bermejo [5])

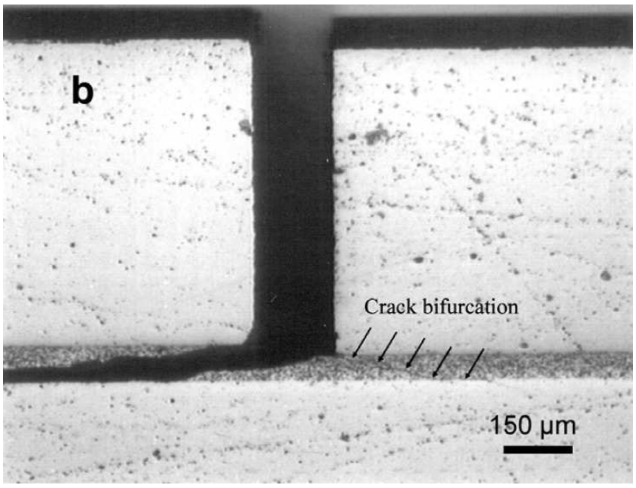


Fig. 6. Crack bifurcation on the interface between layers with tensile and compressive stresses (by courtesy of R. Bermejo [5])

5 Numerical modeling and results

The modeling by finite elements was focused on the explanation of crack bifurcation (deflection), because the crack should (according to assumptions) propagate perpendicular to the interface under mode I. The four point bending test and residual stresses were simulated (see Fig. 7) by FEM. For calculations the commercial finite element system Ansys was used.

The tangential stress $\sigma_{\theta\theta}$ and the strain energy density factor S were investigated for an estimation of crack deflection. Crack propagation was assumed in the direction of maximum tangential stress (MTS criterion, see [7]):

$$\left(\frac{\partial\sigma_{\theta\theta}}{\partial\theta}\right)_{\gamma} = 0 \quad , \quad \left(\frac{\partial^2\sigma_{\theta\theta}}{\partial\theta^2}\right)_{\gamma} < 0 , \tag{1}$$

or in the direction of minimum strain energy density factor, e.g. [8]:

$$\left(\frac{\partial S}{\partial\theta}\right)_{\gamma} = 0 \quad , \quad \left(\frac{\partial^2 S}{\partial\theta^2}\right)_{\gamma} > 0 . \tag{2}$$

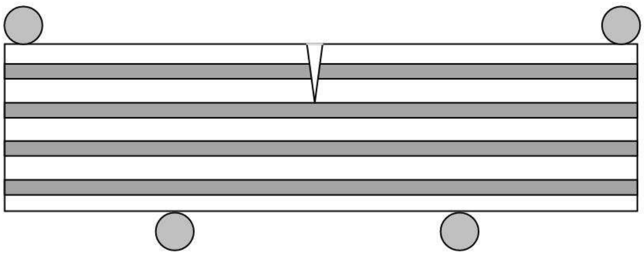


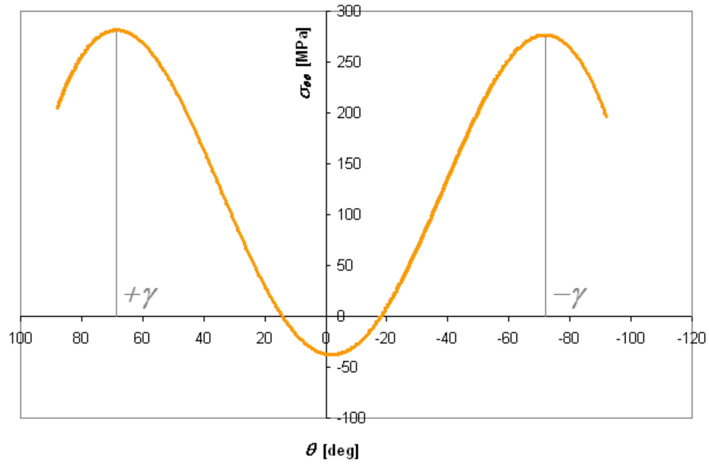
Fig. 7. Scheme of ceramics laminate body under four point bending test

For the estimation of crack propagation direction the critical radius r_c = 0.05 mm was chosen. This value corresponds to the critical distance expressed from failure stress σ_f of material of layer estimated from following expression:

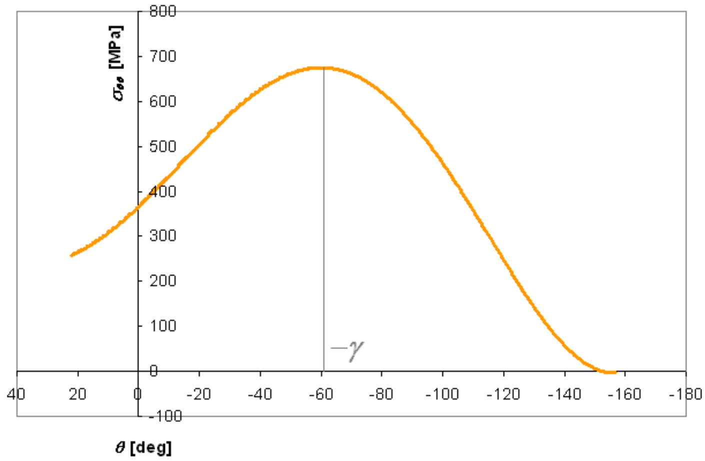
$$r_c = \frac{K_{IC}^2}{2\pi\sigma_f^2}. \qquad (3)$$

K_{IC} in Eq. 3 is fracture toughness of AMZ or ATZ layer respectively.

Loading by residual stresses (cooling from sintering temperature 1250°C to the room temperature) and mechanical loading caused by four point bending was modeled. 2D calculations were done under plane strain conditions. Crack propagation direction was determined on the first three interfaces by both of the methods mentioned. Results from MTS criterion are shown in Fig. 8A,B,C.



A)



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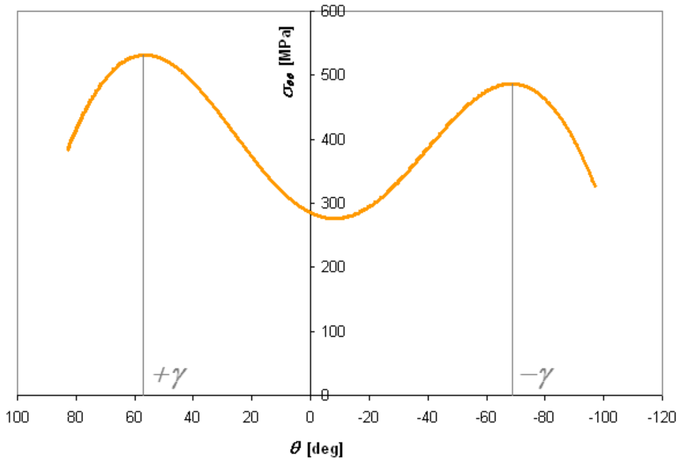


C)

Fig. 8. Directions of crack propagation estimated by MTS criterion. Angle $\theta = 0$ represents original direction of crack propagation and the angle γ deviation from the original direction on interface. Figures A, B, C represent dependences of tangential stress $\sigma_{\theta\theta}$ on polar coordinate θ for 1st, 2nd or 3rd interface

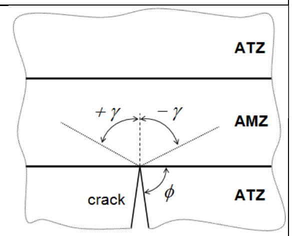
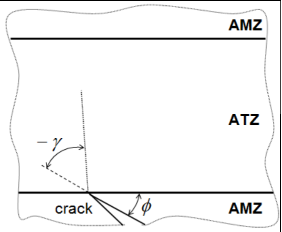
Fig. 8A shows that the propagation direction of a crack touching the first interface (ATZ/AMZ) can deflect approximately under an angle of 65 degrees from the original direction perpendicular to the interface. It is evident that the crack deflection angle γ can be positive or negative. It means that crack growth can occur under an angle of +65 degrees or -65 degrees or in the perfect symmetric case (original crack is in this case nearly perpendicular to the interface) can bifurcate under an angle where γ = 65 degrees.

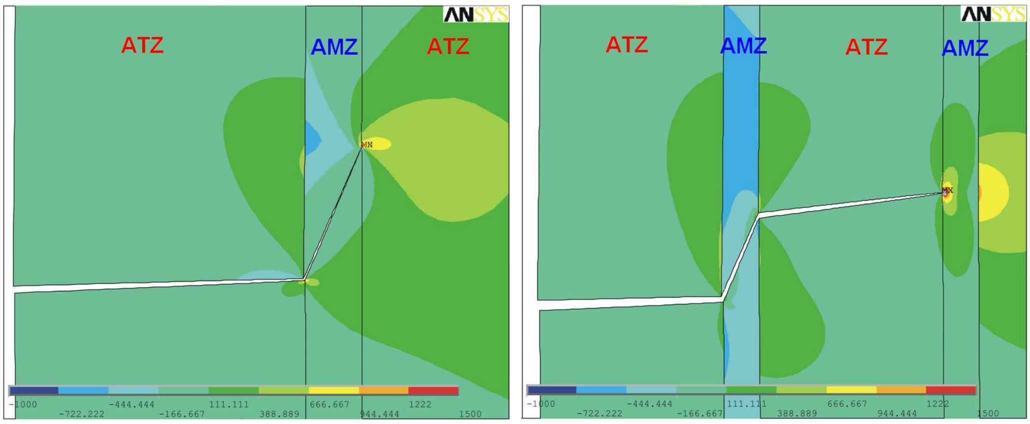
On the second interface (see Fig. 8B) the next crack propagation in the second material is under an angle of -60 degrees, i.e. nearly perpendicular to the material interface. It means that the crack will propagate perpendicularly to the tensile residual stresses in ATZ layer under mode I of loading. FE results with gradients of tangential stress are shown in Fig. 9.

The angles of crack propagation directions for first four interfaces for both used criteria are introduced in Table 2.

The sensitivity of the crack deflection on the initial angle ϕ was studied on the first interface (ATZ/AMZ). Both of the methods for crack propagation direction introduced earlier were used. The results summarized in Table 3 show that the angle of next crack propagation ϕ_1 is not dependent on the value of initial angle ϕ and the crack will propagate through the AMZ layer under constant angle ϕ_1 for a wide range of initial angles ϕ.

Table 2. Resulting angles γ of crack deflection on interfaces obtained from maximum tangential stress criterion (MTS) and strain energy density factor criterion (SEDF)

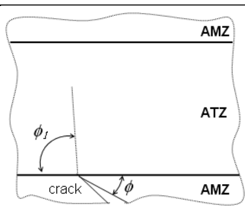
interface	ϕ [deg]	γ (MTS) [deg]	γ (SEDF) [deg]	scheme
1	88	69 - 72	62 - 65	
3	83	57 - 69	58 - 72	
2	23	- 60	- 50	
4	23	- 60	- 50	



A) B)

Fig. 9. FE solution of distribution of tangential stresses around the crack tip touching the interface between layers of laminate: A) crack tip on the 2nd interface; B) crack tip on the 3rd interface

Table 3. Values of crack propagation direction on the 1st interface given by angle ϕ_1 for different values of initial angle ϕ

ϕ [deg]	ϕ_1 (MTS) [deg]	ϕ_1 (SEDF) [deg]	scheme
88	70.7	63.5	
85	70.7	63.2	
80	70.6	63.0	
70	70.7	62.1	
60	70.5	60.7	

6 Conclusion

Crack growth in a ceramics laminate body was investigated with regard to change of crack propagation direction on material interfaces. During experimental testing the discrepancy in crack propagation direction occurred in contrast to expectations (straight propagation under mode I of loading was assumed). Conditions of experimental method (four point bending) were modeled by the finite element method. The maximum tangential stress criterion and a criterion based on strain energy density factor were used for the estimation of crack propagation directions on material interfaces. Both of these methods produced similar results, which are in very good agreement with the observations. The bending of the laminate body and different material properties of individual layers cause high values of shear stresses close to the ATZ/AMZ interface (crack growths from the layer with tensile stress to the layer with strong compressive stress). Due to bending loading, the propagating crack can strongly deflect on the ATZ/AMZ interface. This deflection is higher than 60 degrees measured from a straight direction and is nearly constant for different original crack orientations. In the case of the crack propagating (almost) perpendicularly to the ATZ/AMZ interface the crack starts to bifurcate/deflect on the ATZ/AMZ interface. On the second kind of interface (AMZ/ATZ) the crack changes propagation direction to the direction normal to tensile stresses in the ATZ layer. The result is stepped crack propagation through the laminate ceramics body.

The behaviour described is characteristic for bending loading of a laminate body during a four point bending test and seems to be mainly the result of the specific loading conditions of a laminate body. More research should be focused on the capability of the interface to decline the propagating crack, conditions under which the deflection occurs and mainly on mechanisms for the toughening of the ceramics laminate. This knowledge is crucial for the design of new flaw tolerant ceramics.

The paper presented demonstrates possibilities for the estimation of crack behaviour during its growth in ceramics laminates. The results obtained can be used for the design of new layered ceramics and the reliable estimation of crack behaviour in the materials considered.

Acknowledgement

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