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Staatliche Materialprüfungsanstalt Darmstadt (MPA)
Fachgebiet und Institut für Werkstoffkunde (IfW)

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HELSMAC Symposium on Materials and Coatings for High Temperatures

Evolution of the crack driving force and fracture resistance during thermal cycling

Cambridge, April 7, 2016

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Outline

- Impact of thermal cycling on coating stresses and damage progression
- Coating life: crack driving force vs. fracture resistance
- Crack driving force
  - Constrained vs. free standing sintering
  - In-plane vs. out-of-plane stiffness
- Fracture resistance
  - Cohesive vs. adhesive fracture toughness
  - Vertical crack resistance
- Summary & Conclusions

Load situation during operation

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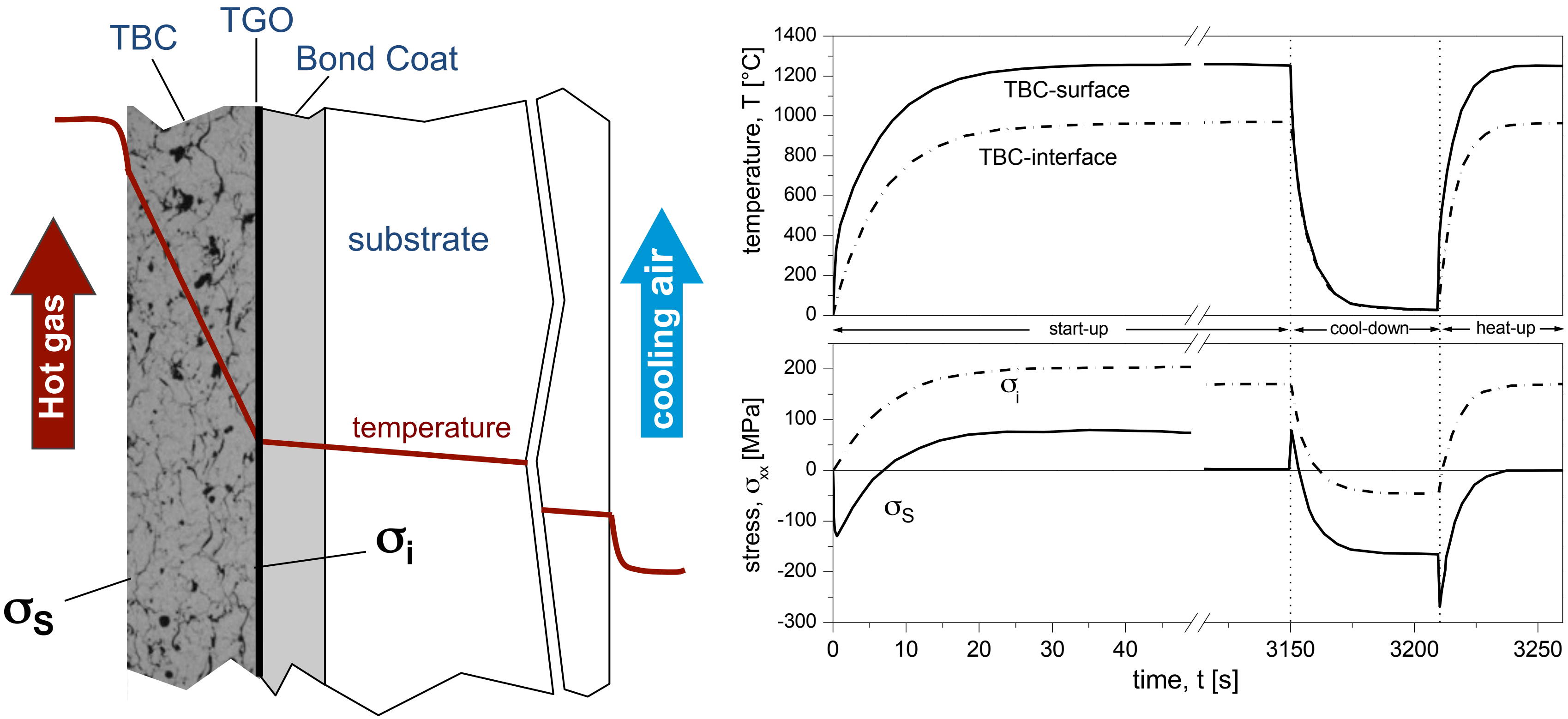
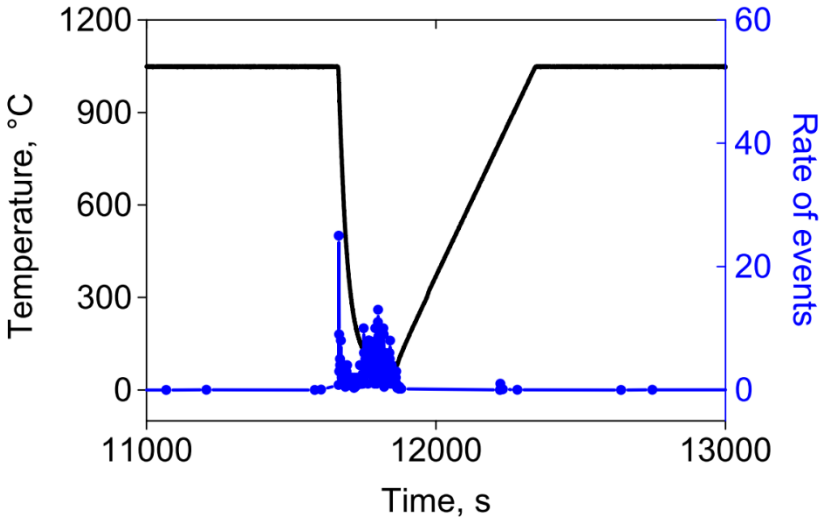


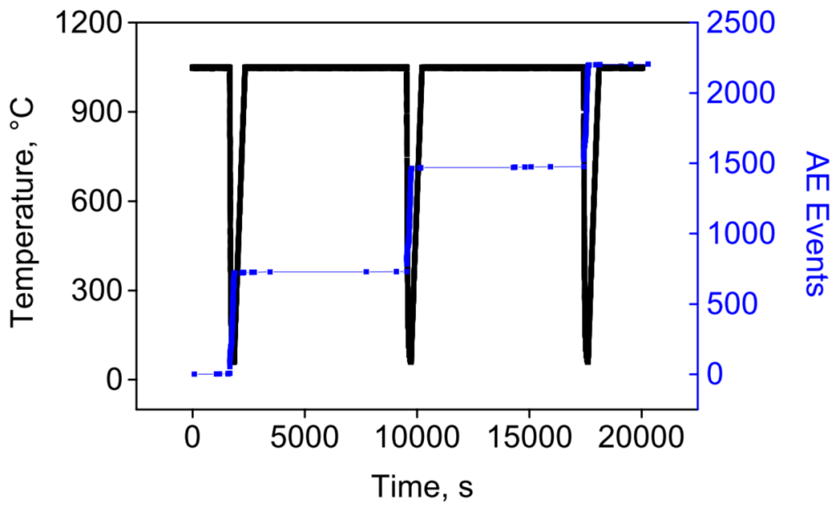
[M. Oechsner, Bd. 18, VDI Fortschrittsberichte Nr. 263. Düsseldorf: 2001]

- Layer stresses due to thermal misfit & thermal gradient
- Stress relaxation during stationary dwell time
- Thermal shock of ceramic surface during heat-up and cool down

Coating Damage progression during cyclic loading

Damage detection using acoustic emission

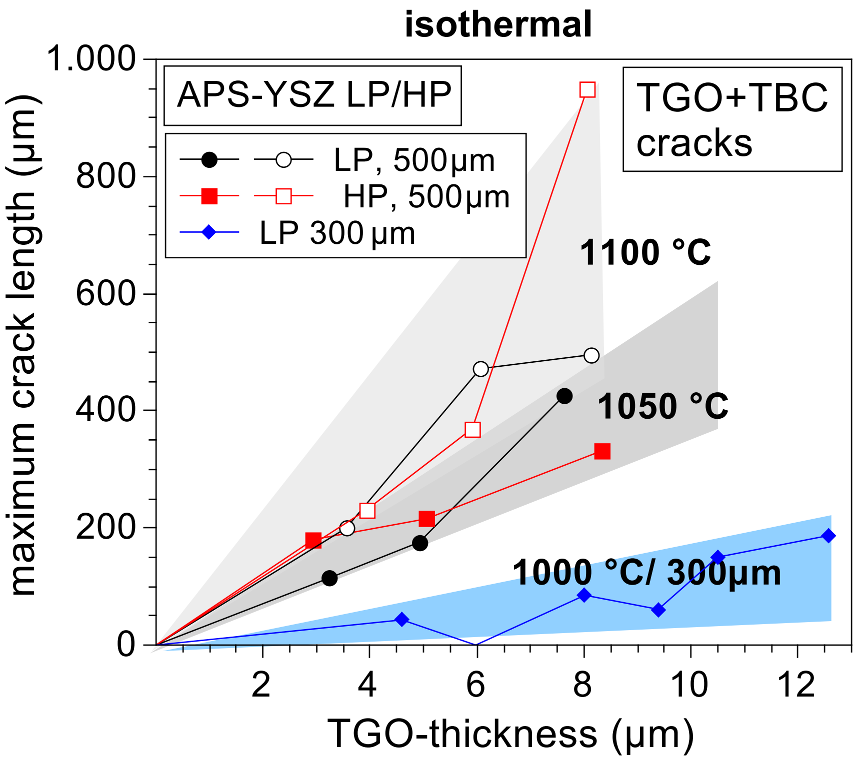


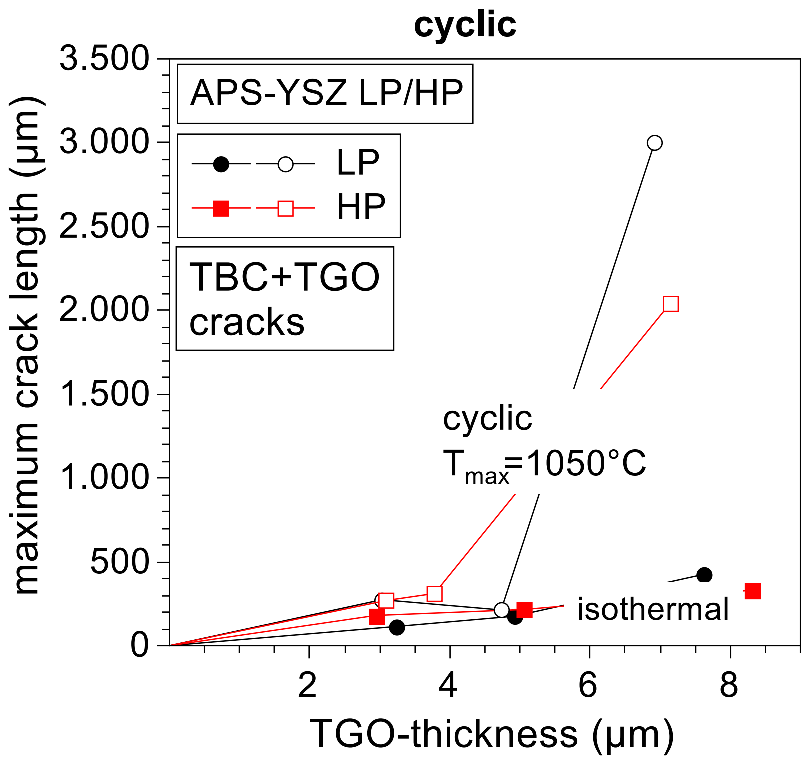


[O. Trunova, RWTH Aachen, 2006]

Acoustic emission signals are detected during cool down phase

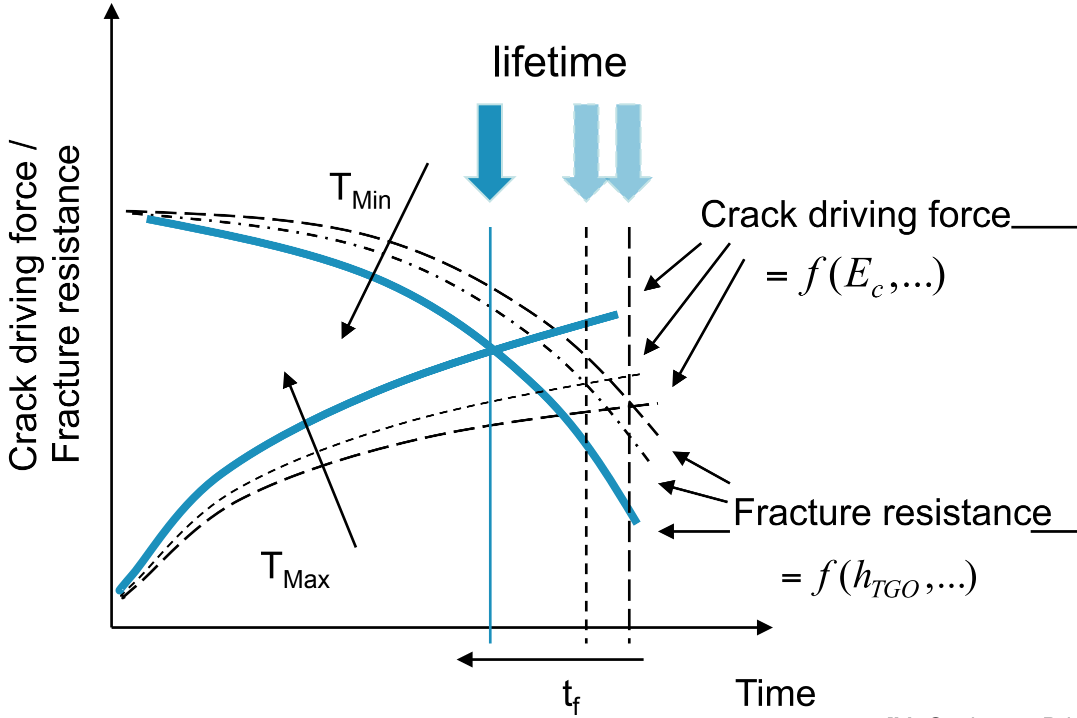
Accumulated damage during cyclic oxidation

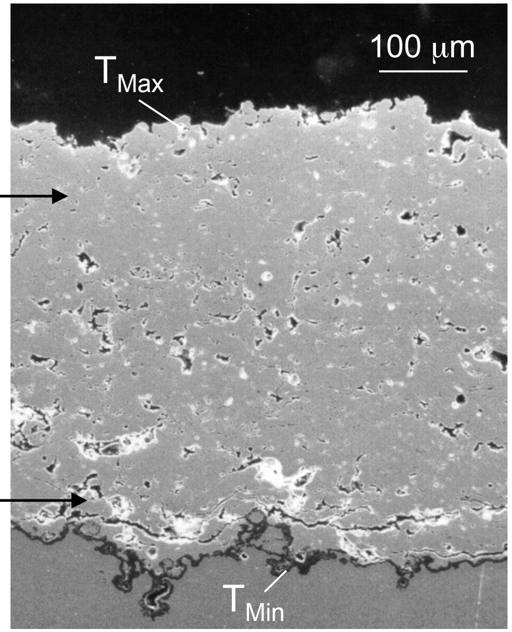




- Macroscopic crack growth after „incubation time“ (t@T)
- Cyclic loading results in faster crack growth kinetics

Approach to assess TBC life time



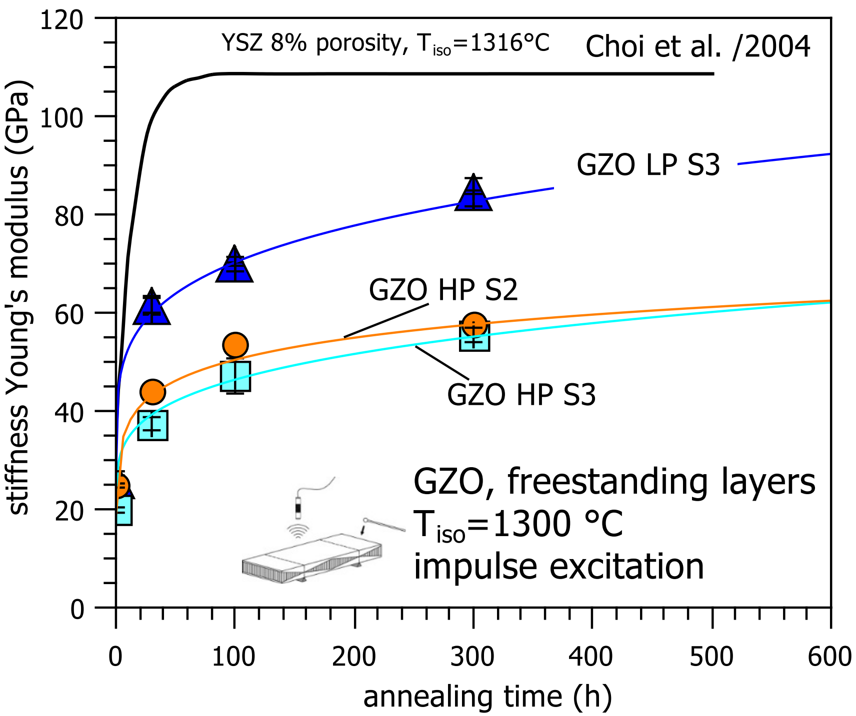


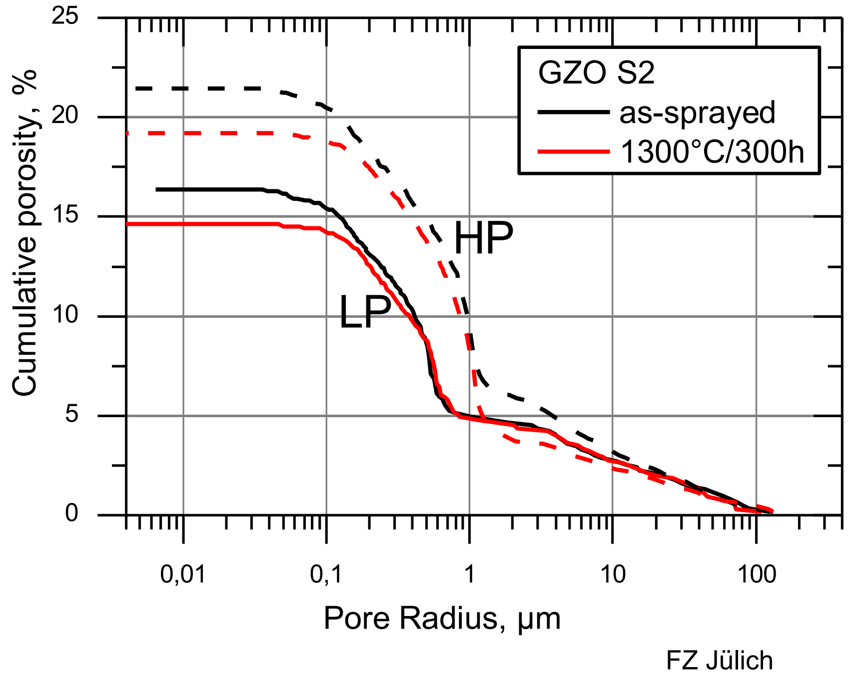
[M. Oechsner, Bd. 18, VDI Fortschrittsberichte Nr. 263. Düsseldorf: 2001]

- Crack driving force and toughness against crack propagation are time dependent
- Kinetics are determined by the surface and interface temperature

Crack Driving Force

Crack Driving Force
Increase in Coating Stiffness

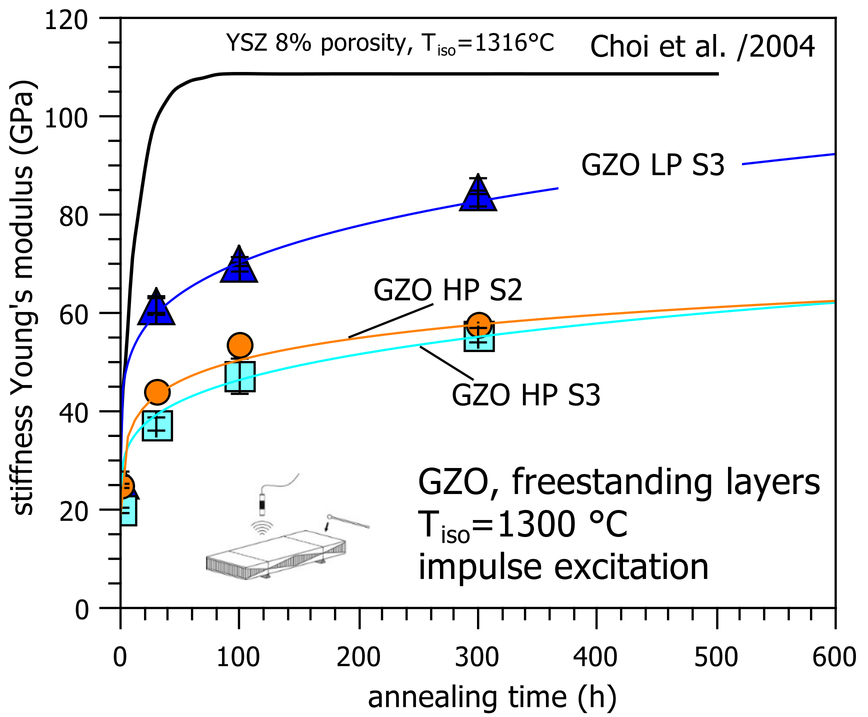


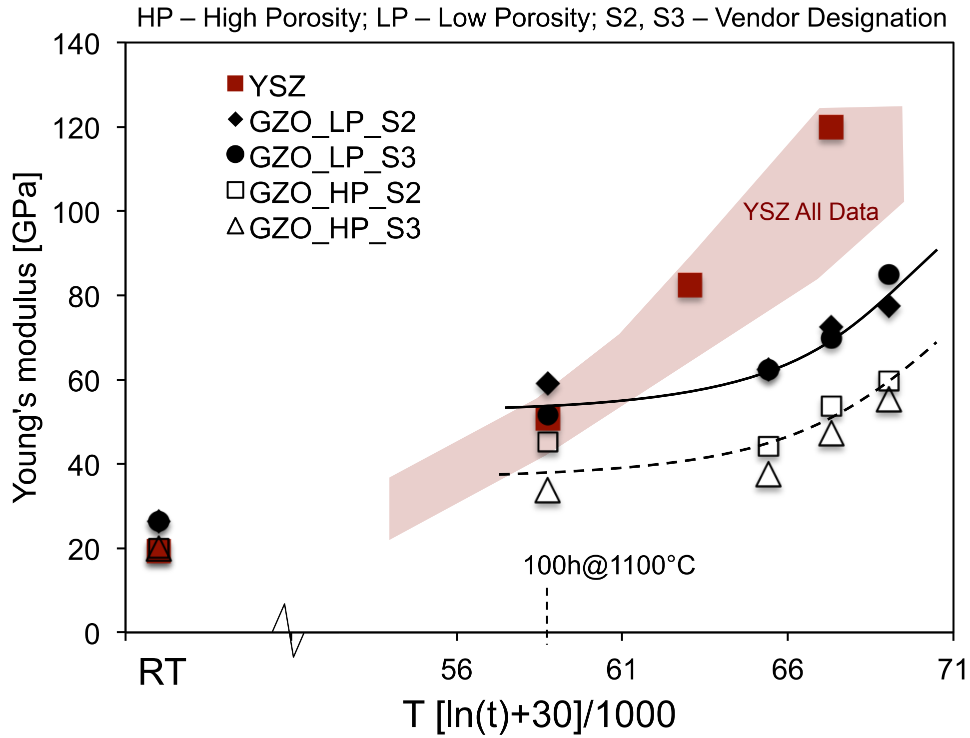


- Stiffness und thus the Crack Driving Force increase due to sintering
- Increase in stiffness is mainly correlated to healing and sintering of “submicron” defects

Crack Driving Force

Time-Temperature-Parameter



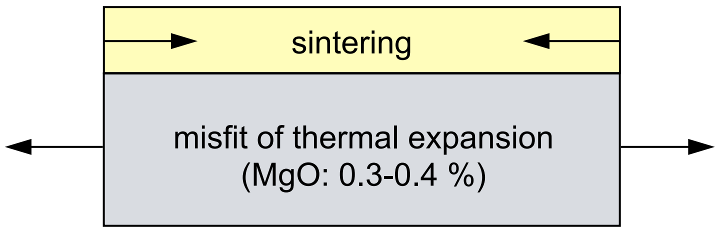


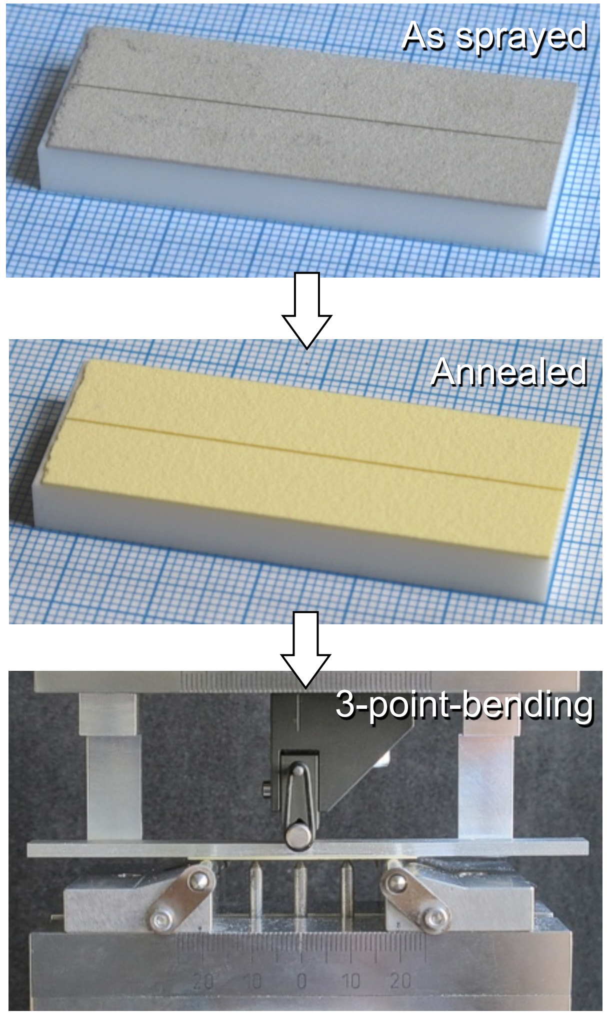
Change in Young's modulus can be described by a time-temperature relation

Crack Driving Force

What impact has constraint on sintering?

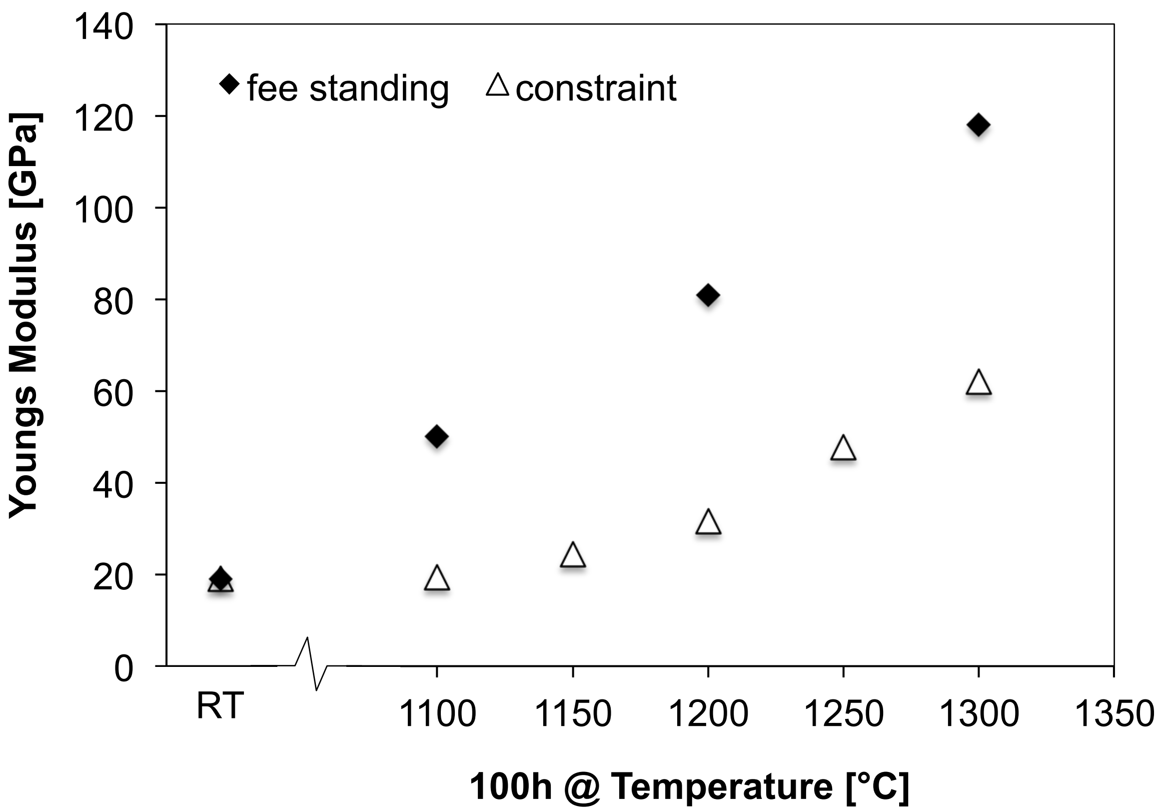
- YSZ has been sprayed on Magnesia (MgO) specimens in order to allow high temperature exposure while being constraint by a substrate
- Note that the CTE of Magnesia is larger than the CTE of YSZ, mimicking the constraint conditions present at nickel-based superalloys



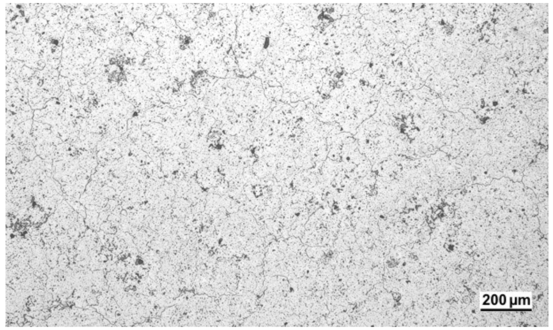


Crack Driving Force

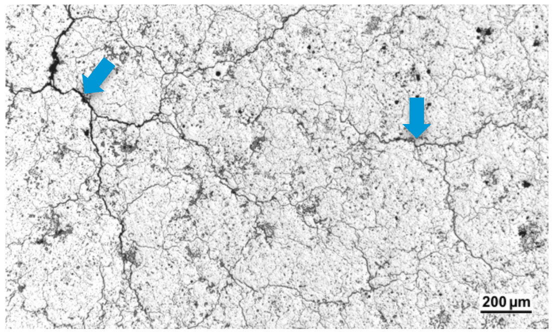
Approximation of local stiffness properties



Free standing



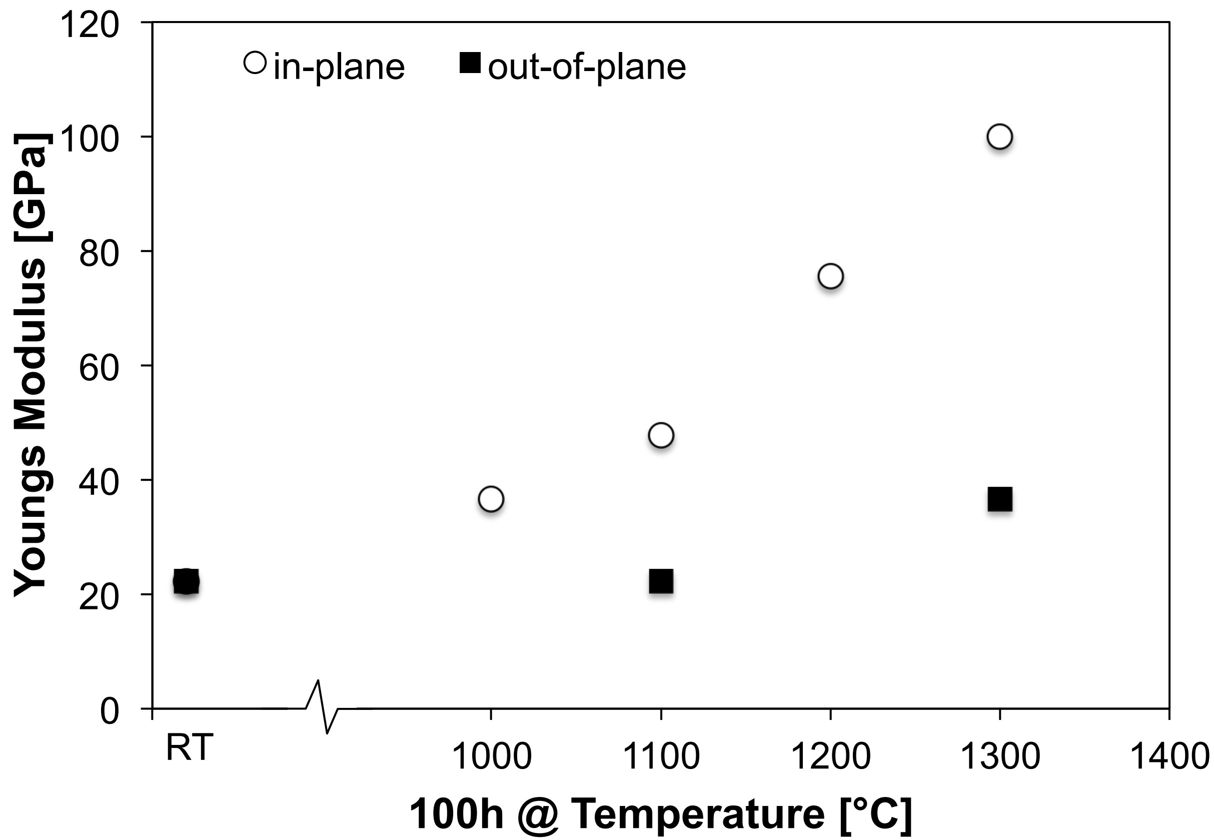
Constraint (ε ≈ 0.4%)



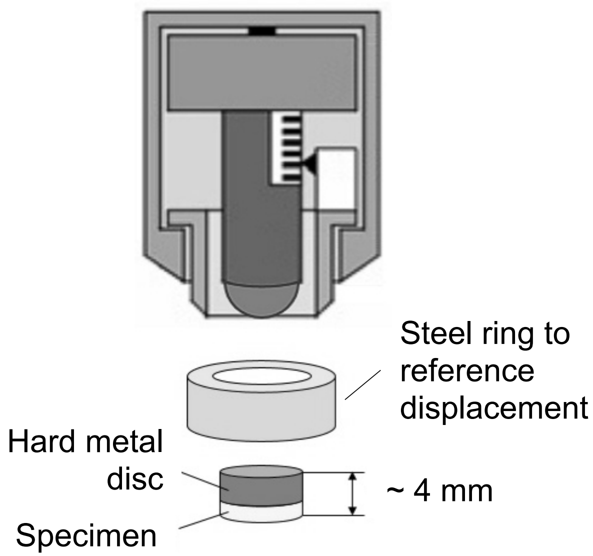
[P. Wittig, unpublished]

- Constraint during sintering reduces increase in stiffness
- Segmentation cracks in coating after constraint sintering visible

Anisotropy of elastic properties



Miniature Compression Test



Significant stiffness difference of free standing sintered samples ($E^{\perp} < 0{,}6 \cdot E^{=}$)

Validation
Young's Modulus on Combustor Component

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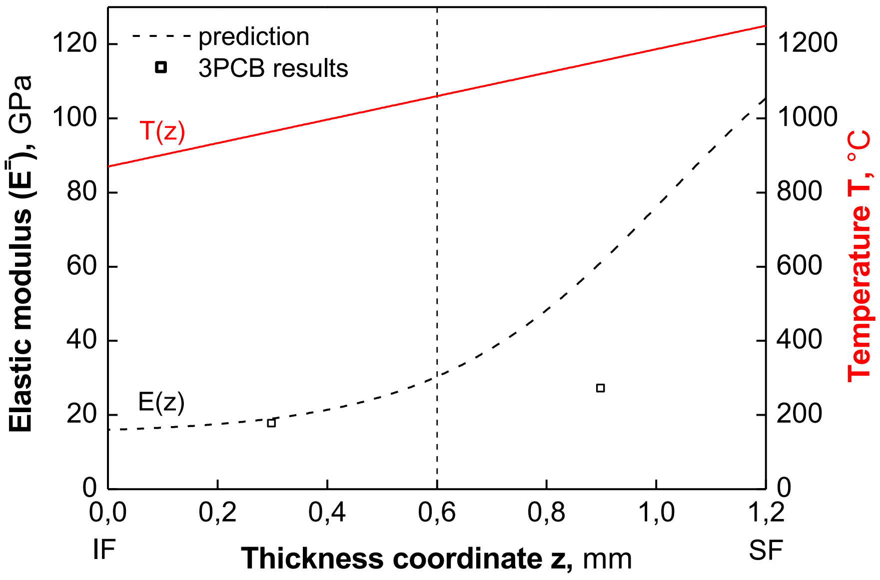
Heat Shield
Siemens SGT-4000F

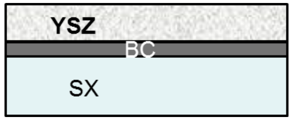
$T_{Surface}$ ≈ 1250°C
$T_{BondCoat}$ ≈ 870°C
$t_{Operation}$ ≈ 6.600 hrs.

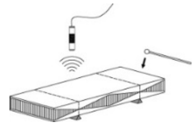
Validation

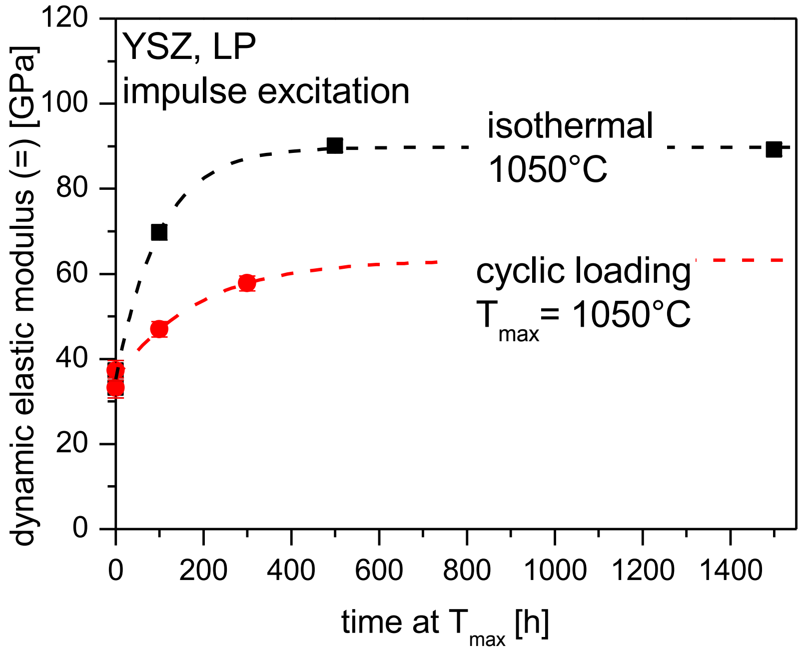
High temperature modulus over-estimated by prediction

Effective planar elastic modulus, $E^{=}$







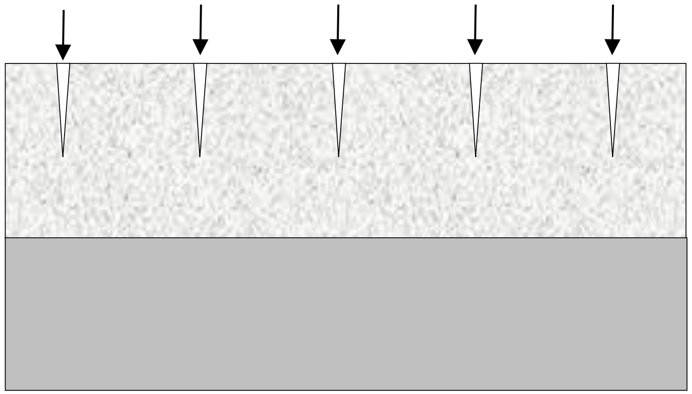


Low temperature modulus is captured well by prediction, however high temperature modulus is predicted too low

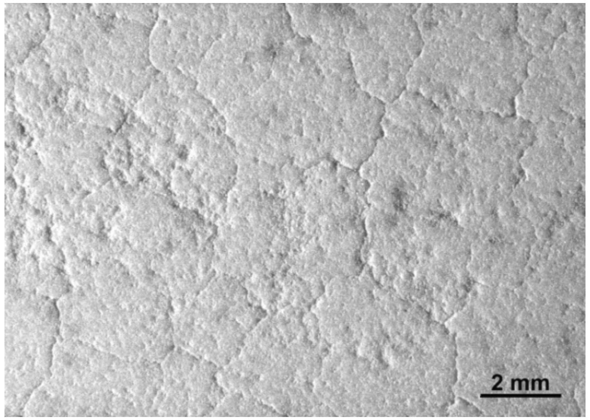
→ Potential impact of segmented TBC from cyclic loading?

Combustor tiles show segmentation cracks
Explanation for reduced stiffness?

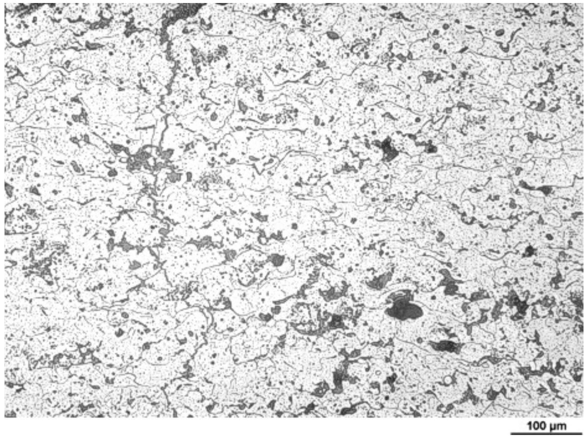
Sintering under constraint + cyclic loading introduce segmentation cracks, lowering the in-plane stiffness



Top view



Cross section



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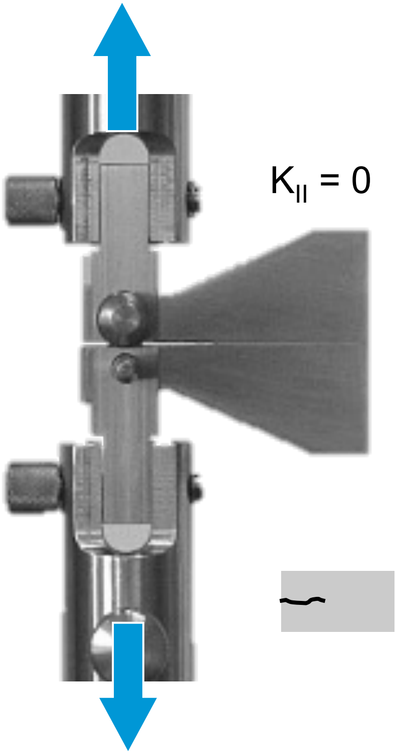
Fracture Resistance

Fracture Resistance

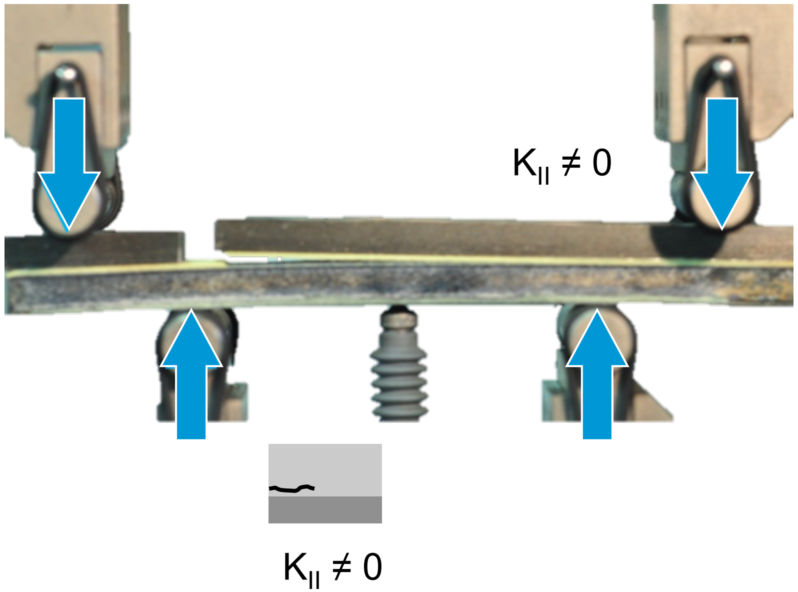
In-plane Fracture Toughness

TDCB
Tapered Double Cantilever Beam



→ Cohesive Fracture Resistance

Modified 4-Point Bending Test



→ Interfacial Fracture Resistance

Fracture Resistance
Local Evolution

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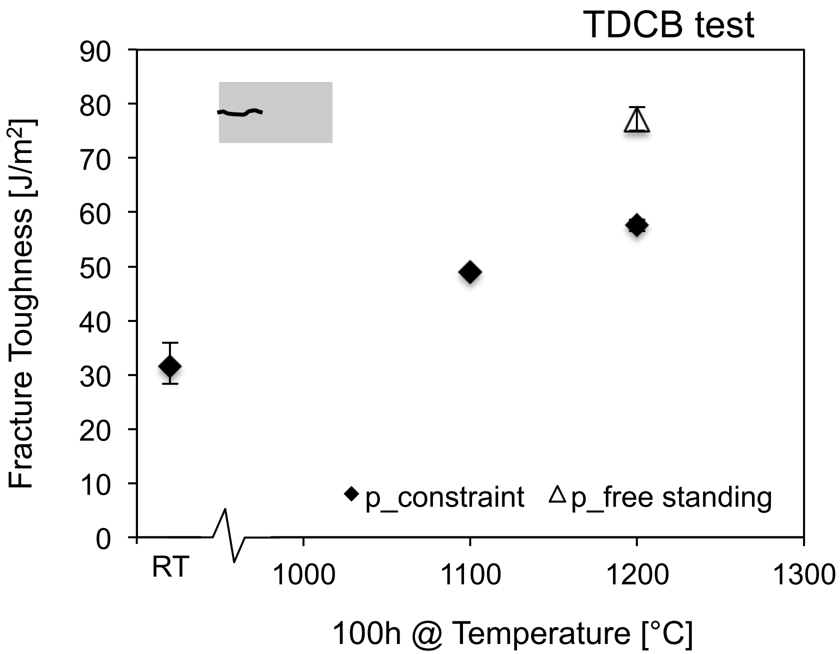
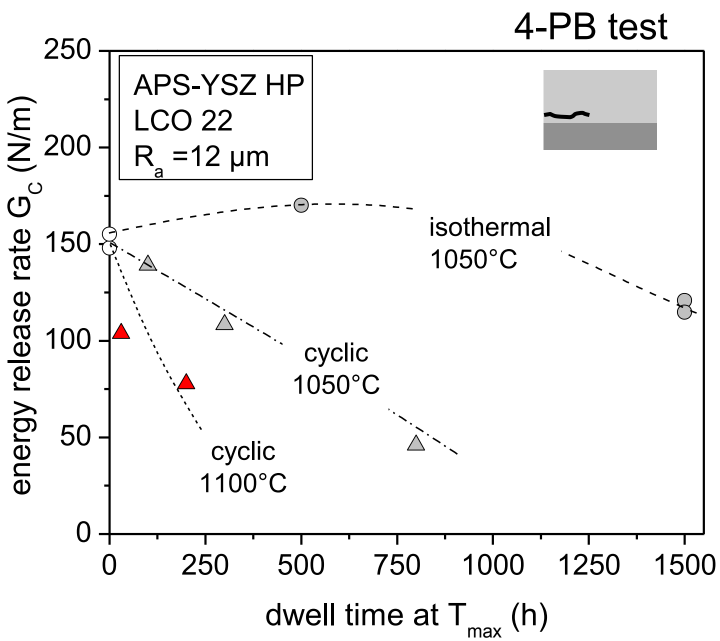
Cohesive fracture toughness



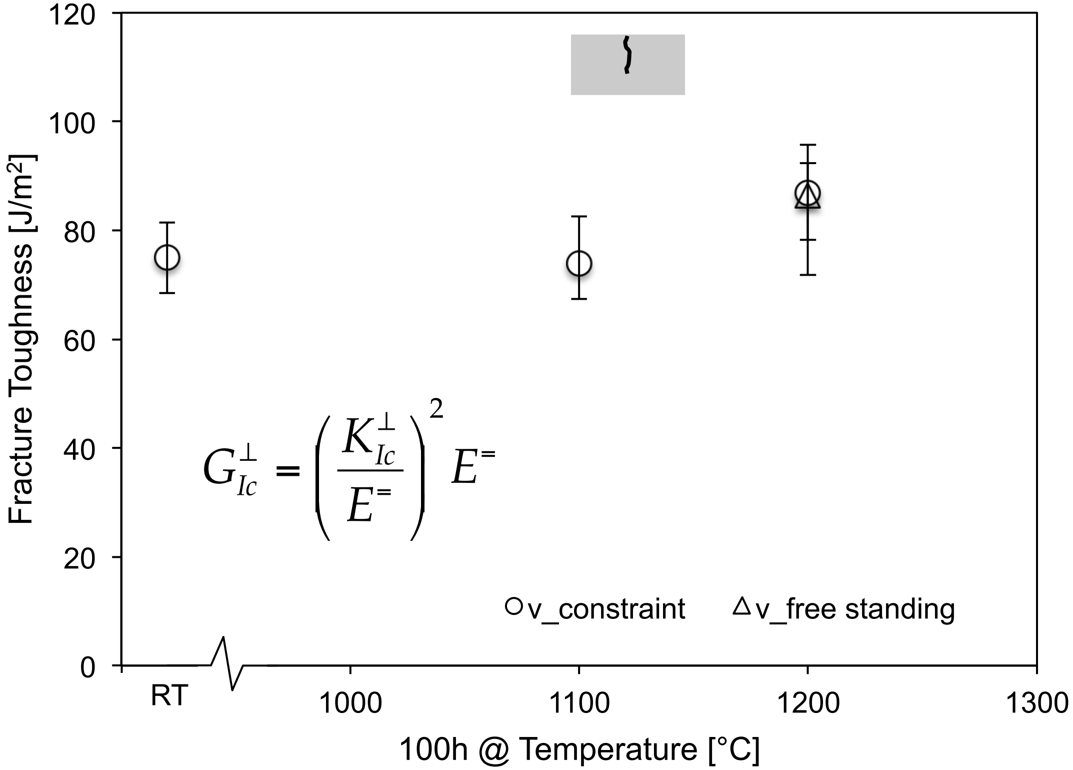
Interface fracture toughness



- Sintering results in an increase in toughness
- Influence of segmentation is limited

- Damage accumulation due to subcritical crack growth
- TGO growth induces damage

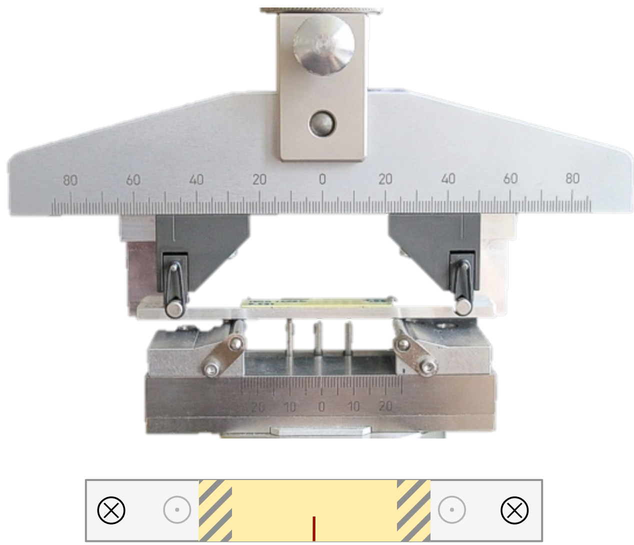
Fracture Resistance
Anisotropy



$$G_{Ic}^{\perp} = \left(\frac{K_{Ic}^{\perp}}{E^{=}}\right)^2 E^{=}$$

SENUD

Single Edge Notched Uniform Displacement



Slight increase in fracture toughness due to sintering

Validation
Prediction vs. Experiment

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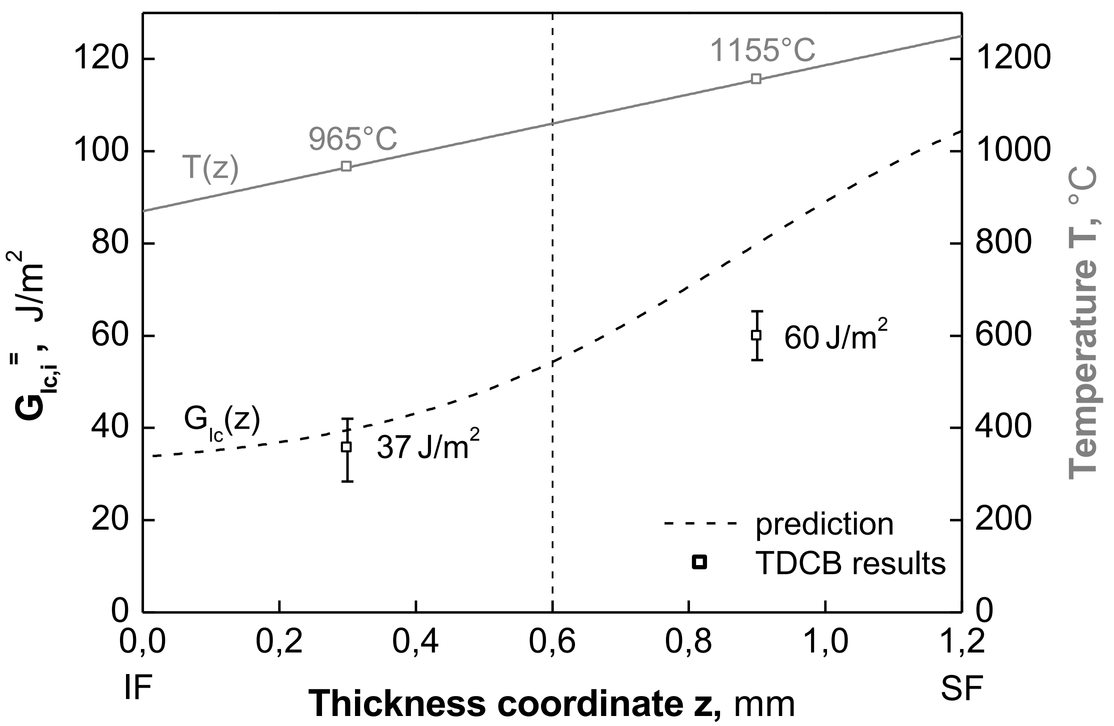
Critical energy release rate **$G_{Ic}^{=}$** (small cracks)



[data: P. Wittig]

Model prediction over-estimates the observed fracture toughness

Summary & Conclusions

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- Thermal cycling accelerates coating degradation
- Crack driving force & fracture resistance change with time, temperature and cyclic loading conditions
- Crack driving force
  - Sintering under constraint conditions reduces increase in coating stiffness
  - Sintering under constraint conditions introduces vertical cracking
  - Cyclic loading introduces coating segmentation
  - Out-of-plane stiffness changes at a slower rate compared to in-plane stiffness
- Fracture resistance
  - Cohesive fracture toughness increases with time@temperature
  - Adhesive fracture toughness decreases with growth of TGO
  - Only slight increase in resistance against vertical cracking due to sintering
- Comparison with service experienced components confirms general trend


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