Local strain response of a TBC system under thermal mechanical loading by in-situ synchrotron X-ray Diffraction

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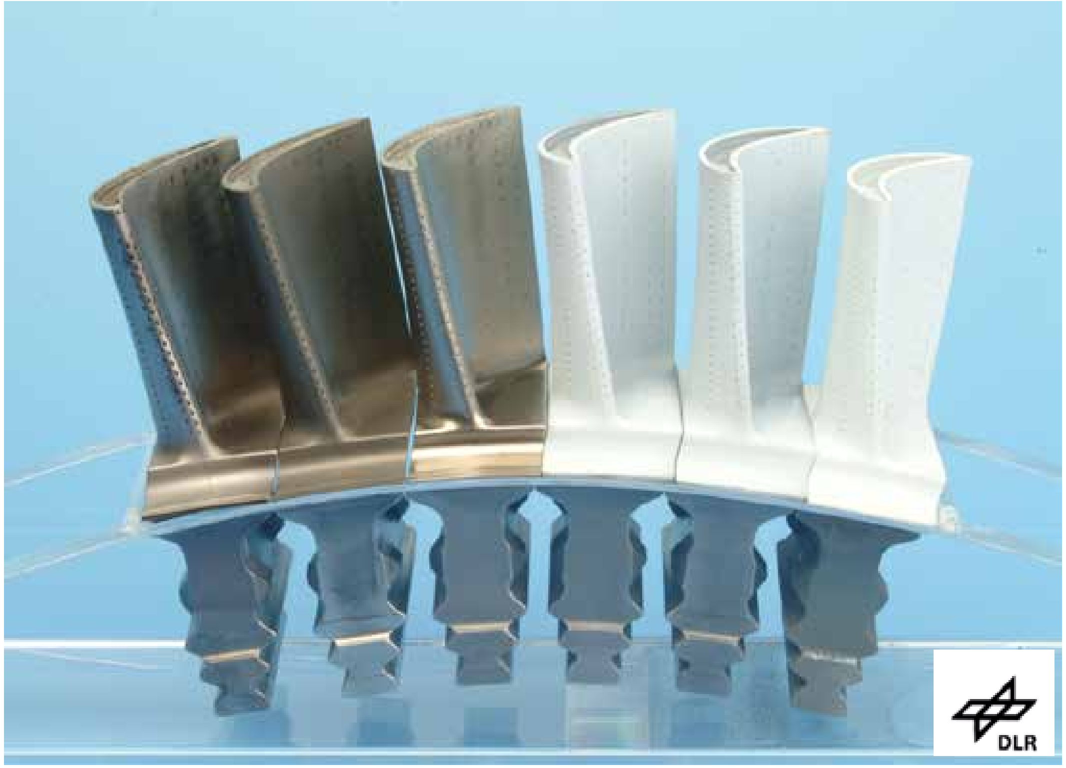
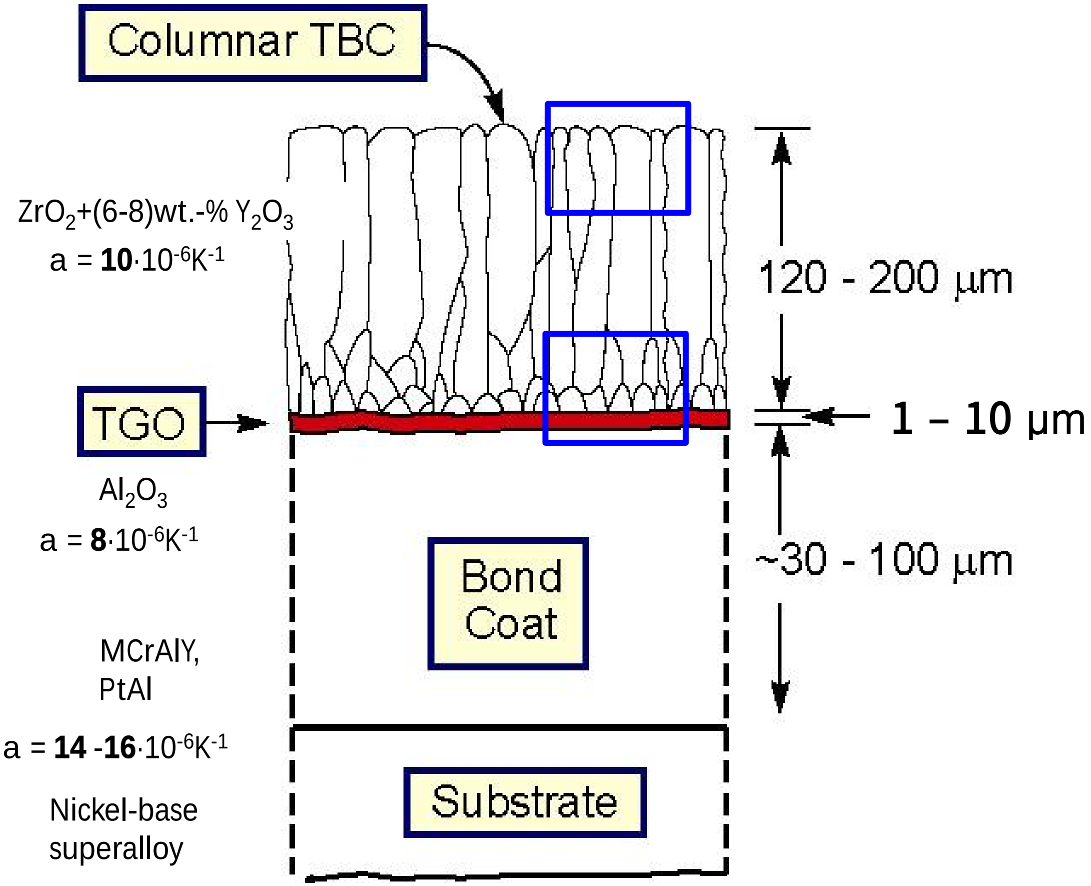
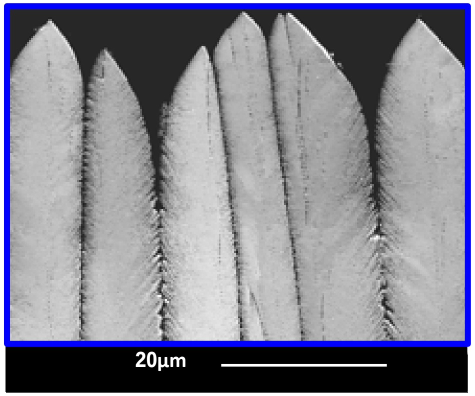
Motivation: Understand and capture behavior of coating systems under realistic loading conditions



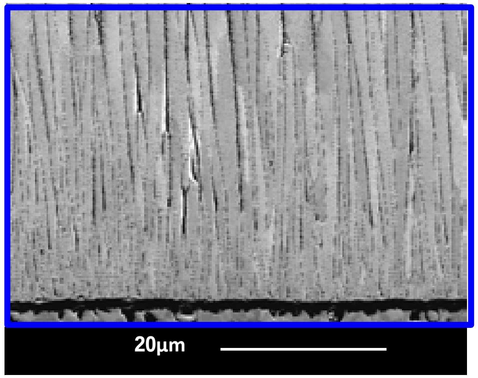
Gas turbine blades for aeroengines

Investigated coating system



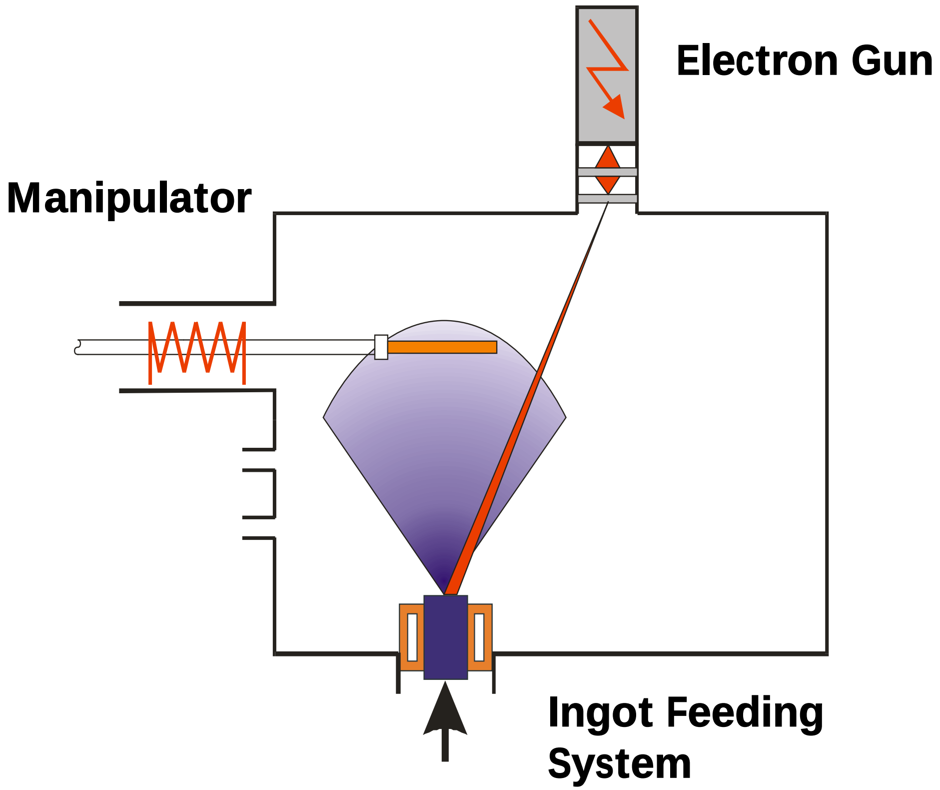


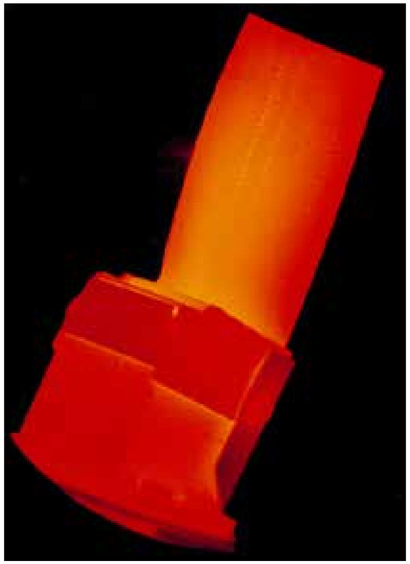
near surface



near TGO

Stress free at homogenous temperature of 1000°C



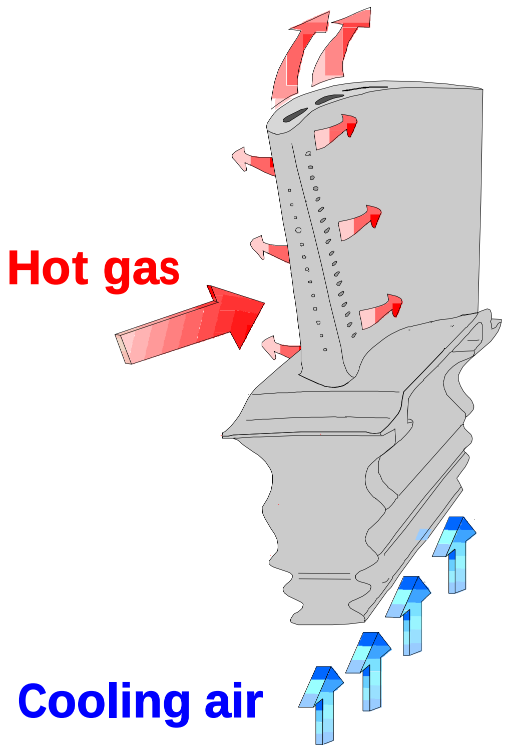


Deposition temperature: ca. 1000°C

Electron Beam - Physical Vapor Deposition (EB-PVD)

Þ **high residual stresses at ambient temperature**

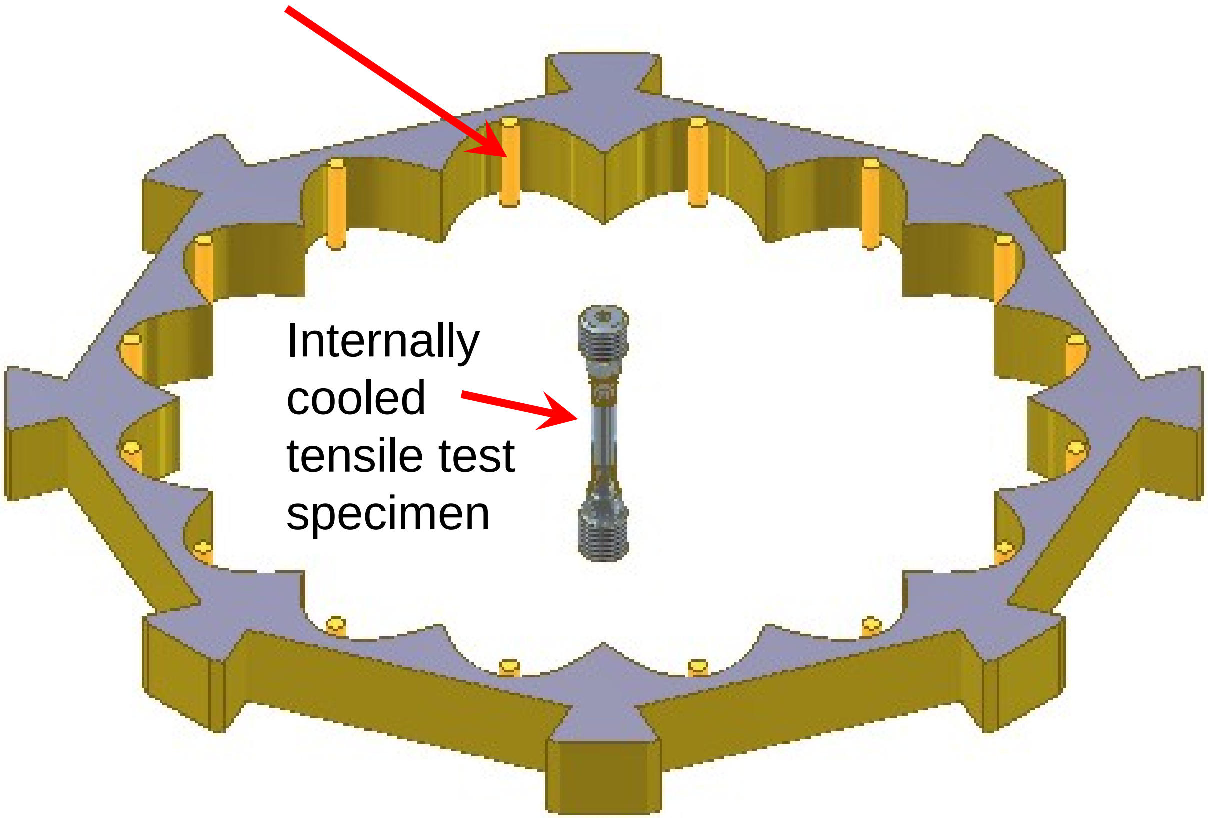
Summarizing thermal and mechanical loads

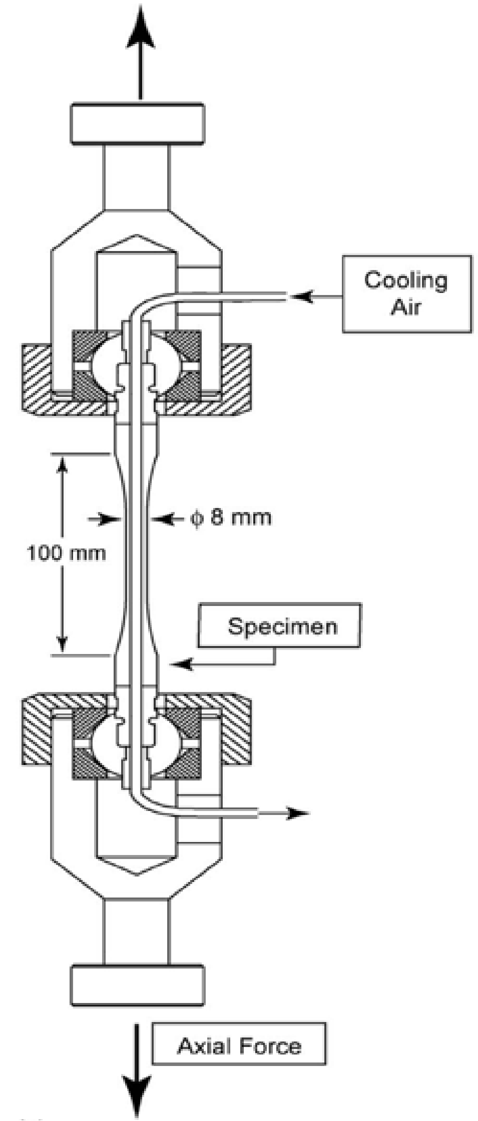


- Maximal material temperatures ca. 1000°-1100°C
- Thermal gradient (about 80°-150°C temperature drop over 100-200µm thick ceramic TBC)
  - Multiaxial thermally induced stresses
- High thermal transients (heating and cooling rates)
- Superposed mechanical loads (centrifugal forces on rotating blades)

Test facility for thermal gradient mechanical fatigue

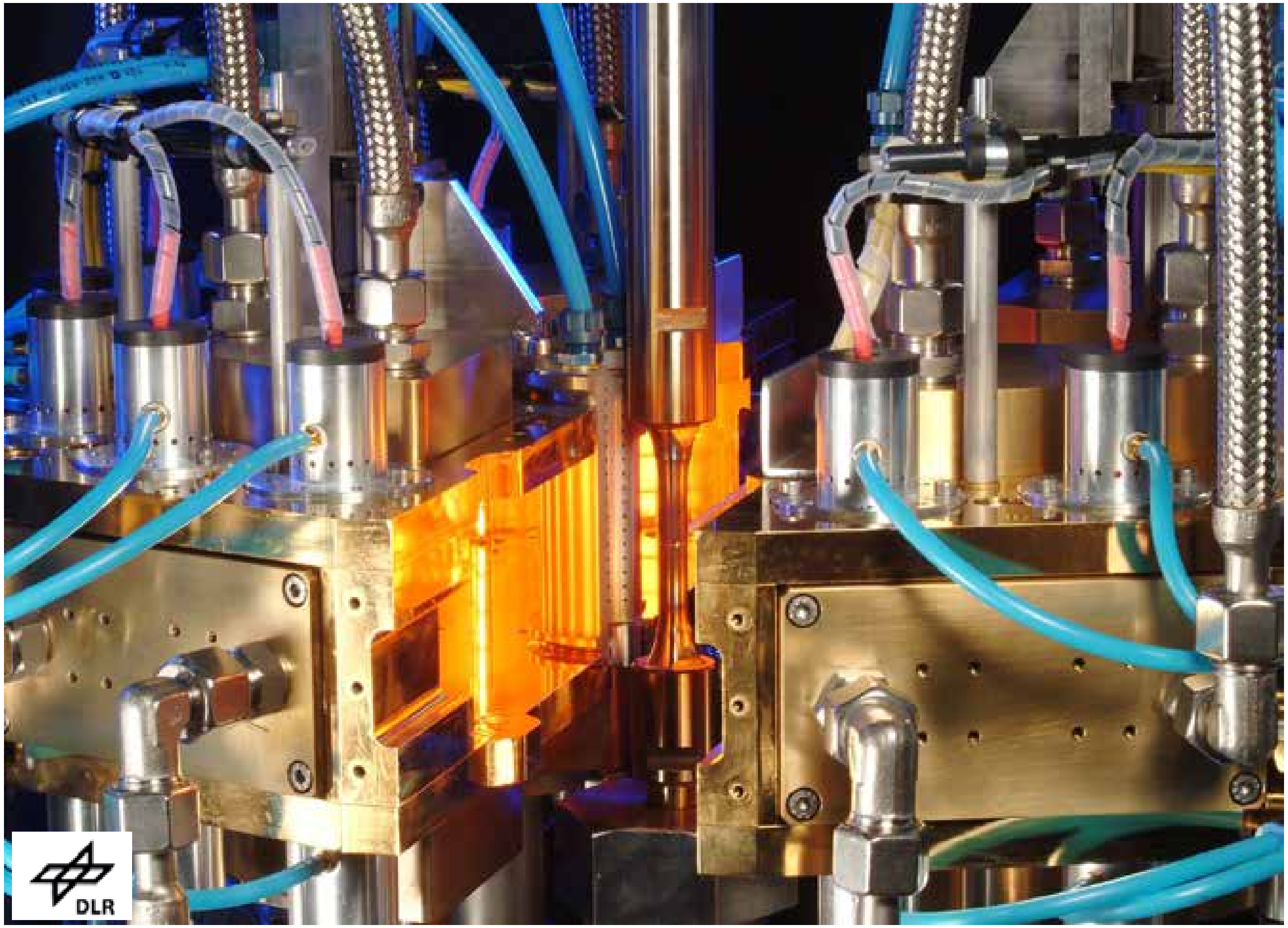
16 Quartz lamps, 1 kW each



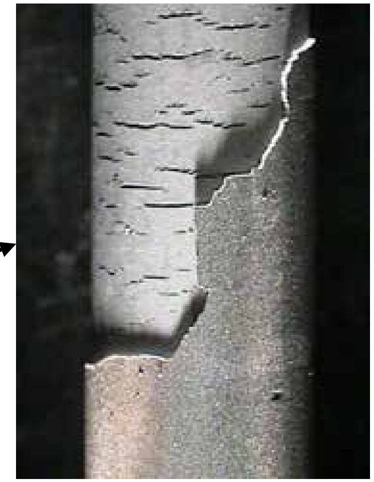


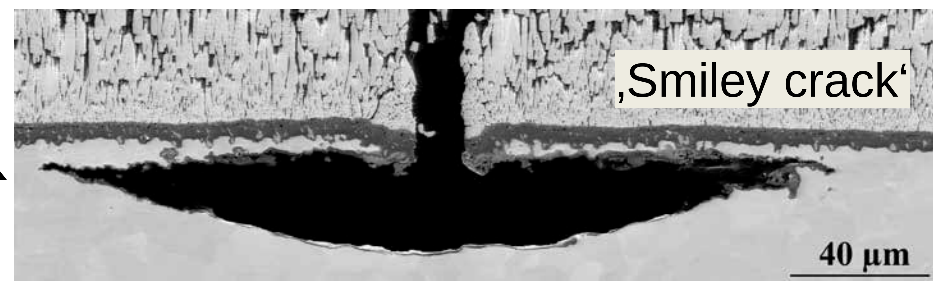
Thermal Gradient Mechanical Fatigue = TGMF

View of open furnace



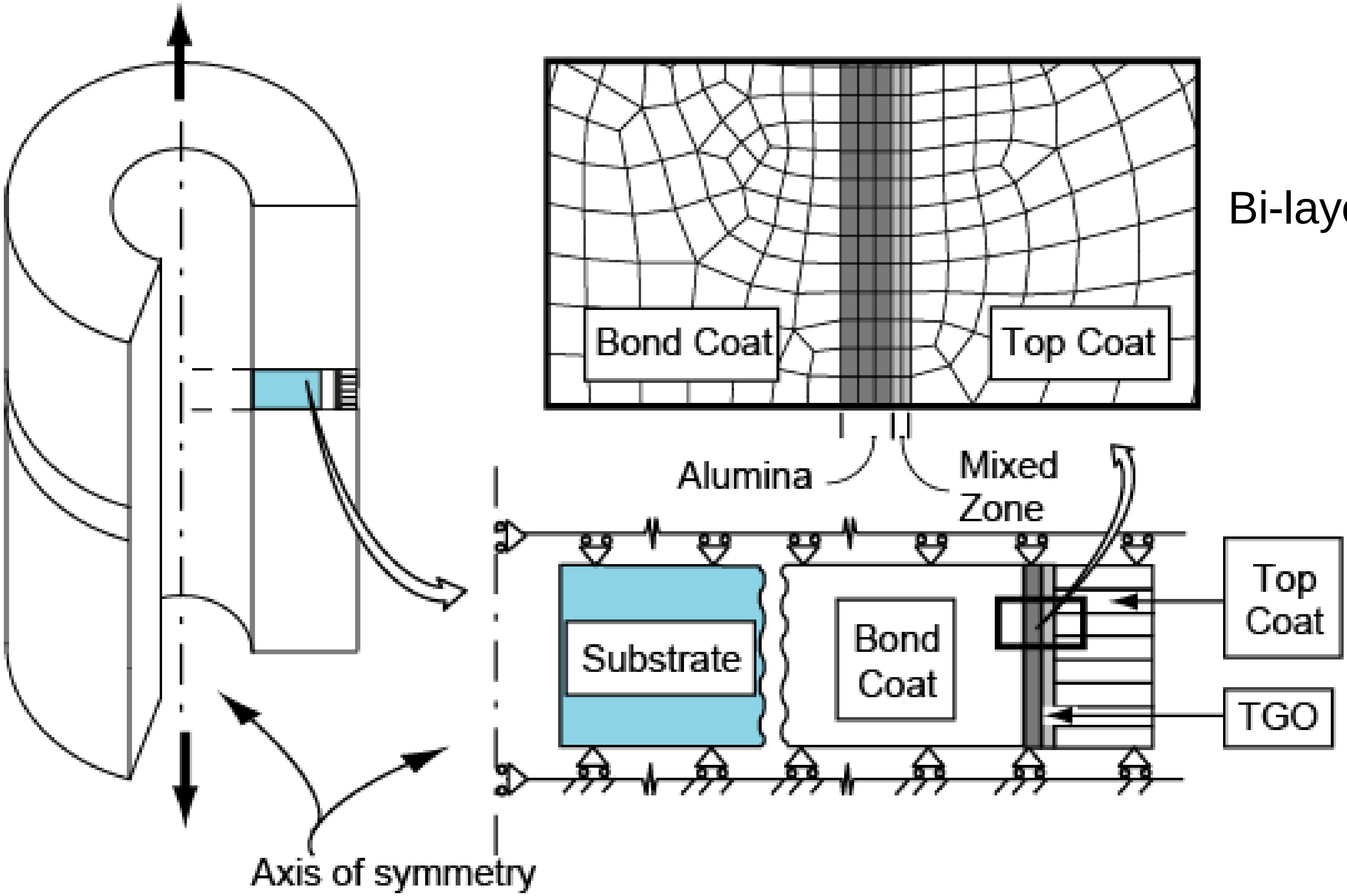
Failure after thermomechanical laboratory testing





after 933 TGMF-cycles &
500h pre-ageing at 1000°C

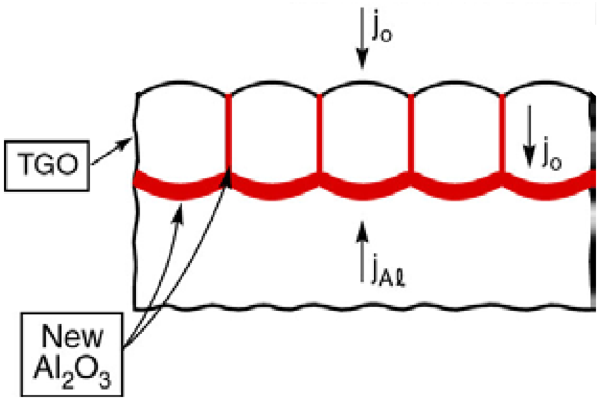
Numerical model: Geometry and boundary conditions



Bi-layered TGO

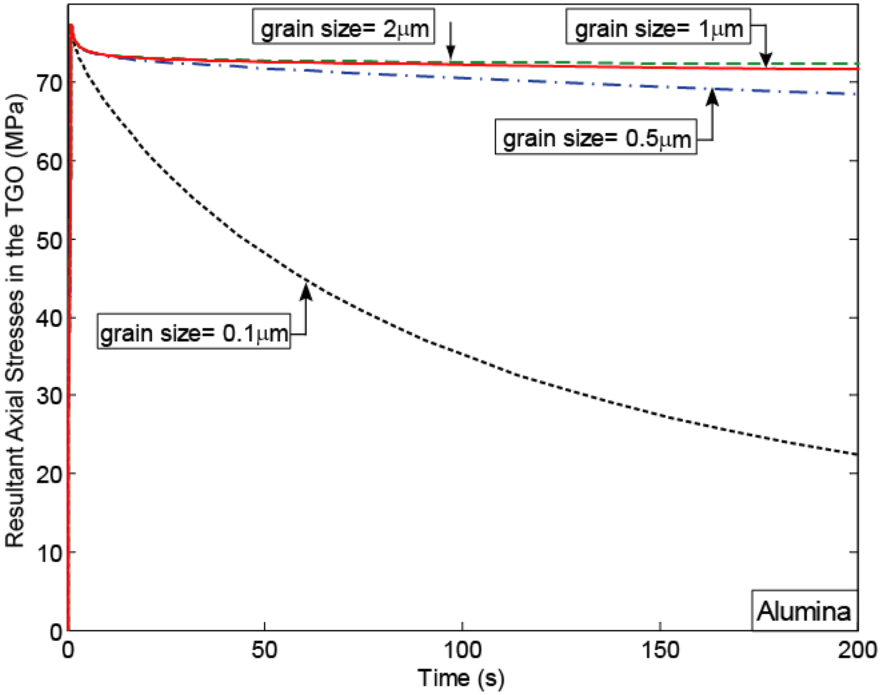
[*M. Hernandez, A.M. Karlsson, M. Bartsch: Surface Coatings & Technology 203, 3549-58, 2009*]

Including time dependent TGO properties: growth strain and creep / relaxation



Thickening ε_t and lengthening ε_l growth strain

$$\varepsilon_l = 0.1 \cdot \varepsilon_t$$



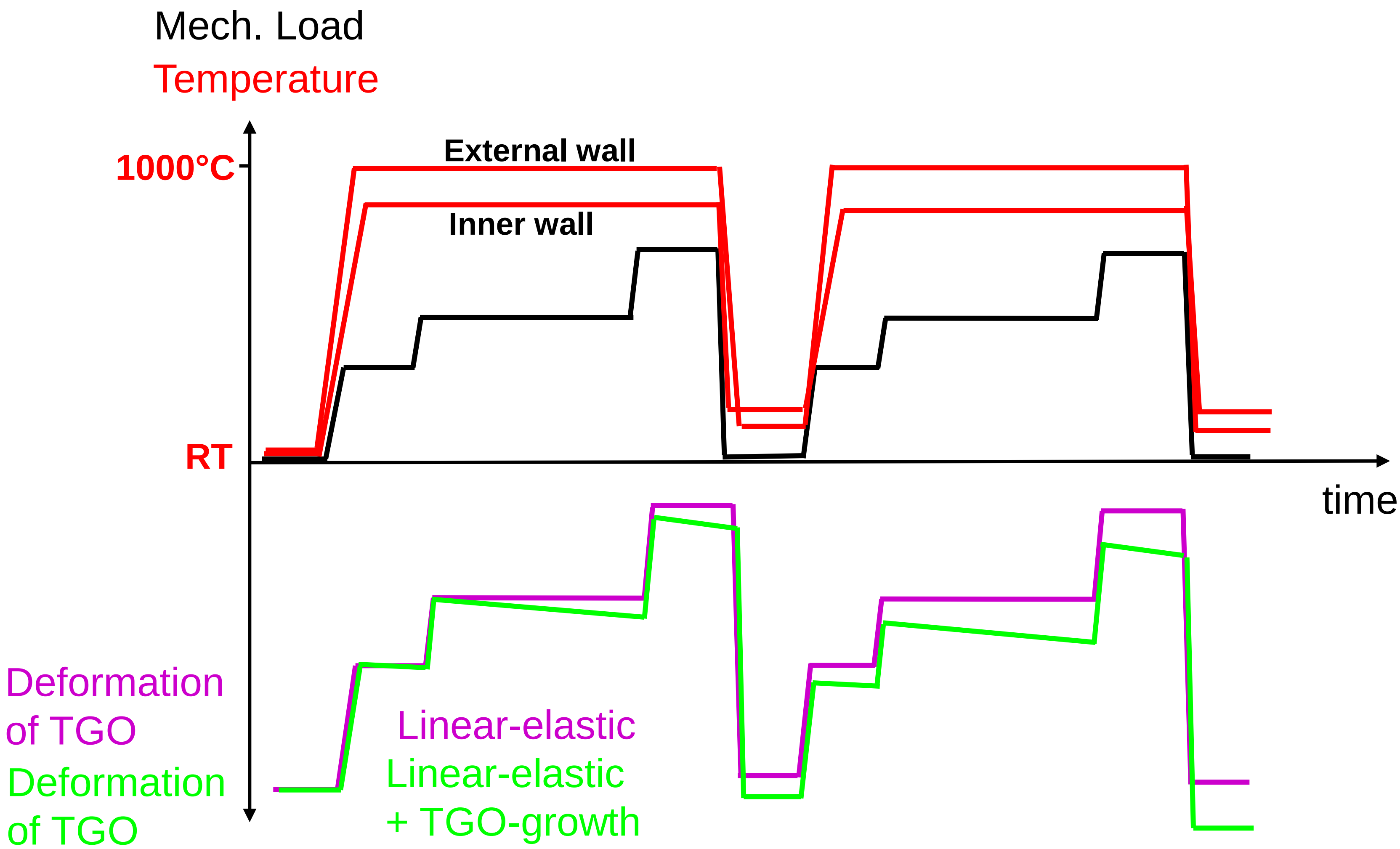
Growth strain increases the compressive stress in TGO!

Relaxation decreases the compressive stress in TGO!

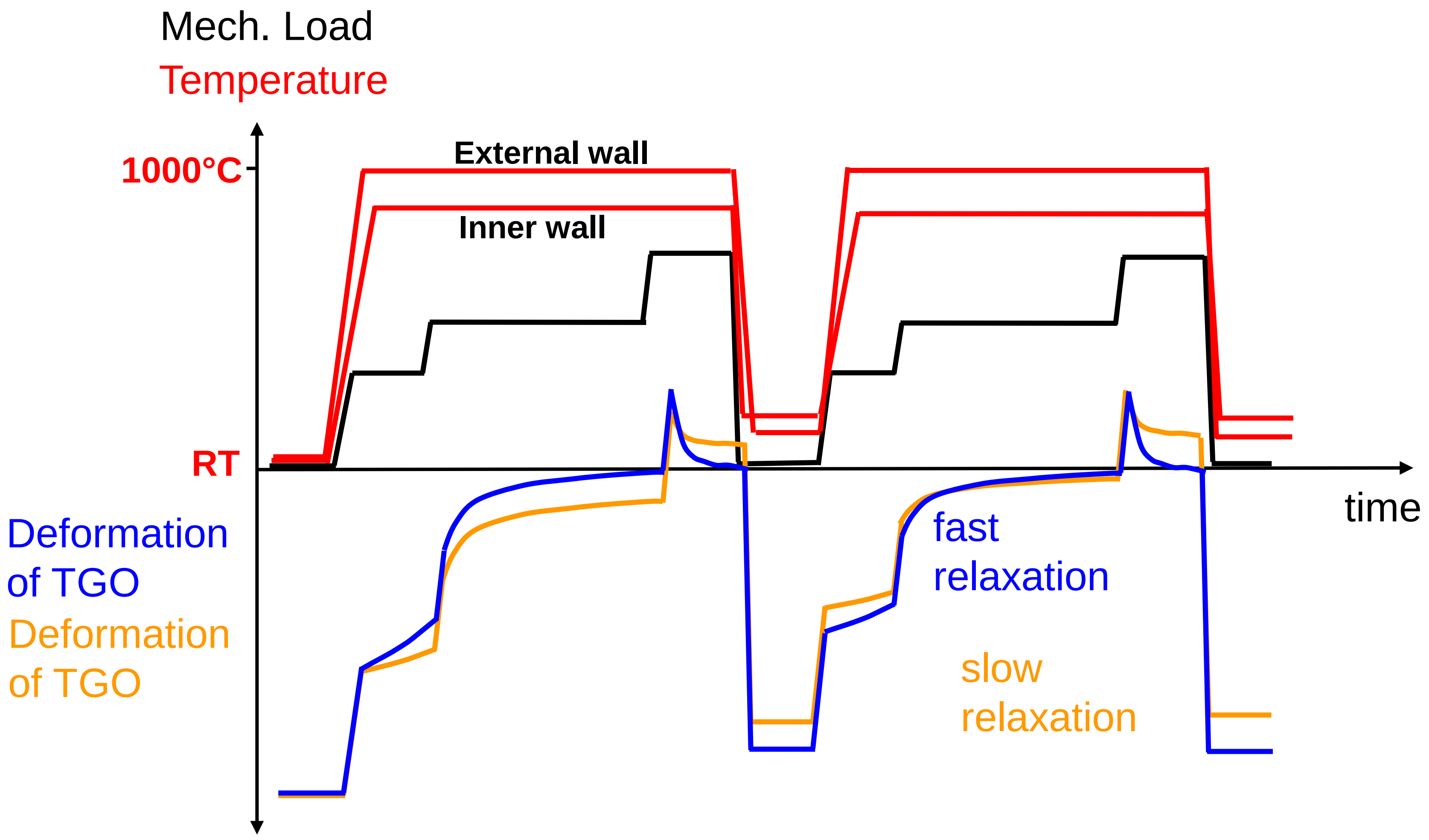
Karlsson, A.M. and A.G. Evans,. Acta Materialia, 2001 ***49****(10): p. 1793-1804*

Data partially taken from J.D. French, J.H. Zhao, M.P. Harmer, H.M Chan, G.A. Miller. J. American Ceramic Society 77 (1994)

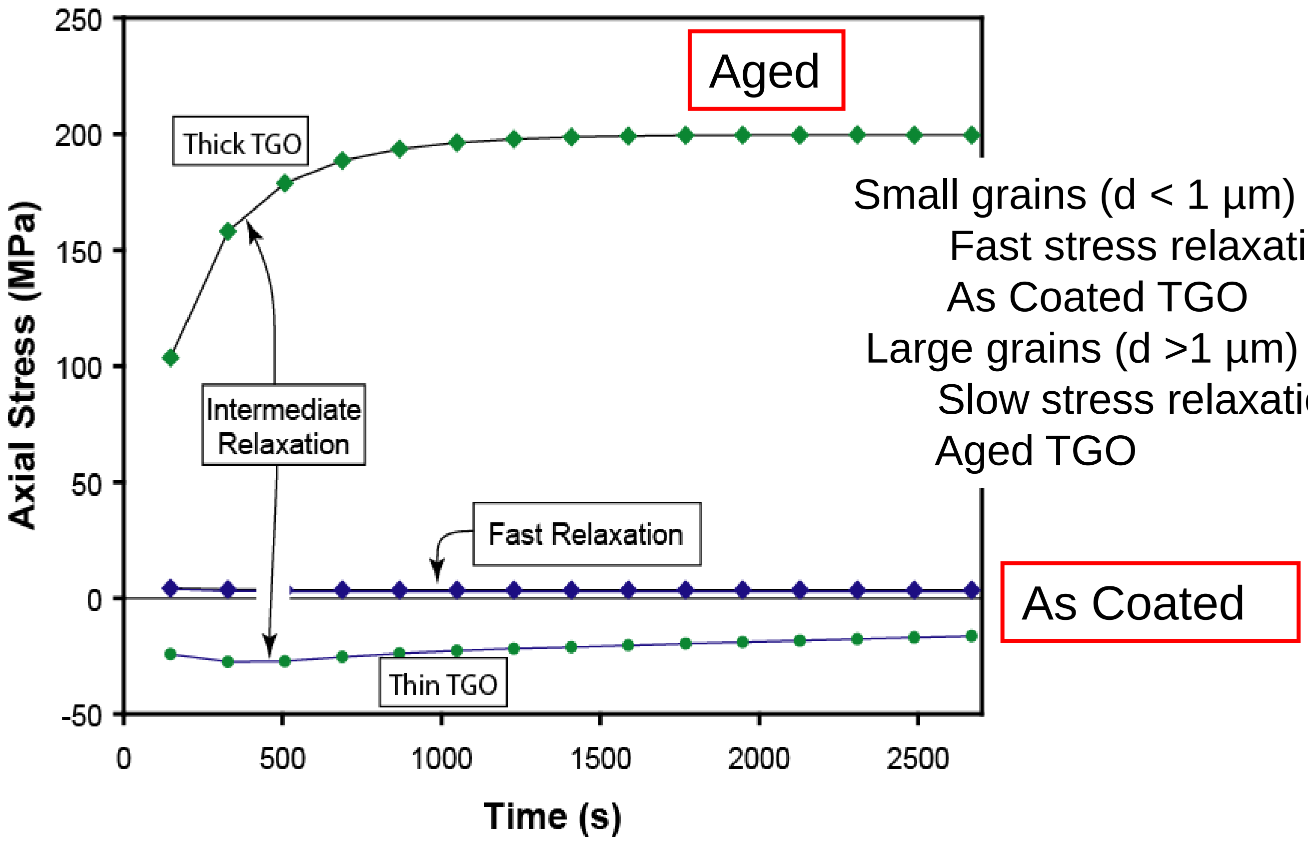
Effect of TGO properties on stress accumulation



Effect of TGO properties on stress accumulation



Parameter study on evolution of axial TGO-stresses



Small grains (d < 1 µm)
Fast stress relaxation
As Coated TGO
Large grains (d >1 µm)
Slow stress relaxation
Aged TGO

Hypothesis: Initiation of fatigue crack in TGO due to accumulation of tensile stress during subsequent TGMF-cycles

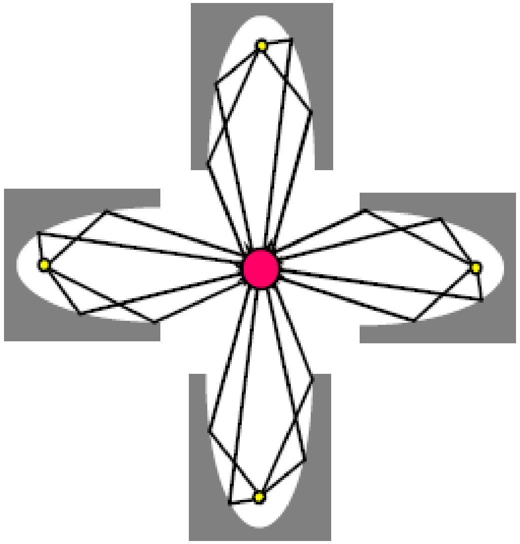
→ **Need for experimental material data backing the hypotheses**

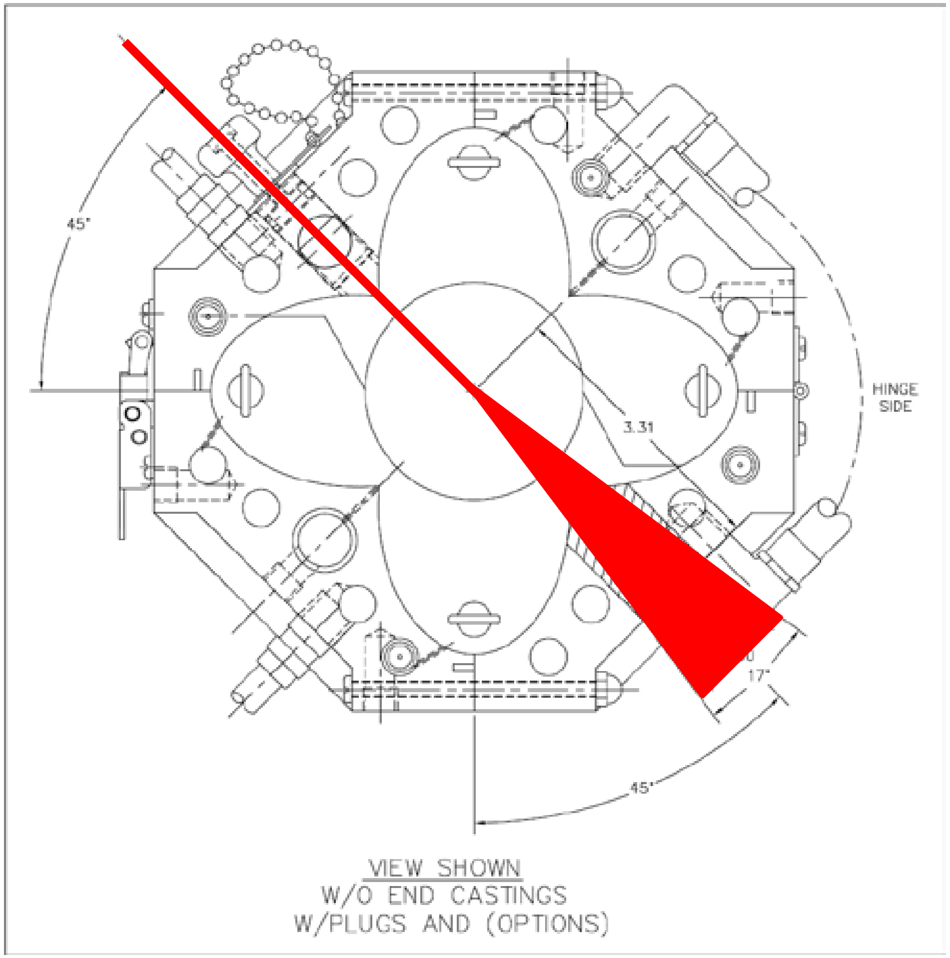
In situ strain measurement by combining Thermal Gradient Mechanical test setup with synchrotron X-ray diffractometry

- Argonne National Laboratory, Argonne, Illinois
- Synchrotron high energy monochromatic X-Ray beam-line; 65 keV beam energy

Top view of heater and beam

- 4 focused infrared lamps
  - 8 kW total
- Beam exit window
  - 17^0 4θ





S. F. Siddiqui et al., Rev. Sci. Instr., 84 - 083904 (2013)

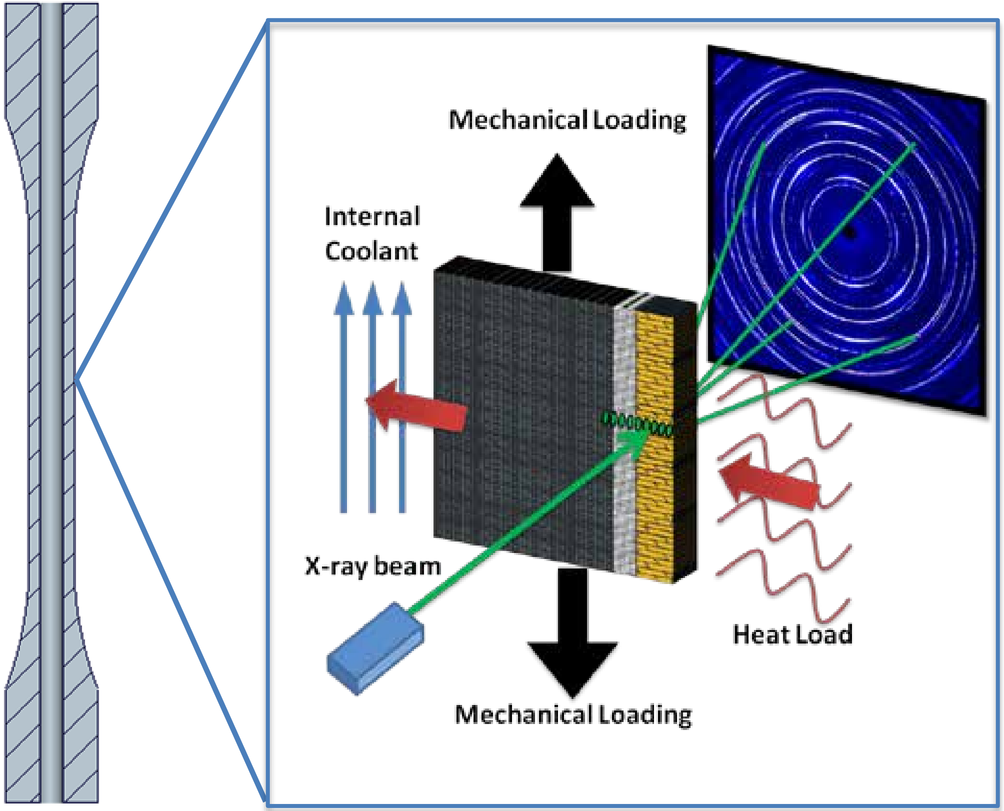
Servohydraulic testing machine on µm - positioning rig

Assembling heater, grips and specimen at Argonne APS

Testing and measurement methods

Loading options:

- superposition of mechanical and thermal load
- superposition of controlled thermal gradient by variation of cooling flow rate
- outer surface temperature max. 1000°C, temperature difference between outer and inner surface ca. 150°C

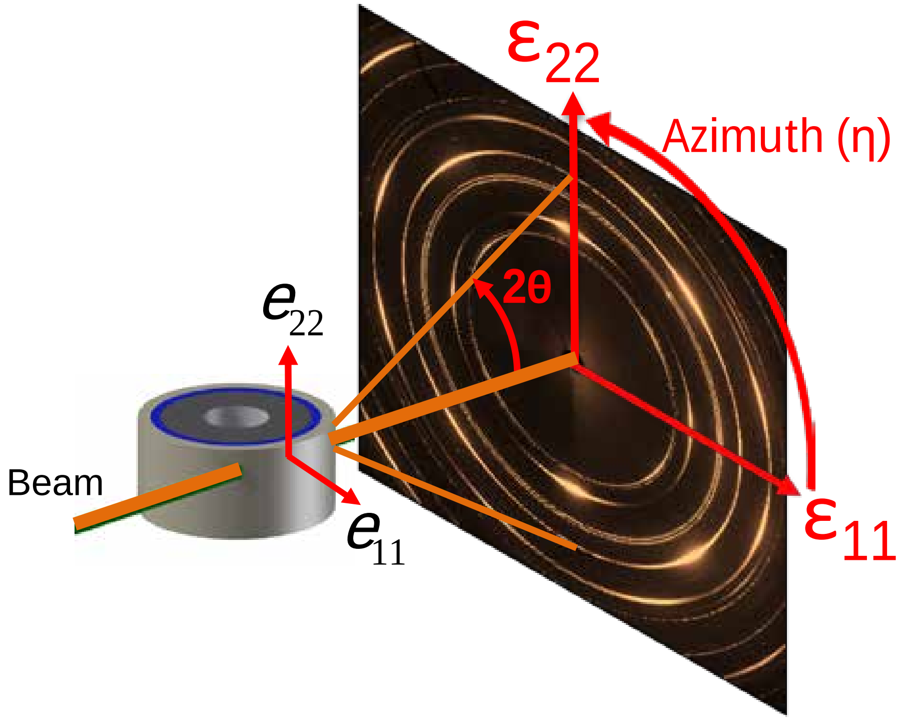


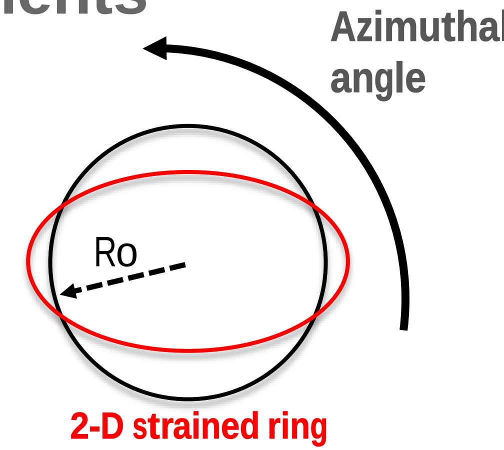
Beam parameter:

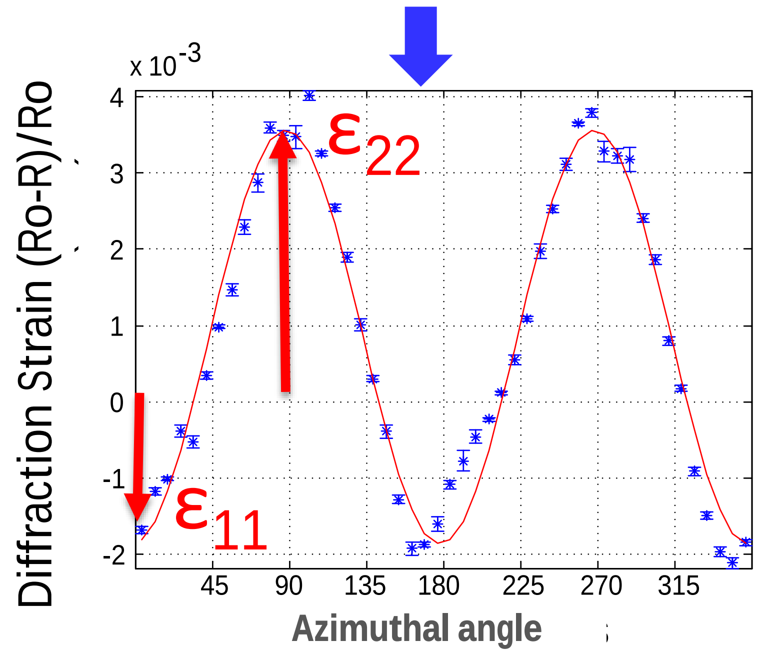
- 65 keV beam energy
- exposure time 0.5 to 15 sec.

K. Knipe et al., AIAA Structures, Struct. Dynamics & Mat. Conf., Boston, MA, 2013

X-Ray diffraction 2-D strain measurements





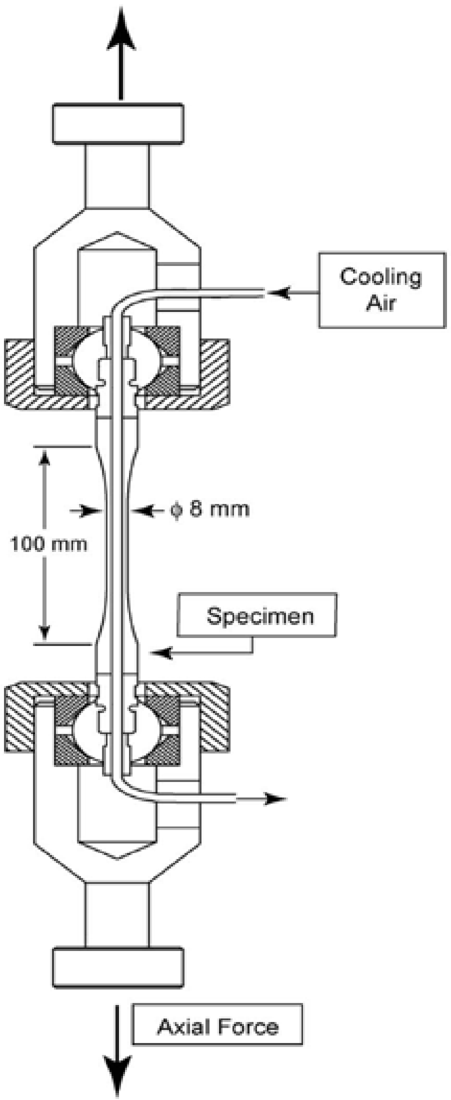


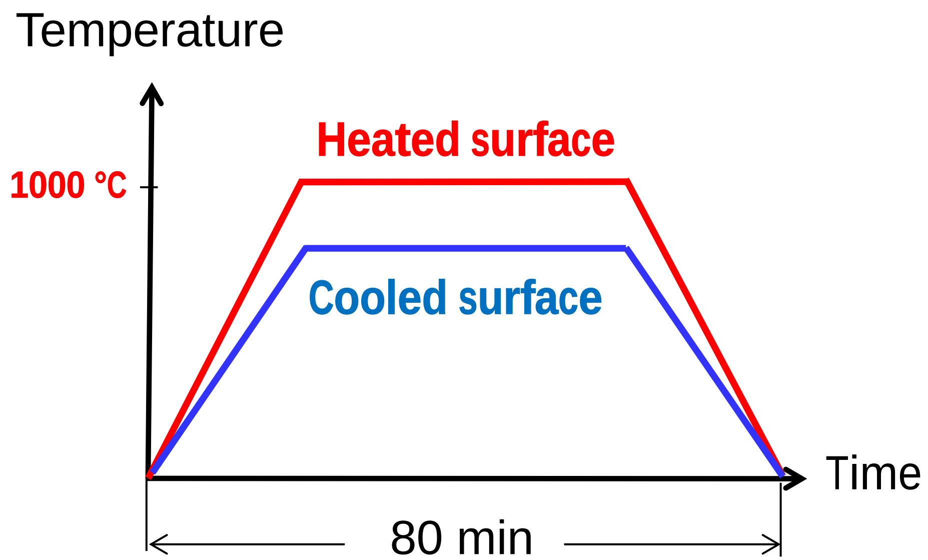
- Measure radial position around azimuthal angle
- Calculate each directional strain using (Ro-R)/Ro
  - R = measured radius
  - Ro = strain free radius

K. Knipe, Nature Comm. 5 (2014) article Nr. 4559

DLR

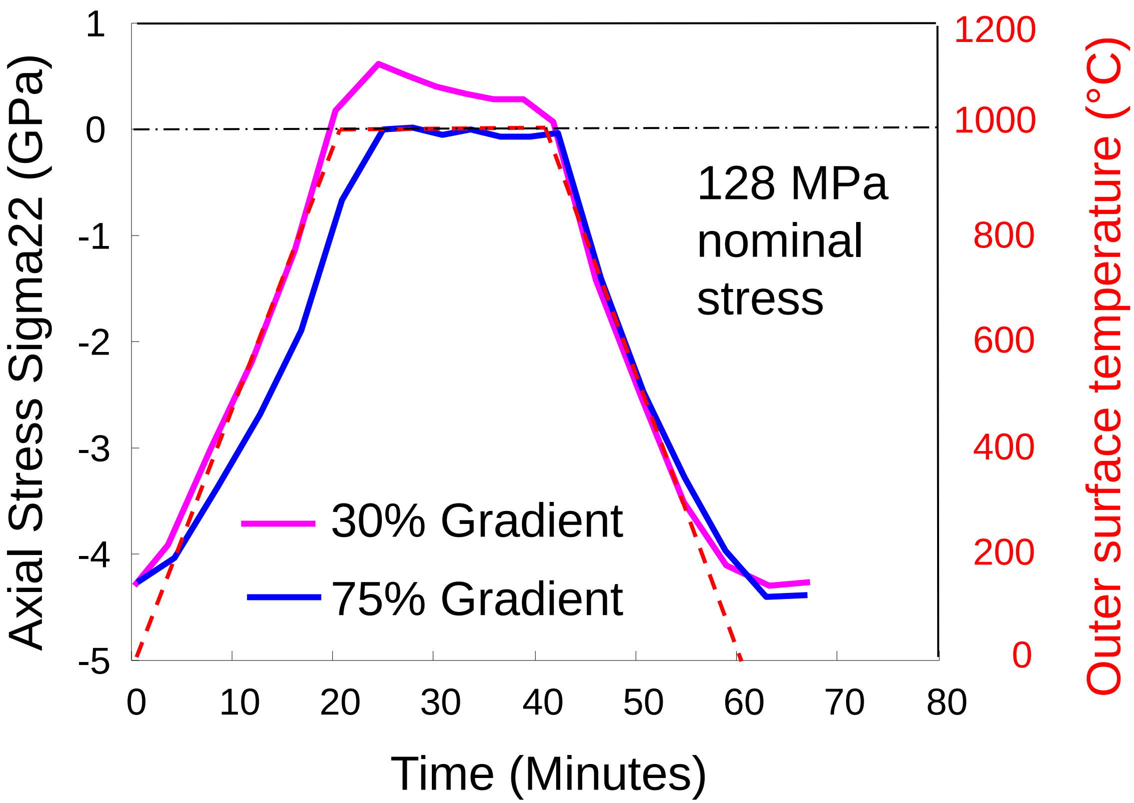
TGO strain measurement during cyclic loading





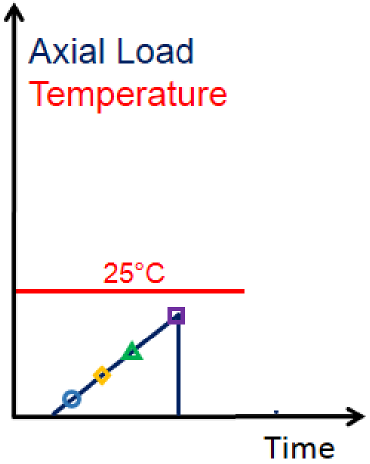
- Outer surface ramped up to 1000°C
- Constant coolant flow rate
  (30, 50, and 75 % max. flow, 100 SLPM* max)
- Constant nominal mechanical stress
  (32, 64 and 128 MPa applied)

TGO stress during thermal cycle

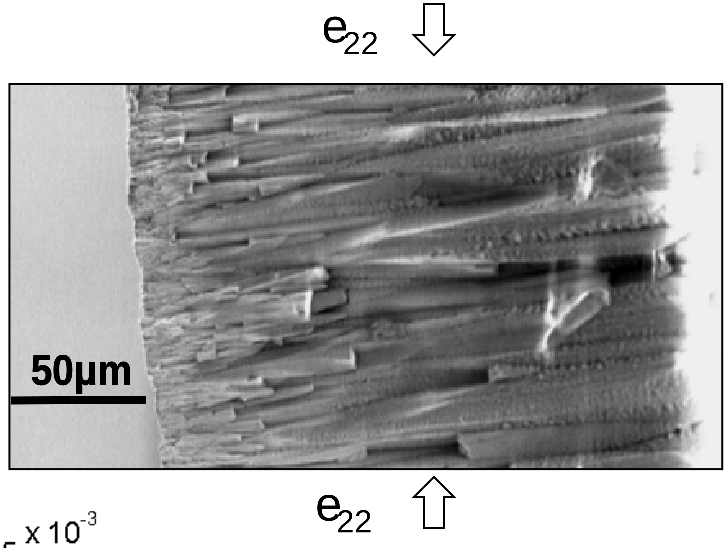


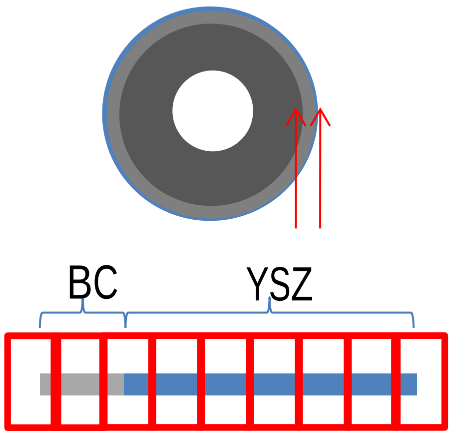
- the TGO experience tensile stresses under TGMF loading depending on applied mechanical tensile load and thermal gradient.
- Relaxation occurs during dwell time at high temperature, which is a condition for accumulating tensile stress during cycling.

YSZ: effect of microstructure gradient on local strain

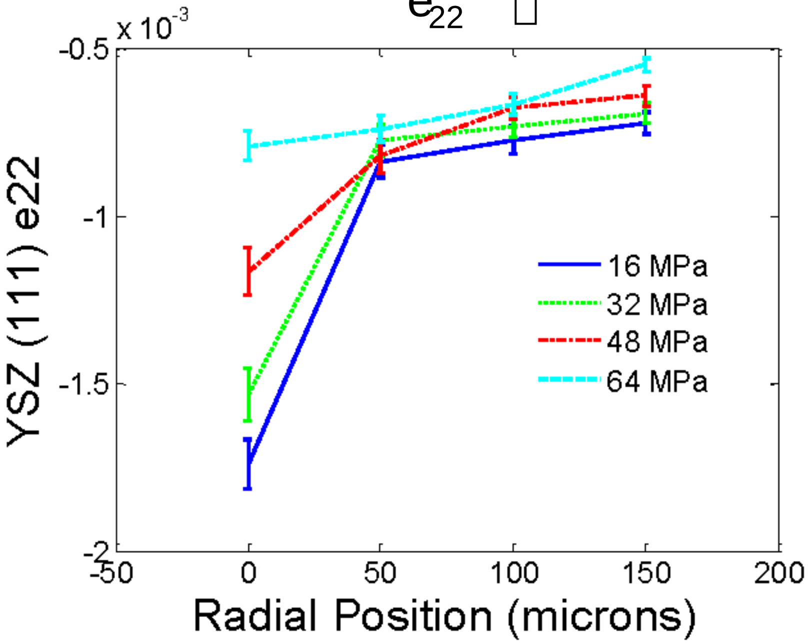


- No thermal gradient
- 25°C
- variation of mechanical load

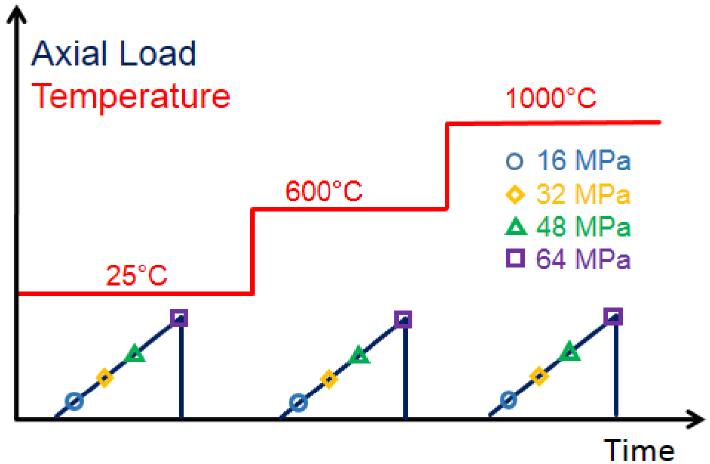


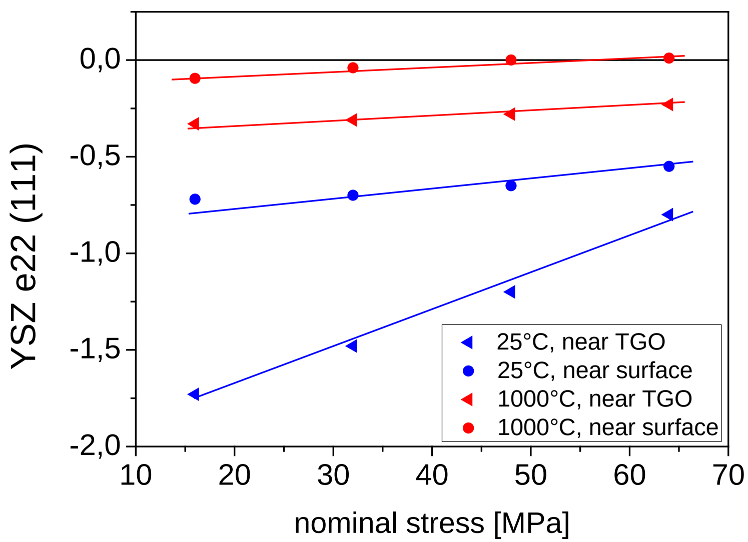


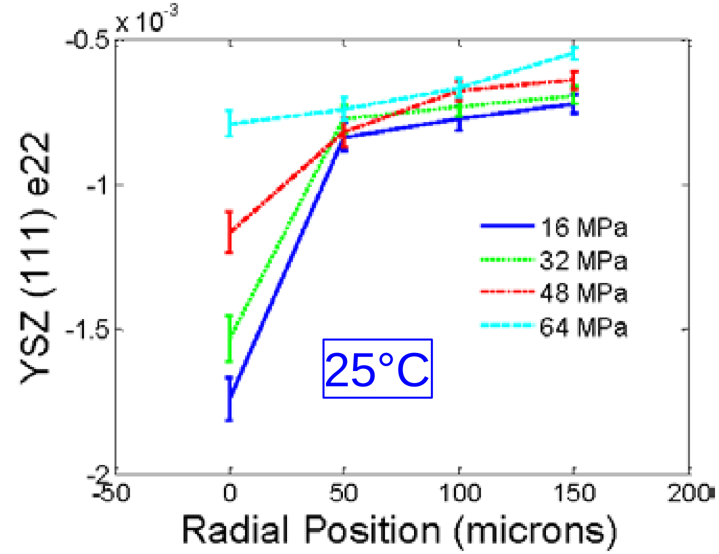
- X-Ray scan through coating thickness
- every 3.5 minutes
- window size 30 x 300 microns
- 10 window scans

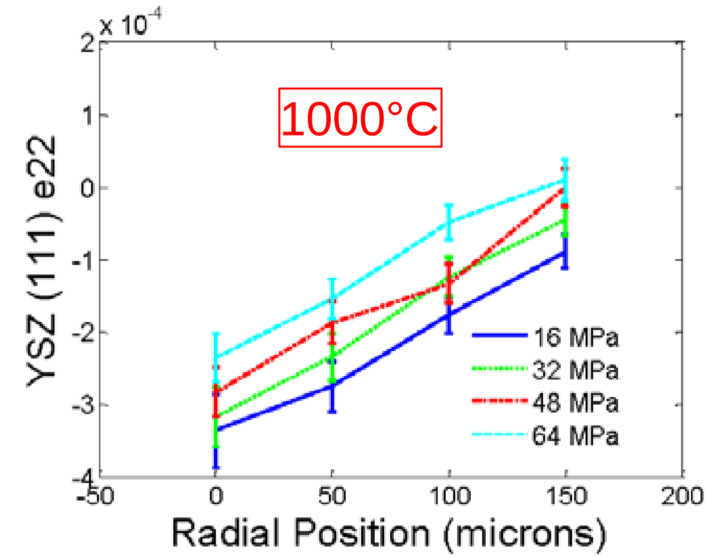


YSZ strain at different temperatures and mechanical loads



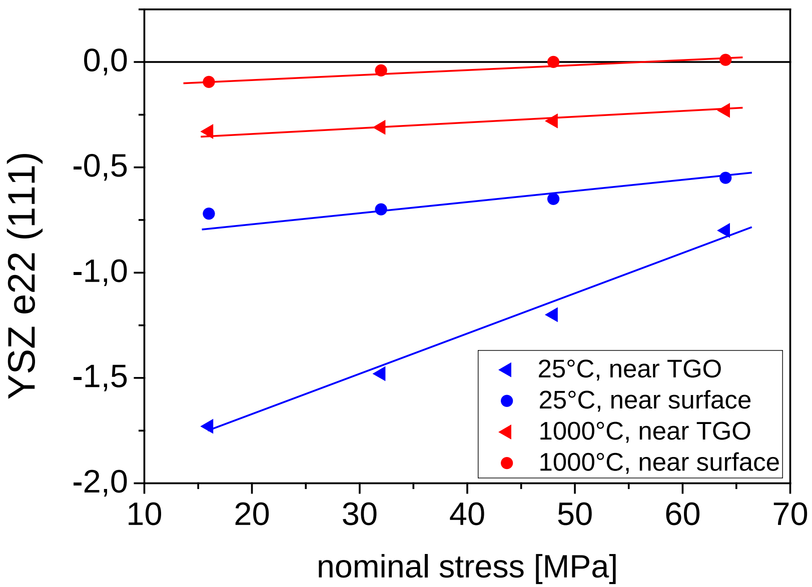


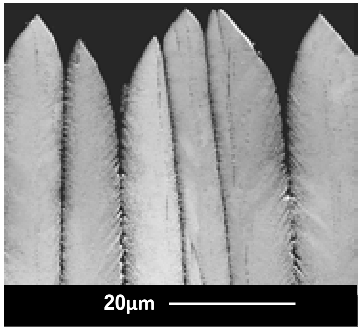




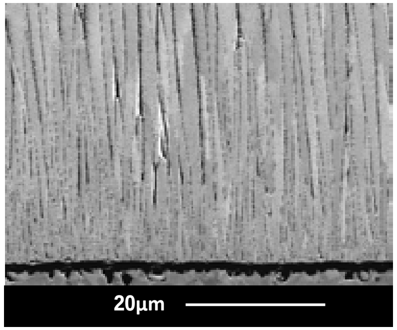
DLR

YSZ stress as function of temperature and location





near surface

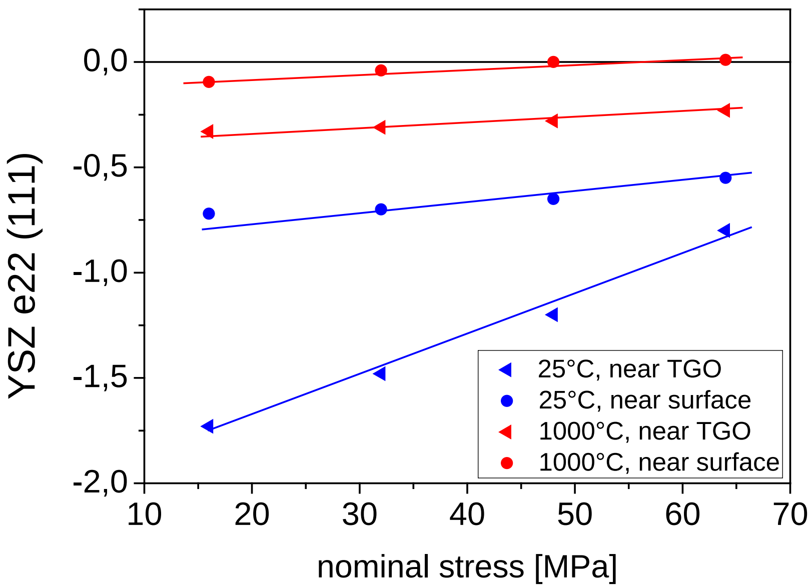


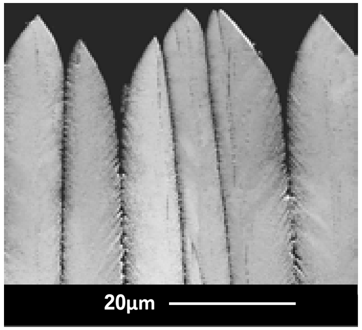
near TGO

- At RT:
  - High compressive strain
  - 4-times higher coating stiffness near to the TGO (more dense coating) than near to the free surface (highly porous coating)
- At 1000°C
  - Lower strain level but not strain-free
  - compressive near to the TGO interface
  - no significant difference in stiffness between location near to the interface and near to the surface

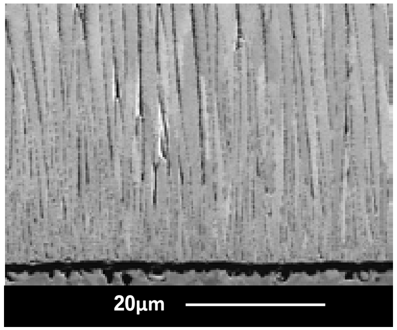
→ Strain dependency of elastic behavior

YSZ stress as function of temperature and location



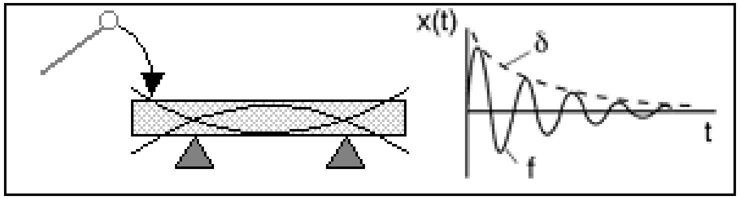


near surface



near TGO

Independent measurements by impulse excitation technique on a comparable coating system yield average in-plane coating Young's moduli at room temperature of 38 to 46 GPa. *

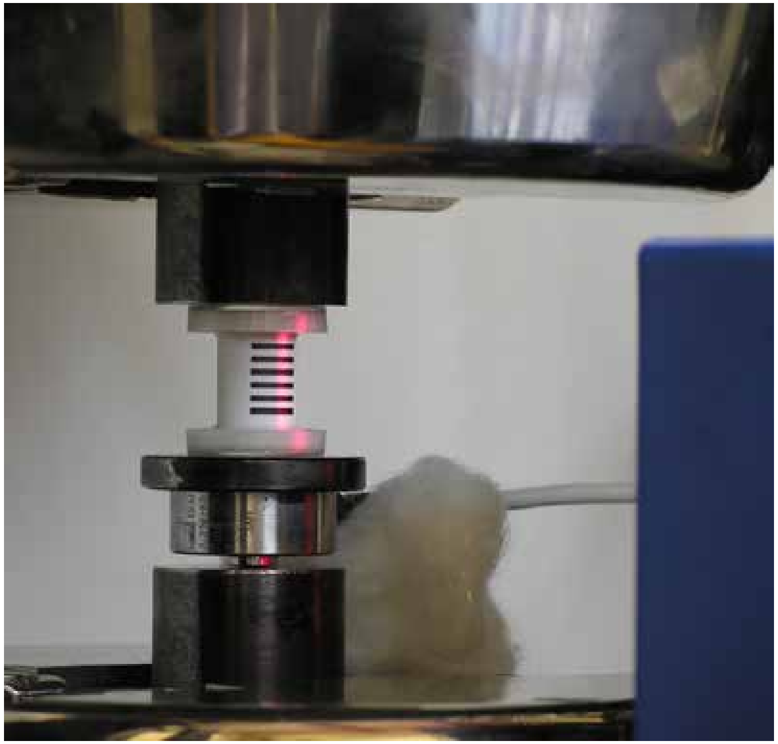


Calibration with IET-data results in RT in-plane E-Modulus of

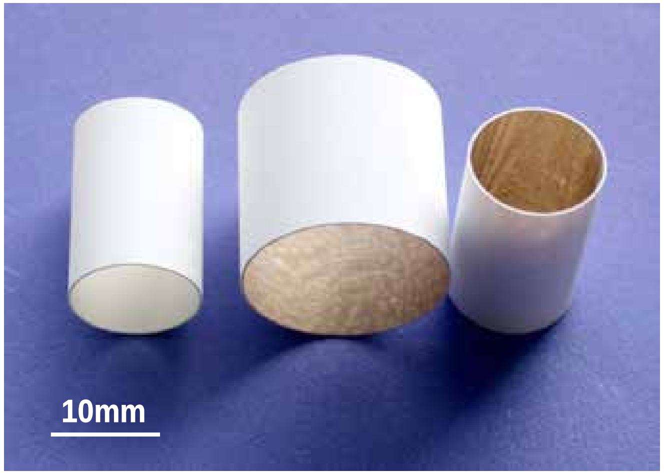
~ 65 GPa near TGO and
~ 15 GPa near surface

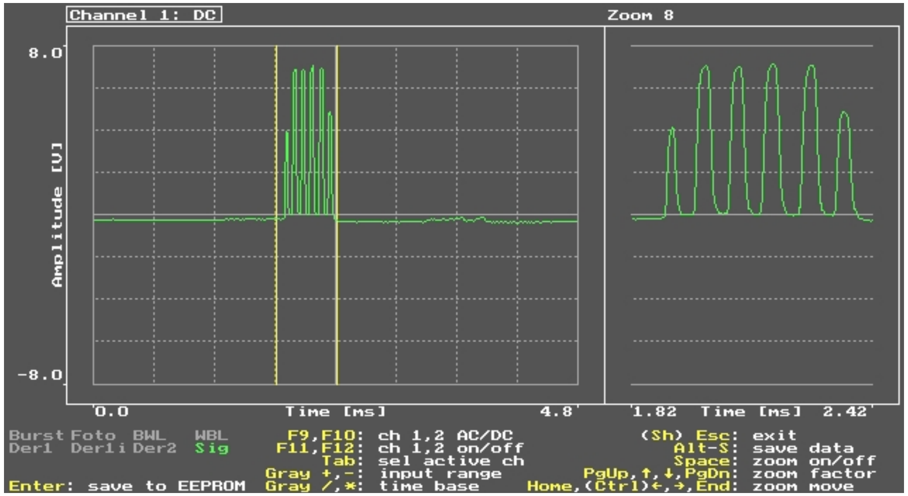
** IET-results: T. Lauwagie et al., Materials Science Forum Vols. 492-493 (2005) pp. 653-658*
N. Tassini et al, Journal of the European Ceramic Society 27 (2007) 1487–1491

Contact- free strain measurement of free standing EB-PVD coatings under compression



Laser-extensometer





Presented at Japanese – German TBC-Workshop, 2009 in Kyoto

Overview of results by independent global methods

	Free standing			Constraint in the coating system	
	Non aged	Literature	aged (1130°C/20h)	Non aged	aged (1000°C/1000h)
loading – unloading cycles	18 - 27 GPa	10 -15GPa	55-70 GPa	30-40GPa	68 - 77 GPa
	0.15% strain	-	not stress dependent	at ca. 0.5% strain due to thermal mismatch	
	hysteresis	-	no hysteresis		

Difference between free standing and constrained TBC indicates strain dependence of elastic behavior – consistently with XRD-results.

**IET-results: I. Mircea, PhD-Thesis, TU-Darmstadt, Germany 2006*

Conclusions

- Local mechanical behavior of the coating materials has been captured at RT and high temperature, based on in-situ X-ray diffraction data
    - strain gradient over the EB-PVD YSZ layer observed and attributed to the porosity gradient
    - stress dependency of elastic response – attributed to columnar microstructure
    - TGO relaxation during high temperature hold

- Independently determined data for in-planeYoung's Modulus yield consistent results (IET and compressive test on free-standing coatings)

- Further evaluation of data and improvement of methods ⇨ ongoing

Thank you for your attention!

Questions?

Acknowledgements:

- This material is based upon work supported by the National Science Foundation Grants OISE 1157619 and CMMI 1125696
- German Science Foundation (DFG) grant SFB-TRR103, project A3
- Use of the Advanced Photon Source, an Office of Science User Facility operated for the U.S. Department of Energy (DOE) Office of Science by Argonne National Laboratory, was supported by the U.S. DOE under Contract No. DE-AC02-06CH11357.

Publication list

Publications

- T. Lauwagie, K. Lambrinou, I. Mircea, M. Bartsch, W. Heylen, O. Van der Biest: *Determining the Elastic Moduli of the Individual Component Layers of Cylindrical Thermal Barrier Coatings by means of a Mixed Numerical - Experimental Technique*, Materials Science Forum Vols. 492-493 (2005) 653-58. DOI: 10.4028/www.scientific.net/MSF.492-493.653
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- S. F. Siddiqui, K. Knipe, A. Manero, C. Meid, J. Schneider, J. Okasinski, J. Almer, A.M. Karlsson, M. Bartsch, S. Raghavan: *Synchrotron X-Ray Measurement Techniques for Thermal Barrier Coated Cylindrical Samples under Thermal Gradients*, Review of Scientific Instruments, 84 - 083904 (2013). http://dx.doi.org/10.1063/1.4817543
- K. Knipe, A. Manero, S. F. Siddiqui, C. Meid, J. Wischek, J. Okasinski, J. Almer, A. M. Karlsson, M. Bartsch & S. Raghavan: *Strain response of Thermal Barrier Coatings captured under extreme engine environments through Synchrotron X-ray Diffraction*, Nature Communications 5 (2014), article number 4559, doi:10.1038/ncomms5559
- A.C. Manero II, S. Sofronsky, K. Knipe, C. Meid, J. Wischek, J. Okasinski, J. Almer, A.M. Karlsson, S. Raghavan, M. Bartsch: Monitoring Local Strain in a Thermal Barrier Coating System under Thermal Mechanical Gas Turbine Operating Condition, JOM 67 (7) (2015) 1528-1539. http://link.springer.com/article/10.1007/s11837-015-1399-3?no-access=true

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