

Crack Morphology in a Columnar Thermal Barrier Coating System

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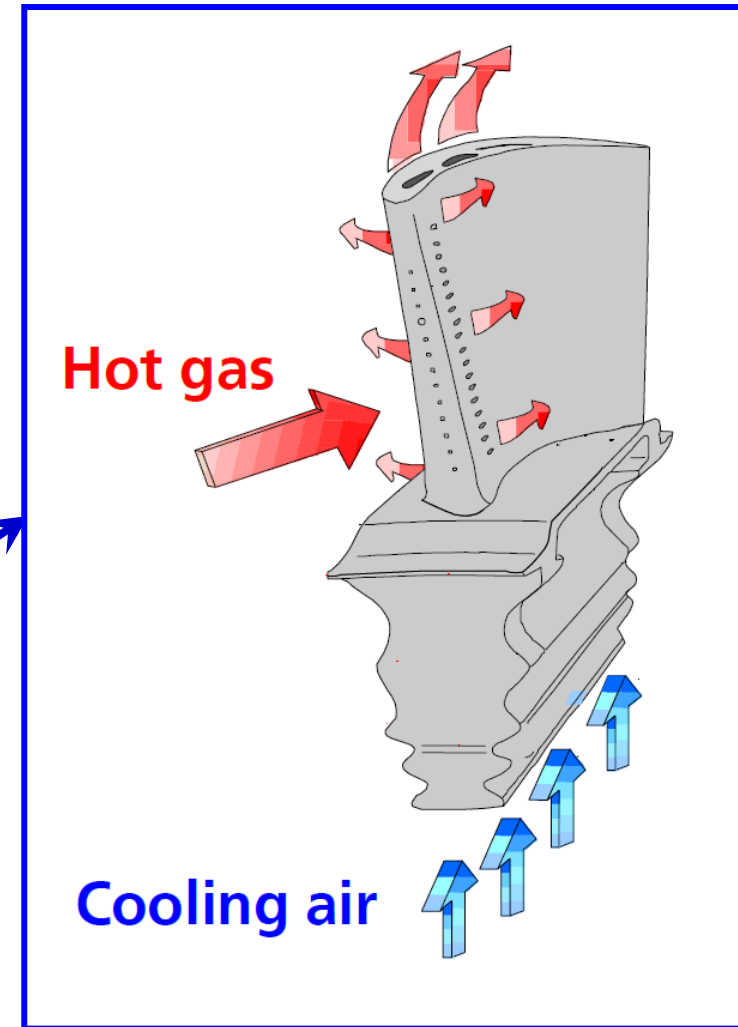
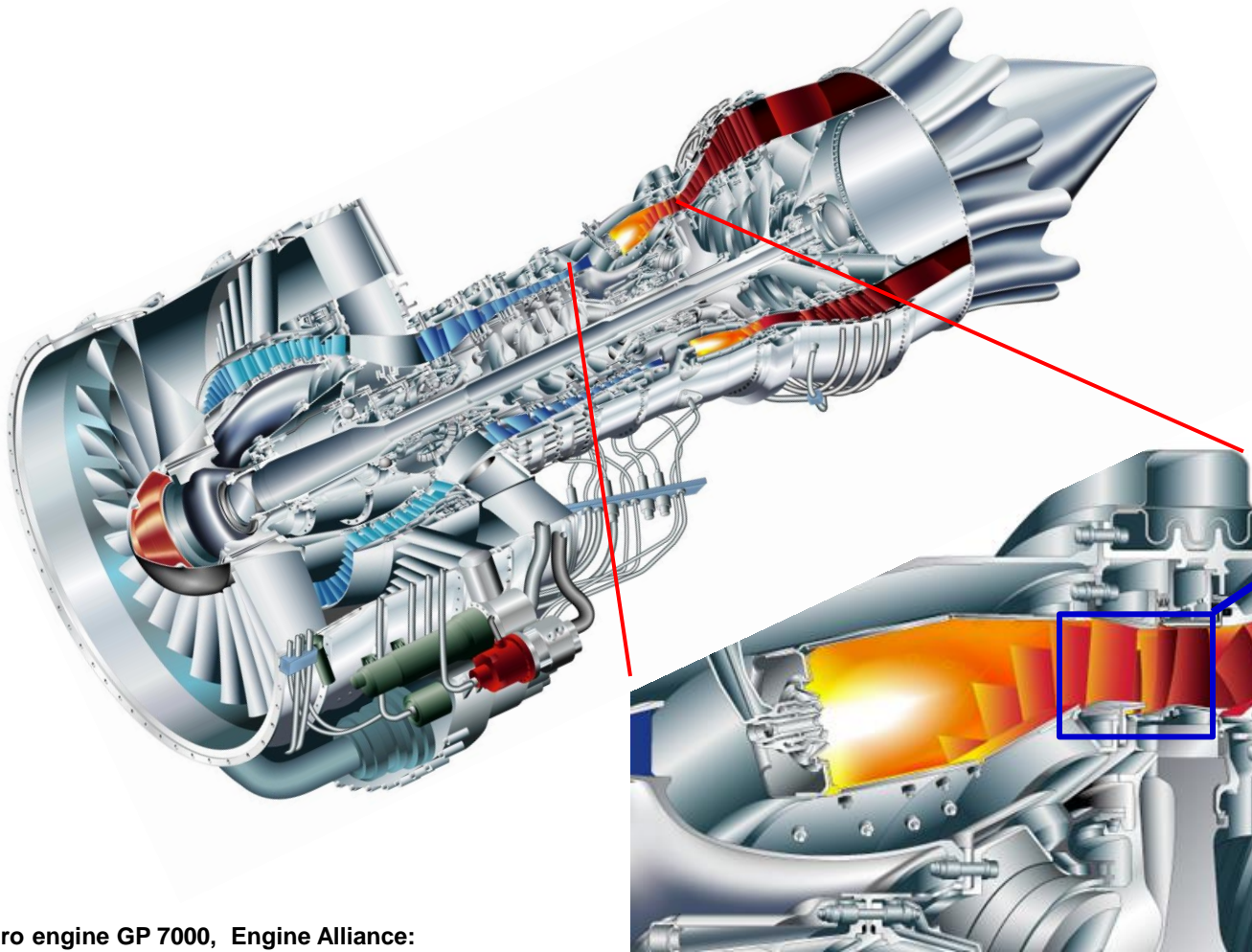
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Outlook

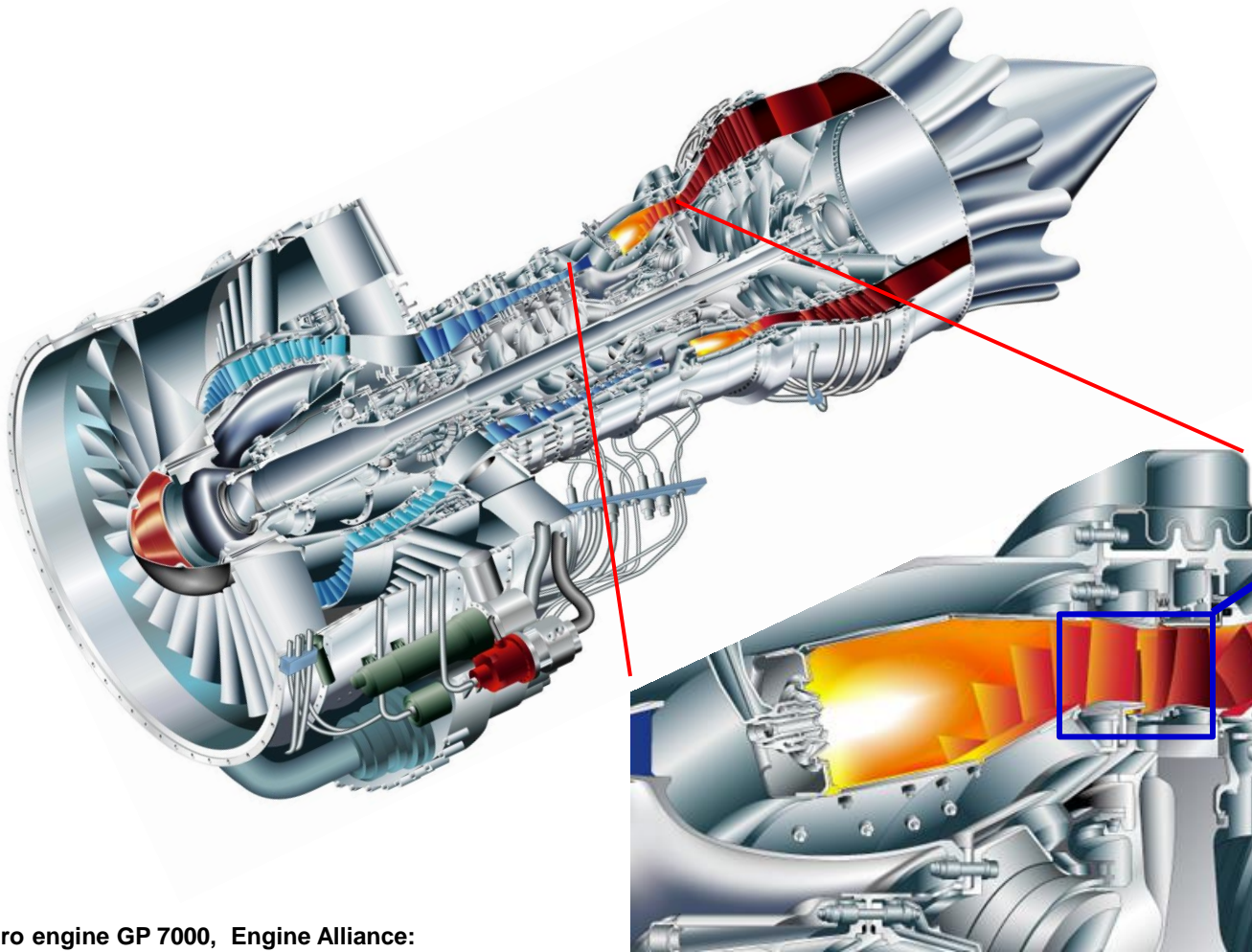
- **Introduction**
- **Damage features in service and laboratory experiments**
- **Laser Shock Adhesion Test (LASAT)**
- **Characterization of damages introduced by LASAT**
- **3 dimensional imaging by FIB-slice & view**
- **Summary and conclusions**

Application of Thermal Barrier Coatings

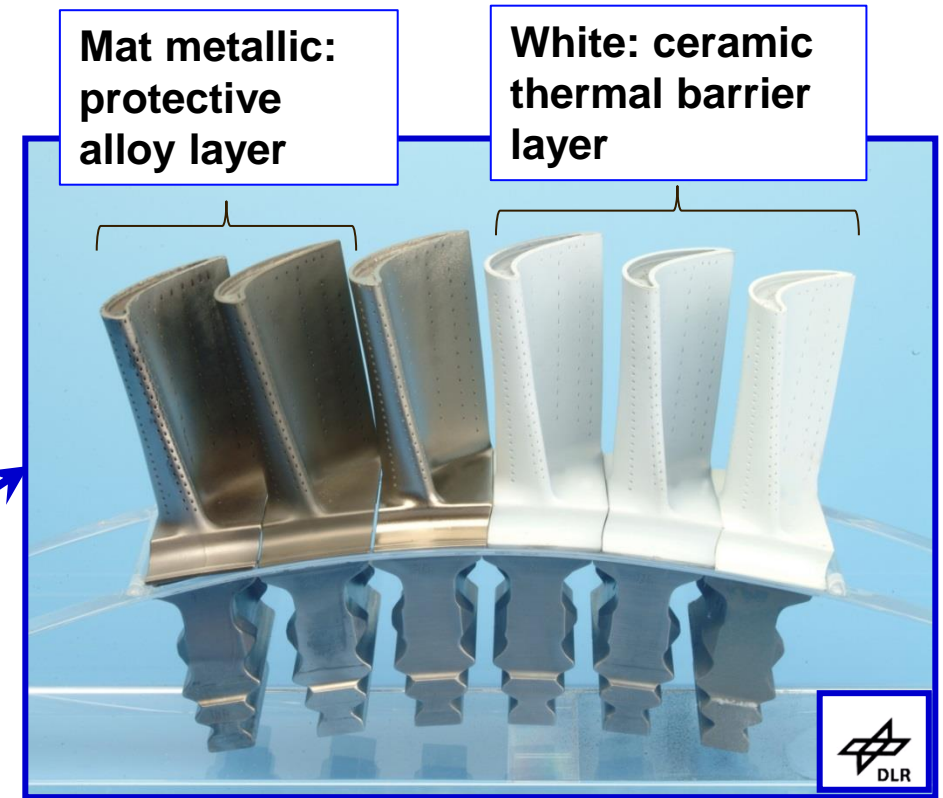


Aero engine GP 7000, Engine Alliance:
GE Aircraft Engines and Pratt & Whitney
Artwork: Engine Alliance

Application of Thermal Barrier Coatings

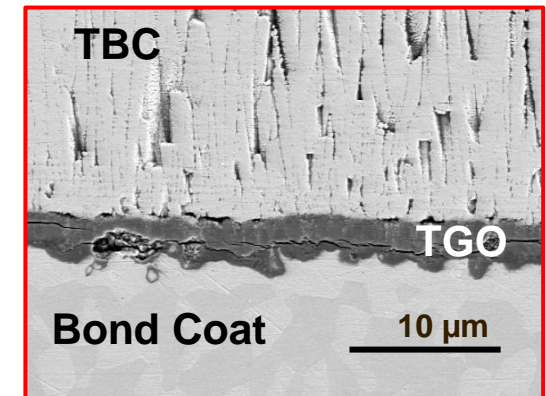
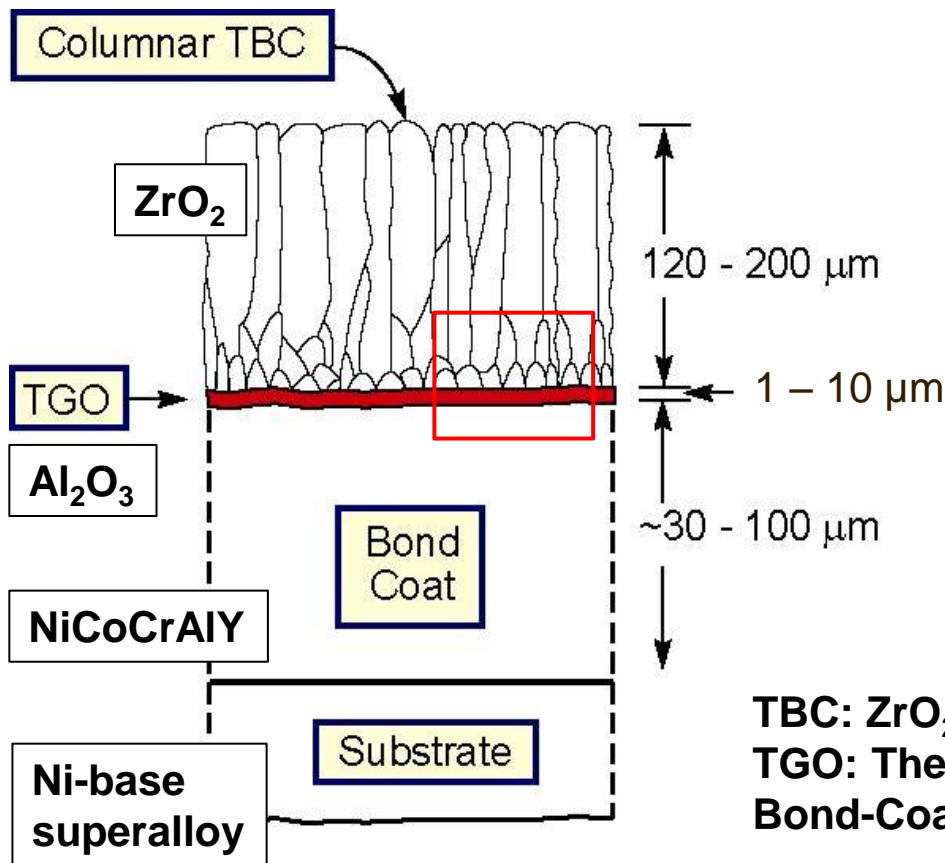
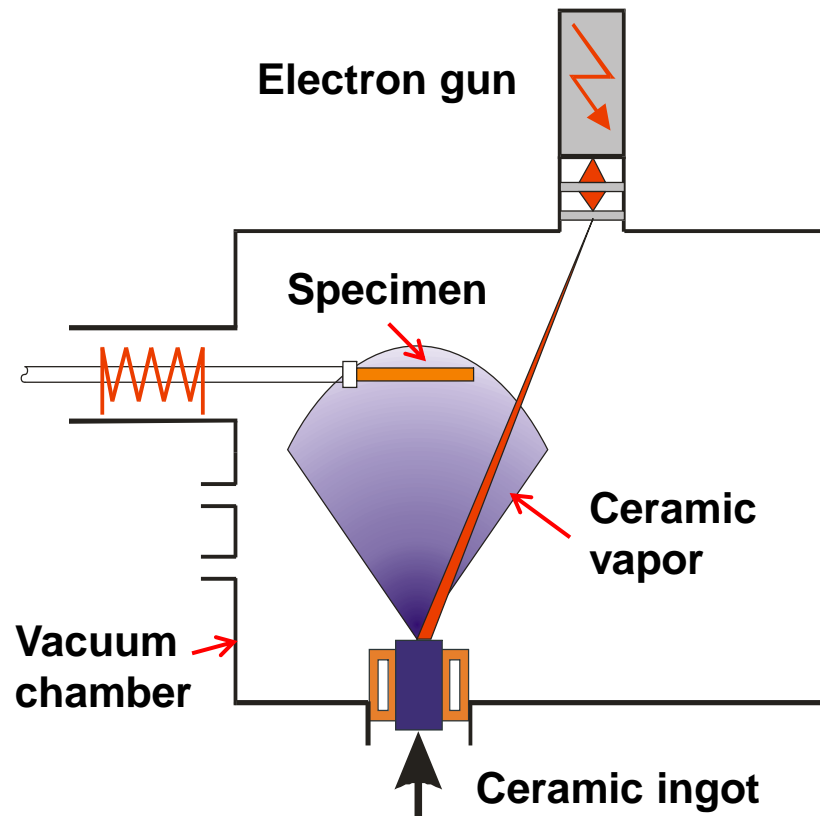


Aero engine GP 7000, Engine Alliance:
GE Aircraft Engines and Pratt & Whitney
Artwork: Engine Alliance



Coated turbine blades for aero engines

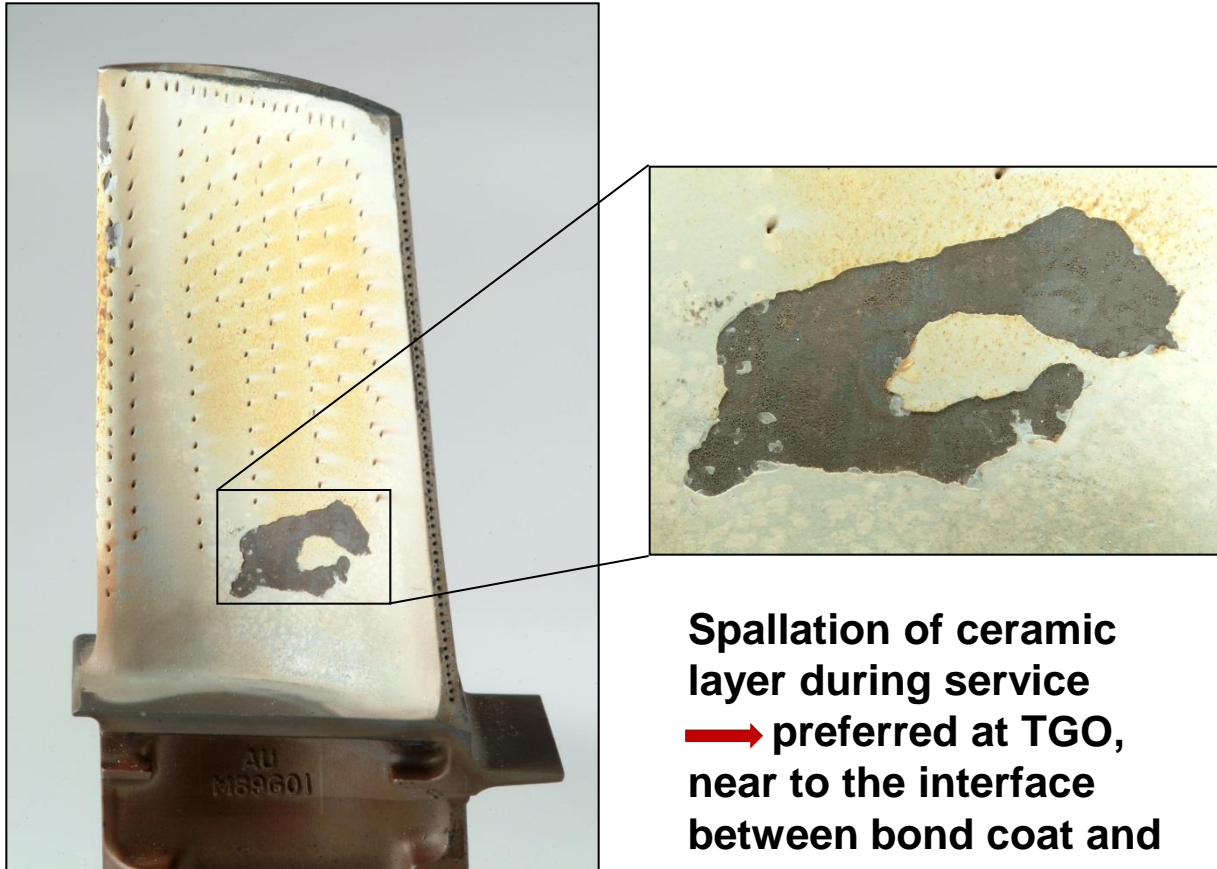
Processing and microstructure of columnar TBC's by EB-PVD



TBC: ZrO₂ stabilized with 6-8 wt % Y₂O₃
 TGO: Thermally Grown Oxide, Al₂O₃
 Bond-Coat: Aluminum rich alloy

Electron Beam - Physical Vapor Deposition

Damage features in service and laboratory experiments



Turbine blade of aero engine

Spallation of ceramic layer during service
→ preferred at TGO, near to the interface between bond coat and ceramic top coat

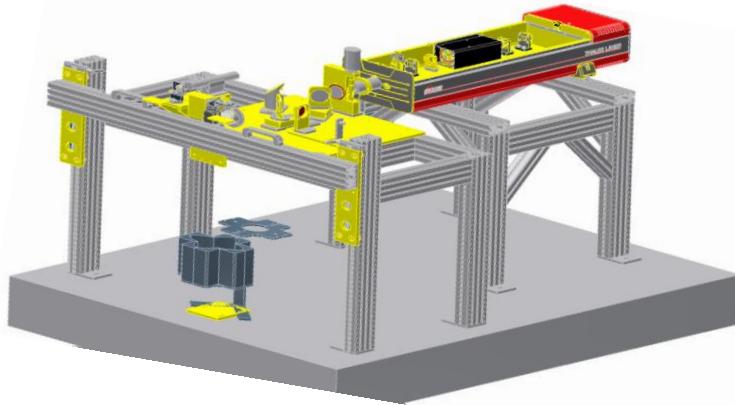
For characterizing the adhesion of a coating system:

- The properties of that specific interface have to be assessed
- Laboratory tests should induce delamination at this interface

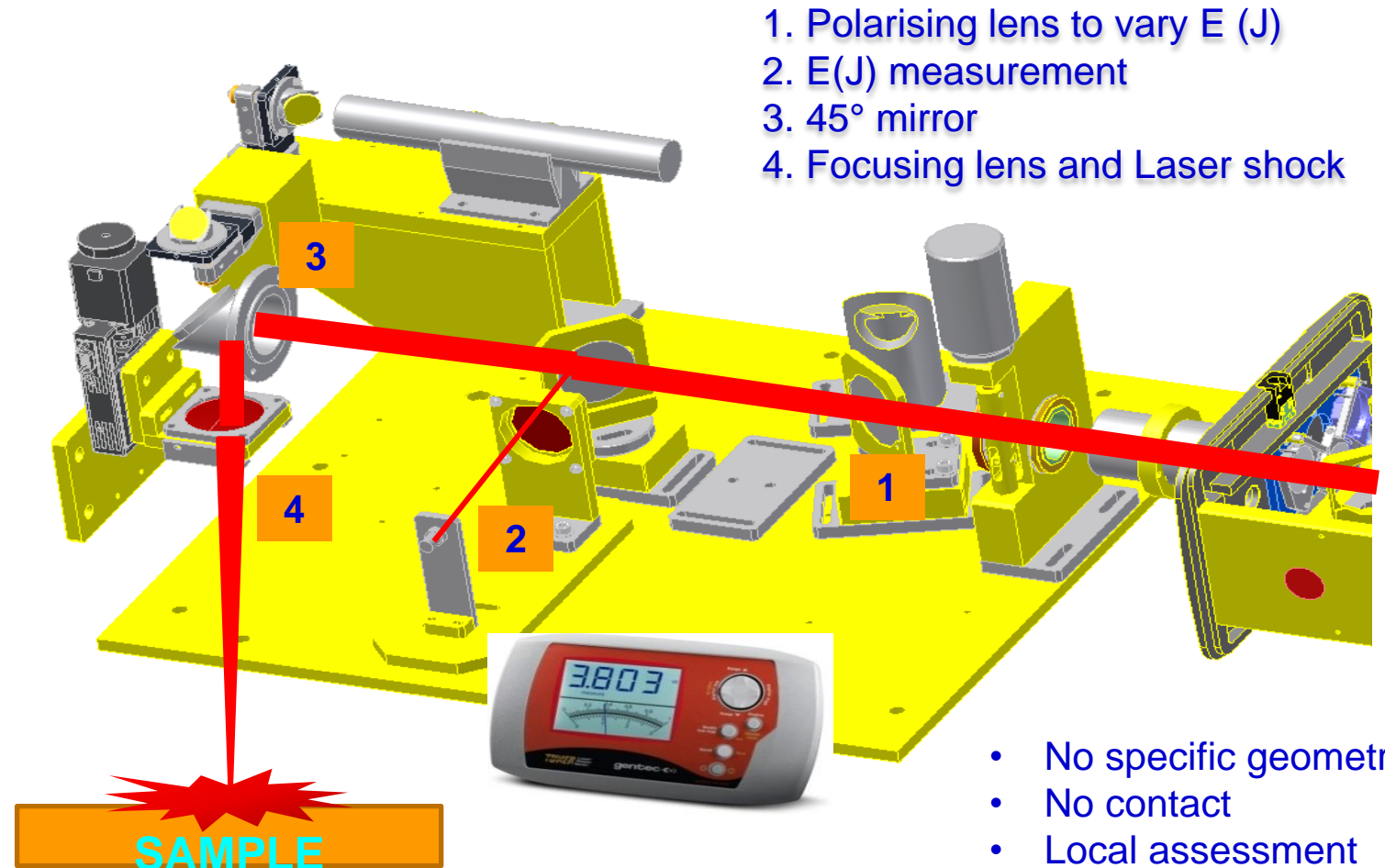
A facility to characterize TBC adhesion has been developed at MINES ParisTech:



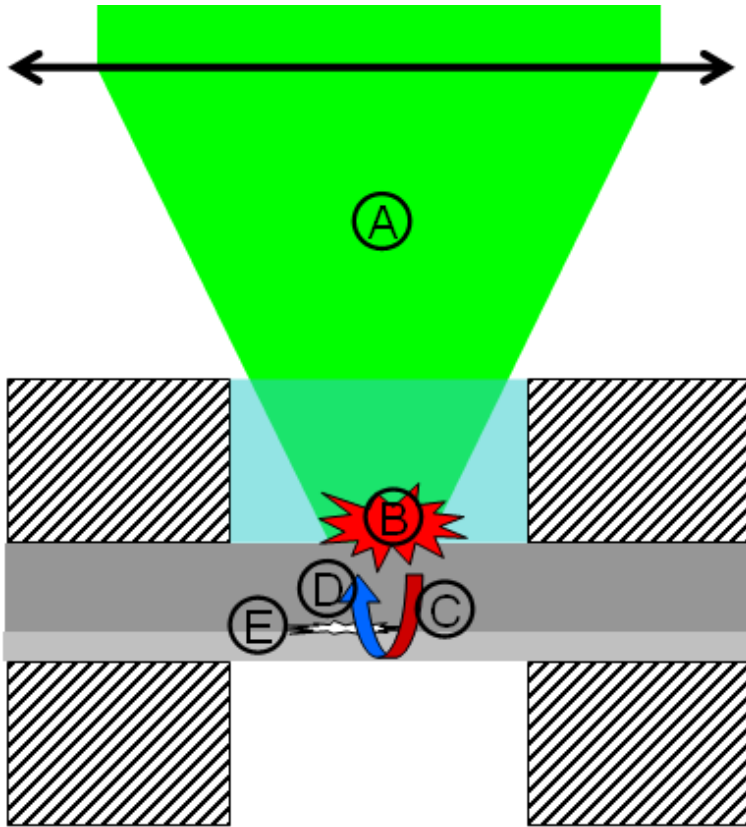
Laser Shock Adhesion Test - LASAT facility @ MINES ParisTech



Saga –Thales Laser:
maximum energy 2J
pulse duration 7 ns
wavelength 532 nm
power density 0,1-10GW/cm²



LAser Shock Adhesion Test (LASAT)



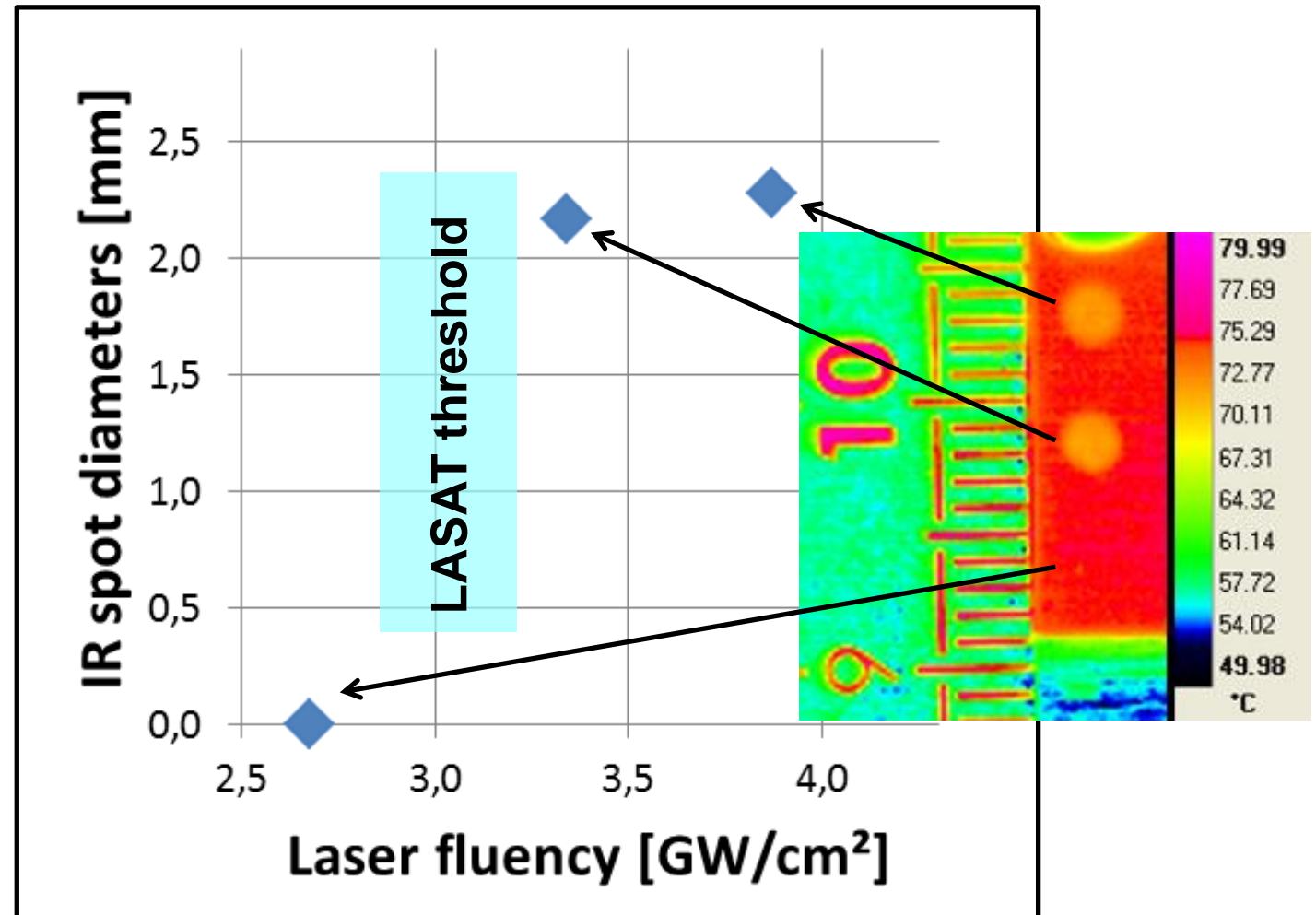
- A tool to characterize adhesion
- Principle of LASAT:
 - (A) focused high power short pulse laser
 - (B) sudden expansion of generated plasma
 - (C) Compressive shock wave, reflected on the opposite free surface
 - (D) tensile shock wave (by reverberation phenomenon & to the opposite direction)
 - (E) debonding the ceramic coating for high loading stress

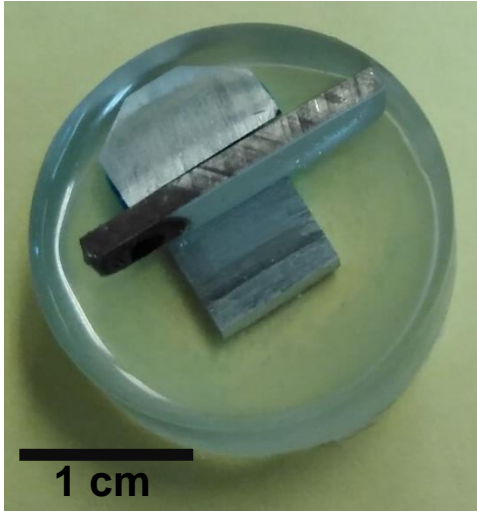
Aim of the work

- **Producing a known defect in size and location by LASAT**
- **How to characterize the “morphology” of the crack tip in a brittle multi-layered system?**

Series of LASAT and IR thermography

- Find the LASAT threshold using shocks with decreasing laser energy
- Infra-red thermography: first control for damage at the position treated & estimation of delamination diameter

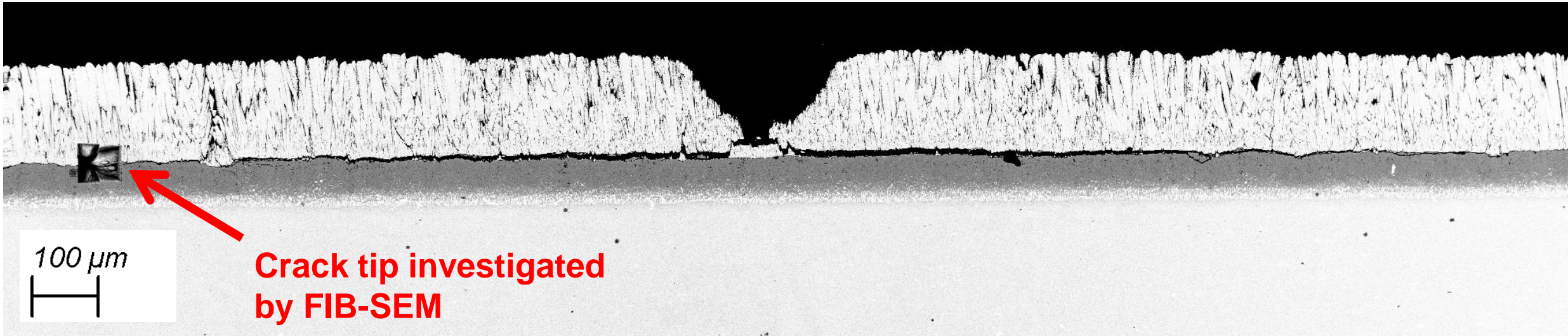




Sample preparation & SEM

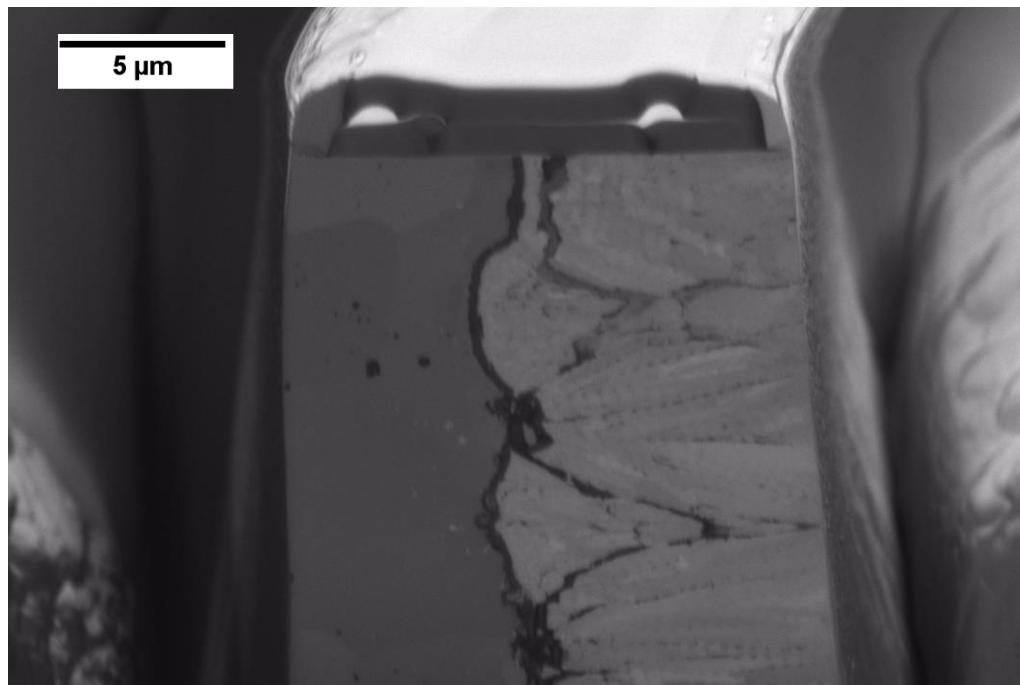
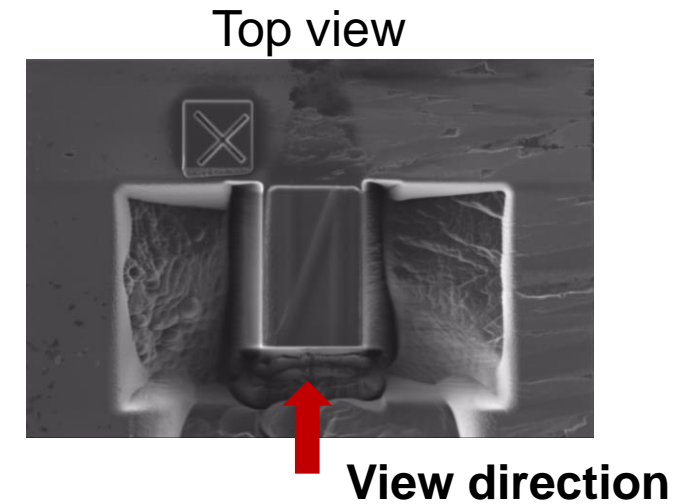
- sample embedded in transparent resin to analyze details
- during grinding and polishing: check for appearance of crack by optical microscope

SEM: crack by LASAT in the cross section

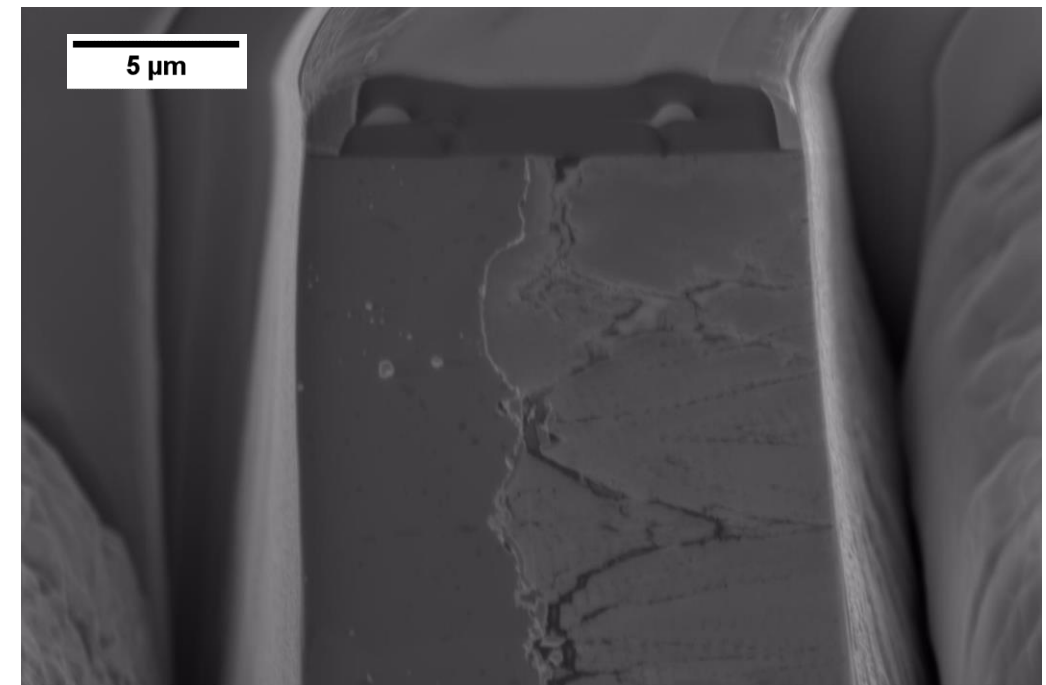


FIB-SEM experiment

Subsequent slicing by focused ion beam and imaging by SEM provides information for 3-D construction of the crack tip region



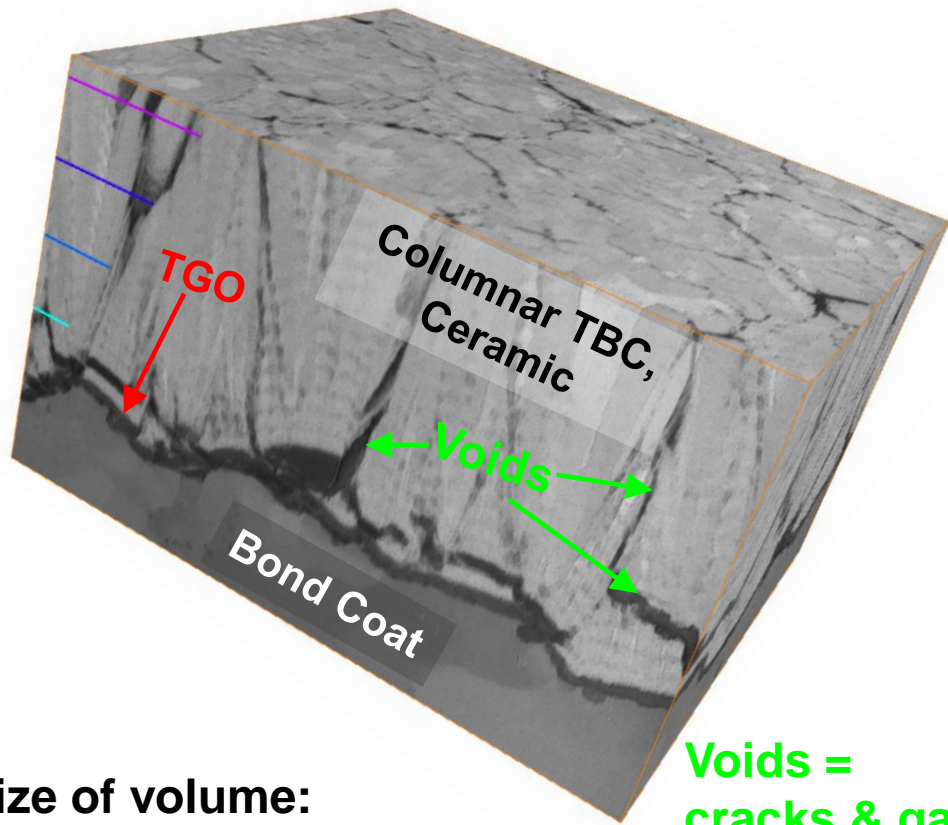
Observation with backscattered electrons (BSE)



Observation with secondary electrons (SE)

Microstructure in ceramic coating

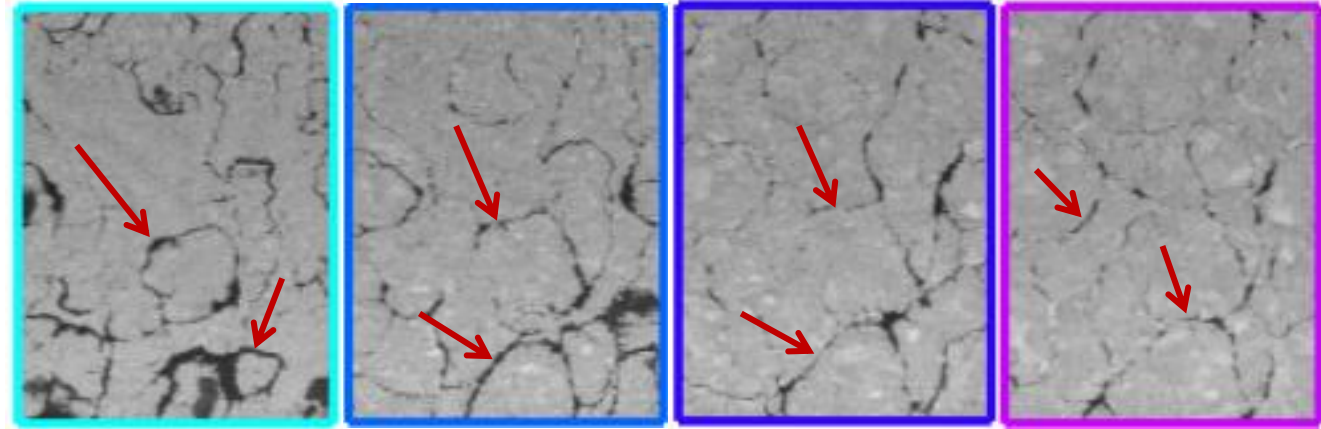
Volume obtained after alignment
and combination of the image slices



Size of volume:
(11.0 x 18.88 x 14.2) μm^3

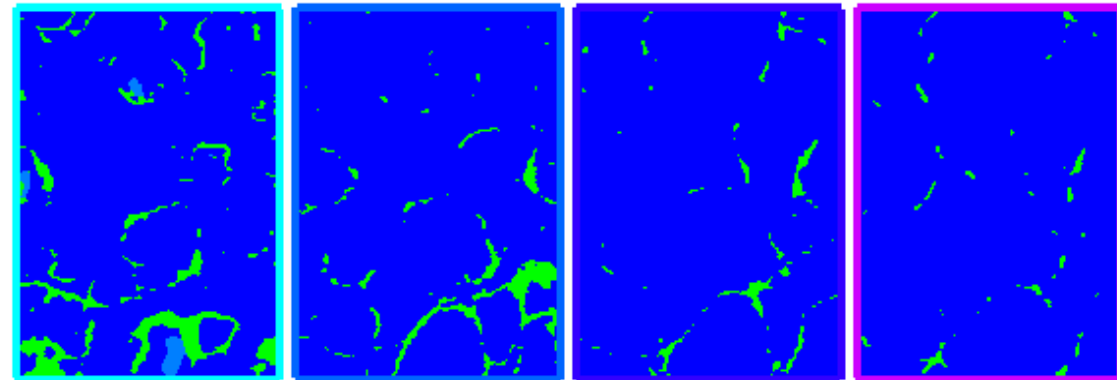
Voids =
cracks & gaps

Cross sections:



Gaps between columns indicated

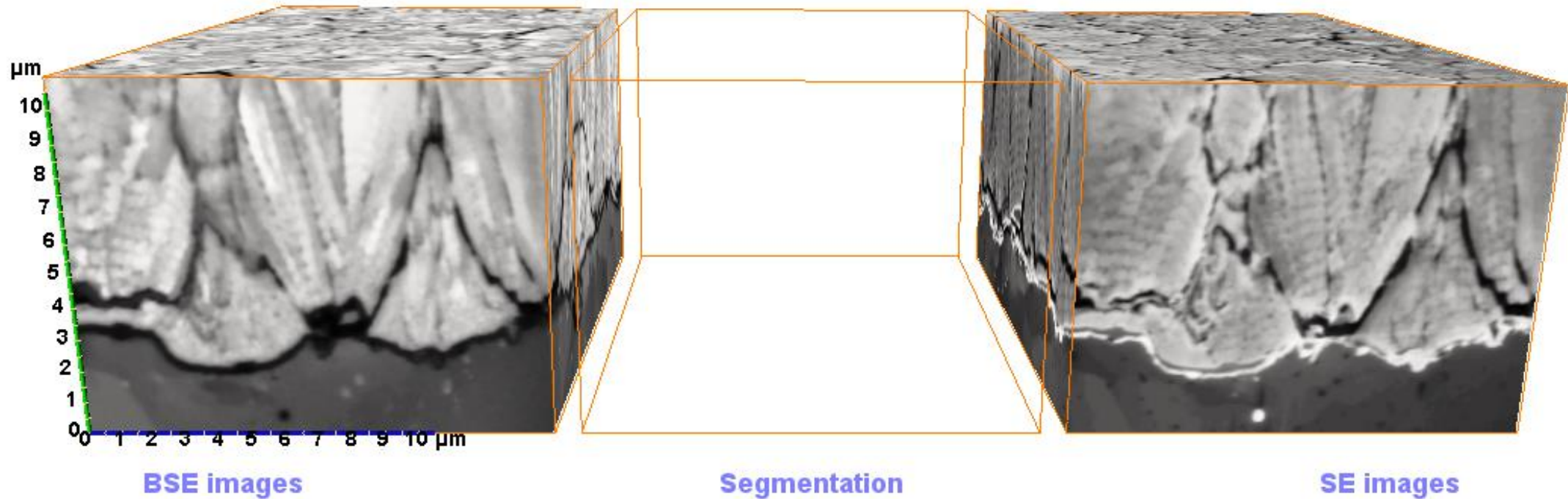
Material segmentation for further analyses:



Green:
segmented
gaps
between
columns

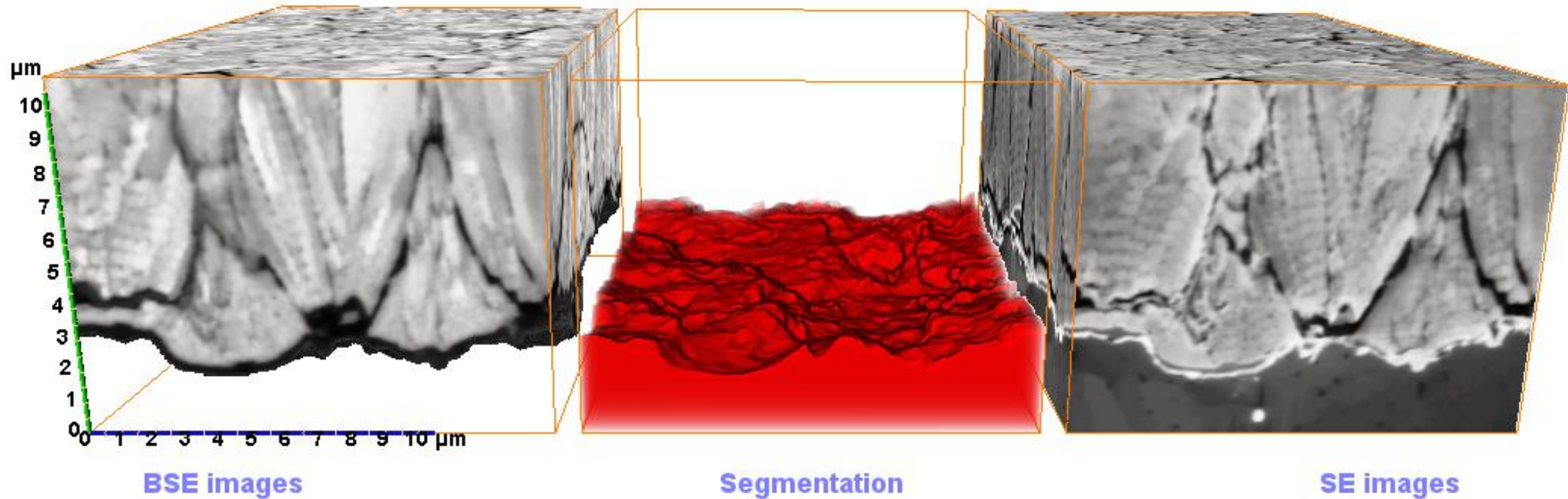
Segmentation of image stack

- Using both image stacks



Segmentation of image stack

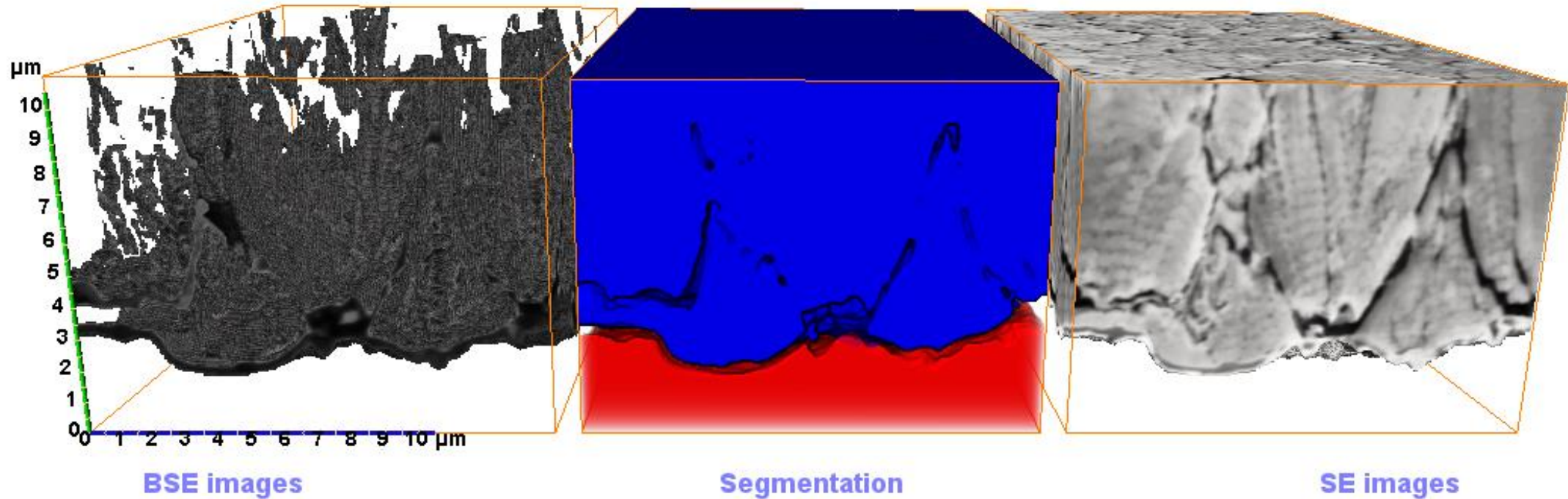
- Using both image stacks
- Assign bond coat



Red = bondcoat

Segmentation of image stack

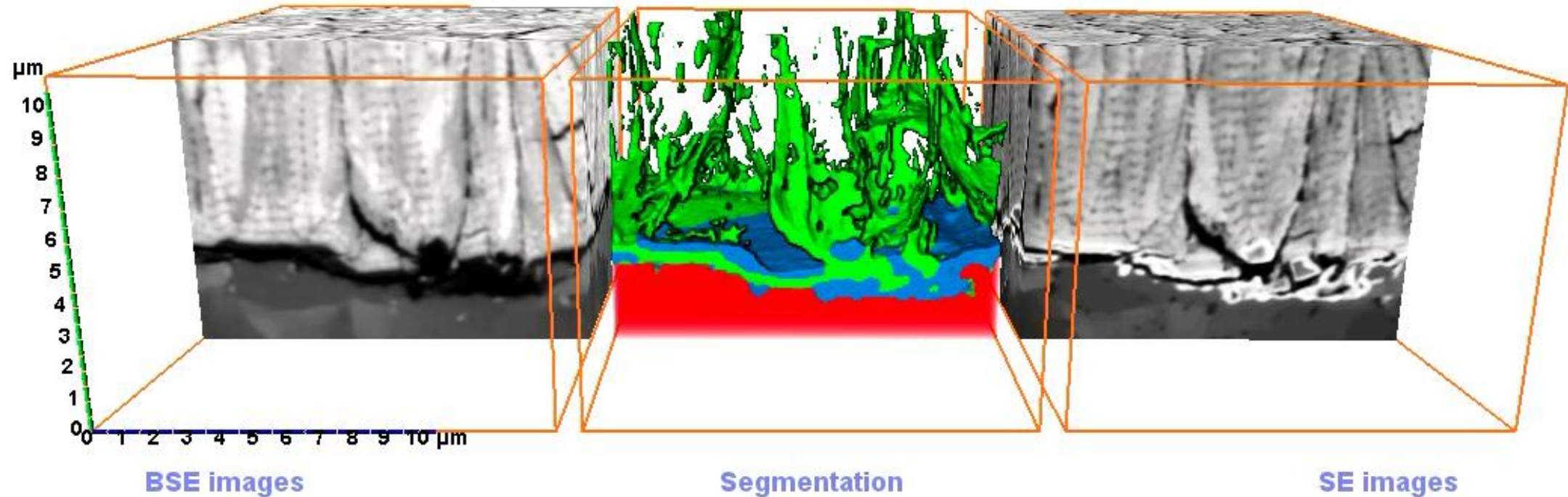
- Using both image stacks
- Assign bond coat
- Assign ceramic



Red = bondcoat Blue = YSZ ceramic

Segmentation of image stack

- Using both image stacks
- Assign bond coat
- Assign ceramic
- Use SE images to assign TGO and voids



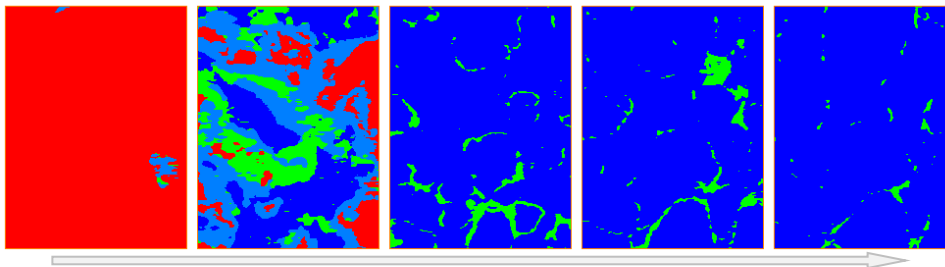
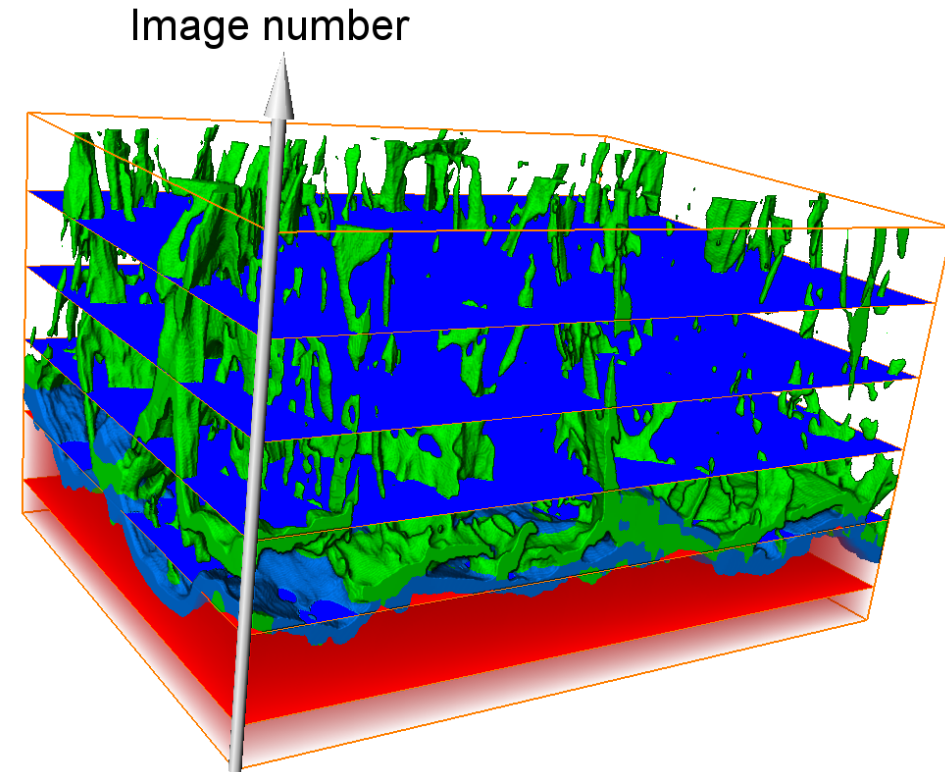
transparent = YSZ

red = bond coat

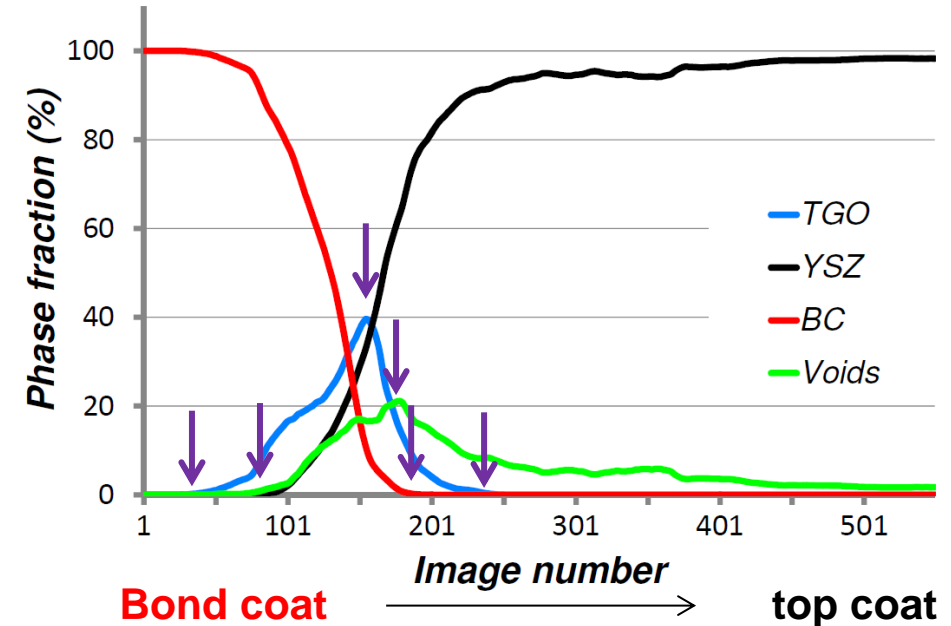
blue = TGO

green = voids (= cracks + gaps)

Phase distribution along coating thickness



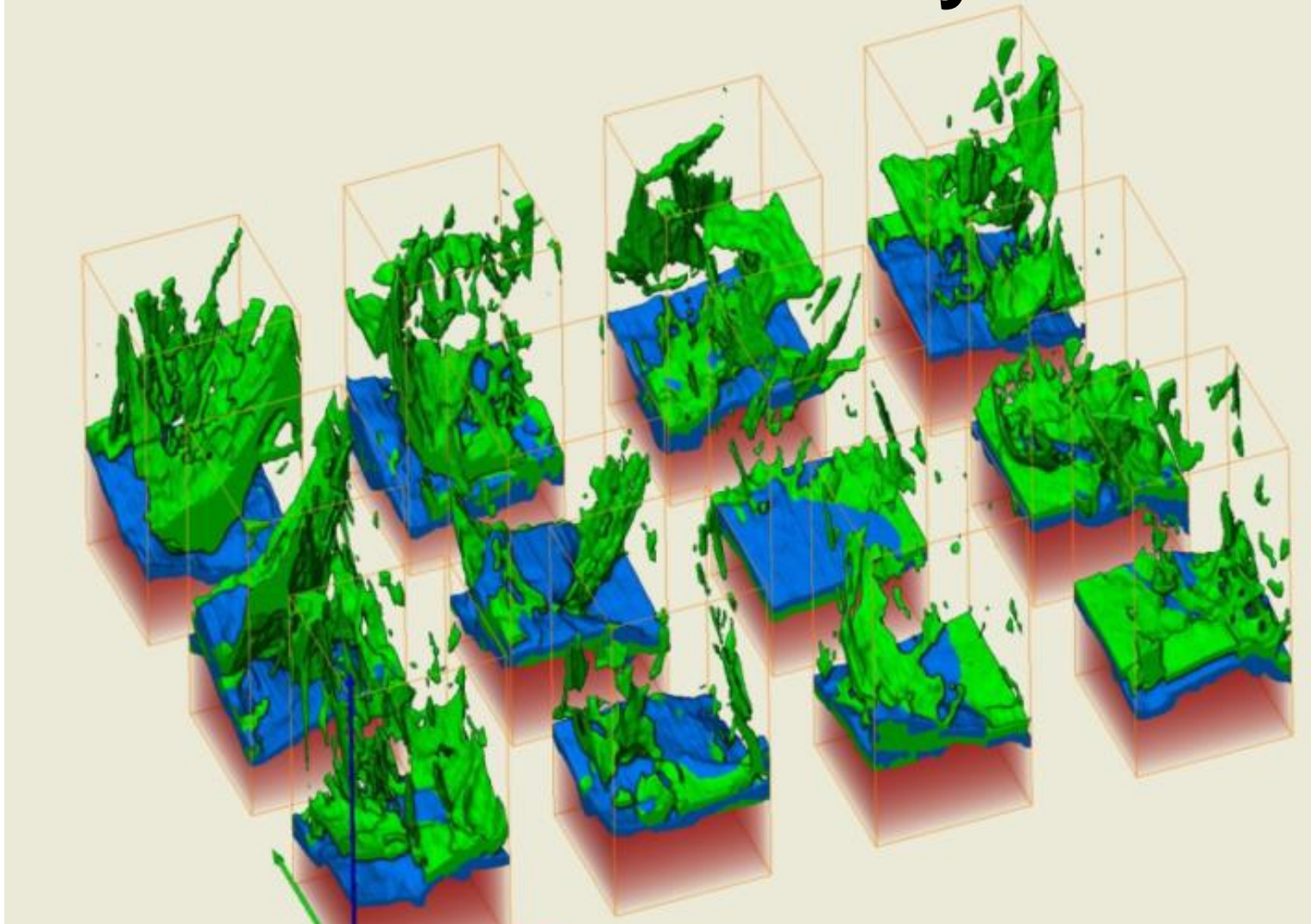
Segmentation for each horizontal slice



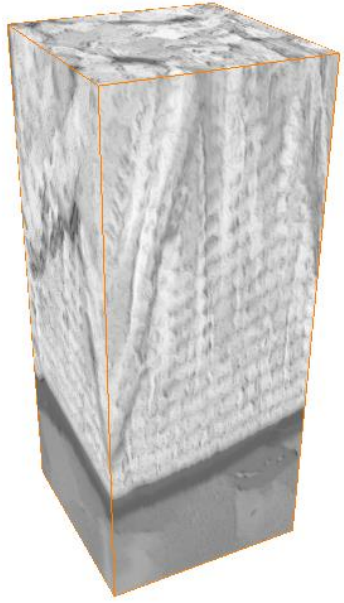
Calculated volume fractions of each phase as detected for each slice/image

- Presence of multiple phases due to rough interfaces
- Characteristic locations: first occurrence of a phase and maximum volume fraction of phases

Use of sub-volumes to analyze crack path



Use of sub-volumes to analyze crack path



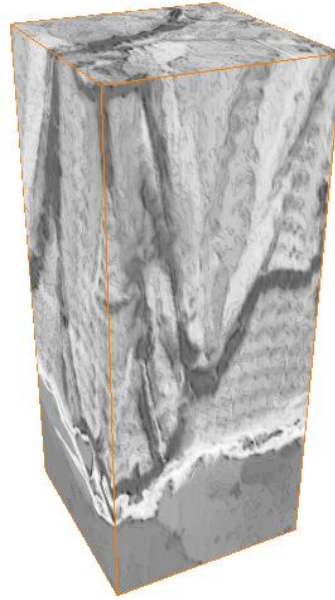
BSE image



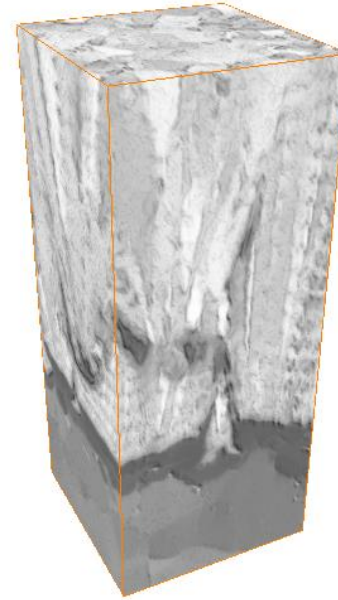
SE image



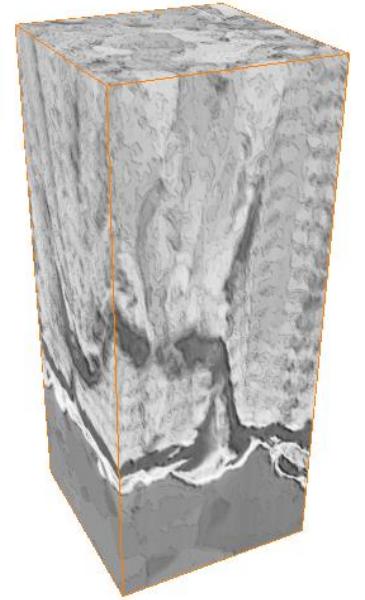
BSE image



SE image

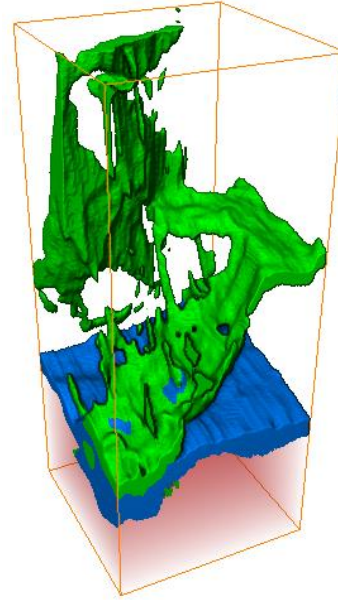
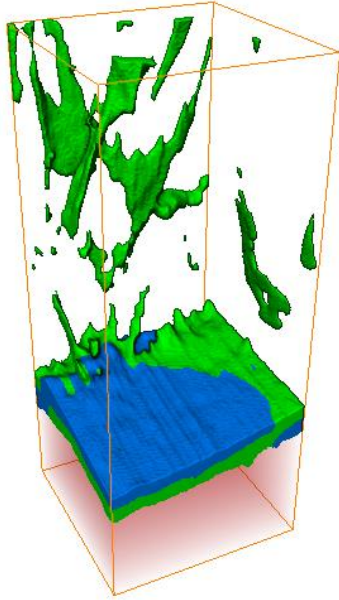


BSE image

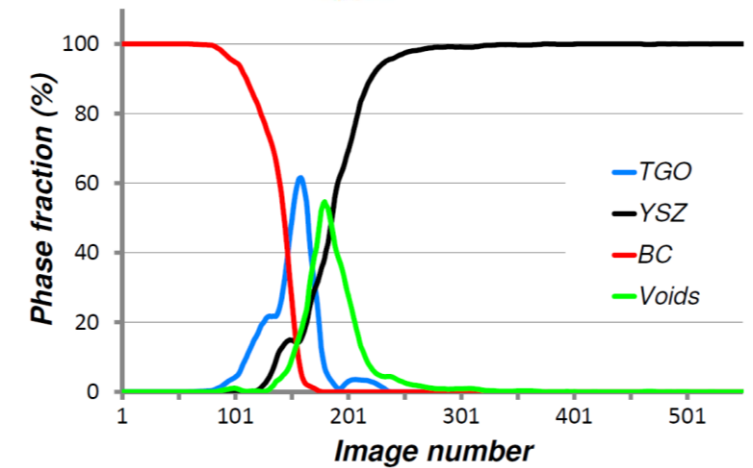
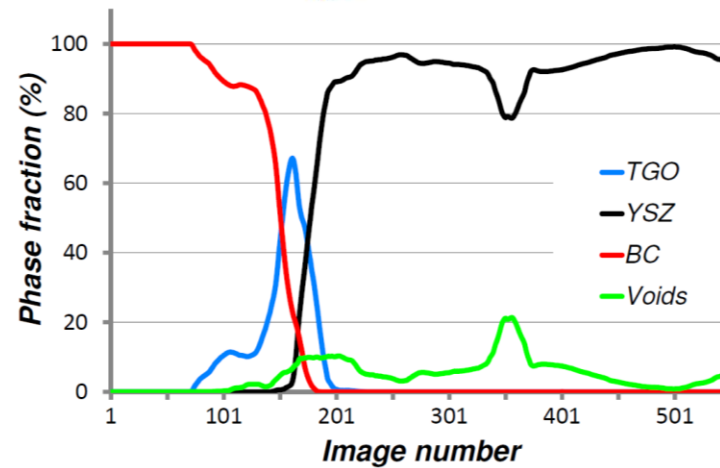
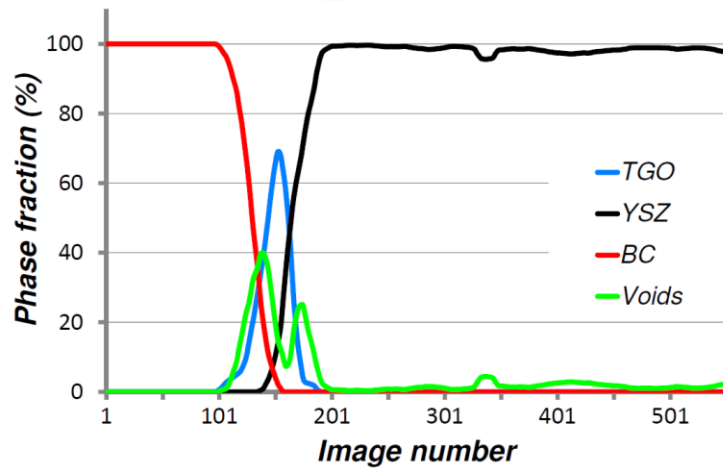
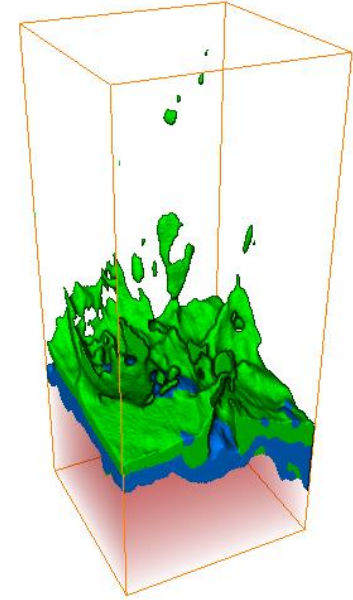


SE image

Use of sub-volumes to analyze crack path



*Differentiation
between
cracks and
gaps*



- Crack below and on top of TGO
- Small crack in ceramic

- Larger crack in ceramic and some gaps

- Crack on top of TGO

Summary and conclusions

- **Damage of TBC system induced by LASAT**
- **3D characterization of microstructure and crack (FIB slice & SEM):**
 - Columnar microstructure of the ceramic coating, with connections and gaps between the columns
 - Cracks between bond coat and TGO, inside the TGO as well as between TGO and ceramic but also inside the ceramic columns
 - Cracks + gaps: complex system of voids
 - Systematic analysis of sub-volumes allows crack path analyses (crack positions and orientation)
- **Characterization method can be further utilized for analyzing crack morphologies in TBC systems after service and laboratory tests such as LASAT**

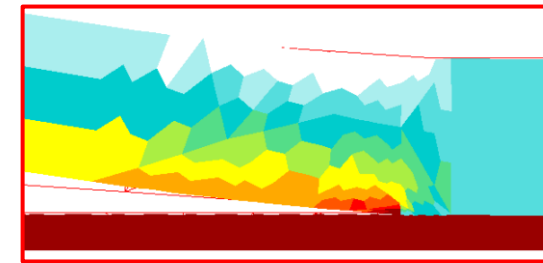
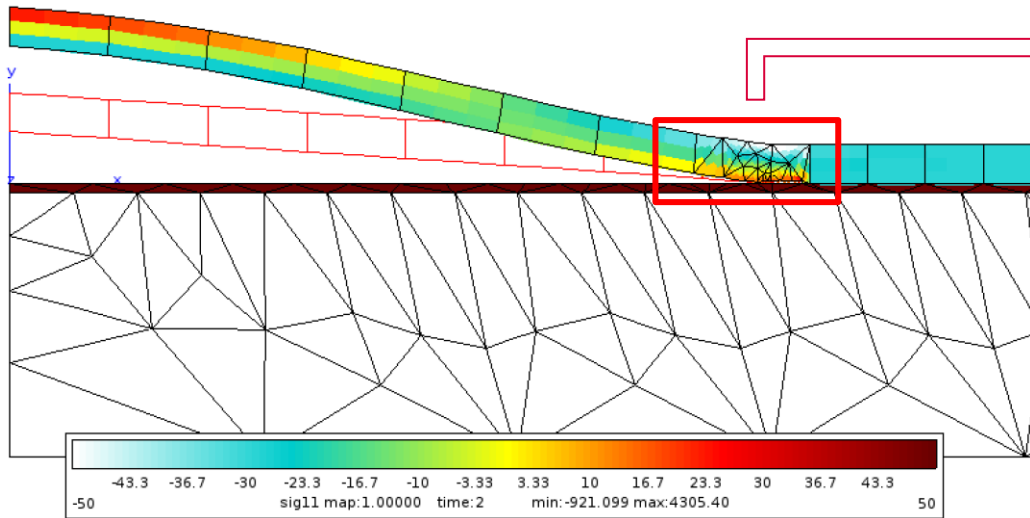
Acknowledgement

- The Authors thank for the financial support supplied by Mines ParisTech and acknowledge the Zuse-Institute Berlin (ZIB) for helpful discussions and providing access to the image analyses program AVIZO.
- Part of this work was carried out within the MATMECA consortium and supported by the ANR under contract number ANR-10-EQUIPEX-37.

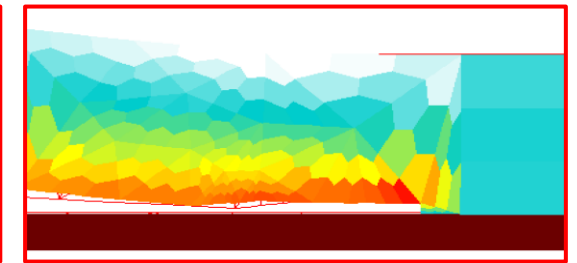
Thank you for your attention!

Supplementary information

Based on the proposed segmentation 3D realistic FEA could be achieved (elastic analysis)



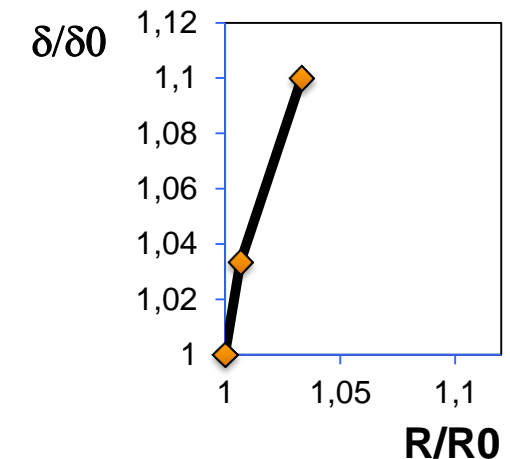
Radius = IR measurement: 3 mm



Radius = IR + 100 μ m defect

Systematic error by IR measurement \sim 100 μ m

radius	deflection
R0 = IR measured	30 μ m
R0 + 20 μ m	31 μ m
R0 + 100 μ m	33 μ m



Impact of uncertainty of crack tip measurement

3D realistic FEA can be used to further determine the role of real morphology on

- Heat flux and subsequent thermal conductivity
- Localization of strain and stress
- Process zone associated to the crack tip

https://www.researchgate.net/profile/Vincent_Maurel

Supplementary information →

Supplementary information

Related publications by authors:

H. Sapardanis, V. Maurel, A. Köster, S. Duvinage, F. Borit, & V. Guipont, *Influence of macroscopic shear loading on the growth of an interfacial crack initiated from a ceramic blister processed by laser shock*. Surf. Coat. Techn. 291(2016) 430-443.

R. Soullignac, V. Maurel, L. Rémy & A. Köster, Cohesive zone modelling of thermal barrier coatings interfacial properties based on three-dimensional observations and mechanical testing. Surf. Coat. Techn. 237 (2013) 95-104.

M. Bartsch, B. Baufeld, S. Dalkilic, L. Chernova, M. Heinzelmann: *Fatigue cracks in a thermal barrier coating system on a super alloy in multiaxial thermomechanical testing*, Int. J. fatigue 30 (2008) 211-18. doi:10.1016/j.ijfatigue.2007.01.037

M. Hernandez, A. Karlsson, M. Bartsch: *On TGO creep and the initiation of a class of fatigue cracks in thermal barrier coatings*, Surf. Coat. Techn. 203 (2009) 3549-3558. DOI: 10.1016/j.surfcoat.2009.05.018

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.

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