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MODELLING OF EDGE AND TUNNELLING CRACKS INITIATION IN CERAMIC LAMINATES USING THE STRESS-ENERGY CRITERION

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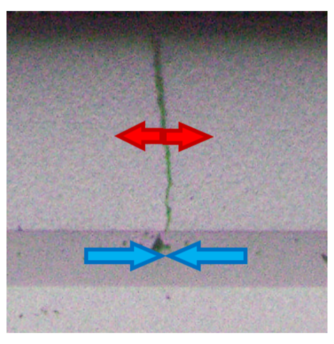
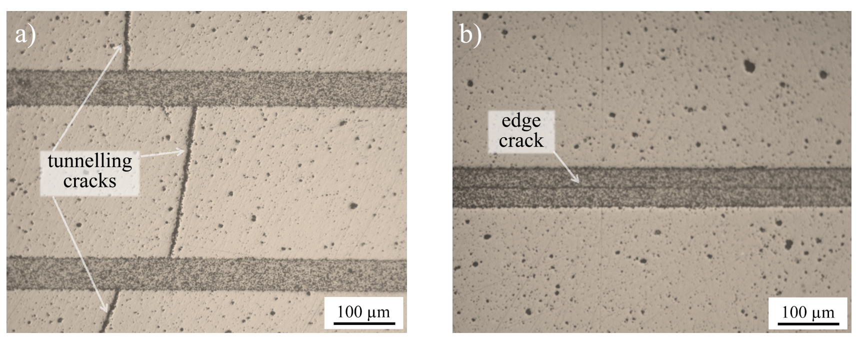
I Background: Multi-material design

✓ **Advantage of design:**
Damage tolerance of ceramics can be enhanced through a multi-layer design and induced residual stresses. Key design parameters are in-plane compressive residual stresses, microstructure and architecture.



Example of a crack arrested by compressive stress

! **Design limitations:**
a) Large in-plane tensile stresses → (through-the-thickness) tunnelling cracks
b) Large out-of-plane tensile stresses → (surface) edge cracks in compressive layers



Example of tunnelling cracks (left) and an edge crack (right) (R. Bermejo, 2017)

II Motivation: Understanding limitations

? **Hypothesis:**
Certain combinations of layer thickness and residual stress can prevent fracture.

→ **Objective**:
Create a model able to predict initiation of edge/tunnelling cracks and analyse the influence of layer thickness and residual stress magnitude.

III Modelling: Approaches and methods

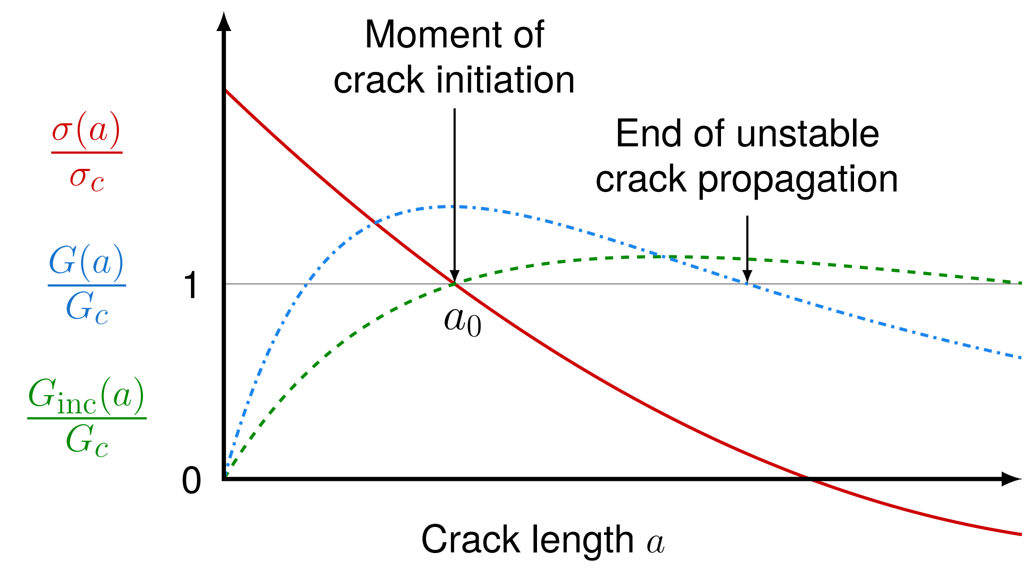
✗ **Griffith criterion (Linear elastic fracture mechanics – LEFM):** Always assumes an existing crack which propagates, when the energy release rate, G, is higher than fracture energy of the material, G_c. However, it doesn't allow prediction of the crack initiation.

✓ **Coupled criterion (Finite fracture mechanics – FFM):**
A new crack of a finite length, a_0, occurs in a brittle material, when both stress and energy conditions are simultaneously fulfilled (D. Leguillon, 2002):

(i) There must be enough available energy ($G_{\mathrm{inc}} \geq G_c$) to create a crack
(ii) The stress must be greater than the tensile strength ($\sigma \geq \sigma_c$) all along the prospective crack path.

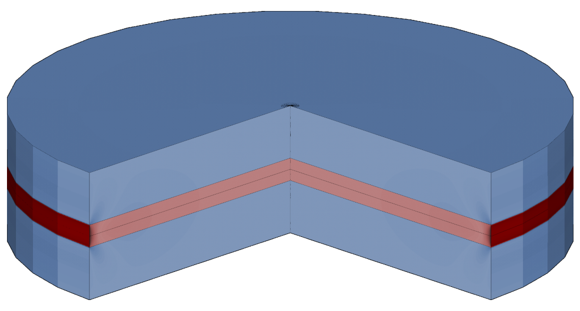
ⓘ **Finite element method (FEM):**
Stress and strain energy are calculated using FEM for various (initial) crack lengths in different samples.

$$G = -\frac{\partial E_p}{\partial a} \qquad G_{\mathrm{inc}} := -\frac{E_p(a)-E_p(0)}{a}$$



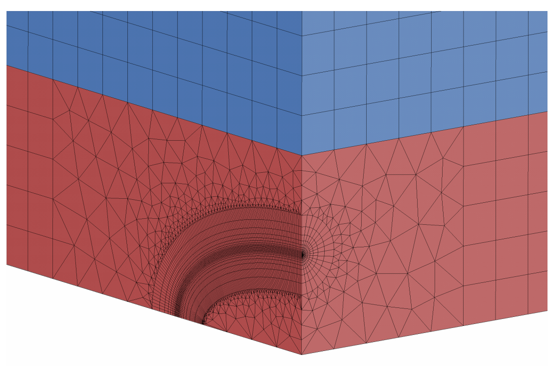
Stress and energy conditions for crack initiation

IV Model of an edge crack



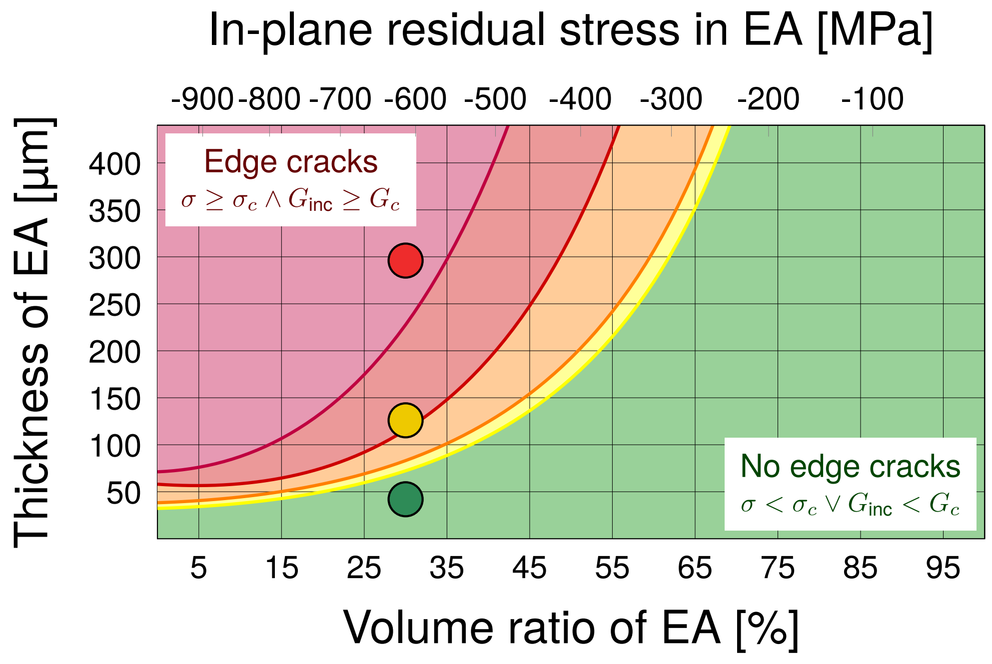
- axisymmetric model
- alumina (EA) layer embedded between two zirconia-toughened alumina (ZTA50) layers
- circumferential ring-shaped crack in the layer with compressive residual stress

V Model of a tunnelling crack



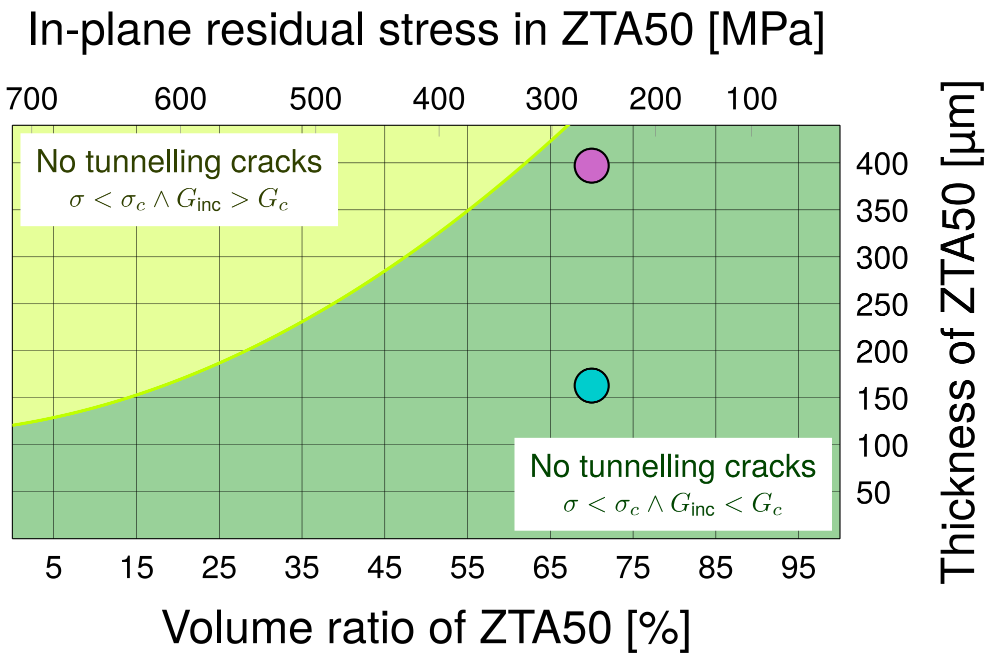
- octosymmetric model
- zirconia-toughened alumina (ZTA50) layer embedded between two alumina (EA) layers
- elliptic crack with various aspect ratios in the layer with tensile residual stress

VI Results



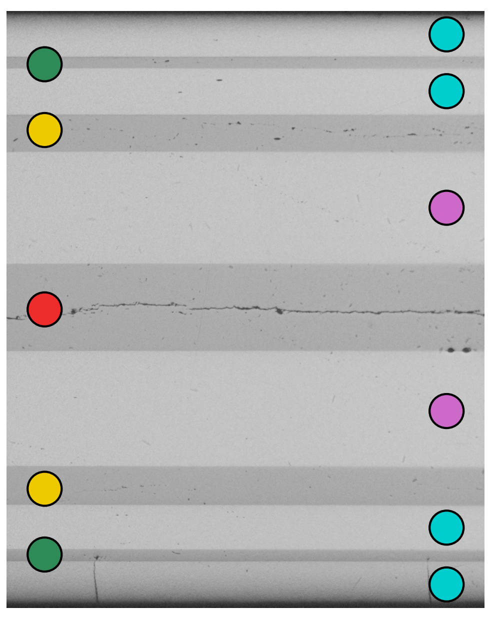
Edge crack predicted for small volume ratios and thick layers

No tunnelling crack are predicted

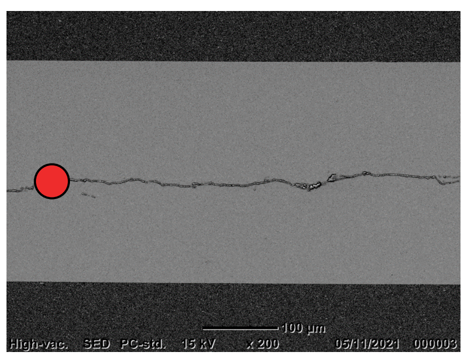


VII Verification of the model

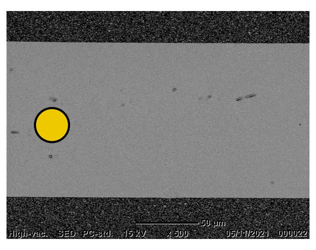
- Two **bi-material plates** (40 mm×40 mm×2 mm) made out of 11 layers were fabricated. (A.-K. Hofer et al., 2021)
- Outer EA layers ● were predicted and observed to be edge crack-free.



- In the inner EA layer ● edge cracks were predicted and also observed.



- Intermediate EA layers ● could contain cracks if the strength was low, but no prominent cracks were observed.



VIII Conclusions

✓ Edge crack were observed only in layers for which they were predicted.

✓ No through-the-thickness tunneling crack were observed, as predicted.

✓ By suitable combination of material volume and layer thickness, edge and/or tunnelling cracking can be avoided.

→ **Outlook:**
Calculations and experiments for other ceramics with different σ_c and G_c (for prediction and evidence of tunnelling cracks).

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