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Mechanical stability limits of bi-layer thermal barrier coatings

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[1] R.A. Miller, J.L. Smialek, and R.G. Garlick, in Science and Technology of Zirconia, A. H. Heuer and L. W. Hobbs, Eds., Columbus, OH, USA: The American Ceramic Society, (1981) 241-253. [2] R. Subramanian, A. Burns, and W. Stamm, in Proceedings of ASME Turbo Expo 2008: Power for Land, Sea and Air, ASME, (2008). [3] R. Vaßen, F. Traeger, and D. Stöver, International Journal of Applied Ceramic Technology, vol. 1, no. 4 (2004) 351-361

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Mechanical Stability Limits of Bi-Layer Thermal Barrier Coatings

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DFG FVV

Thermal Barrier Coatings IV, Irsee, 26.06.2014

Materials
Chemical Engineering
Biotechnology

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MAN Diesel & Turbo

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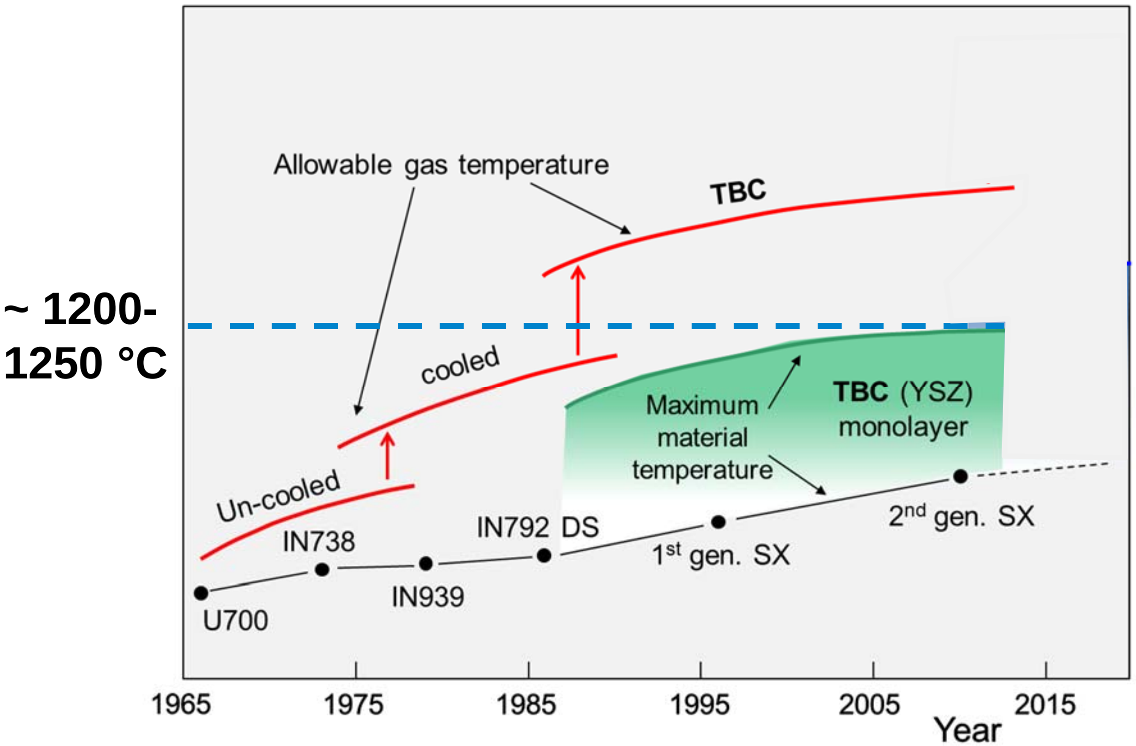
SIEMENS

Rolls-Royce®

Motivation

Ongoing effort to increase operating temperature / efficiency

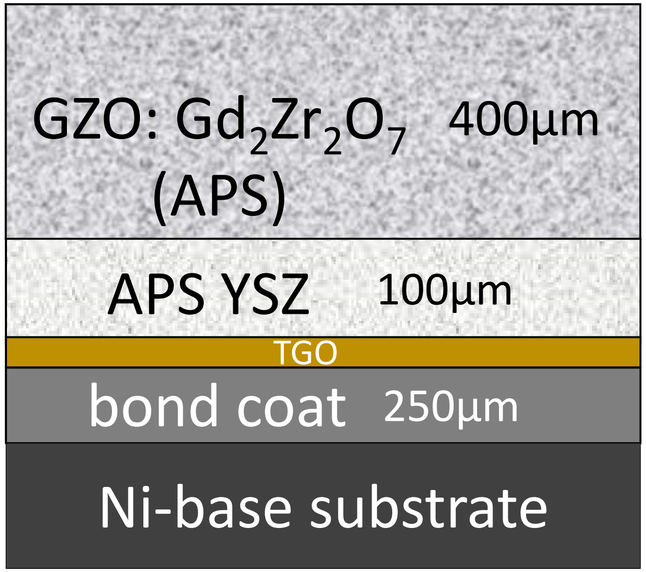


[after: Marini and Morrison; Proc. 7th Int. Charles Parsons Turbine Conf. /2007]

However, the temperature limit of 7YSZ is around 1250°C due to phase transformations above this temperature [1]
→ Search for new materials / new TBC solutions

[1] W. Pan et al., MRS BULLETIN , Vol. 37 (2012)

Approach – Bi-Layer TBC



Bi-Layer Concept:

- surface temperatures > 1250 °C
- crack resistance to TGO growth induced stresses
- avoiding unwanted reactions between GZO and TGO

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- Optimization of spray process
- Sample manufacturing

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- Oxidation testing
- Mechanical testing (Charalambides test, G_{ic})
- TGMF testing

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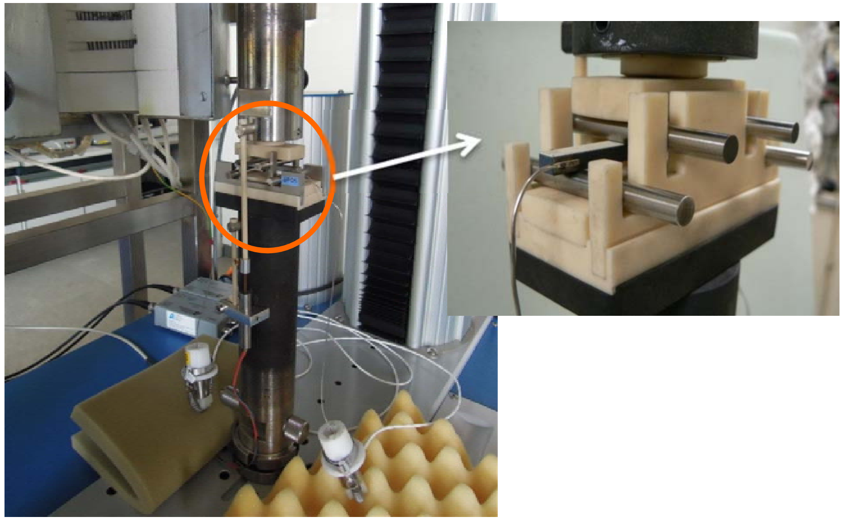
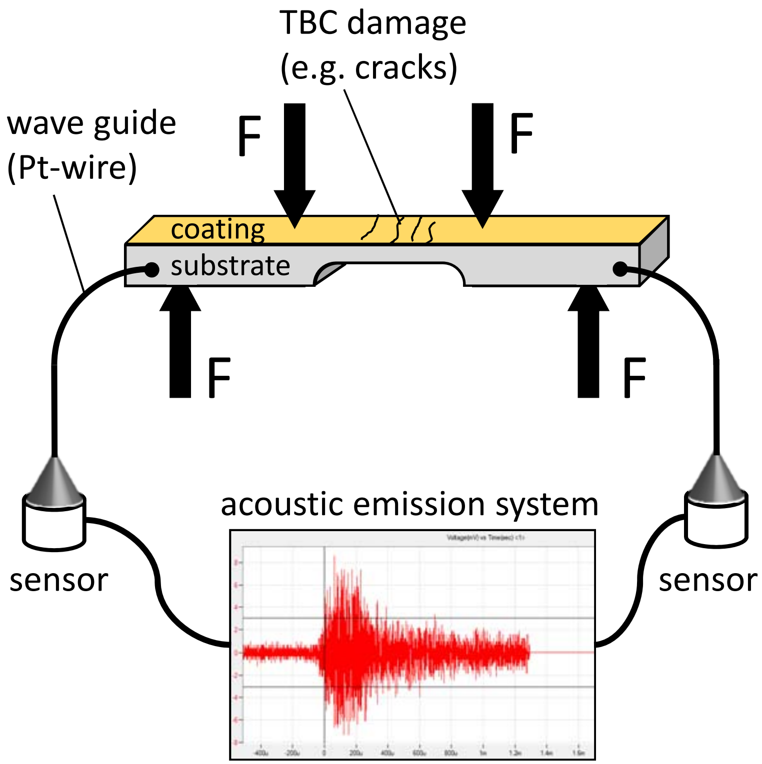
- Oxidation testing
- Mechanical testing (4-point bending test, ε_c)
- Lifetime modeling

4-pt. Bending with Acoustic Emission Measurement

4-Point Bending

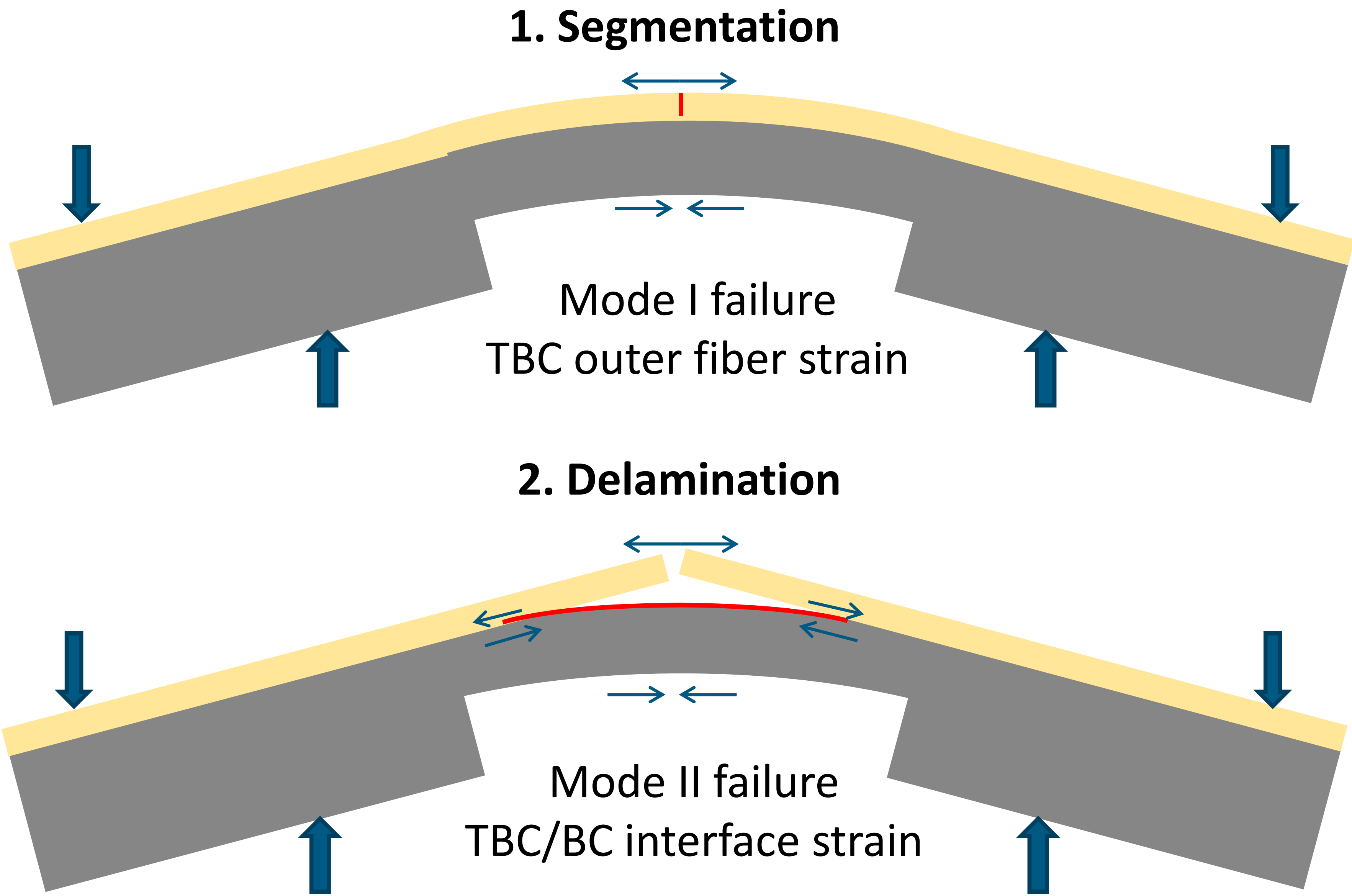


50kN
Universal Testing
Machine

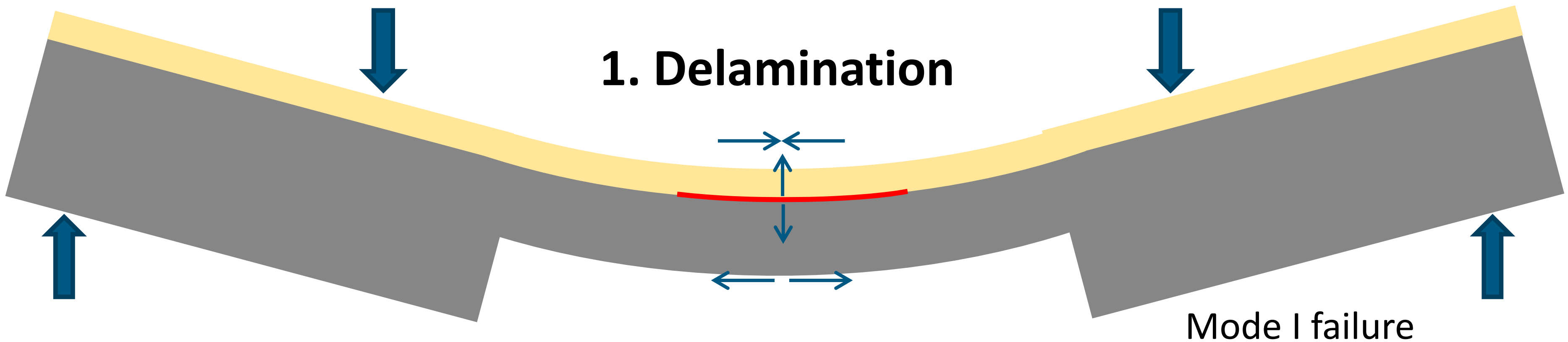


Testing was performed at RT

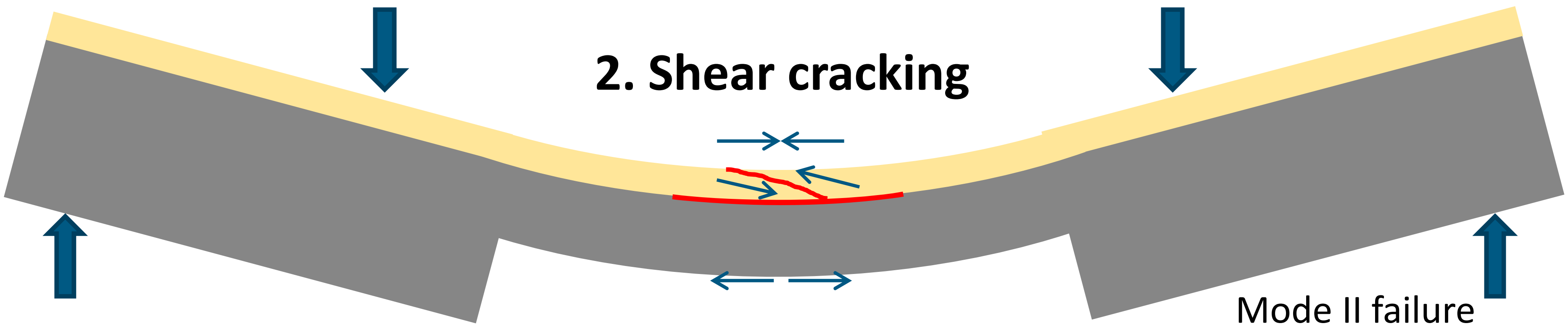
4-Point Bend Testing – TBC in Tension



4-Point Bend Testing – TBC in Compression



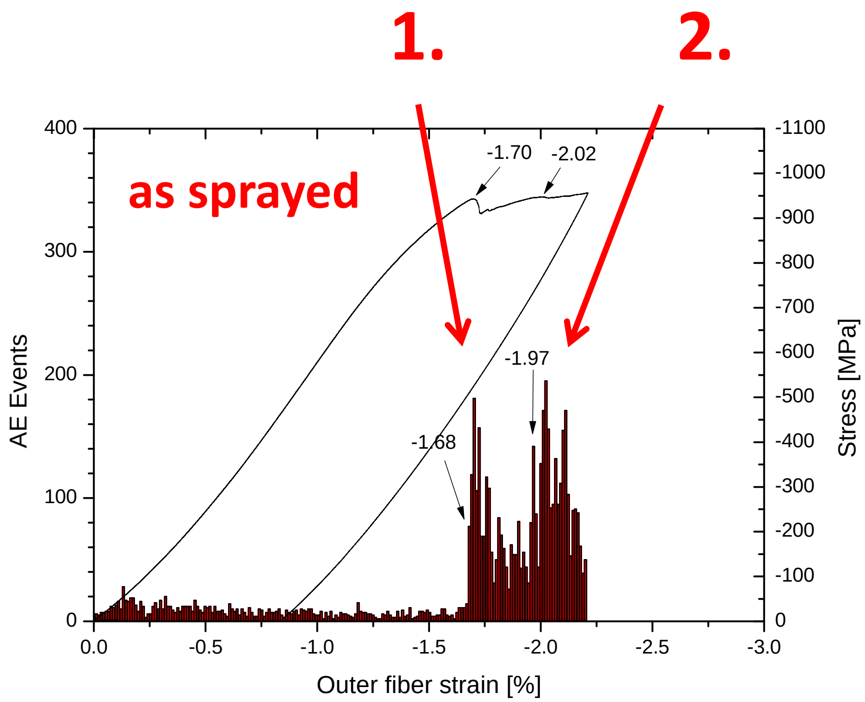
not always observed,
→ strong interface

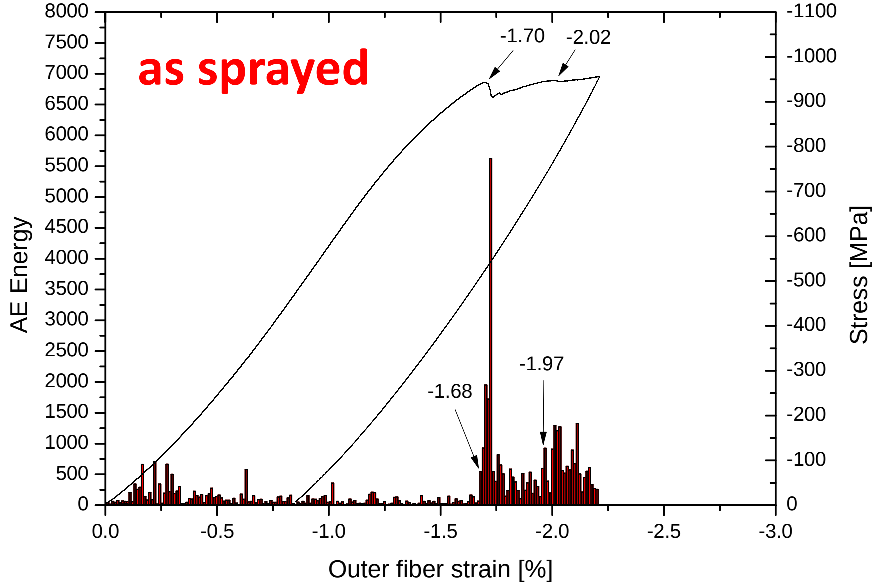


Compressive Loading of TBC,
Bi-Layer System

4-PB Results - Compression

Two distinct peaks can be identified in the acoustic emission signal under compressive loading!

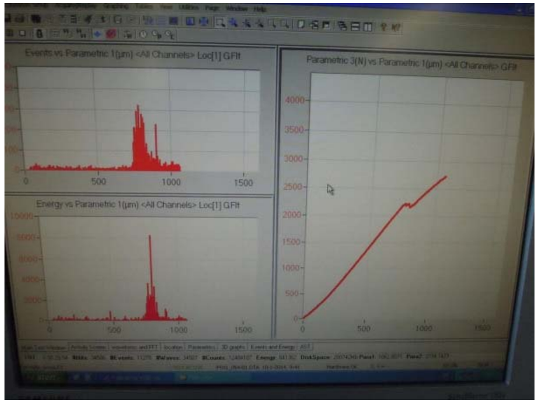




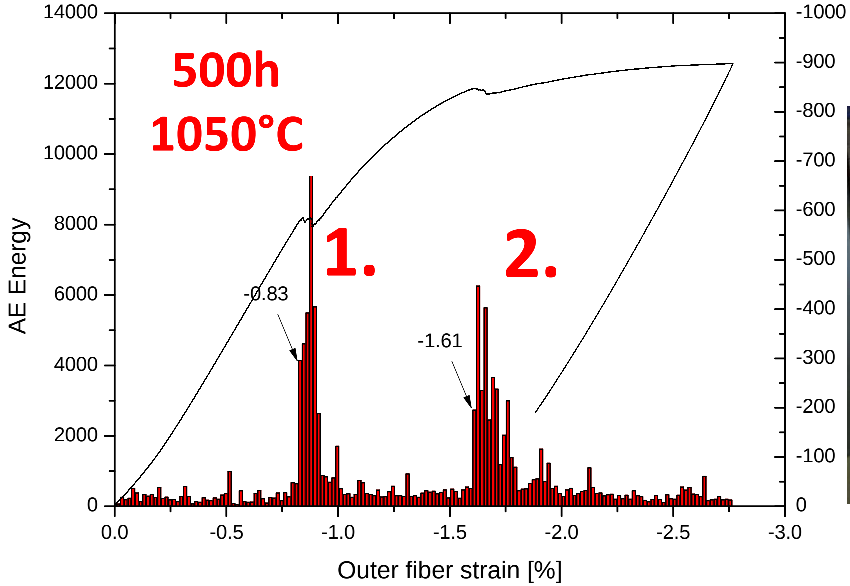
What are the individual peaks?

4-PB Results - Compression

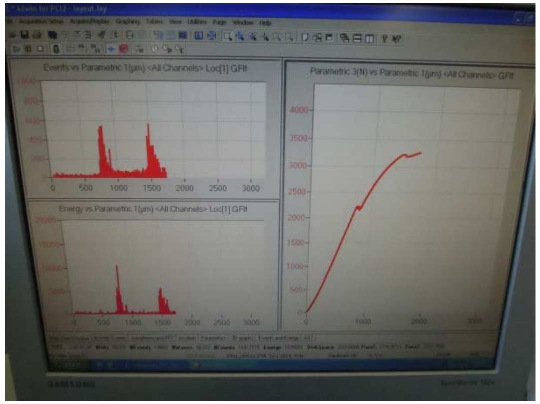
1.

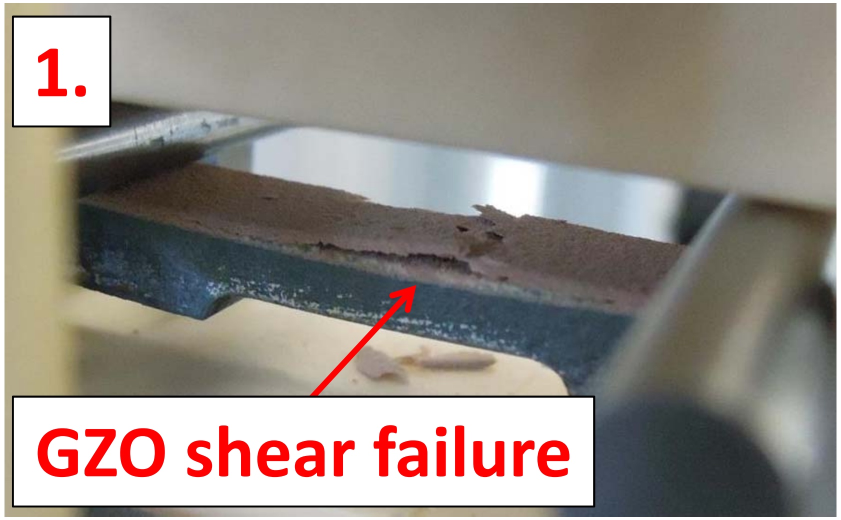


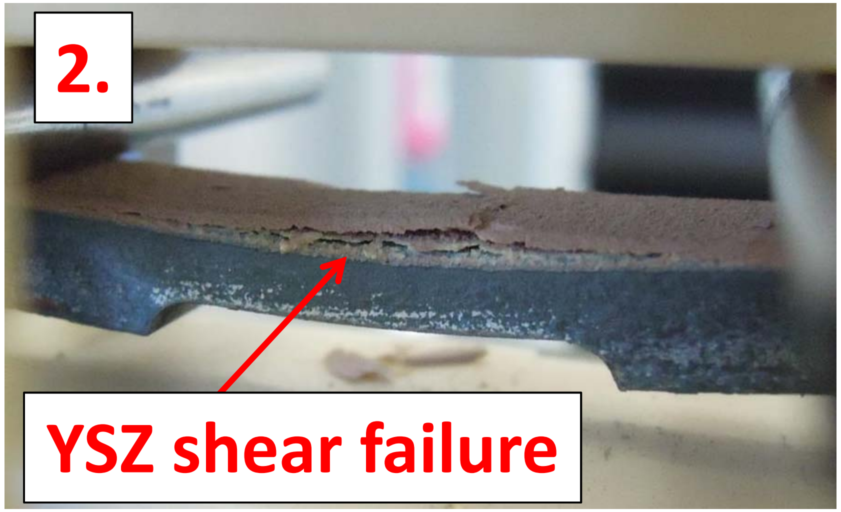
4-PB in compression



2.

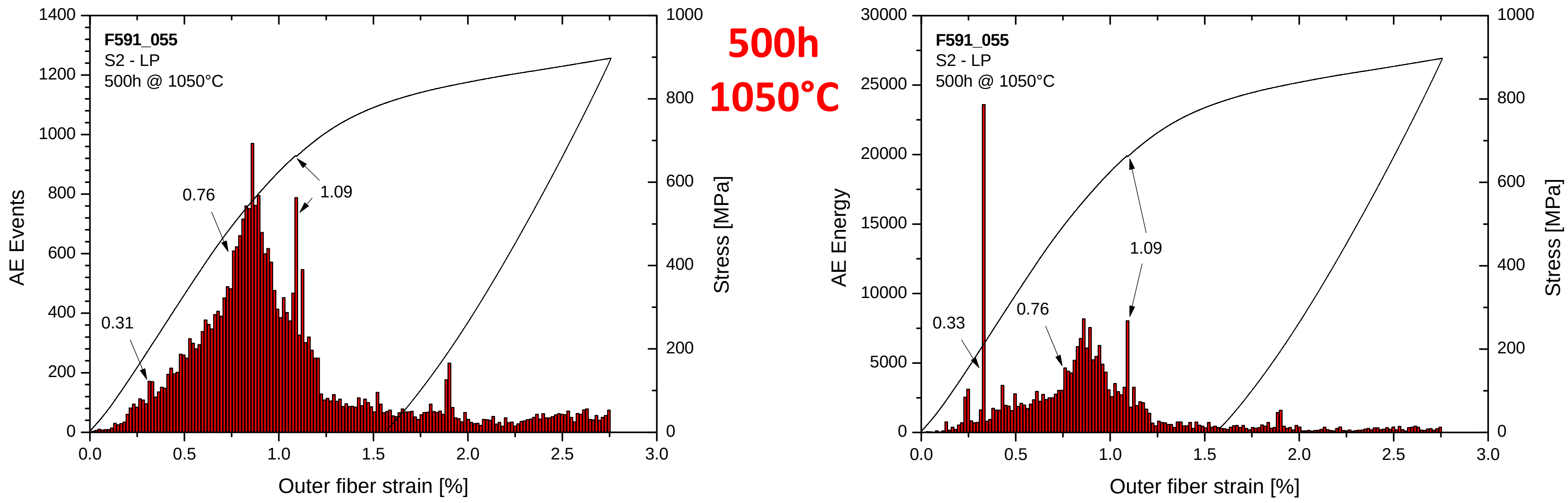






Tensile Loading of TBC, Bi-Layer System

4-PB Results - Tension



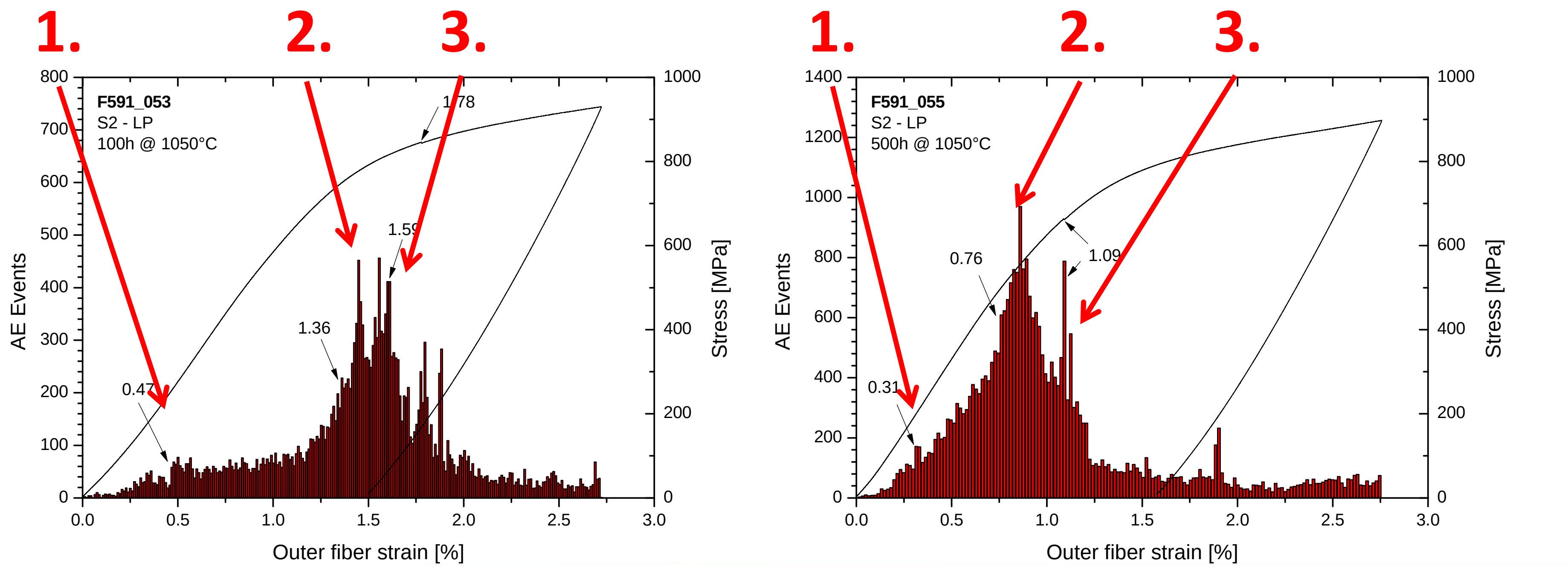
500h
1050°C

4-PB Results - Tension

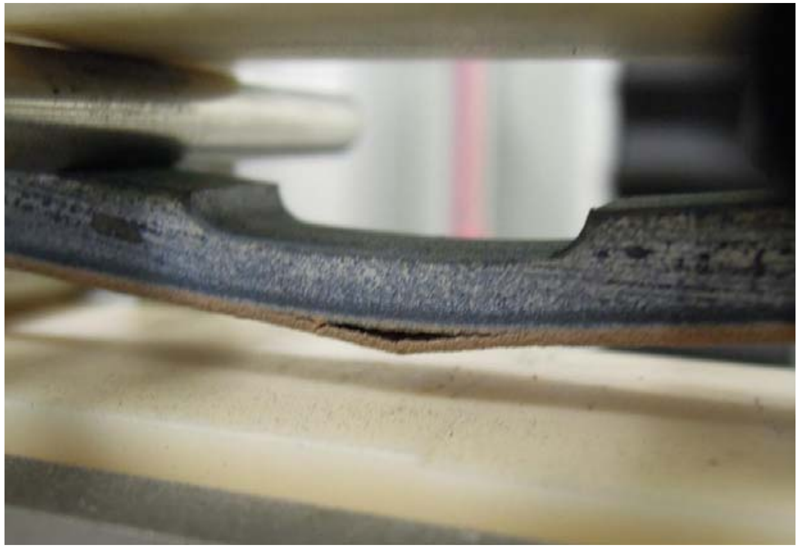
What are the individual peaks?

- Tensile geometry does not lead to well separated peaks
- Some samples show gradually increasing AE signal at the beginning

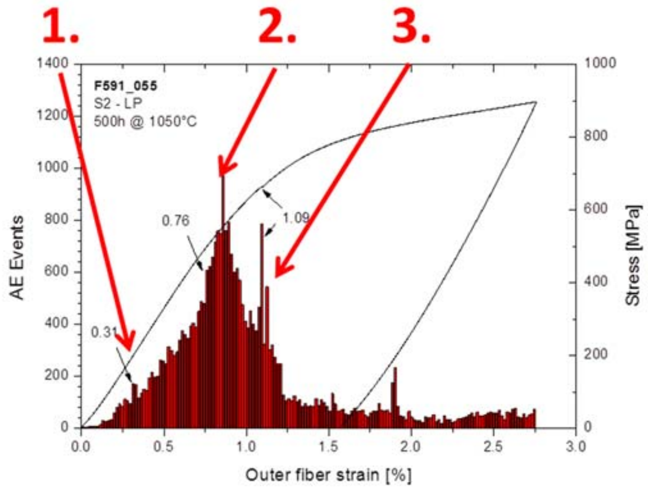
However, maybe 3 signals can be identified:



4-PB Results - Tension

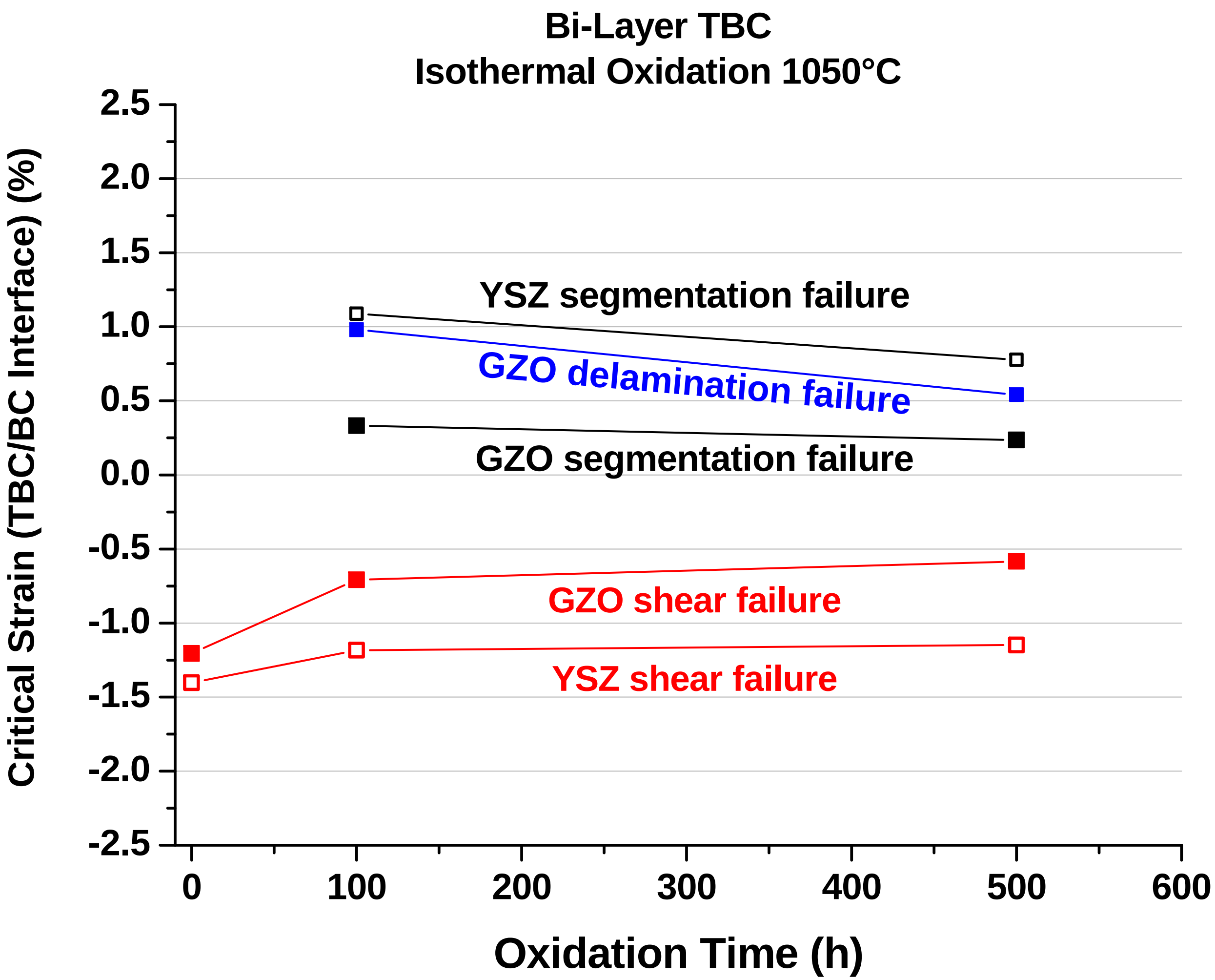


Macroscopic images do not provide sufficient insight. Only final failure can be observed.



1. Segmentation failure of GZO-layer
2. Delamination of GZO along GZO/YSZ interface
3. Segmentation failure of YSZ layer

Critical Strain Values



→ max. tolerable strain at TBC/BC interface

May be used in similar manner as SN-curves for lifetime assessment

Fracture Mechanics Approach

Griffith-Criterion:

$$\sigma_c = \frac{K_c}{\sqrt{\pi c}}$$

$$\varepsilon = \frac{\sigma}{E}$$

Critical Strain:

$$\varepsilon_c = \frac{K_{Ic}}{f \cdot E_{TBC} \sqrt{\pi c}}$$

Material Constant
(But: Measurements may be influenced by sample history)

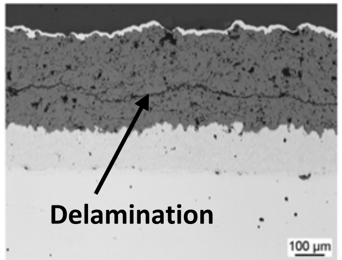
Geometry Factor
(Defect geometry)

Possible Values:
1.12 surface defect of inifinite lentgh
1.0 burried defect
0.64 semi-circular surface defect

Damage Parameters
c – defect size
E – Young's modulus

Possible Failure Modes in 4-Point Bending

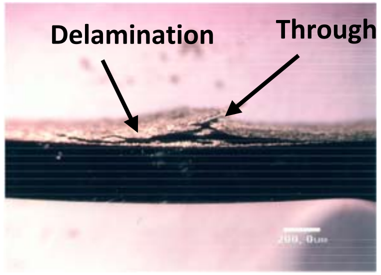
Compression Delamination



$$\varepsilon_c^{d-} = \frac{K_{Ic}}{f \cdot \sqrt{\pi c}} \cdot \frac{(1+r/d)\cdot(1+\nu)}{2E_{TBC}}$$

Compression Shear cracking

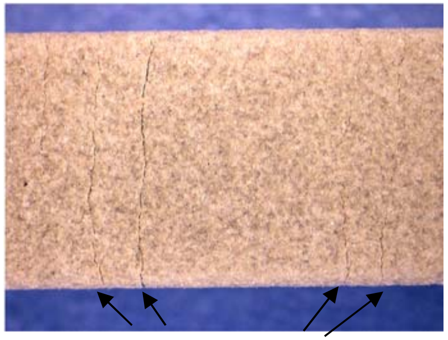
$$\varepsilon_c^{sh} = \frac{2K_{IIc}}{f \cdot E_{TBC}\sqrt{\pi c}}$$



Griffith:

εc is strain in the coating!

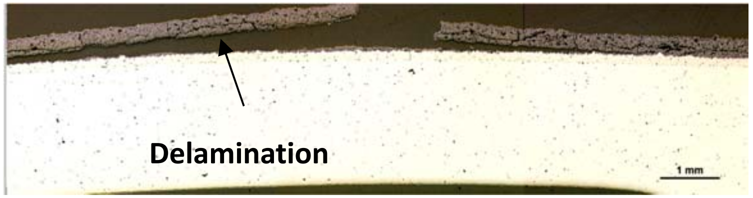
Tension Segmentation



$$\varepsilon_c^{s} = \frac{K_{Ic}}{f \cdot E_{TBC}\sqrt{\pi c}}$$

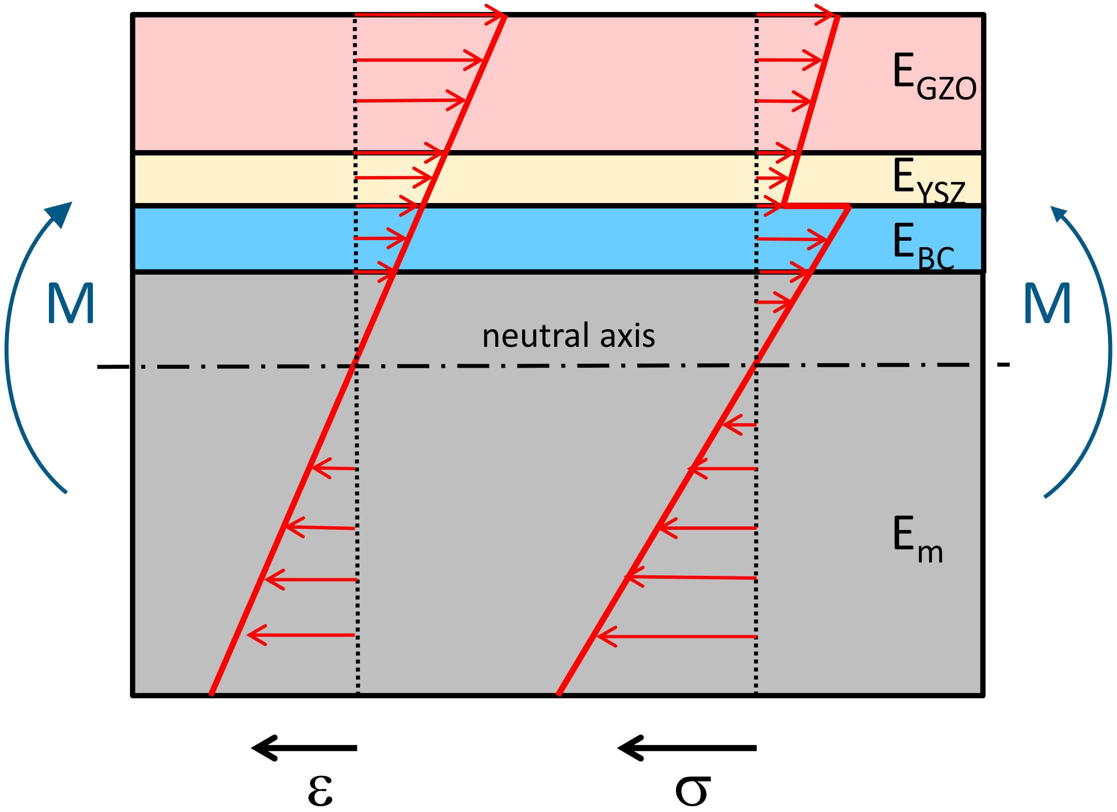
…ion Delamination

$$\varepsilon_c^{d+} = \frac{2K_{IIc}}{f \cdot E_{TBC}\sqrt{\pi c}}$$



M. Schütze, Protective Oxide Scales and their Breakdown, John Wiley, (1997)

Strain gradient across the TBC-thickness under pure bending

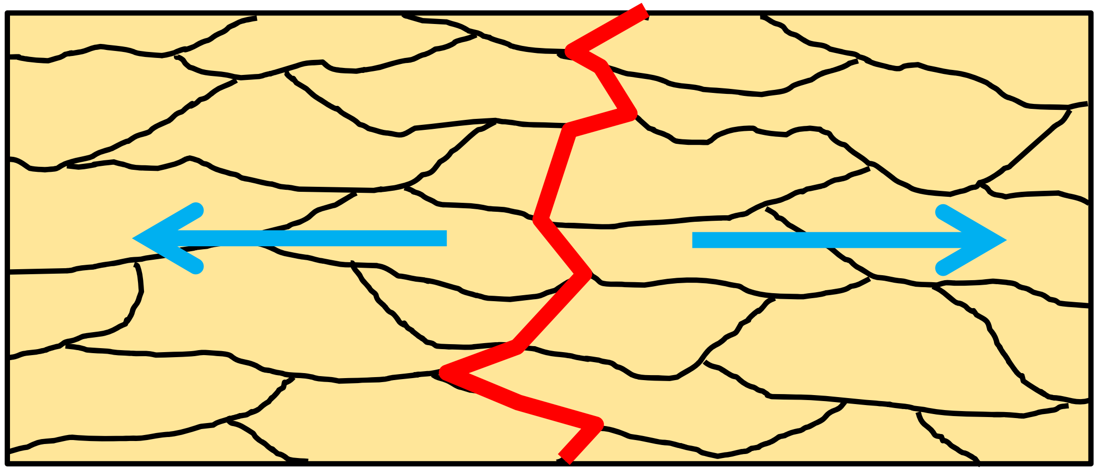


$E_{GZO}=E_{YSZ}<E_m$

$E_{BC}=E_{TBC}$

~30% difference in strain between
TBC/BC interface and outer fiber for 500µm TBC
→ Failure position has to be considered!

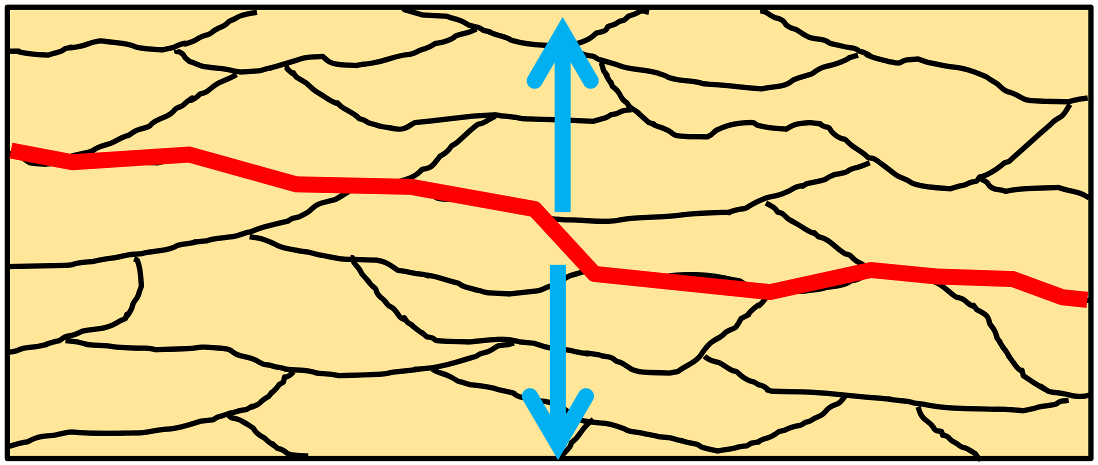
Microstructure has an influence on K_c-values



crack path mostly through spray flats

$K_{Ic}(path1)$

e.g. tensile segmentation



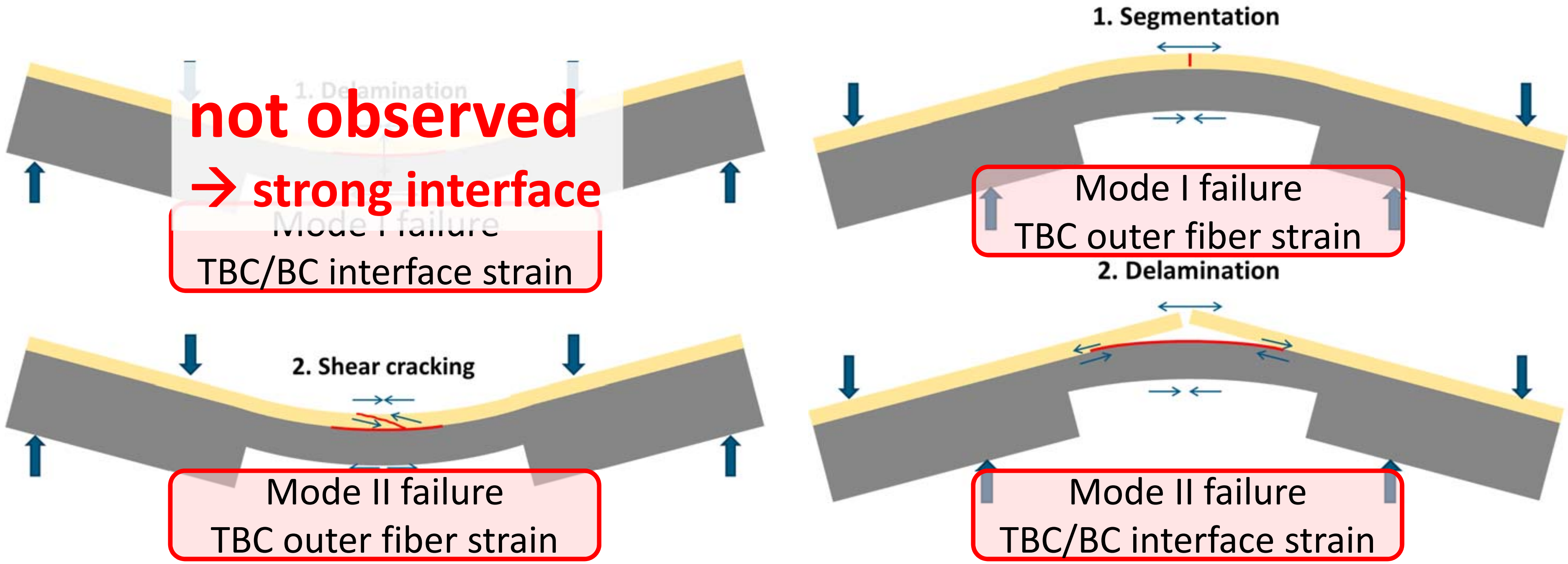
crack path along spray flat boundaries

$K_{Ic}(path2)$

e.g. compressive delamination

$K_{Ic}(path1) > K_{Ic}(path2)$

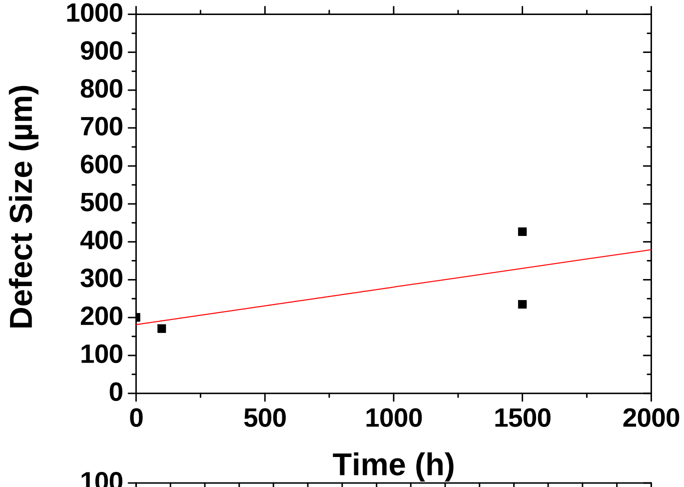
Chosing failure mode and critical strain position

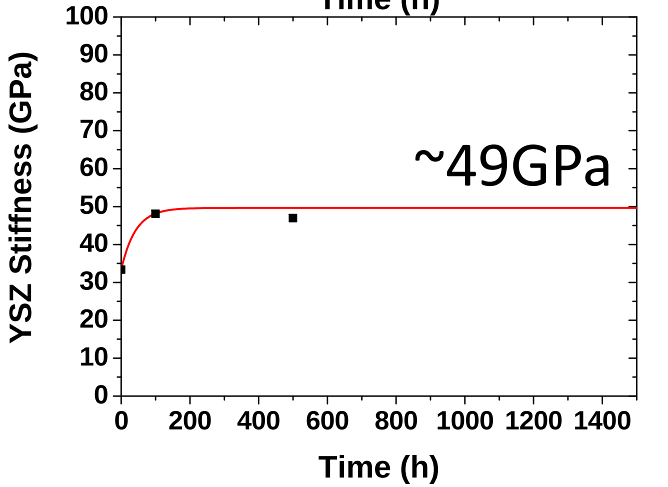


Modeling input values

$$\varepsilon_c = \frac{K_c}{f \cdot E_{TBC} \sqrt{\pi c}}$$

YSZ





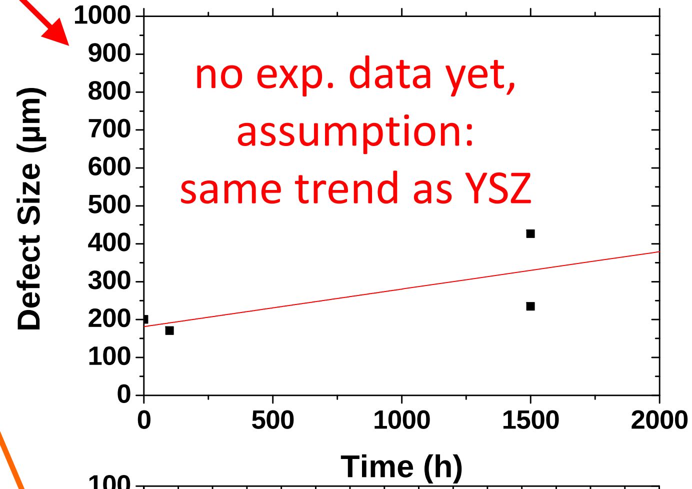
K_{Ic}=5.3 MPa m$^{1/2}$

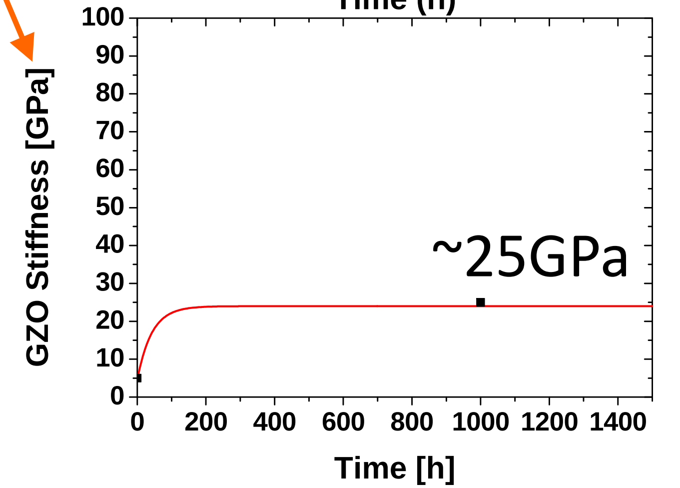
K_{IIc}=10.6 MPa m$^{1/2}$

f=1.0
(buried defect)

K_c currently used as fitting parameter!

GZO





K_{Ic}=2.3 MPa m$^{1/2}$

K_{IIc}=2.8 MPa m$^{1/2}$

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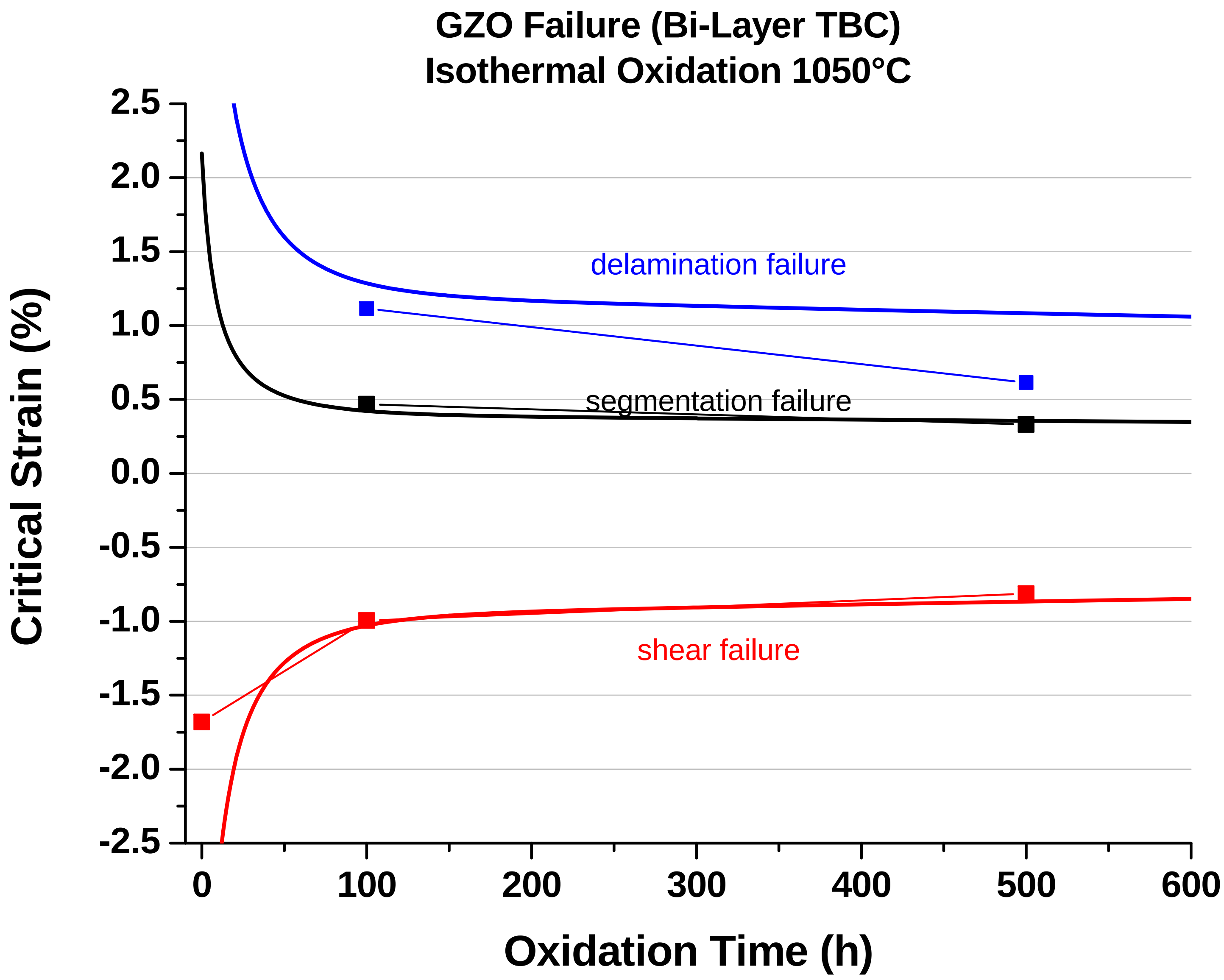
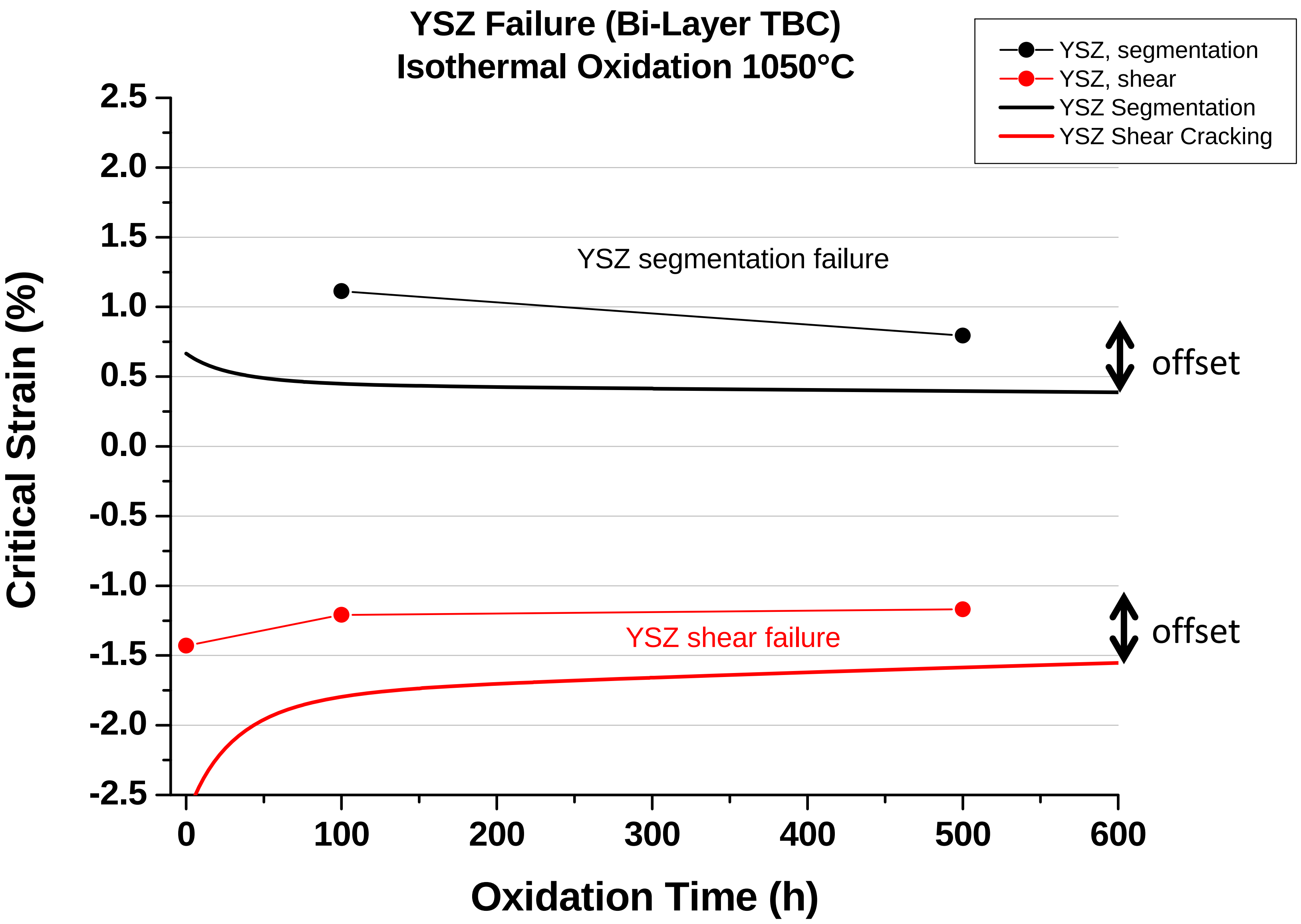
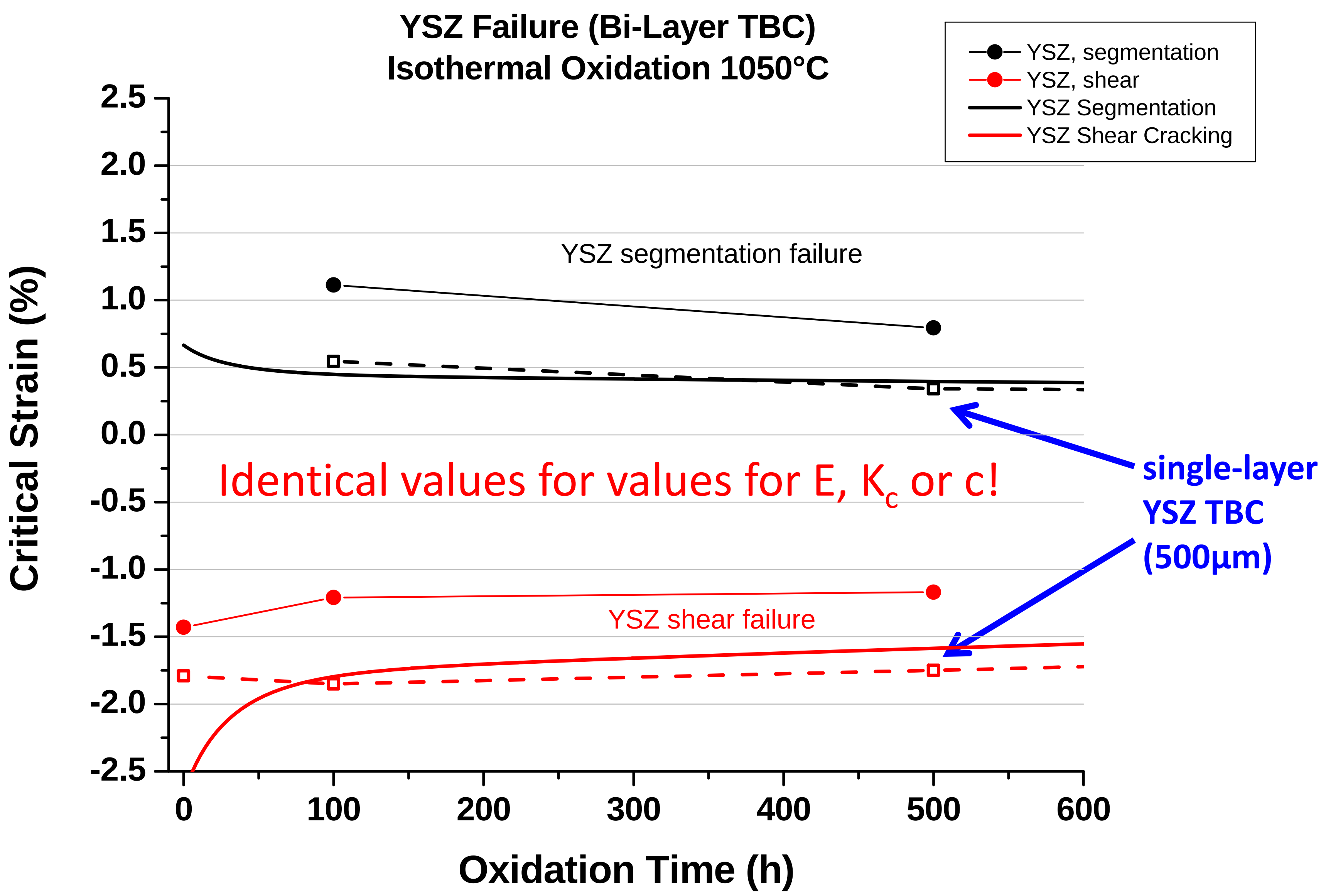
Bi-Layer System – GZO Failure

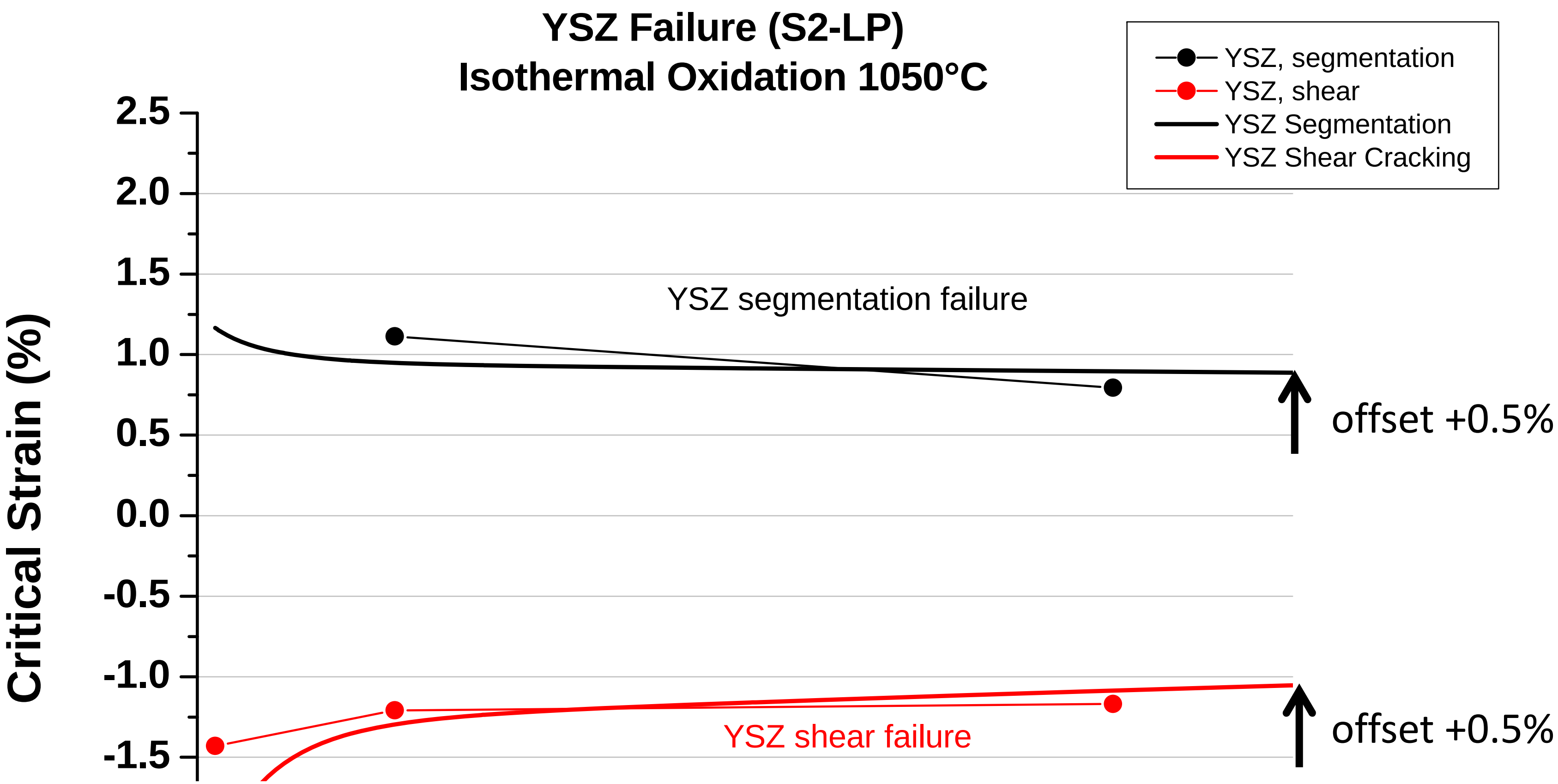


Bi-Layer System – YSZ Failure




YSZ Failure (Bi-Layer TBC)
Isothermal Oxidation 1050°C
YSZ, segmentation
YSZ, shear
YSZ Segmentation
YSZ Shear Cracking
YSZ segmentation failure
Identical values for values for E, Kc or c!
single-layer
YSZ TBC
(500µm)
YSZ shear failure
Critical Strain (%)
2.5
2.0
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
-2.0
-2.5
0
100
200
300
400
500
600
Oxidation Time (h)

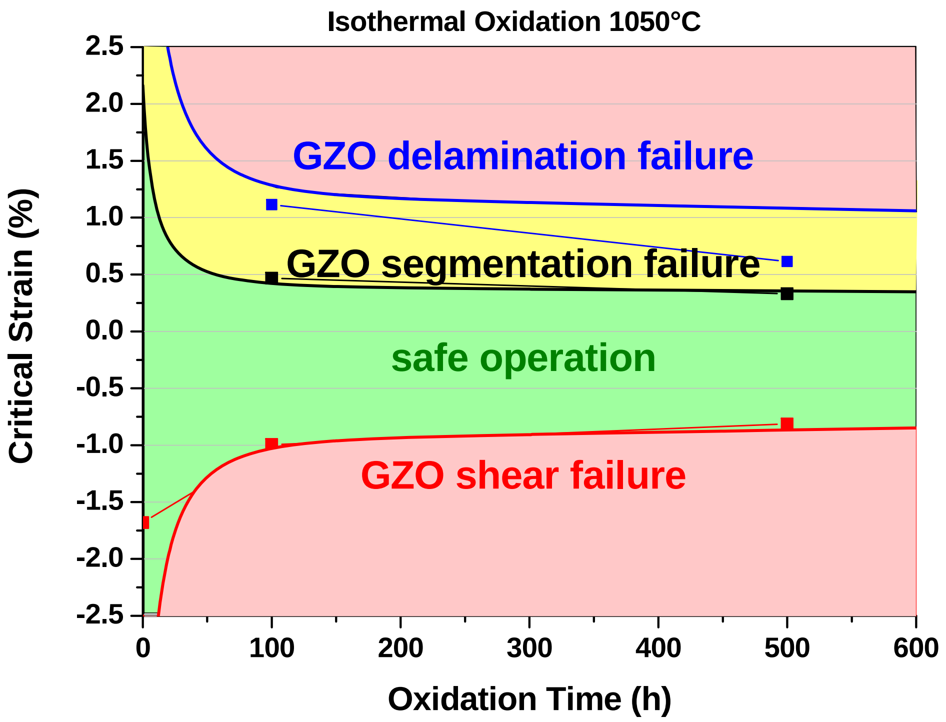
Bi-Layer System – YSZ Failure



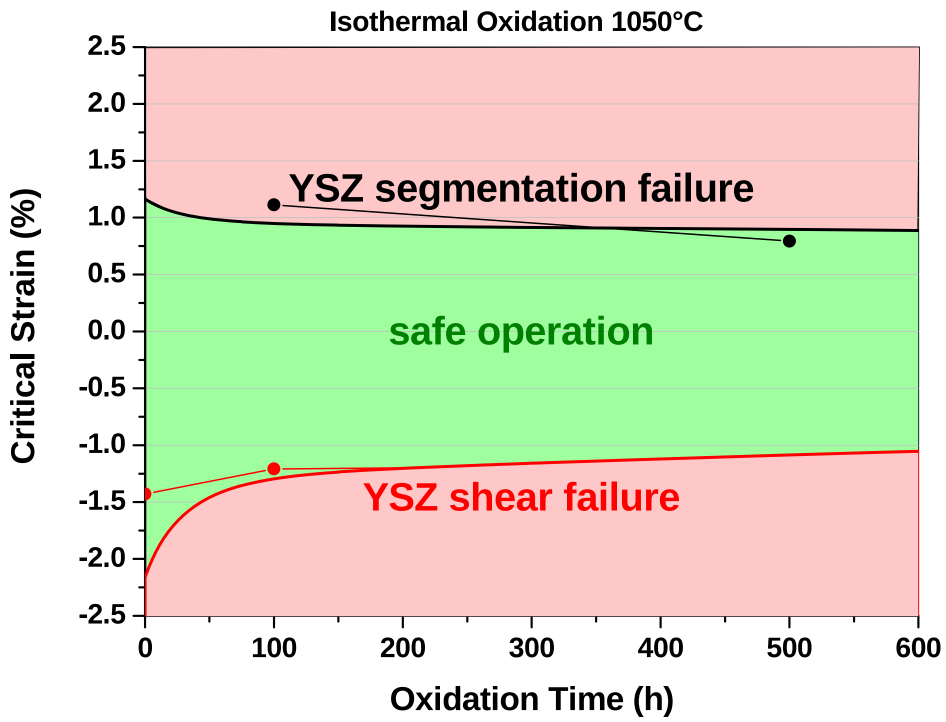
Possible explanation for offset:
Residual stresses in the TBC are relieved by GZO failure prior to measurement of YSZ failure.
...currently under investgation!

Mechanical Stability Diagrams

GZO Failure



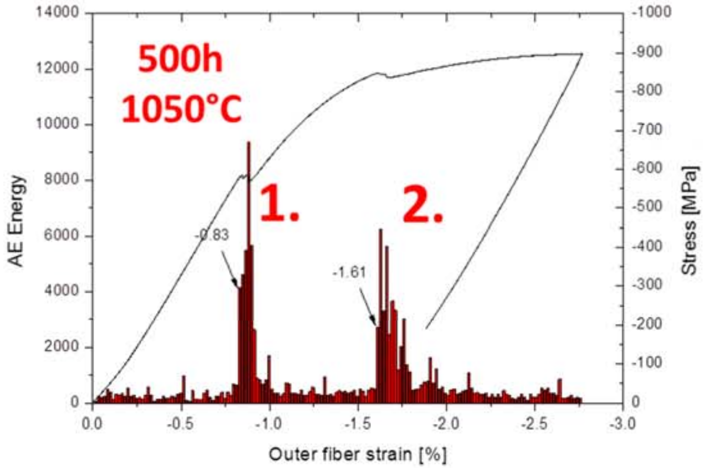
YSZ Failure

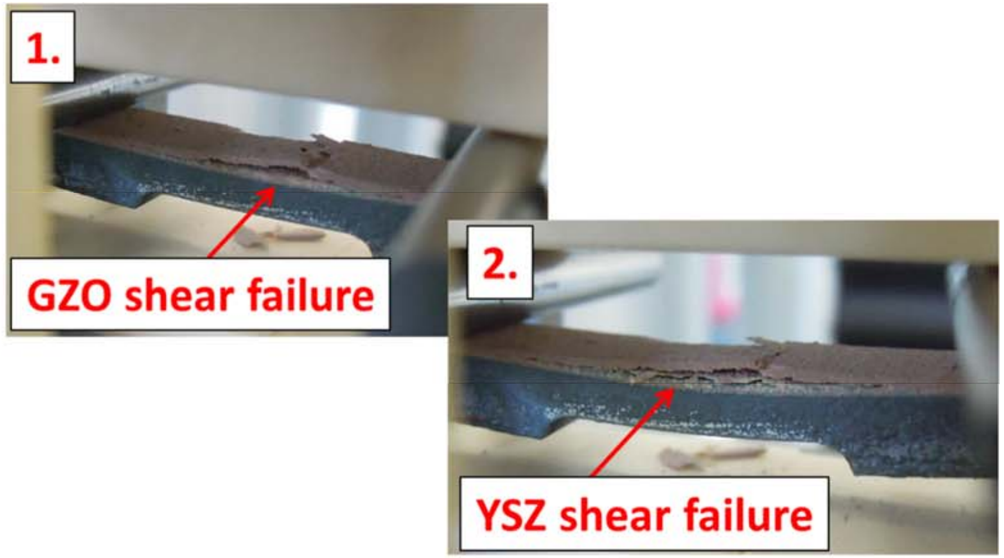


Summary

- Mechanical 4-point bending with in-situ acoustic emission measurement is a valuable tool to assess damage processes in bi-layer TBCs

- A modeling approach for bi-layer TBCs has been developed to delineate areas of safe operation from areas where failure is imminent -> mechanical stability diagram





Thank you for your attention!