In-situ synchrotron X-ray strain measurements in TBC systems during thermal mechanical cycling

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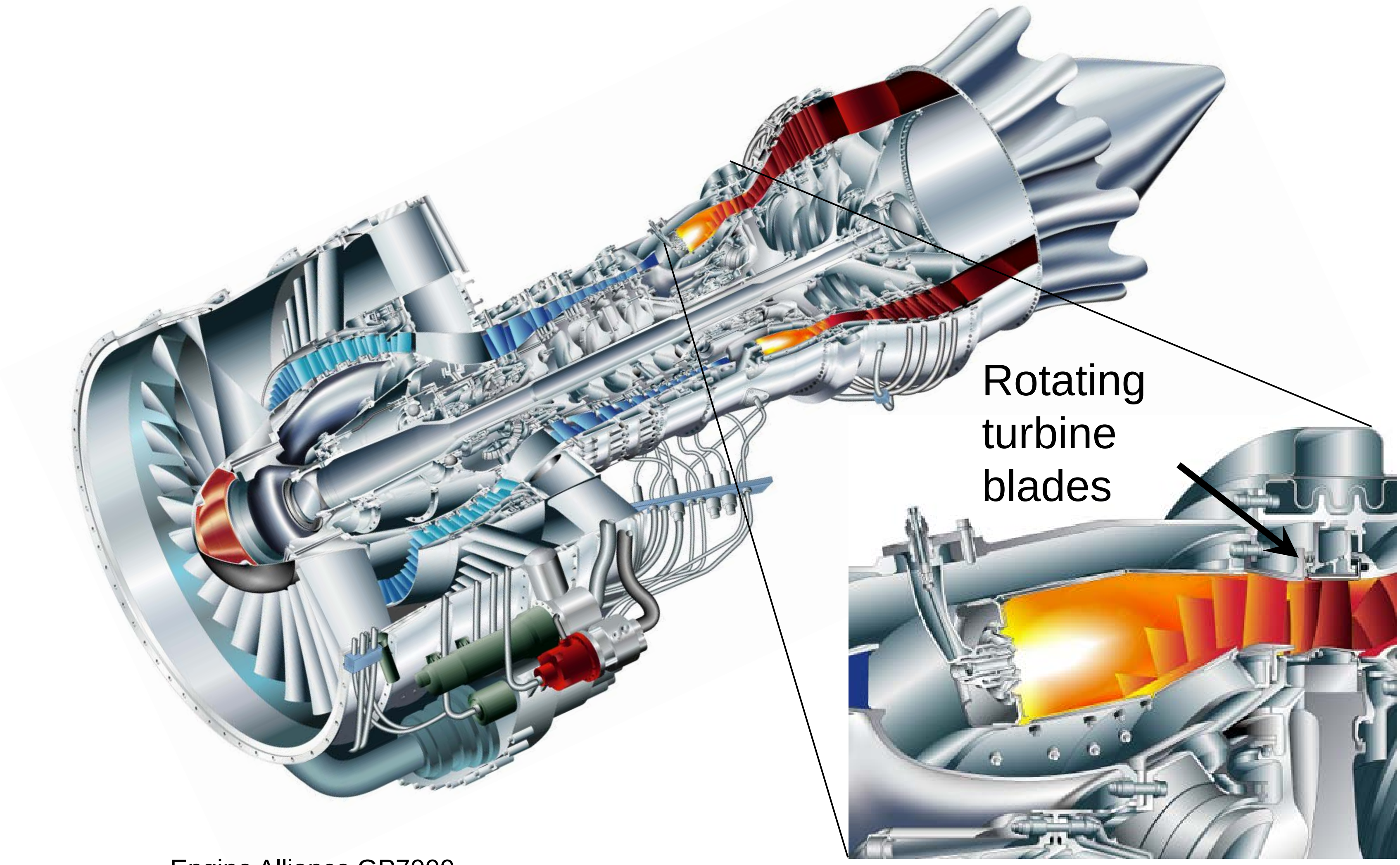
Outline

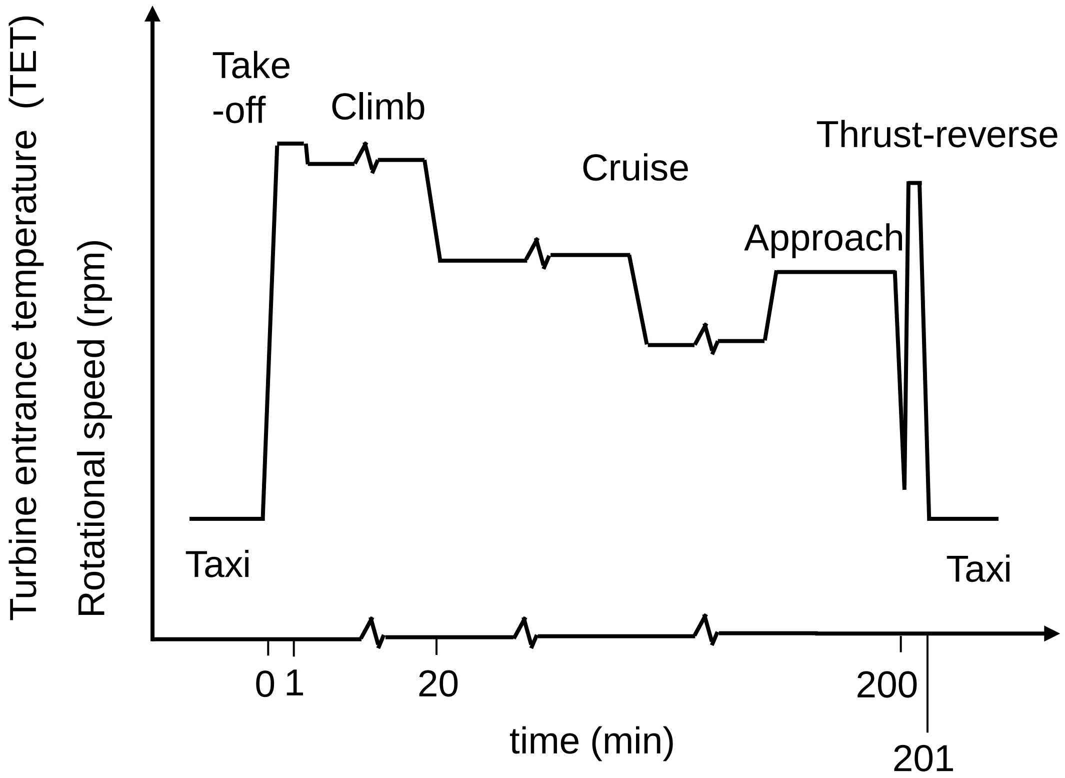
- Motivation of the investigation
  - Experimental test facility at DLR and results
  - Numerical model and simulation results
- Research objective and test set up at Argonne APS
- Test configuration
- Experiments and first results
- Conclusions and project status

Turbine blades in an aircraft engine



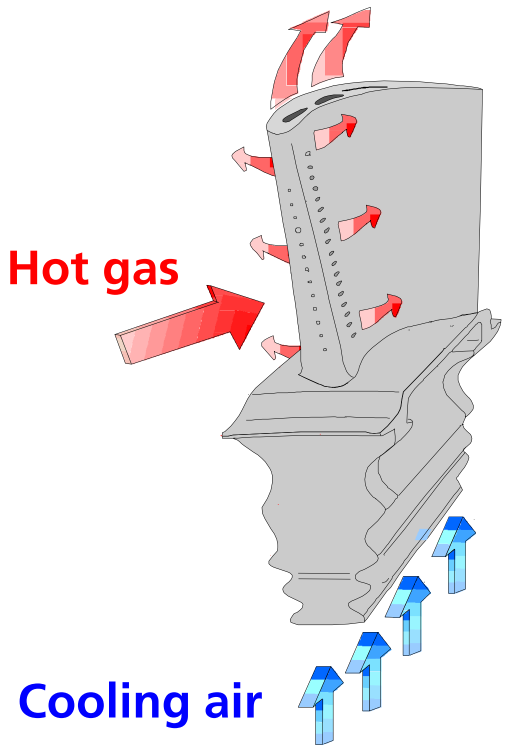
Engine Alliance GP7000

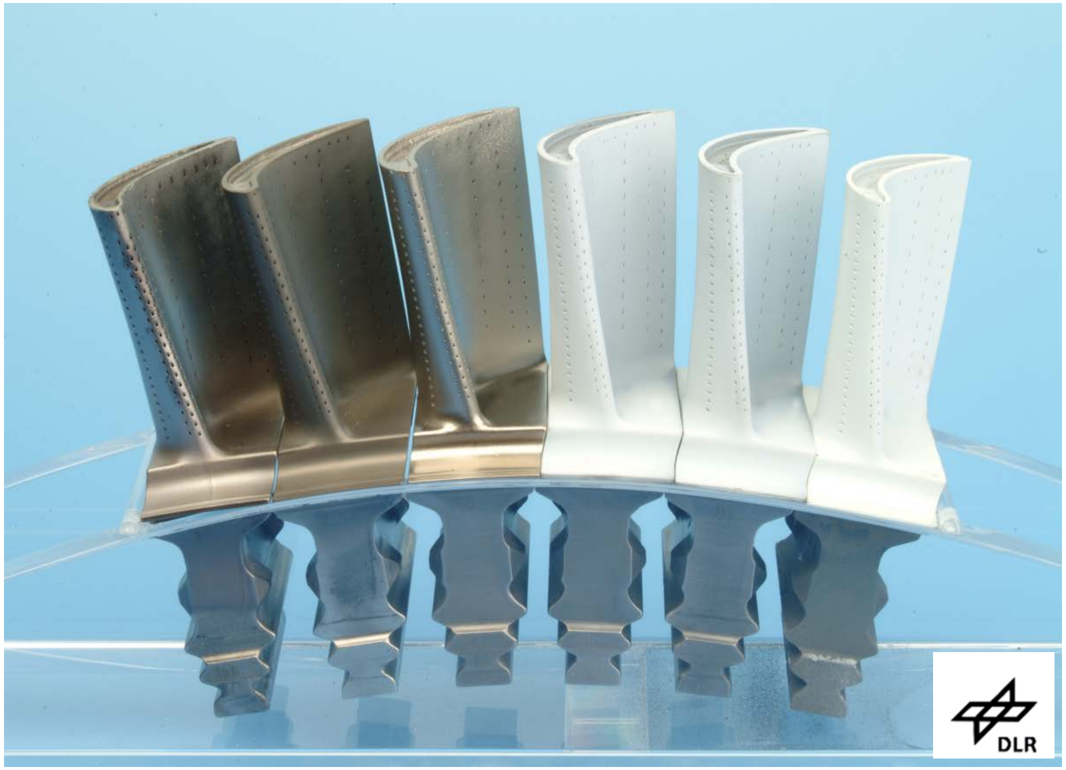
Load and temperature cycle of a flight mission



→ very high heating and cooling rates during take off and after landing

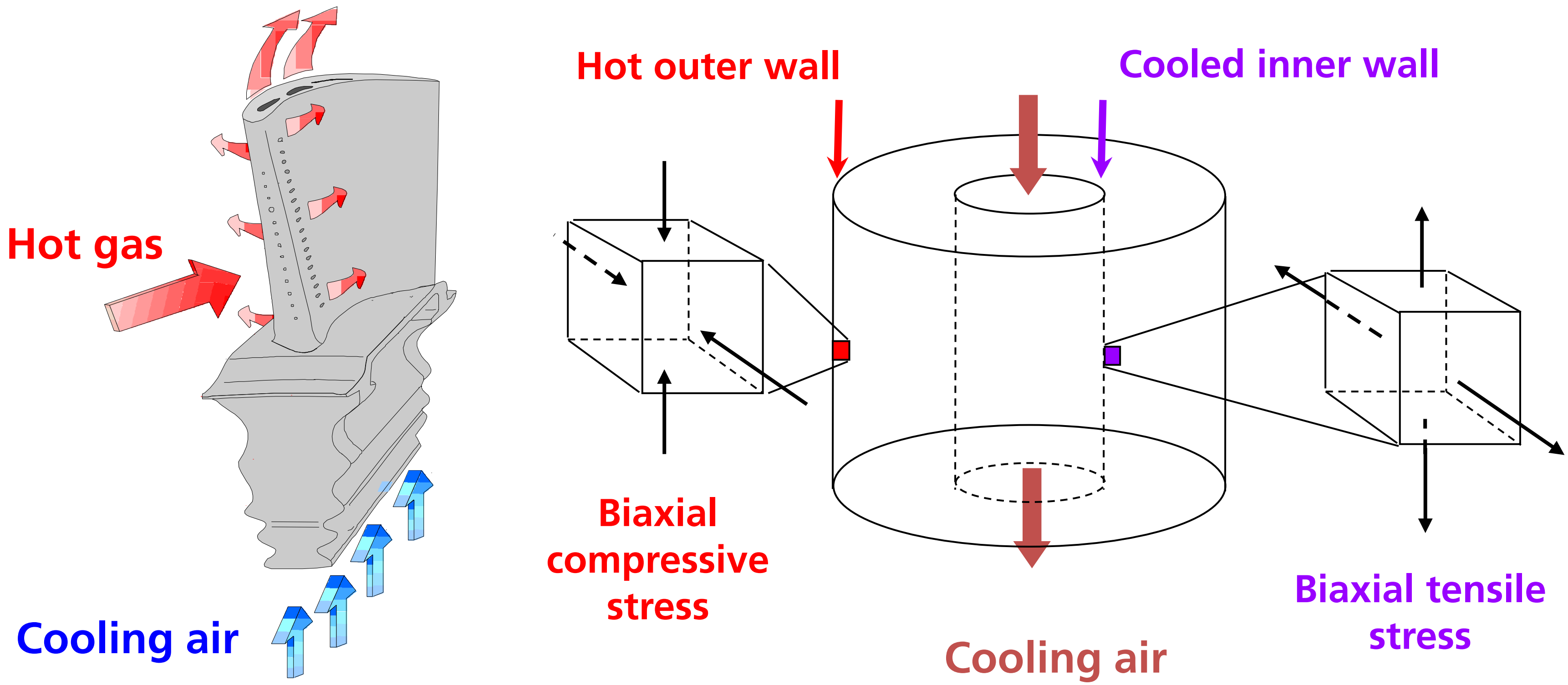
Turbine blades with protective coatings





Temperature difference across TBC: ca. 100°C
⇨ Increase of lifetime ca. 4 - times

Stress distribution due to thermal gradient



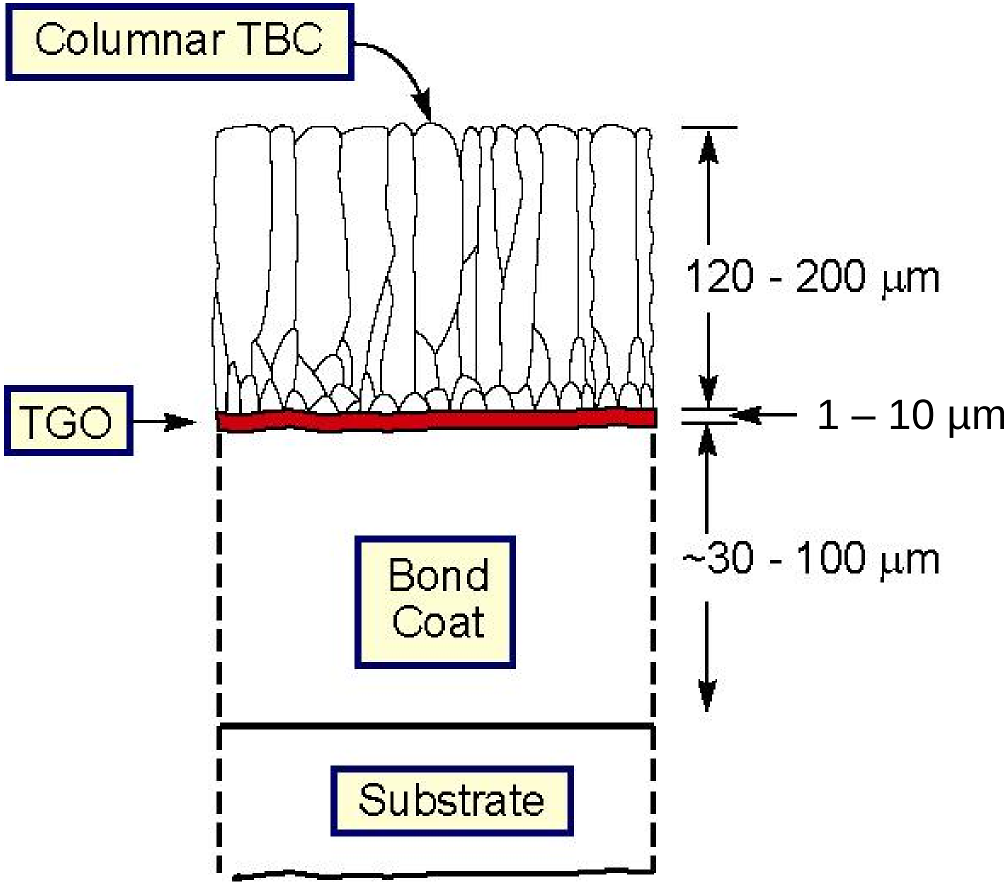
Summarizing thermal and mechanical loads

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

Causing

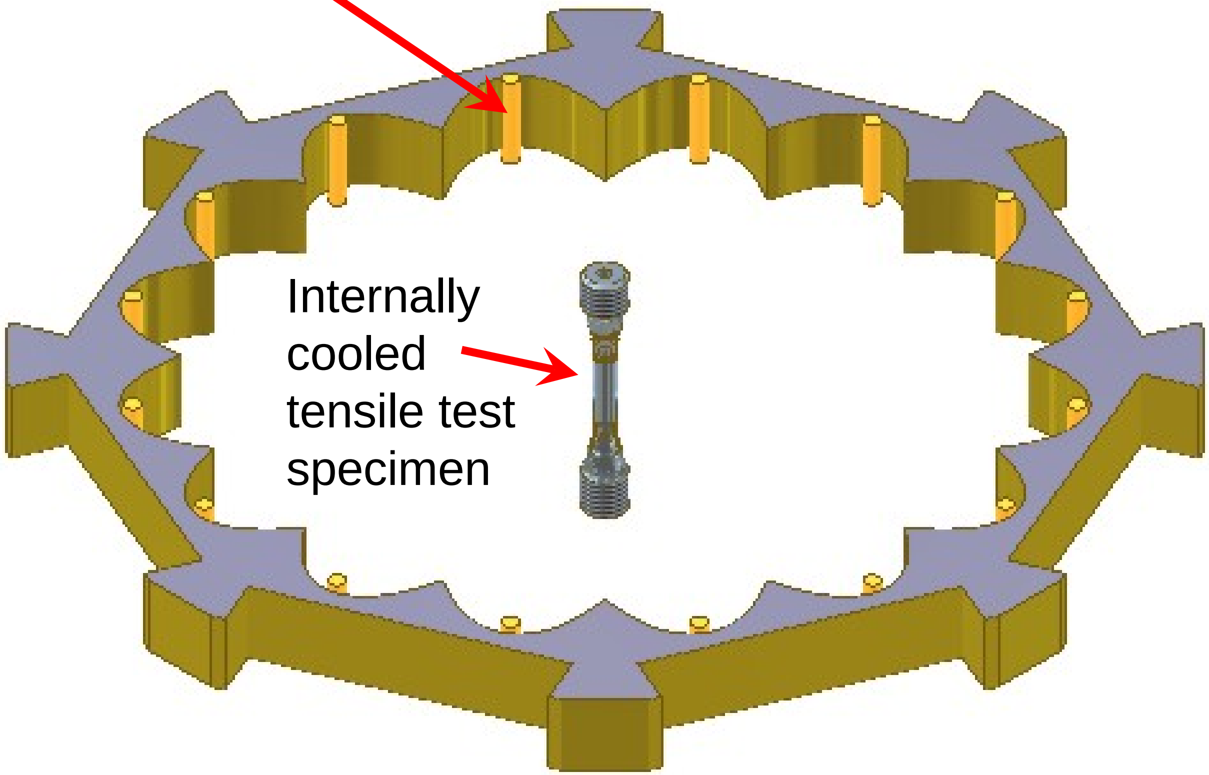
- Ageing of materials
    - Oxidation of the metallic bond coat
    - Sintering of ceramic top coat
- Fatigue damages due to cyclic loading (flight cycle)

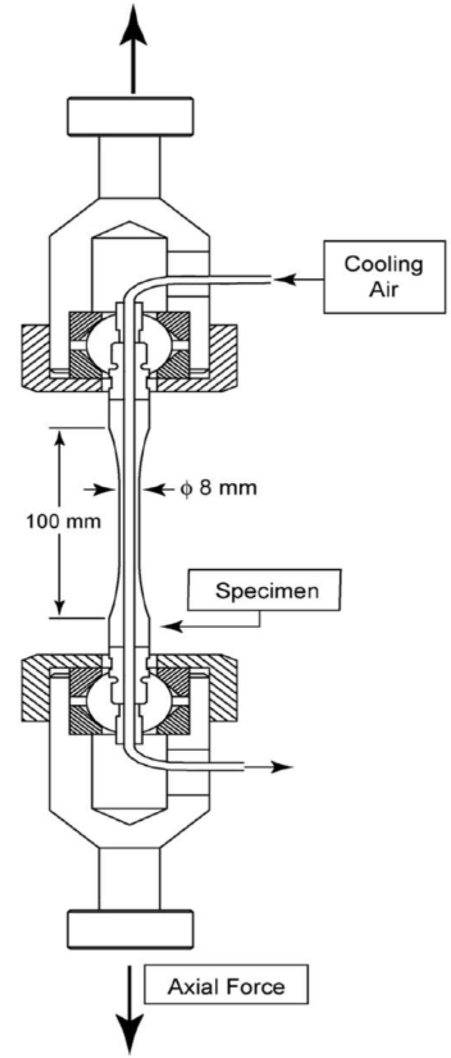
Investigated coating system



Laboratory test facility for thermal mechanical loading

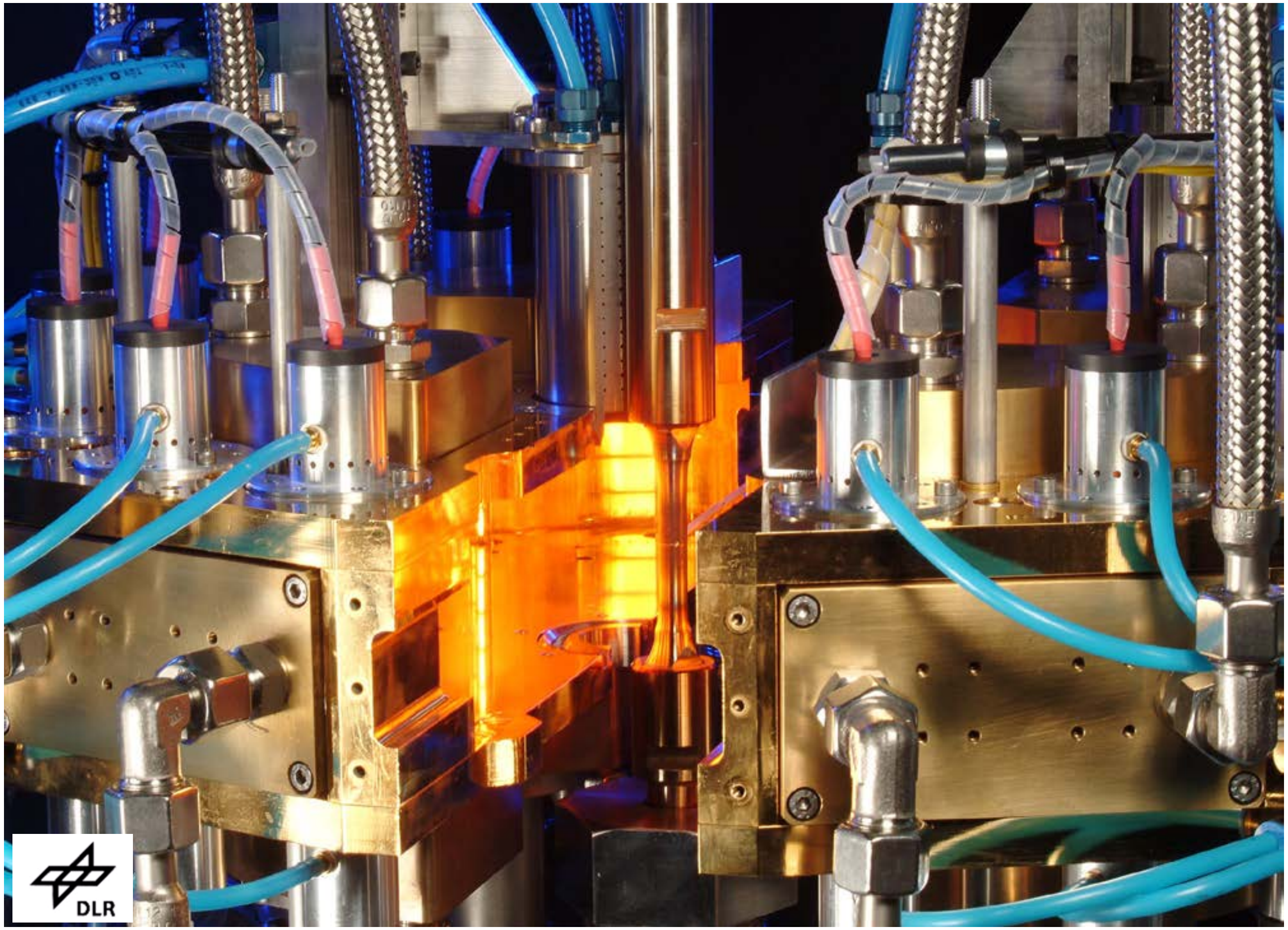
16 Quartz lamps, 1 kW each





Thermal Gradient Mechanical Fatigue = TGMF

View of open furnace



DLR

Time dependent effects

- Oxidation of bond coat at high temperature has major impact on lifetime of ceramic layer

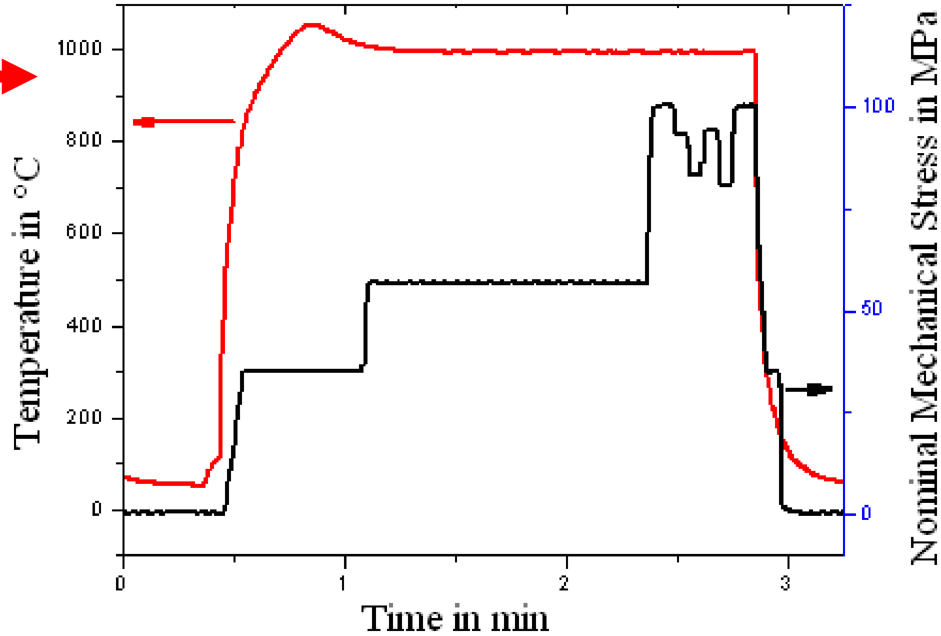
- It is not practical to perform test cycles with realistic cycle duration (e.g. 2 - 10 hour flights)

Scheme for accelerated testing

Time at 1000°C
0 h
250 h
500 h

+

TGMF-cycles
500 (25h)
1000 (50h)
until spallation

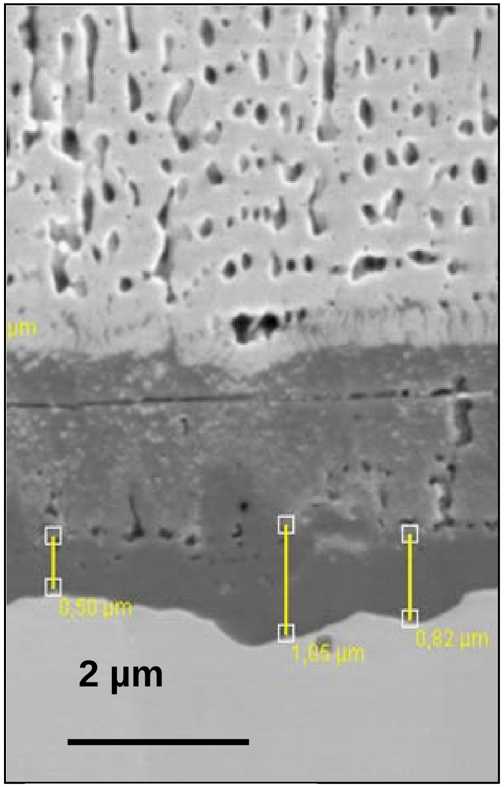


Pre-oxidation + Thermal - mechanical fatigue

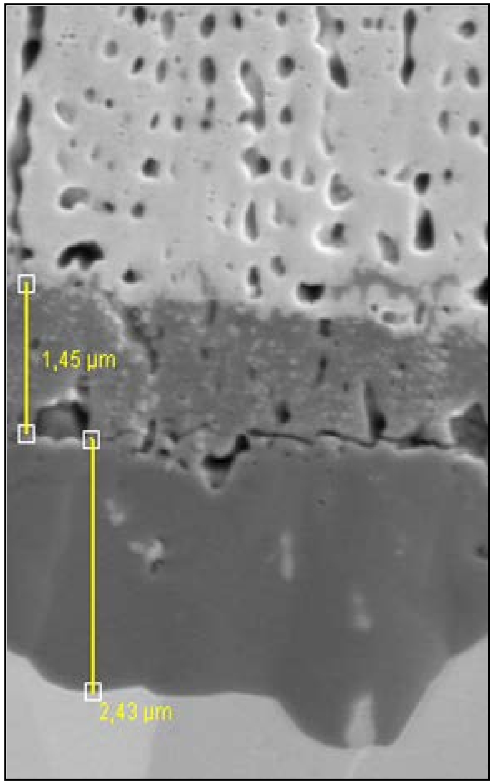
Mechanical loads: servo-hydraulic testing machine

Thermal gradient over specimen wall by internal cooling

After pre-oxidation: bi-layer thermally grown oxide



50h/1000°C

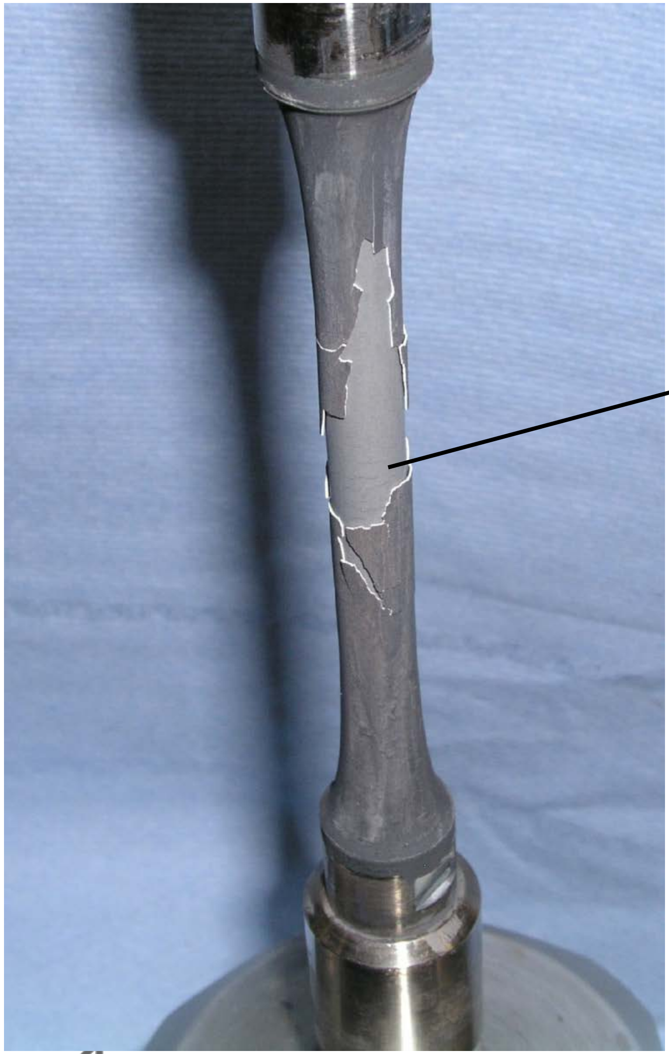


200h/1000°C

Fine grained intermixed zone Al_2O_3 +ZrO_2

Coarse grained Al_2O_3

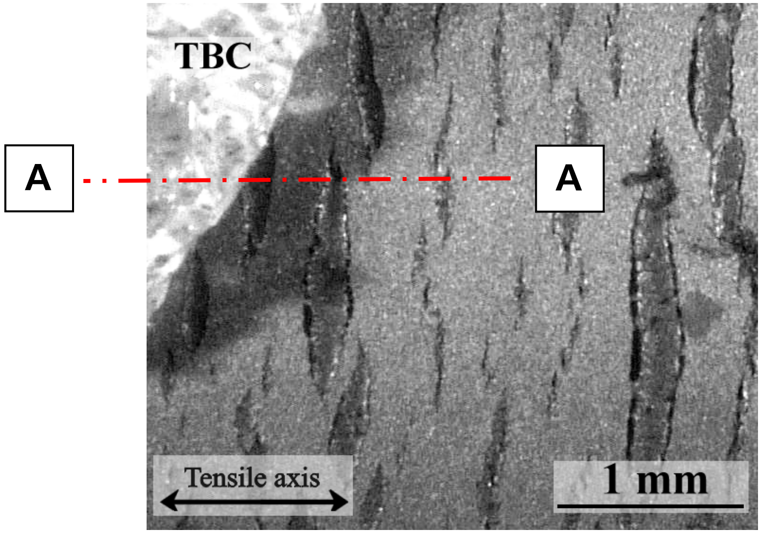
Failure after thermomechanical laboratory testing

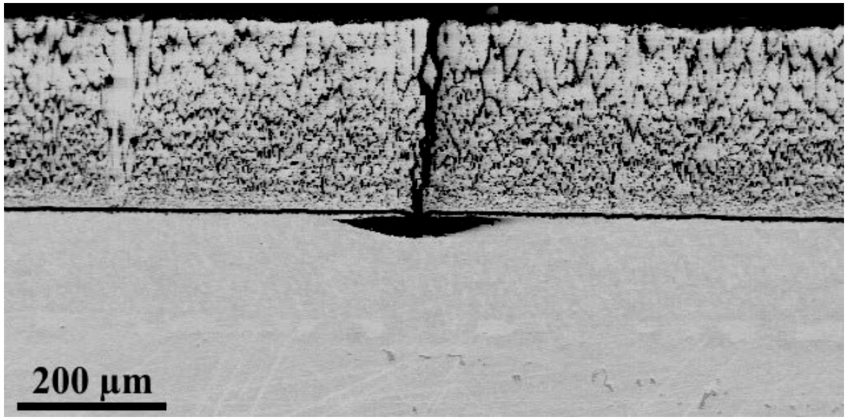


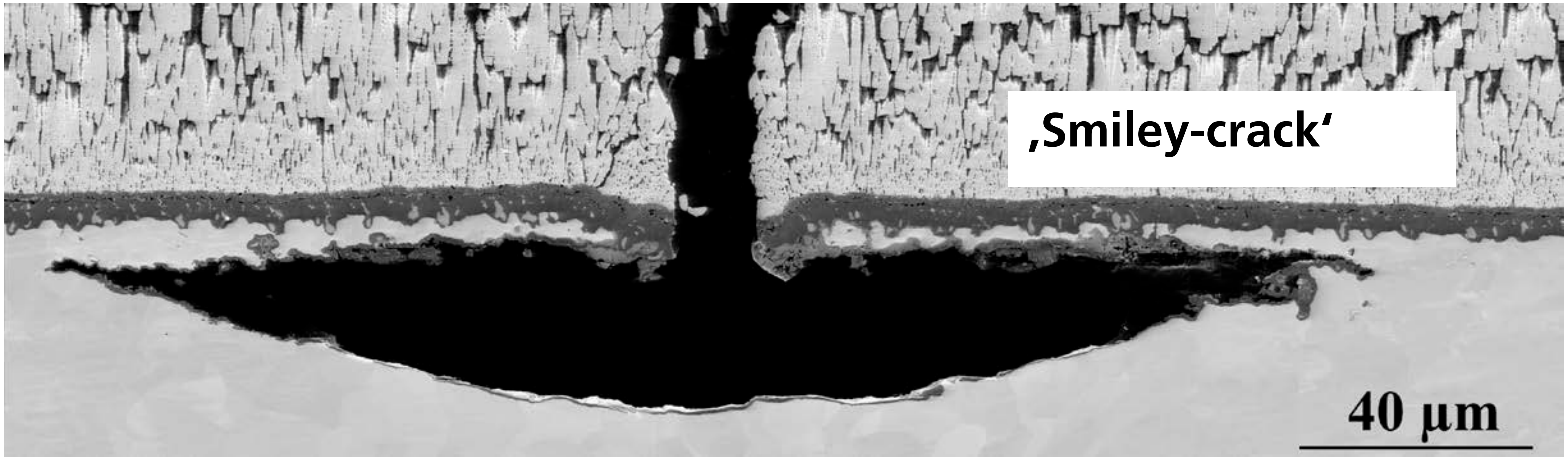
after 933 TGMF*-cycles &
500h pre-oxidation at 1000°C

*TGMF = Thermal Gradient Mechanical Fatigue

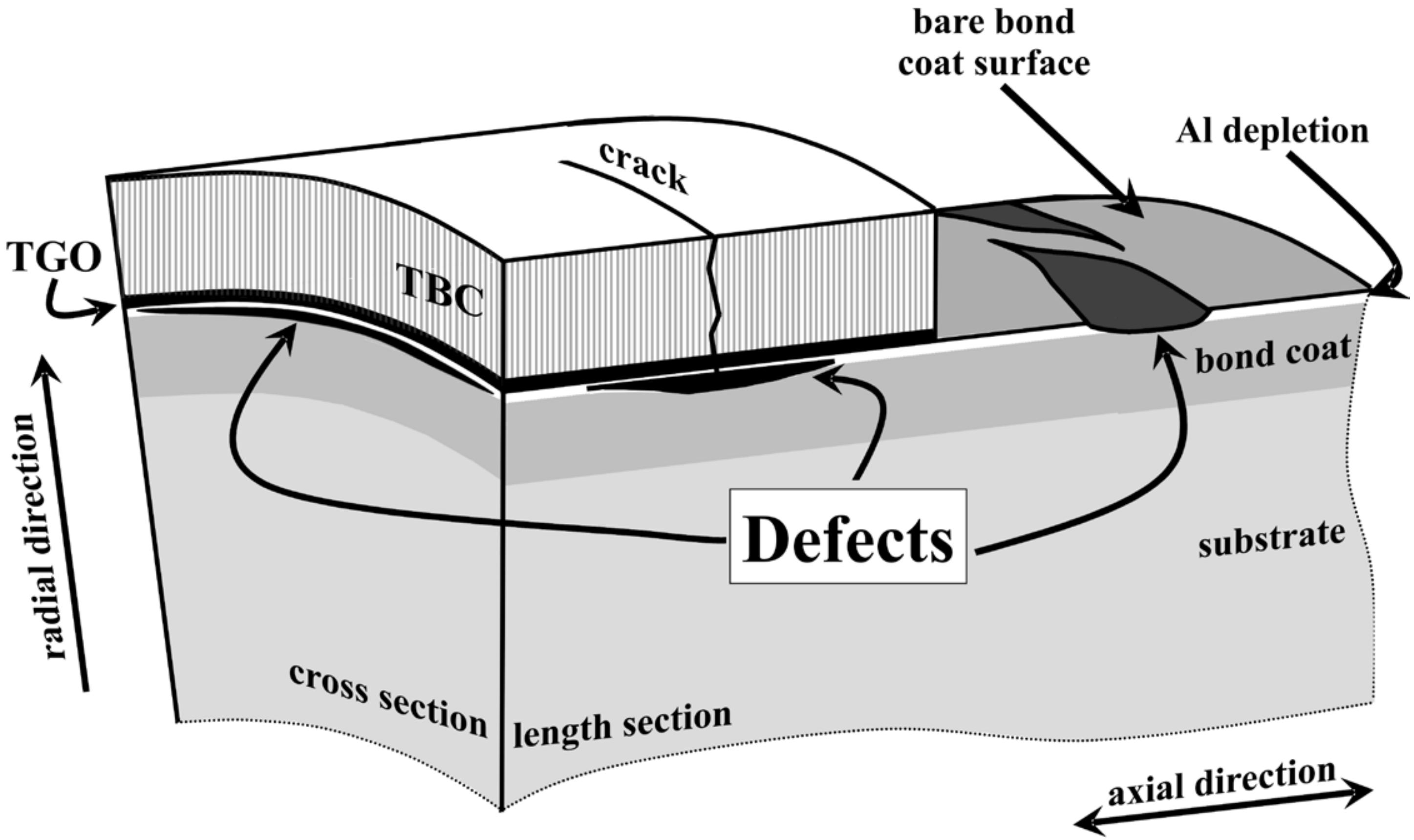
After 994 cycles (pre- oxidized 500 h/1000°C)







3 - dimensional sketch of defects



DLR

Summary of experimental results

Time at 1000°C
0 h
250 h
500 h

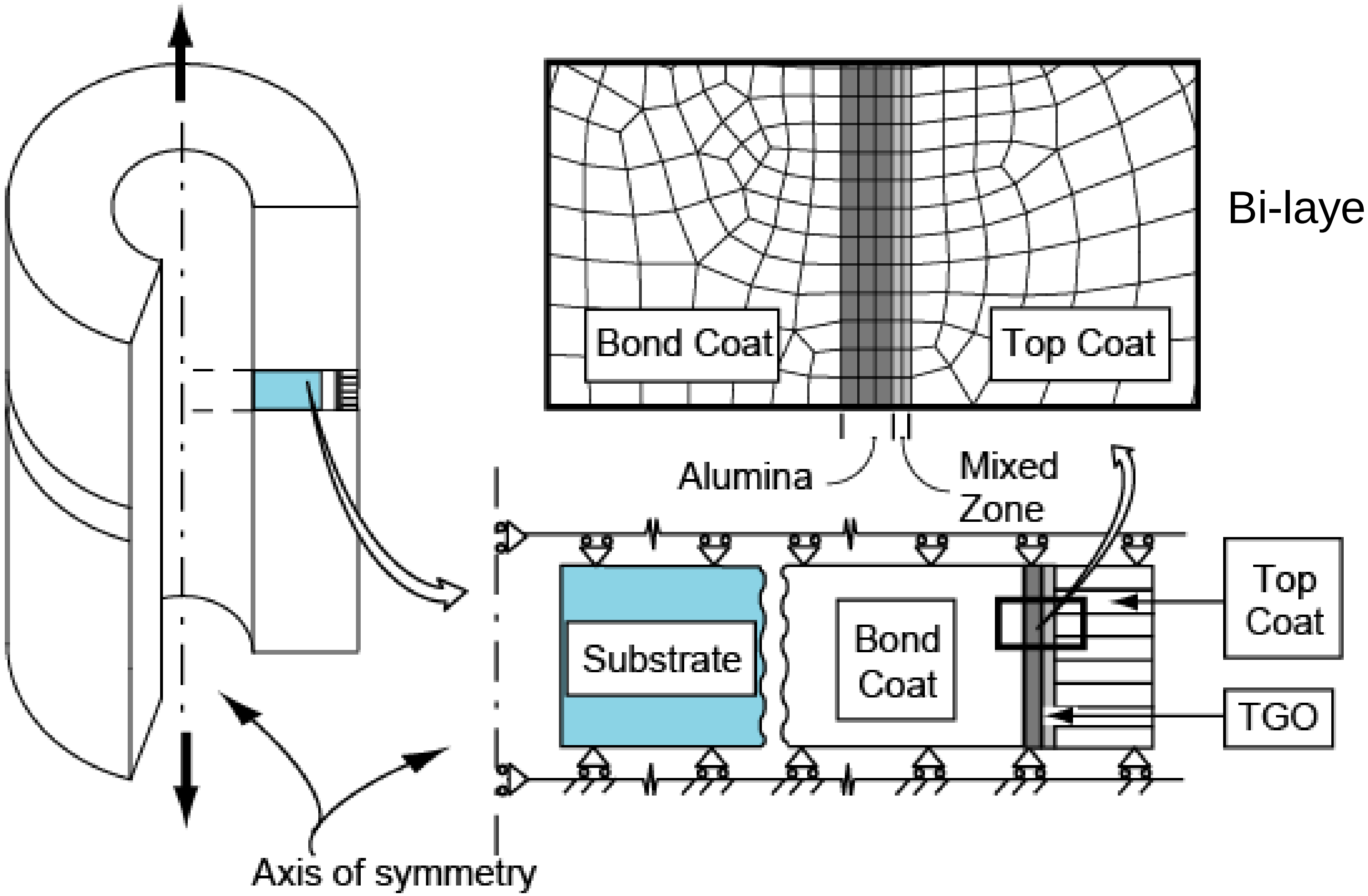
+

TGMF- cycles
1000 (50h)

- Without pre-oxidation no spallation occurred up to 7000 cycles
- 250h (500h) pre-oxidation + 1000 cycles, open delamination cracks, spallation

- Evolution of the ‚smiley‘ cracks is linked to the formation of cracks in the TGO, perpendicular to the applied mechanical load.
- To form the TGO cracks, axial tensile stresses are necessary.
- The questions are
  - how can axial tensile stresses evolve in the TGMF tests?
  - why do they only evolve in pre-aged specimens?

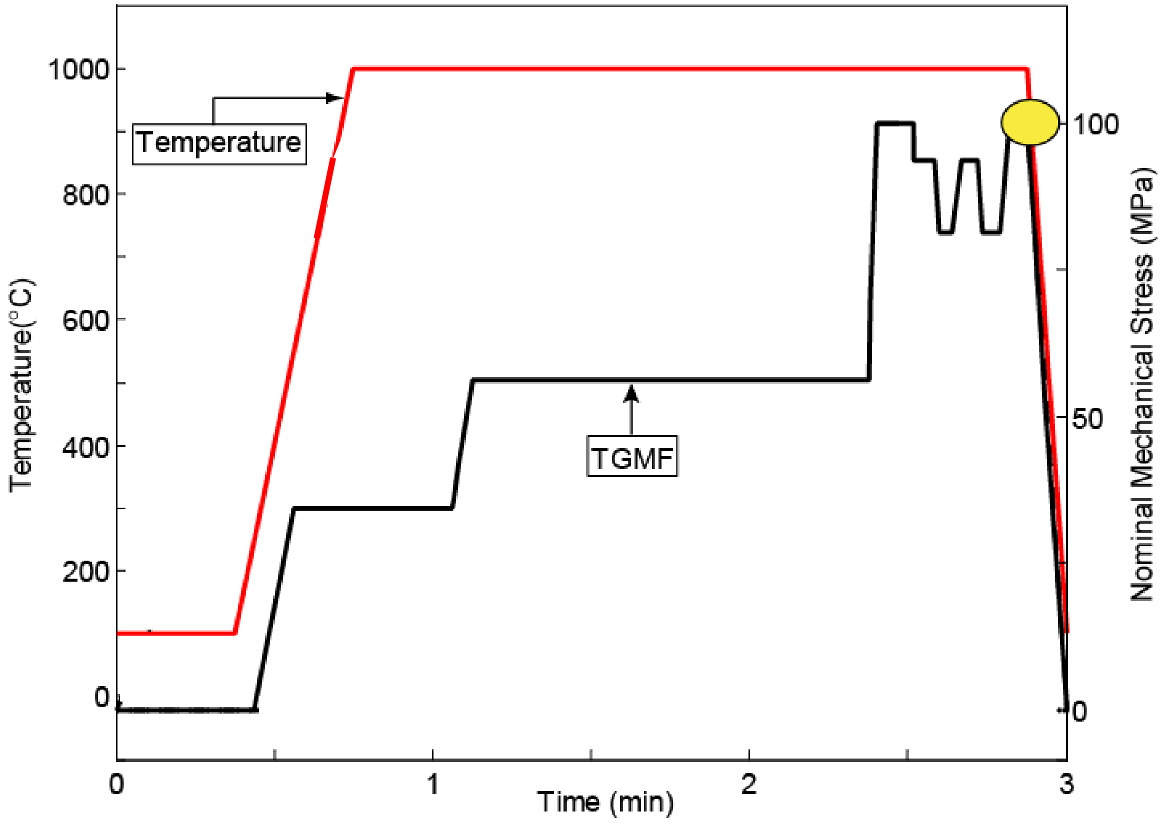
Numerical model: Geometry and boundary conditions

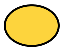


Bi-layered TGO

Numerical model: load cycle

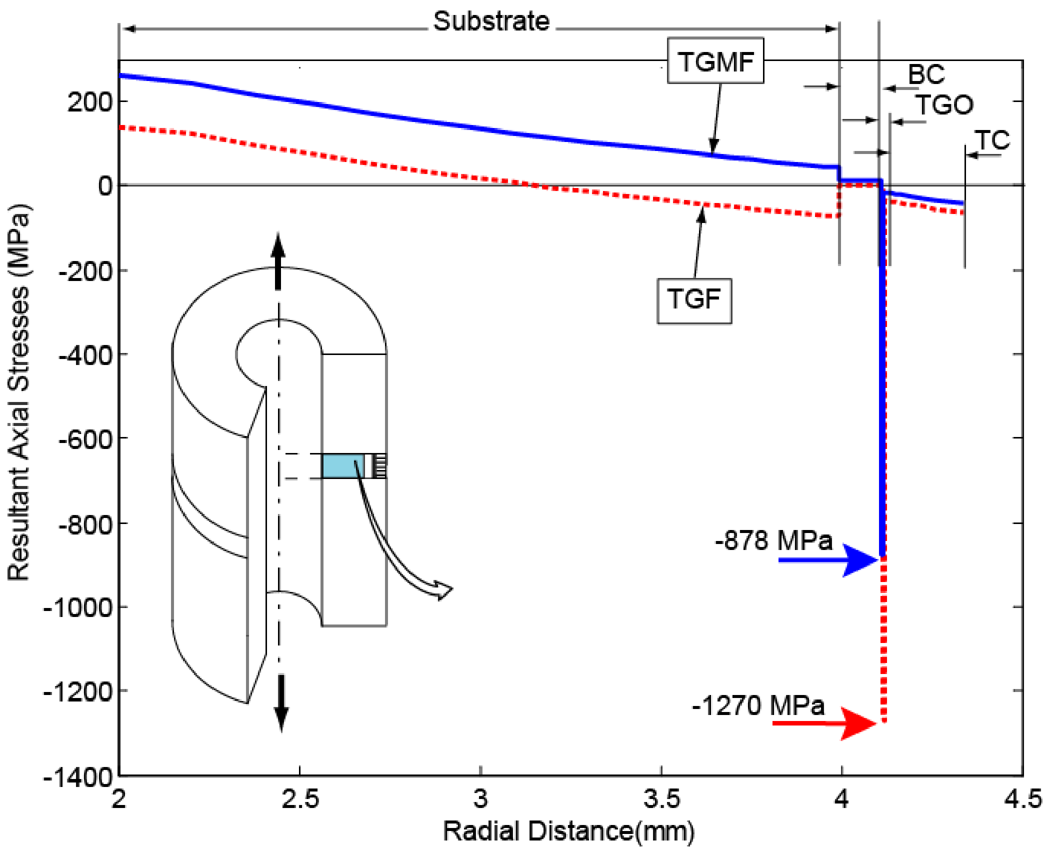
- Temperature at the outer surface is shown
- Thermal gradient: time dependent temperature difference between outer and inner wall (not shown)
- mechanical cycle TGMF





Highest mechanical tensile load, thermal gradient near equilibrium

Axial stresses for elastic – plastic material properties



Stress free at coating temp. (1000°C, homogenous)

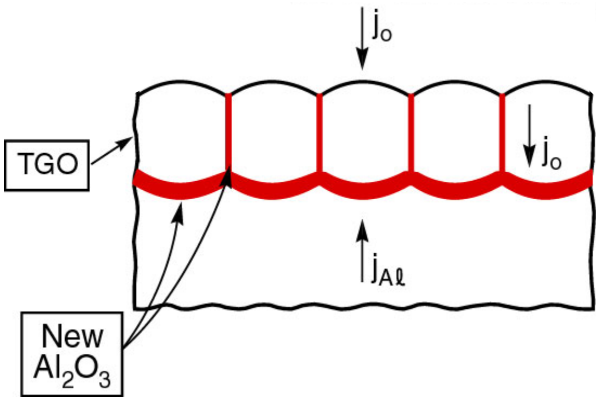
Axial stresses across the specimen wall due to

- thermal gradient
- mechanical load
- property mismatch

→ TGO always under compression

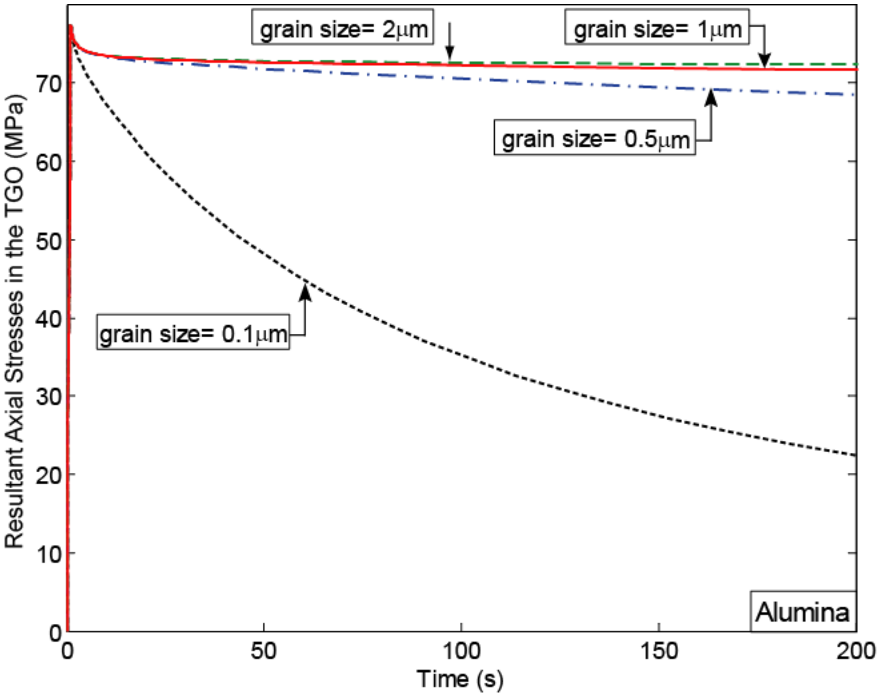
even at highest mechanical tensile load

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



Thickening ε_t and lengthening ε_l growth strain

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



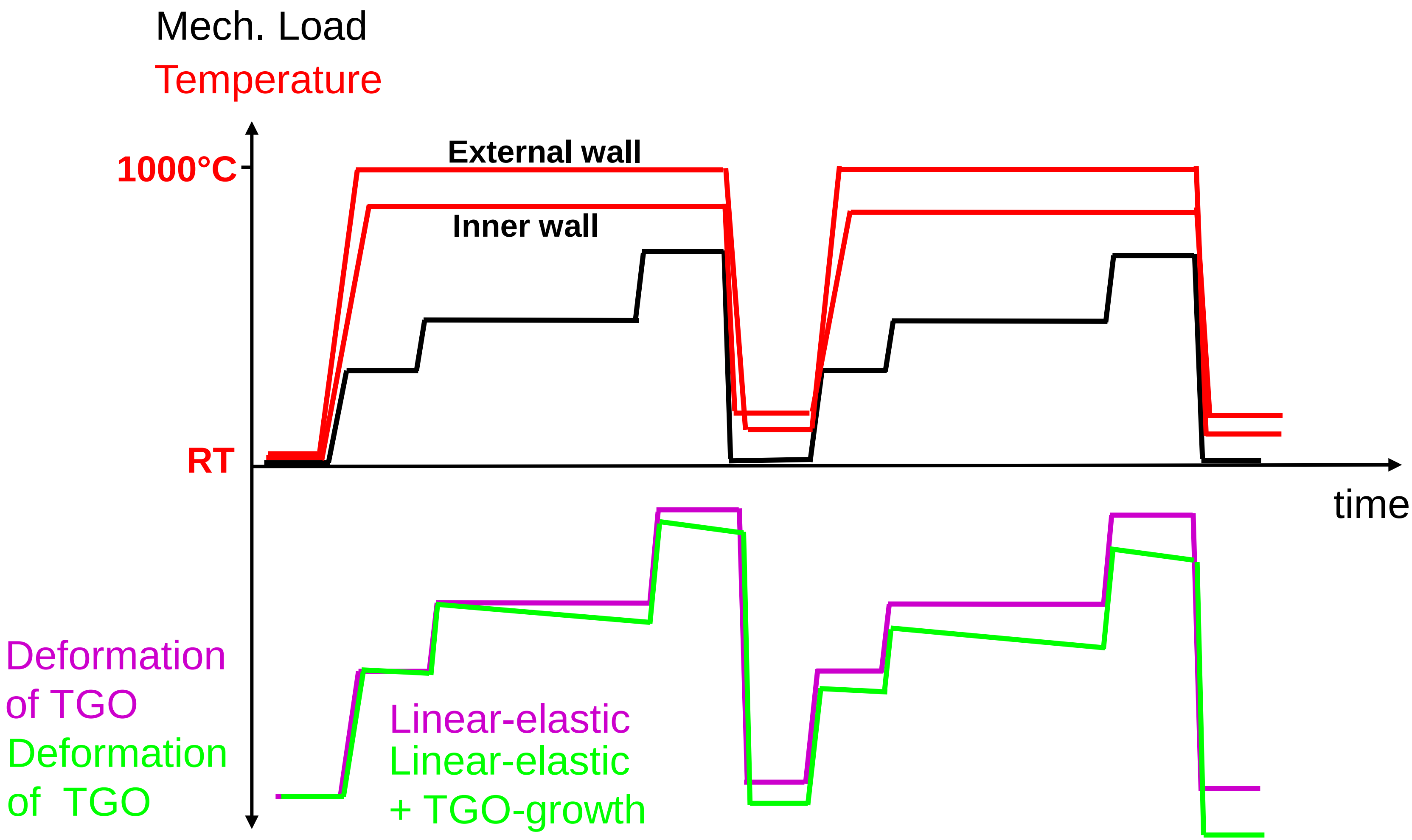
Growth strain increases the compressive stress in TGO!

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

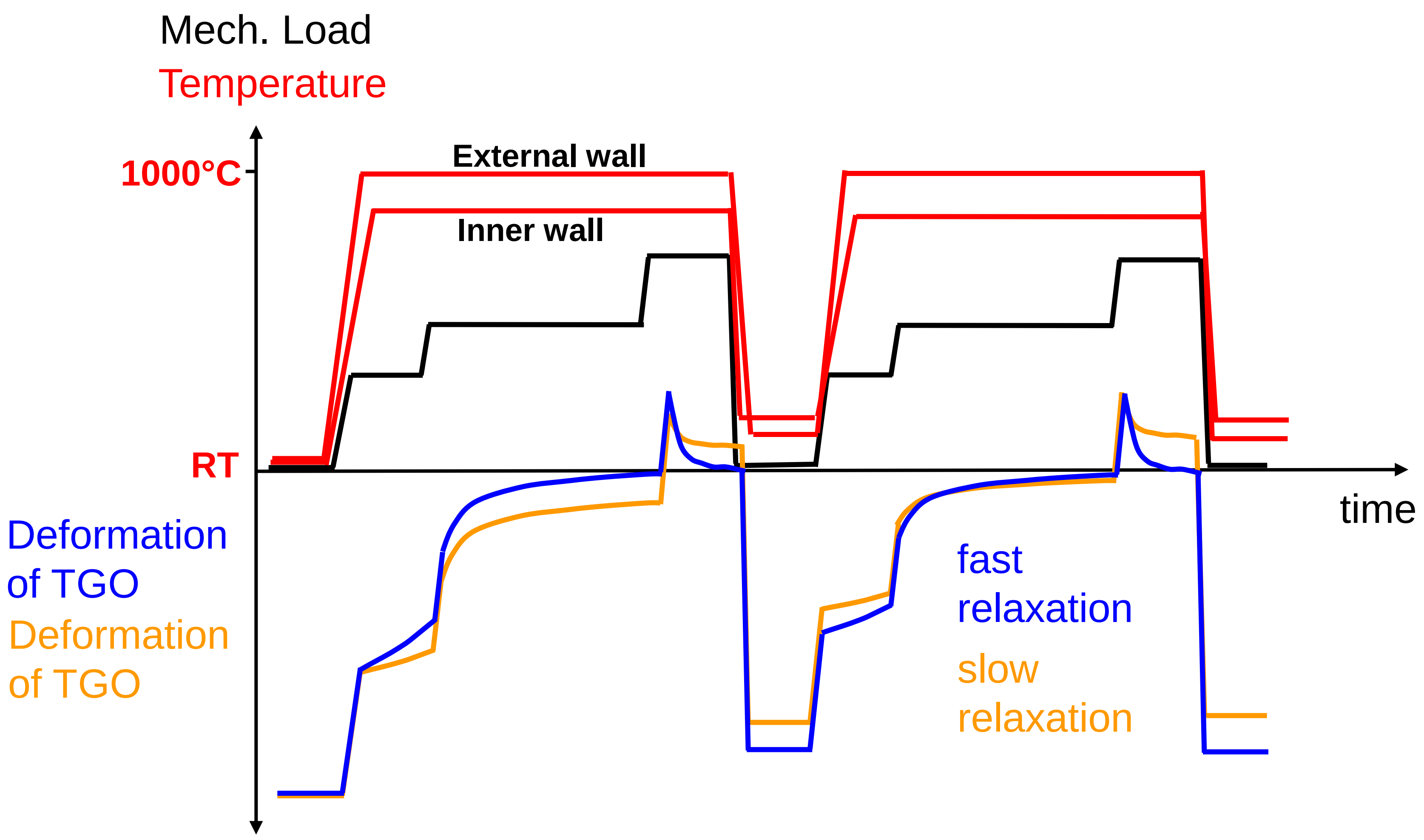
Relaxation decreases the compressive stress in TGO!

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

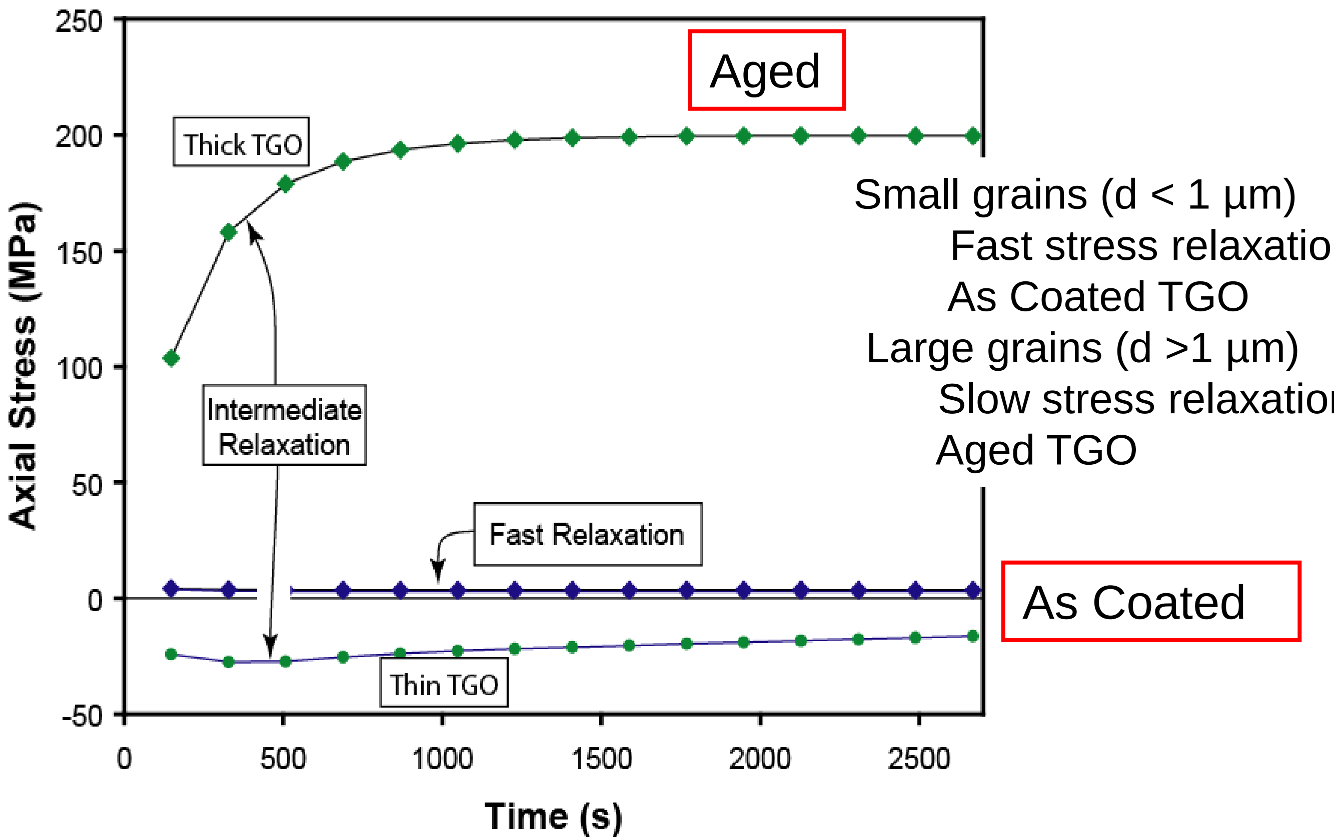
Effect of relaxation properties on stress accumulation



Effect of relaxation properties on stress accumulation



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

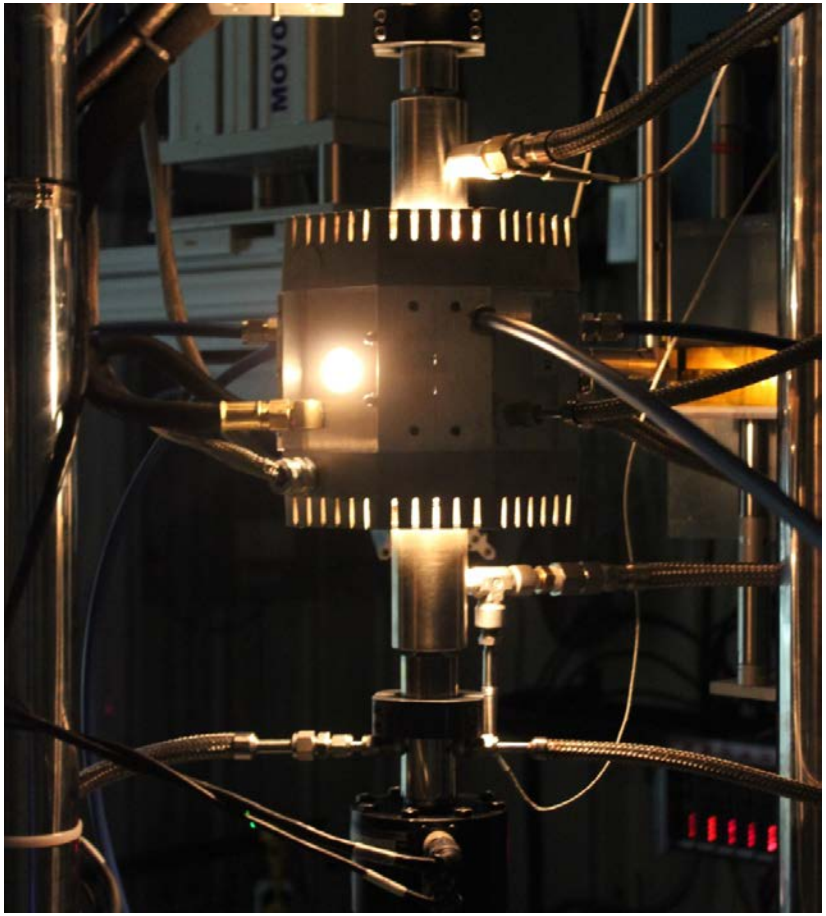
Open questions – things we want to know

- Mechanical material properties of the coating materials are still unknown: Temperature dependent elastic properties, yield strength, creep laws of TGO (intermixed zone and coarse grained layer), bond coat and TBC
- Most sensitive for damage behavior of the coating system are TGO properties
- Measurement of TGO properties is difficult due to small layer thickness (below 10 µm) and complex chemical composition (intermixed zone)

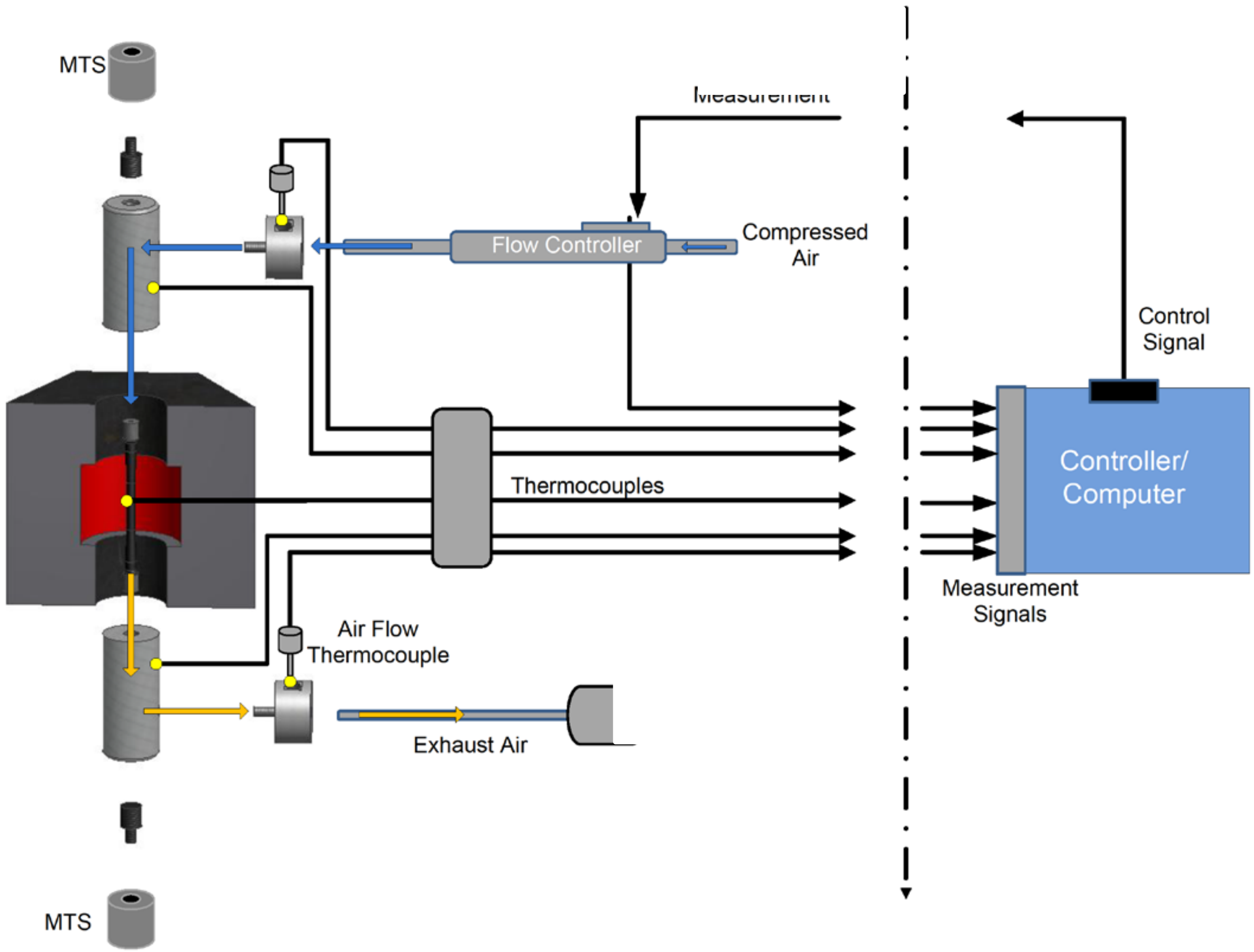
- Strategy:
  - measuring the strains in the coating system during TGMF by means of high energy X-ray diffraction
  - calculating the respective (fitting) material properties by means of finite element simulation

Experimental set-up at Argonne Advanced Photon source

- Argonne National Laboratory, Argonne, Illinois
- 1-ID Synchrotron High Energy X-Ray Beamline; 65 keV Beam Energy

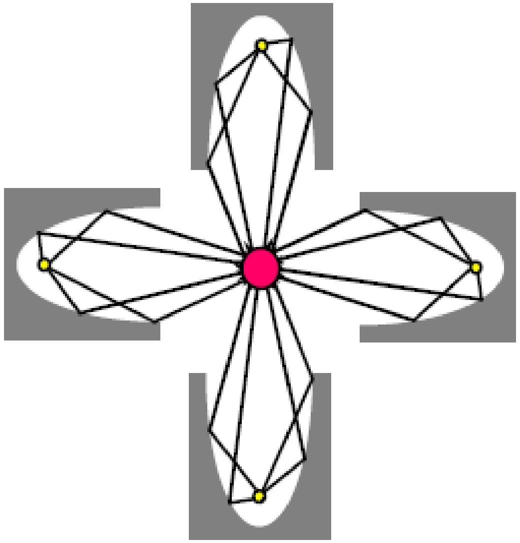


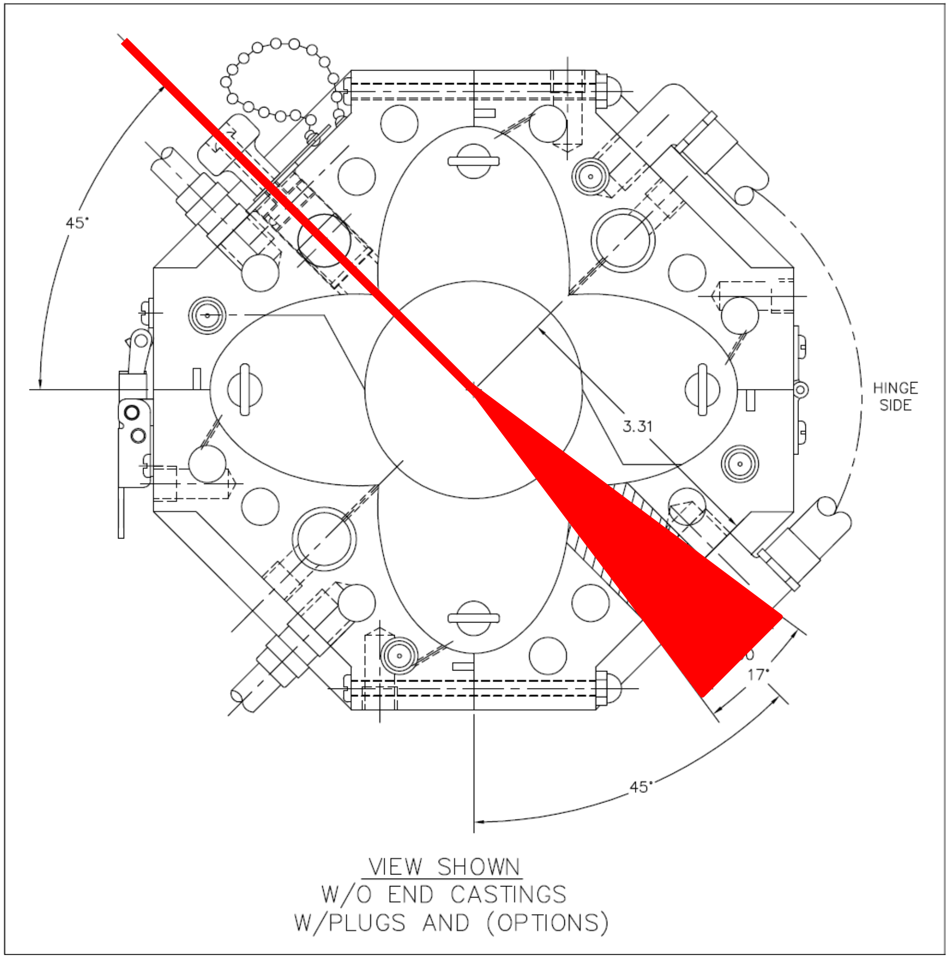
Schematic of test facility configuration



Top view of heater and beam

- 4 Focused IR Lamps
  - 8 kW Total
- Beam Exit Window
  - 17^0 4θ





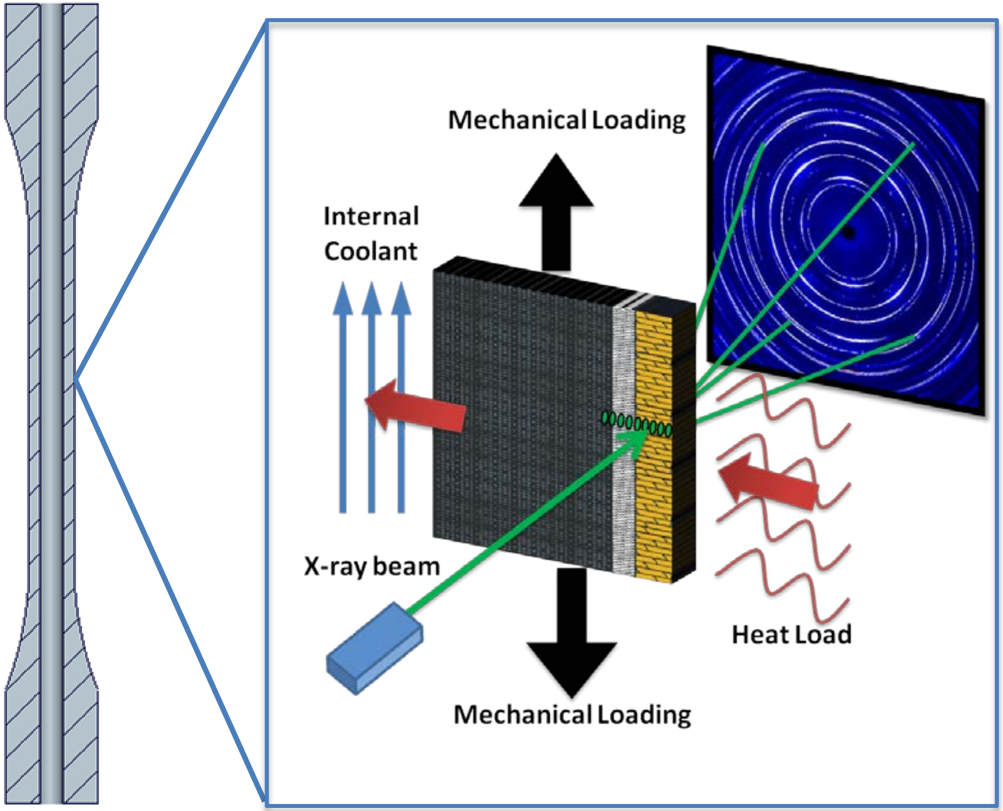
Measurement method

TGMF-Parameter:

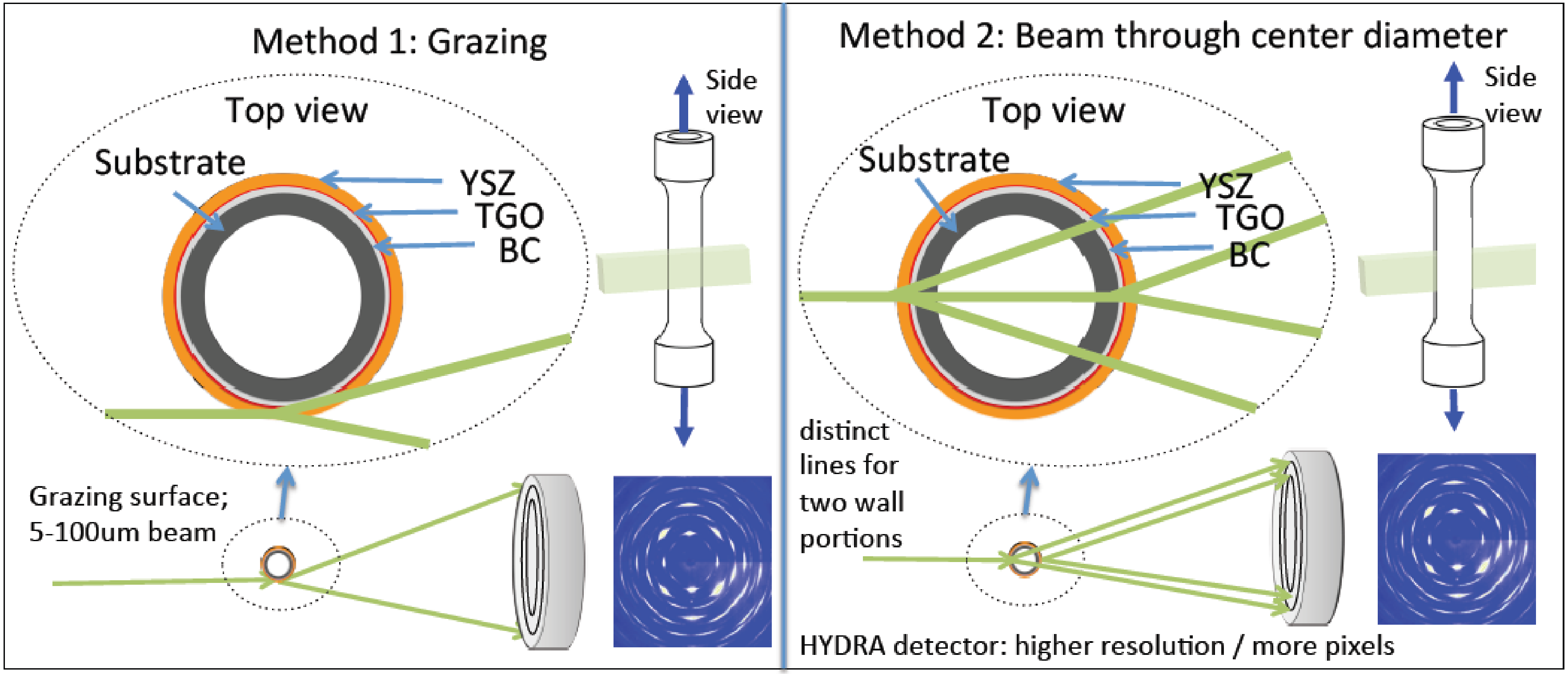
- Thermal mechanical cycle (80min duration)
- outer surface temperature max. 1000°C, temperature difference between outer and inner surface ca. 150°C
- variation of thermal gradient by variation of cooling flow rate
- Superposition of mechanical load cycle

Beam parameter:

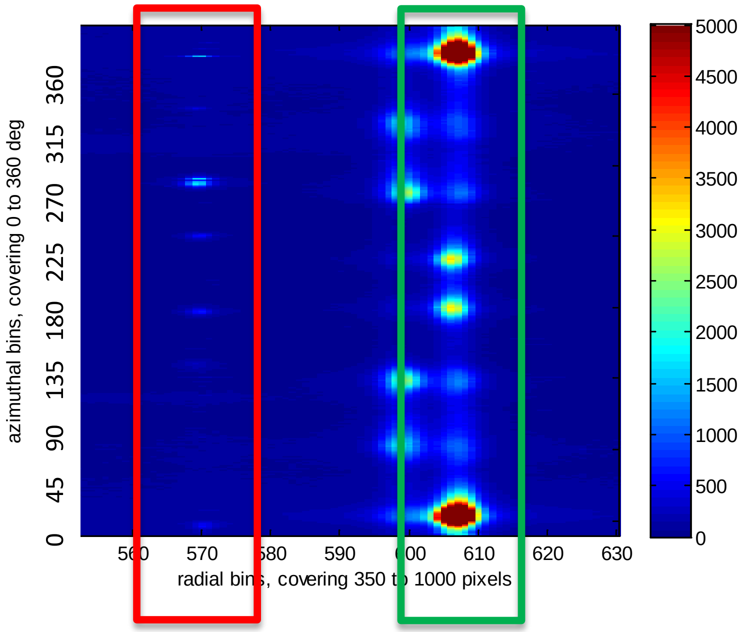
- 65 keV beam energy
- exposure time 0.5 to 15 sec.
- through specimen center and grazing

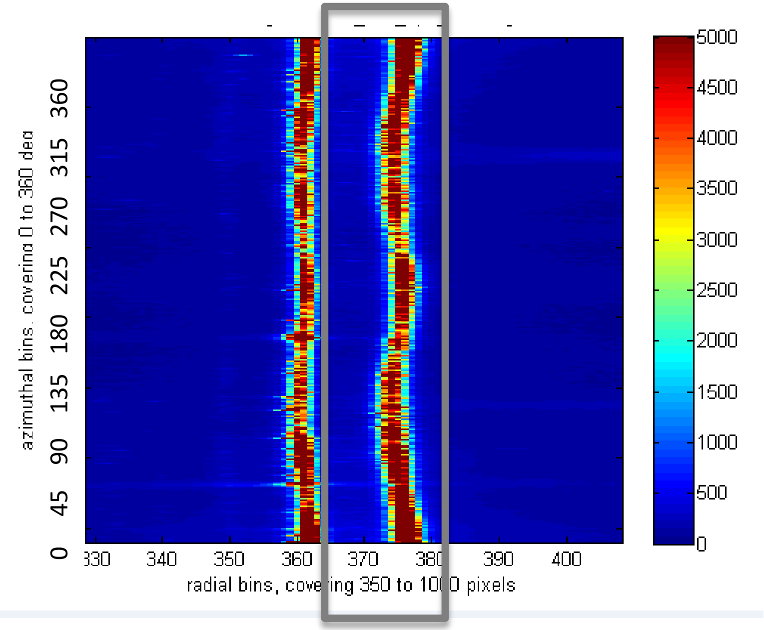


Measurement Methods



Qualitative Strain Results



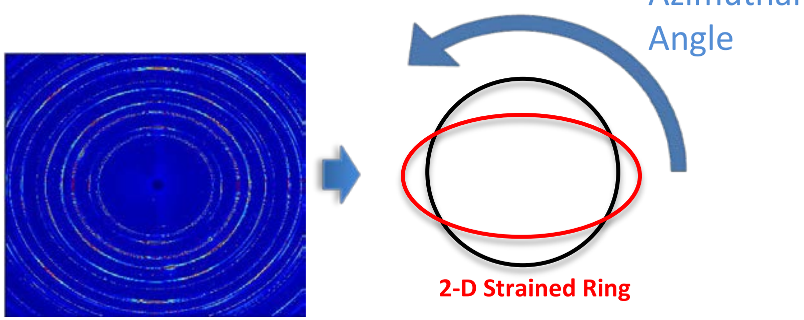


TGO
Al_2O_3 (116)

YSZ
ZrO_2 (202)

Bond Coat
AlNi (110)

- Evaluating radial position of diffraction ring for 0 to 360 degrees azimuthal angle
- strain is displayed by variation in ring radius
- significant strain visible in Bond Coat
- TGO displays texturing



Status of the project

- TGMF-tests have been successfully performed in-situ at the Advanced Photon Source at Argonne National Lab
- Diffraction data acquired for several cyclic loading conditions (up to 1000°C, temperature difference between inner and outer surface up to 150°C, superposed mechanical loads)
- All phases of the coating system are identified
- Significant strain observed in bond coat and TGO (qualitatively, calculation of strains and stresses ongoing)
- TGO and TBC display texture

Acknowledgement

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