Crack Propagation in Laminar Ceramics

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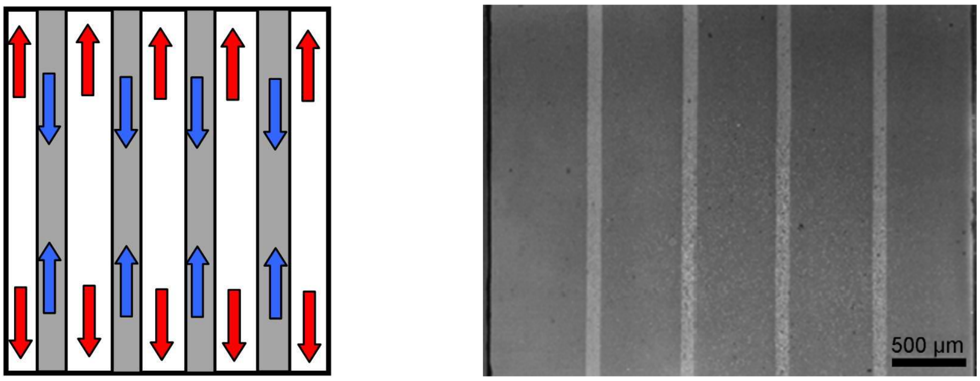
ABSTRACT. *The contribution presented deals with crack propagation in ceramic laminates. Assumptions of linear elastic fracture mechanics and small scale yielding are considered. The crack behaviour in ceramic laminate body under external loading is investigated. Strong residual stresses due to different coefficients of thermal expansion of individual material layers are taking into account in finite element calculations. The change of crack propagation direction on material interface is estimated on the base of strain energy density and maximum tangential stress criteria. The influence of thickness of laminate layers on crack propagation direction is estimated. The stepwise crack propagation path of the crack propagating through* Al_2O_3-ZrO_2 *ceramic laminate is numerically estimated. The comparison of estimated crack path with experimental data is done and mutual good agreement is found. The resistance to crack propagation through laminate body depends on the level of crack deflection on material interfaces, thus the estimation of the crack propagation direction or generally of the crack path is necessary for determination of so-called apparent fracture toughness of the laminate. The procedure suggested can contribute to enhancing of reliability of structural ceramics or generally of layered composites with strong interfaces.*

INTRODUCTION

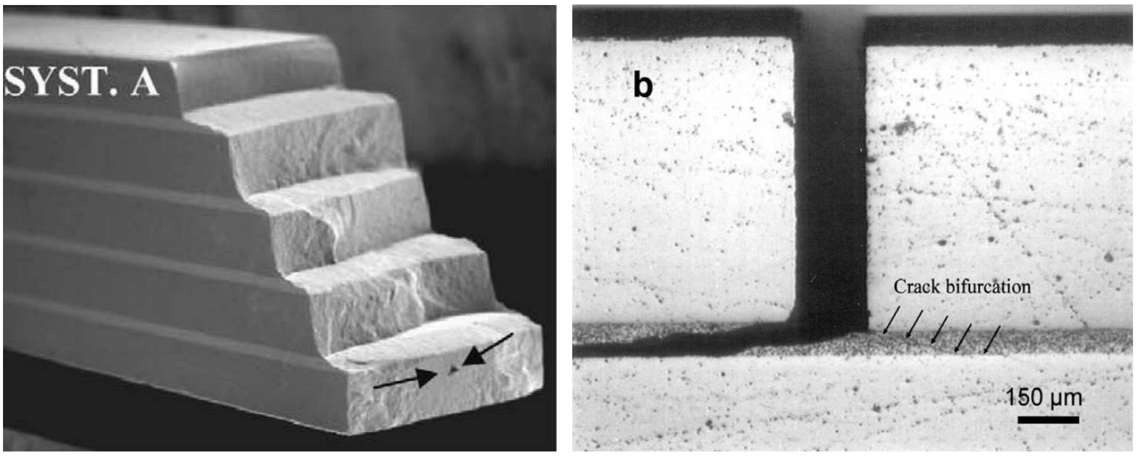
One of the promising approaches for the fabrication of flaw tolerant ceramics is the lamination of different kinds of ceramics. Resistance to crack propagation is based on different thermoelastic properties of individual layers. Due to different coefficients of thermal expansion the strong residual stresses developed during the sintering process cause the closure of a potential crack and contribute to the higher apparent fracture toughness of the laminate, see e.g. [1]. The typical design of a laminate body consists of wide layers loaded by tensile stress and thin layers, where the strong compressive stresses are presented, see Fig 1a. As a typical example of a laminate ceramic the AMZ/ATZ (AMZ - alumina with monoclinic zirconia; ATZ - alumina with tetragonal zirconia) composite can be mentioned, see Fig 1b.

A stepwise crack propagation caused by strong compressive stresses is typical for ceramic laminates under external load, see Figs. 2a,b. This kind of cracking has been observed and described e.g. in [2,3]. In mentioned references the four point bending was used for fracture toughness measurements and the cracks propagated from 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. In the case of crack propagation from the layer loaded by compressive stress to the layer with tensile stress no deflection or bifurcation was observed and the propagating crack returned to the original propagation direction perpendicular to the interface between layers.



(a) (b)

Figure 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])



(a) (b)

Figure 2. a) Stepped crack propagation; b) Crack bifurcation on the interface between layers with tensile and compressive stresses; (by courtesy of R. Bermejo [2])

Generally for these kind of laminates the cracks propagate transversally through the tensile loaded layer (under mode I of loading), then deflects on the interface between layers and propagate skew through the compressive loaded layer under mixed mode conditions. It should be mentioned here that at the interface between tensile/compressive layers the bifurcation can occur (as is shown in Fig. 2b and marked in Fig. 3). The toughening effect is caused especially by the presence of the material interface (more energy is necessary when the crack passes though the interface) and due to deflection (bifurcation) causes a longer crack trajectory and retards the propagating crack.

The aim of the paper is to estimate the crack propagation direction in a laminate body and explain the stepwise crack propagation observed during experimental investigation. Knowledge of crack behaviour can contribute to a better understanding of the failure of ceramic laminates and to the design of new laminates with advantageous properties.

NUMERICAL CALCULATIONS

For numerical study the FE code Ansys was used. The study was performed on a ceramic laminate body AMZ/ATZ (AMZ - Al_2O_3/30vol.%m-ZrO_2; ATZ - Al_2O_3/5vol.%t-ZrO_2). The geometry and material characteristics were taken from references [1,4] and are summarized in Table 1. The particle size of individual material components was about 0.3 μm [4].

Table 1. Thermoelastic material properties of alumina-zirconia laminate

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

The geometry of the numerical model is shown in Fig. 3. Nine layers created the laminate body of constant width 3 mm. Ratio R of layer thicknesses (R = thickness of ATZ layer/thickness of AMZ layer) varied from 2 to 10.

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. The sintering temperature 1250°C can be considered as a residual stress free temperature. The composite specimen is during processing subjected to cooling from sintering temperature to room temperature (20°C).

The considered layer thickness ratios and corresponding magnitudes of residual stresses in individual layers are shown in Table 2. The values were obtained by finite lement calculations. Higher values of R were not considered in further numerical simulations, because no important increase of the magnitude of compressive stresses influencing the crack behaviour appears in this case. For example for R = 100 the laminate contains tensile stresses of 6 MPa and compressive stresses of -793 MPa (see Table 2).

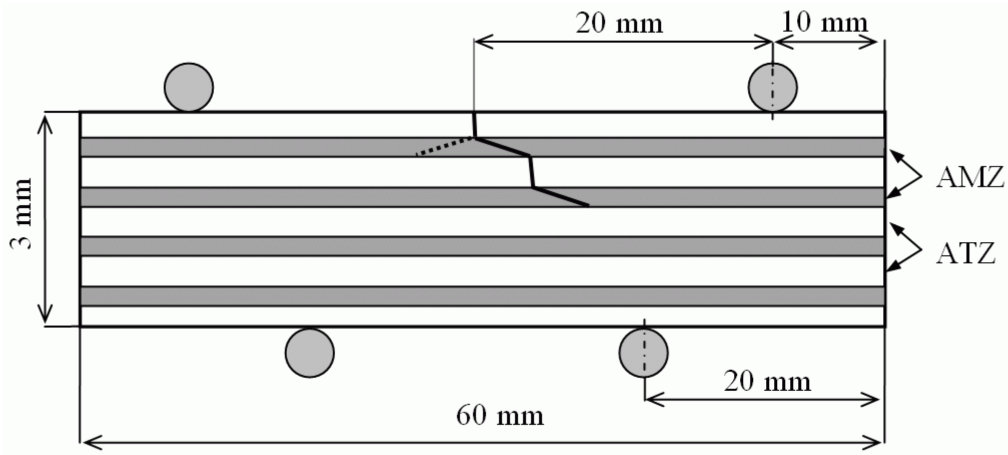


Figure. 3. Geometry of the ceramics laminate body on the base of alumina and zirconia considered for calculations. The typical crack behavior for given conditions (four point bending) is marked.

Table 2. Considered ratio of layer thicknesses R and corresponding magnitudes of residual stresses in the layers (for ideal laminate)

Ratio of layer thicknesses R (ATZ/AMZ)	2:1	5:1	7:1	10:1	100:1
Thickness of ATZ layer [mm]	0.4288	0.5170	0.5384	0.5556	0.5952
Thickness of AMZ layer [mm]	0.2140	0.1038	0.0770	0.0556	0.0060
Residual stresses in ATZ layers [MPa]	247	115	84	60	6
Residual stresses in AMZ layers [MPa]	-620	-715	-737	-754	-793

Estimation of Crack Propagation Direction

For the estimation of crack propagation direction the finite element model (Fig. 3) was loaded by cooling from sintering temperature (1250°C) to room temperature (20°C) and simultaneously by four point bending with reactions in supports of value 15 N. Two different criteria for the estimation of crack propagation direction were applied:

- the maximum tangential stress criterion (MTS) [5] and
- the criterion based on the strain energy density factor S [6],

to obtain crack propagation directions in the cases of crack touching the first (ATZ/AMZ), the second (AMZ/ATZ) and the third (ATZ/AMZ) interfaces.

The MTS criterion assumes that the crack propagates in the direction of maximum tangential stress under angle γ, i.e. in the direction where the following conditions are accomplished:

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

The criterion of minimum strain energy density factor assumes further crack propagation in the direction where:

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

For the estimation of the crack propagation direction a radius r_c where the criteria are applied must be chosen. The value of r_c was determined from the expression:

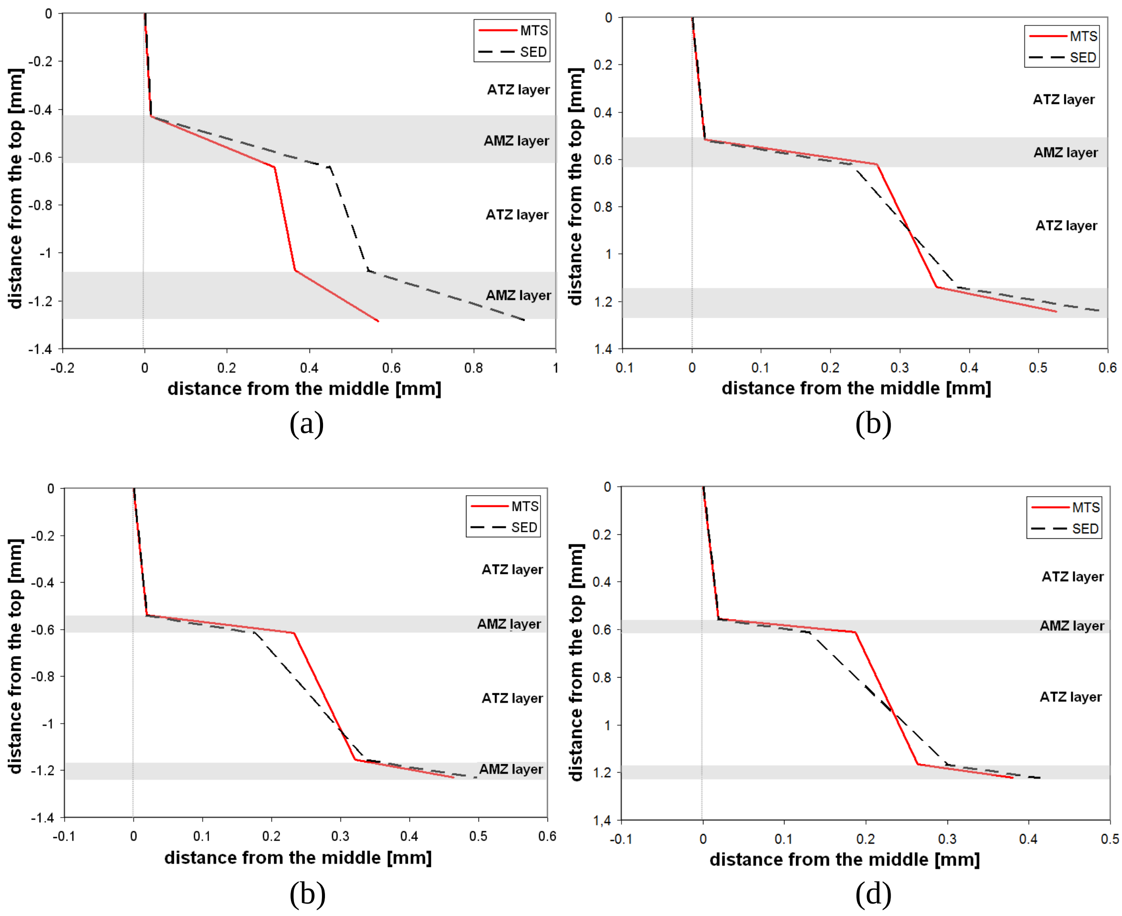
$$r_c = \frac{K_{IC}^2}{2\pi\sigma_f^2}\,, \tag{3}$$

where K_{IC} is the fracture toughness and σ_f the failure stress of AMZ or ATZ layer respectively (phase where the crack propagates to). The value of the parameter r_c was estimated 0.015 mm for ATZ/AMZ interface and 0.007 mm for AMZ/ATZ interface.

The initial angle γ_i of crack propagation from the specimen surface was chosen as 2 degrees (measured from the direction perpendicular to the laminate layers) for all layer thicknesses considered in calculations. Note that the value of the initial angle does not influence further crack propagation path through the laminate (see [7] for details).

RESULTS AND DISCUSSION

The resulting crack deflection angles obtained for the first three interfaces from both criteria used are summarized in Table 3. Figure 4 shows the estimated crack path through the first four layers of the laminate. Both of the criteria used reasonably well predicted the stepwise crack propagation observed during experimental tests described in [1]. Results show typical nearly perpendicular crack propagation in the layer loaded by tension (here ATZ) and skew crack propagation under the comparatively large angle γ(60-70 [deg], see Table 3) in the layer loaded by compression (here AMZ). This value of the deflection is in very good agreement with the experimentally observed. Note that at the ATZ/AMZ interface a bifurcation can occur since the deflection angle γ can be positive or negative of the same value. At the second type of interface (AMZ/ATZ) the crack propagation angle is unambiguous; the crack deflects in a direction perpendicular to the interfaces. Figure 4 shows the influence of the magnitude of residual stresses (influence of layer thickness) on crack deflection too. The deflection angle γ increases with an increase in layer thickness ratio R. Note that ratio R higher than 10 only weakly influences further crack deflection.



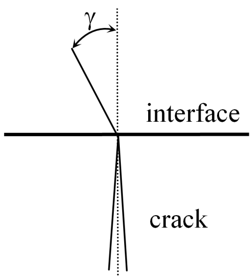
Figuge 4. Schemes of crack propagation through the first four layers of laminate. Comparison of results obtain by MTS and SED criterion: a) for R = 2; b) R = 5; c) R = 7; d) R = 10.

Crack growth in a ceramics laminate body was investigated with regard to change of crack propagation direction on material interfaces. Conditions of experimental method (four point bending) were modeled by the finite element method. Strong residual stresses presented in individual layers of laminate were taken into account. The maximum tangential stress criterion and a criterion based on strain energy density factor were used for the estimation of change of the crack propagation directions on material interfaces. Both of these methods produced similar results, which are in very good agreement with the experimental 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 remote loading, the propagating crack can strongly deflect on the ATZ/AMZ interface. This deflection is higher than 60 degrees measured from a straight direction. 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. Mentioned conclusions are valid for wide range of ratio of layer thicknesses.

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.

Table 3. Values of the deviation angle γ calculated for the first three interfaces for different R ratio and by both method used (MTS and SED).

R	method	1st interface ATZ/AMZ	2nd interface AMZ/ATZ	3rd interface ATZ/AMZ
2	MTS	54.54	6.63	43.38
	SED	63.70	12.55	61.38
5	MTS	67.32	9.50	59.04
	SED	63.72	16.86	63.90
7	MTS	70.20	9.32	61.74
	SED	63.72	16.86	64.26
10	MTS	71.64	7.89	64.44
	SED	63.72	16.68	64.26



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REFERENCES

1. Bermejo, R., Torres, Y., Baudín, C., Sánchez-Herencia, A.J., Pascual, J., Anglada, M. and Llanes, L. (2007) *Journal of the European Ceramic Society* **27**, 1443-1448.
2. Bermejo, R., Torres, Y., Sánchez-Herencia, A.J., Baudín, C., Anglada, M. and Llanes, L. (2006) *Acta Materialia* **54,** 4745-4757.
3. Bermejo, R., Sánchez-Herencia, A.J., Llanes, L. and Baudín, C. (2007) *Acta Materialia* **55,** 4891-4901.

4. Bermejo, R., Llanes, L., Anglada, M., Supancic, P. and Lube, T. (2005) *Key Engineering Materials* **290**, 191-198.
5. Erdogan, F. and Sih, G.C. (1963) *Journal of Basic Engineering* **85D(4)**, 519-527.
6. Sih, G.C. (1973) *Mechanics of fracture I. Methods of analysis and solutions of crack problems*, Noordhoff International Publishing, Leyden.
7. Šestáková, L., Náhlík, L., Hutař, P. and Knésl, Z. (2009) accepted for publication in *Proceedings of International Conference on Fracture (ICF-12)*, Ottawa.