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Interfacial toughness evolution under thermal cycling by laser shock and mechanical testing of an EB-PVD coating system

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Thermal Barrier Coatings V
June 24-29, 2028
Kloster Irsee
Irsee, Germany

Thursday, June 28, 2028: Session 5: Failure Mechanisms
20:30 – 22:00

Interfacial toughness evolution under thermal cycling by laser shock and mechanical testing of an EB-PVD coating system

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OUTLINE

- Context about TBC testing under thermal loading
- Introduction to LASAT applied to TBC

I- Adhesion by LASAT

- as-deposited TBCs
- thermally-cycled TBCs

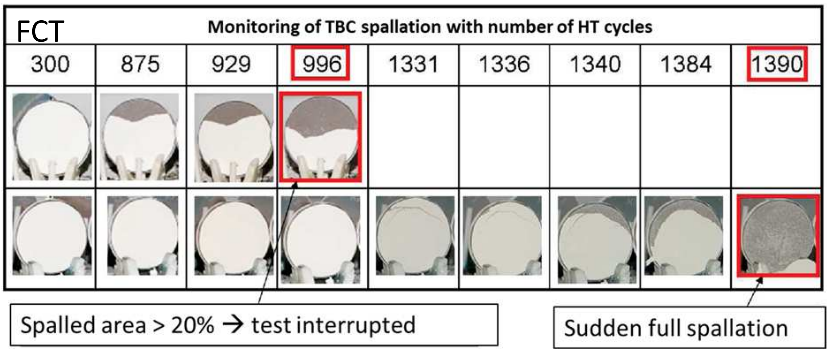
II- Analyses of blisters created by LASAT

- Origin of the blister
- Analyses of blister under:
  - Mechanical loading at room T
  - Thermo-mechanical loading by thermal cycling
- Conclusions

TBC testing under thermal loading

- SPALLATION by CYCLING TEST (furnace, burner rig)

Spallation behaviour is difficult to correlate with evolution of interface strength



Fabre, PHD Thesis, MINES ParisTech, 2014

- BONDING STRENGTH
  - Pull-out test is too dispersive (glued specimens)

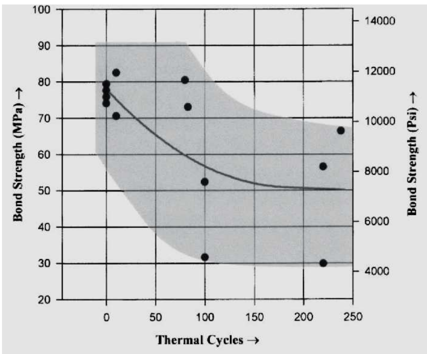
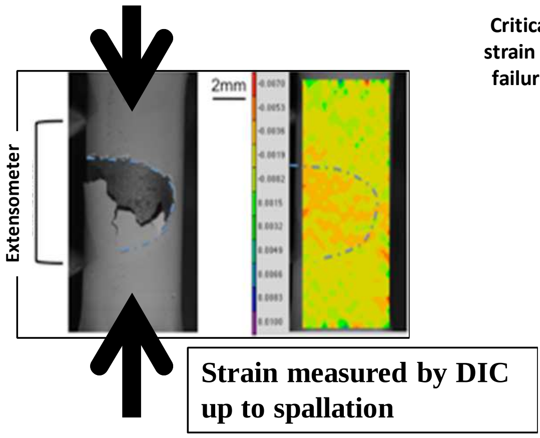


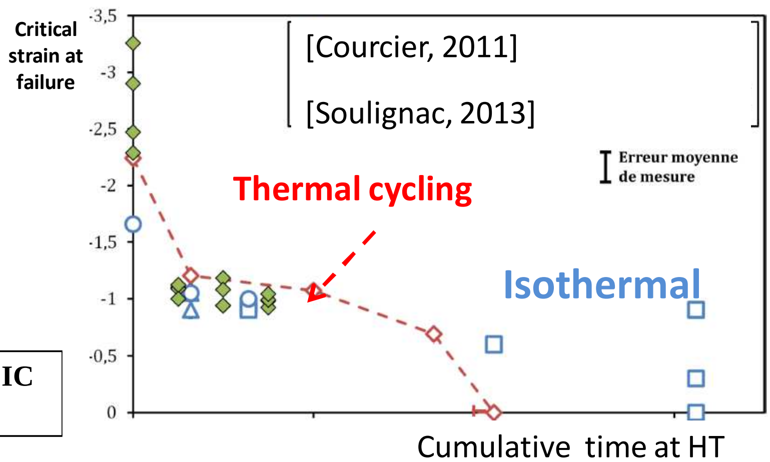
Fig. 8. Bond strength of EB-PVD TBC on Pt–Al with thermal cycling. Each point in the graph represents a sample tested.

M. Gell et al.,, Bond Strength, Bond Stress and Spallation Mechanisms of Thermal Barrier Coatings, *Surf Coat Technol*, 1999

Critical Strain to Spallation of TBC

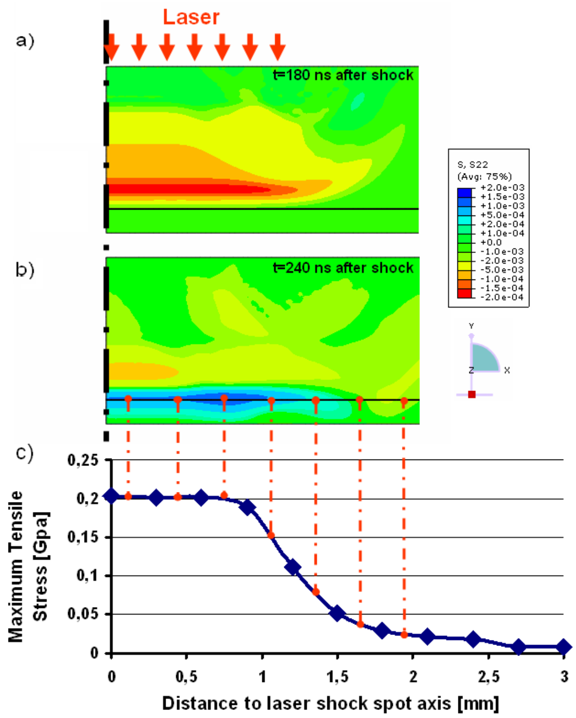
- Macroscopic spallation under compression after thermal cycling or isothermal tests





- Thermal cycling more detrimental than isothermal ageing
- First cycles: failure within the ceramic near the interface
- Increasing N : failure mainly at the TGO/ceramic interface
- Methodology is efficient but scatter is inherent to the method

Principle of Laser Shock Adhesion Test

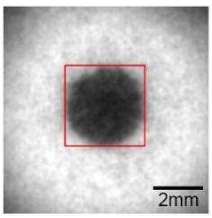


- Stress profile at the interface depends on the dimensions:
  - Target thickness
  - Laser diameter
- Maximum stress level depends on laser energy

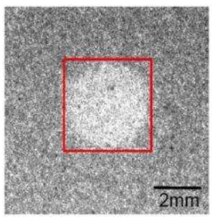
Laser shock to debond ceramic coatings

Characterization by non destructive techniques

Debonded area



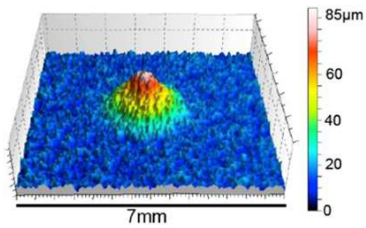
IR Thermography
(+/-30µm)



Optical observation
(+/-59µm)

+

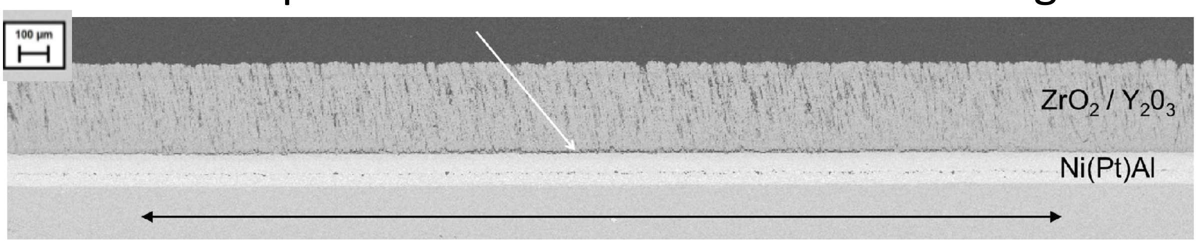
Blister



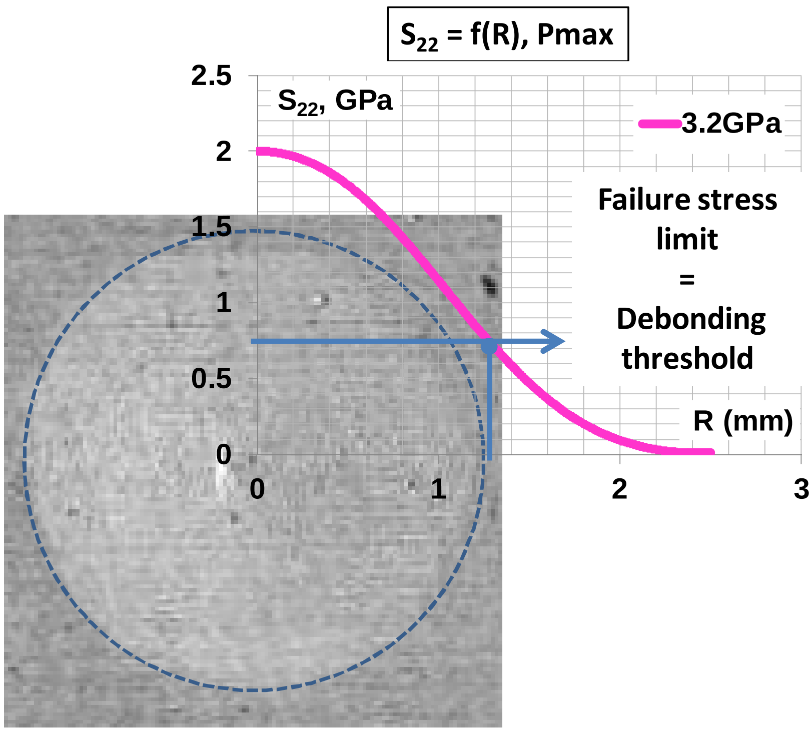
Profilometry

Size of spot = size of Crack

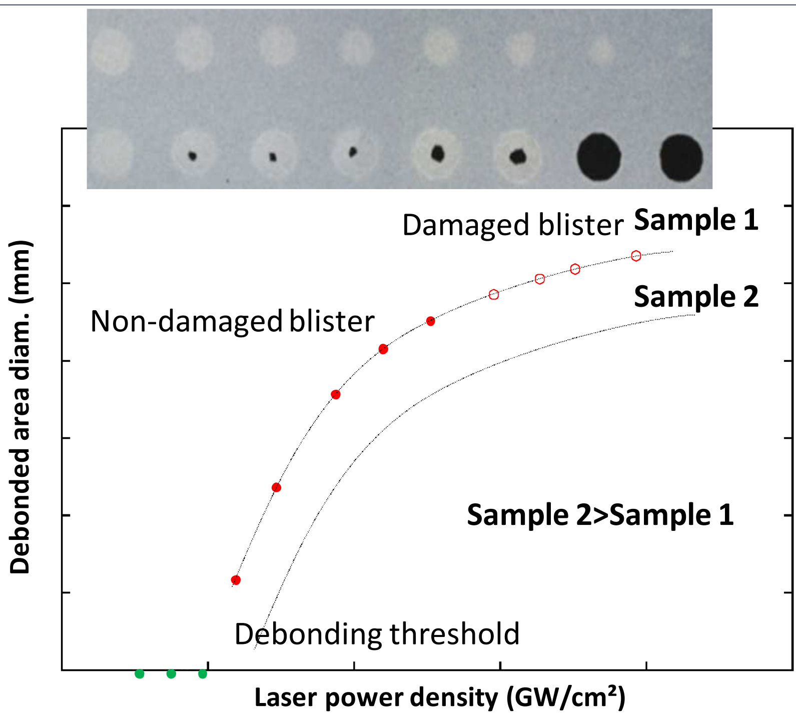
Blister height



LASAT applied to TBCs with 'spot' diagnostic



LASAT-2D curves



- Crack diameter is ↑when laser energy ↑
- Position of LASAT-2D curve → direct comparison of adhesion

e.g.: LASAT-2D on as-deposited SPS TBC

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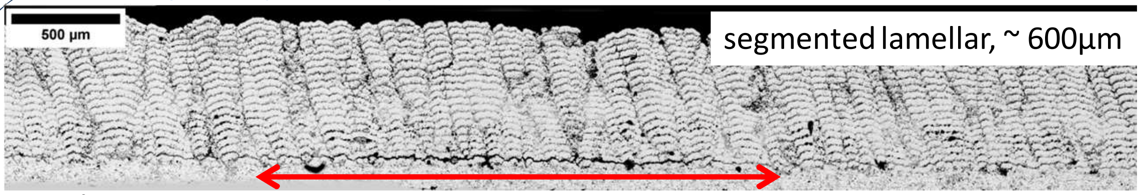
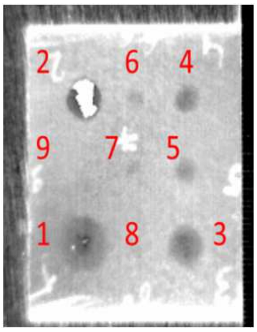
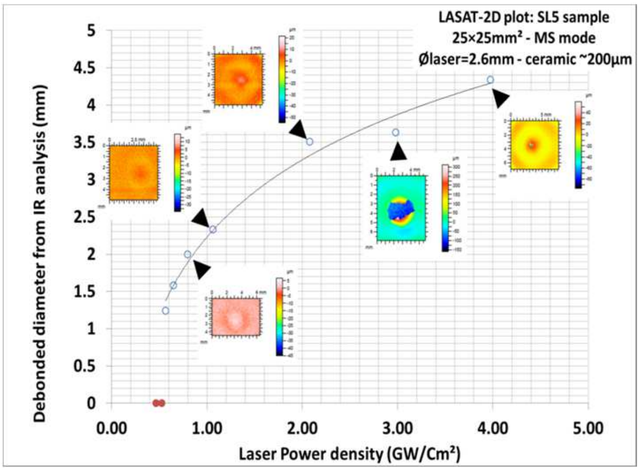


CS mode

R. Chidambaram Seshadri et al,.JTST, 2026, **25**(8), p 2666–2683.



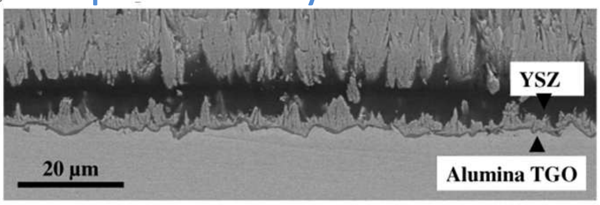
IR imaging after LASAT (200µm thick YSZ)



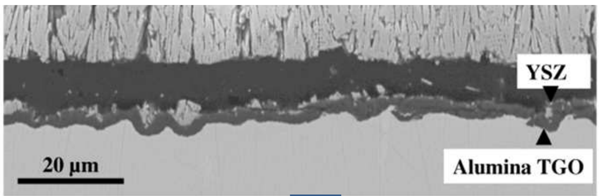
LASAT can be applied on SPS TBC

Crack path induced by laser shock

As-deposited→mainly in the ceramic

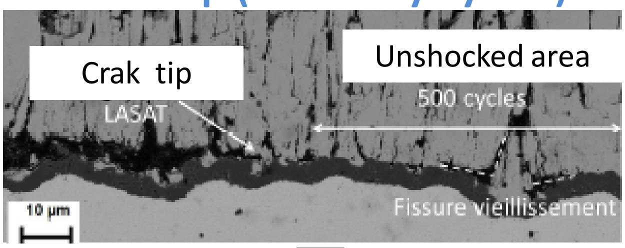


thermally-cycled→ mainly TGO/ceramic

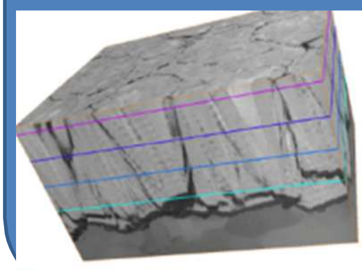


Similar features if compared to spallation damage by thermal cycling

Crack tip (thermally-cycled)



Poster " Crack morphology in a columnar thermal barrier coating system "
M. Bartsch, DLR, Germany, V. Guipont, V. Maurel, F. Gaslain, A. Dennstedt, MINES ParisTech, France



3D imaging by FIB , SEM Crack segmentation

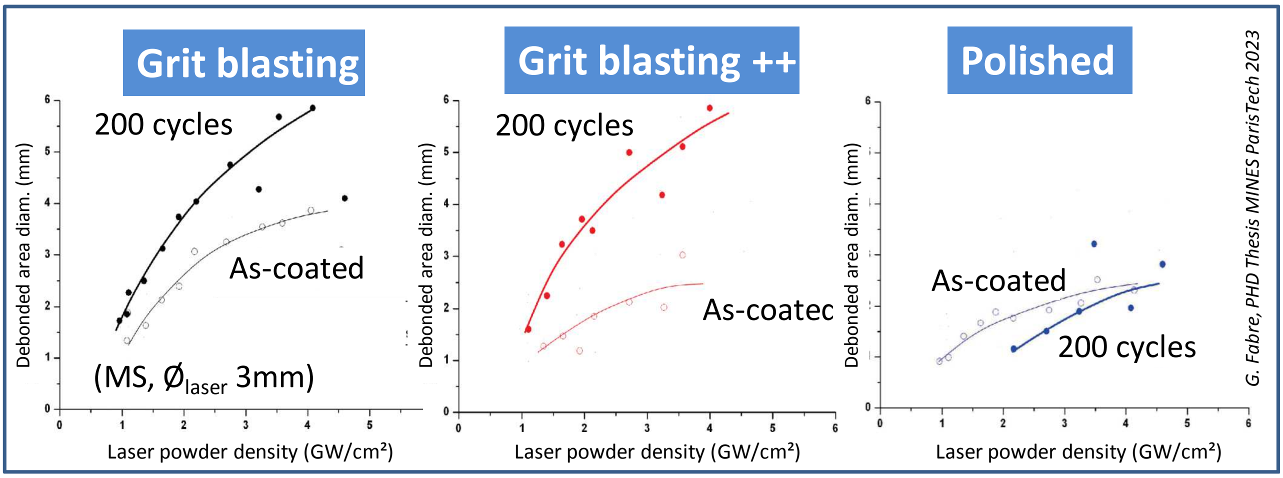
LASAT on TBCs with ‘spot’ analysis

I- Adhesion by LASAT

- **LASAT on as-deposited TBCs** (EB-PVD ,→APS, SPS, PS-PVD)
  - **LASAT on thermally cycled TBCs** (EB-PVD)

LASAT applied on EB-PVD TBC

- 3 samples, as-coated and after 200 cycles 1H/1100°C/Air



- As-coated (with initial TGO < 1µm):
  - Adhesion ↑ for Grit ++
  - Polished = Grit ++ → TGO is playing a predominant role on adhesion
- 200 cycles (With TGO ~ 2-3 µm):
  - Adhesion ↓ for both Grit and Grit++→ cavitation on rough interface
  - Adhesion ↑ for polished: potential effect ceramic toughening

LASAT on TBCs with ‘white spot’ analysis

II- blister analysis

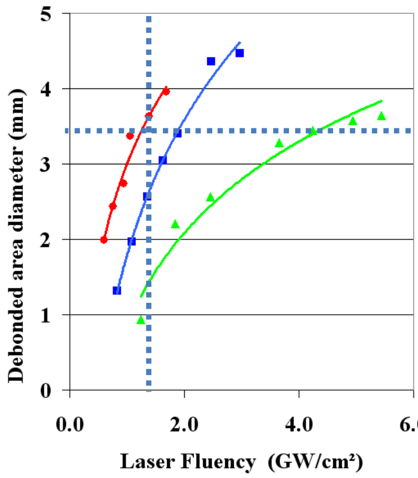
- **Origin of the blister**

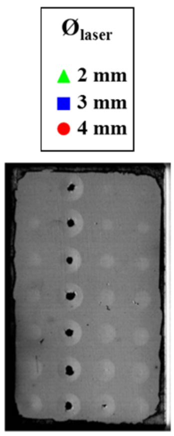
→ **further analyses of crack propagation & out-of-plane deformation on blisters created by LASAT**

Origin of the blister after LASAT

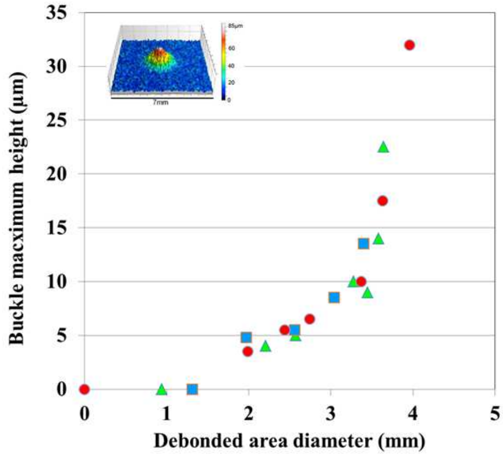
Same TBC sample, $Ø_{laser}$=2, 3 or 4mm

LASAT 2D curves
D_{crack}(mm)= f(φ, GW/cm²)





$H_{blister*}$(µm) =f(D_{crack}, mm)



** Undamaged only*

Blisters heights after LASAT are not depending on $Ø_{laser}$
→ Buckling is driven by the compressive residual stress release

e.g.: LASAT-2D on as-deposited SPS TBC

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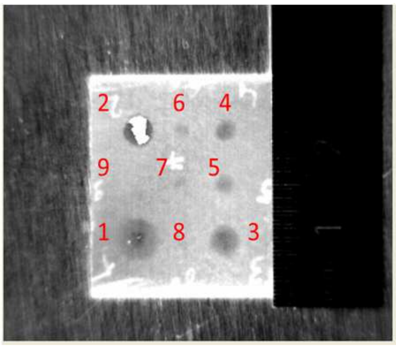
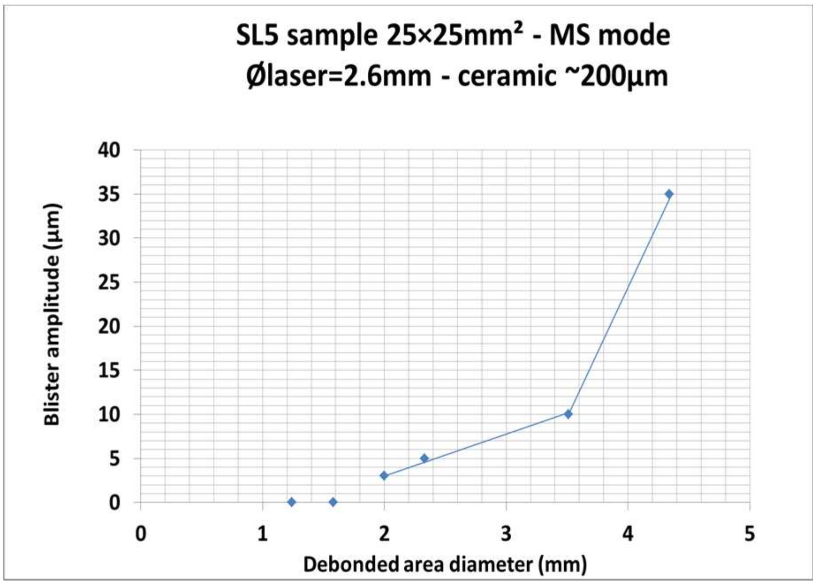


IR imaging after LASAT

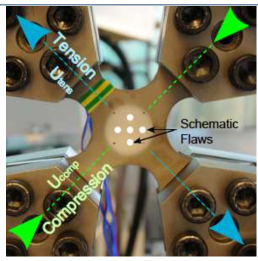
LASAT-2D plot



Blister analysis after LASAT can be achieved on SPS TBCs

In situ blister analysis at room temperature

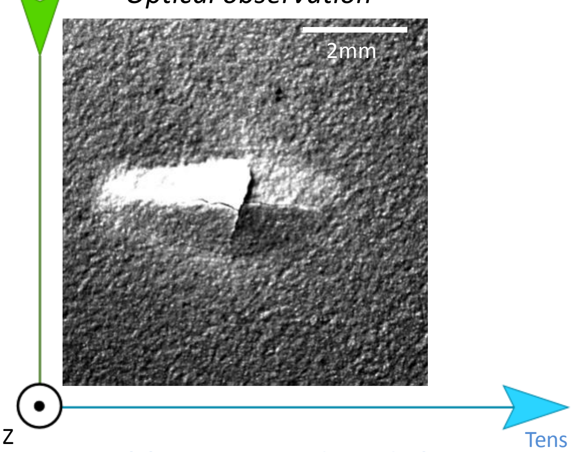
Biaxial mechanical testing mode I+II + (III)



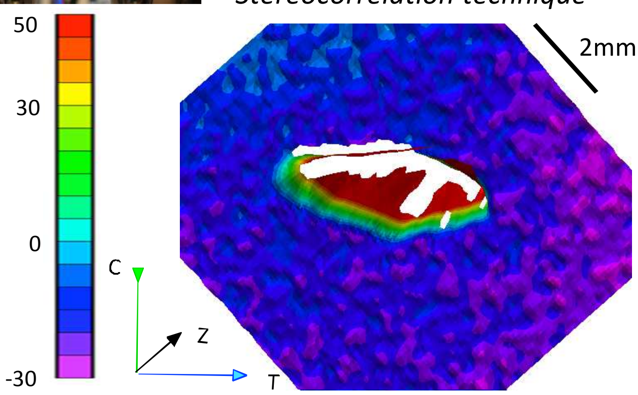
SS304L/APS alumina (70 µm)
Macroscopic shear loading:
$\rho = U_{tract}/U_{comp} = -1$

Comp

Optical observation



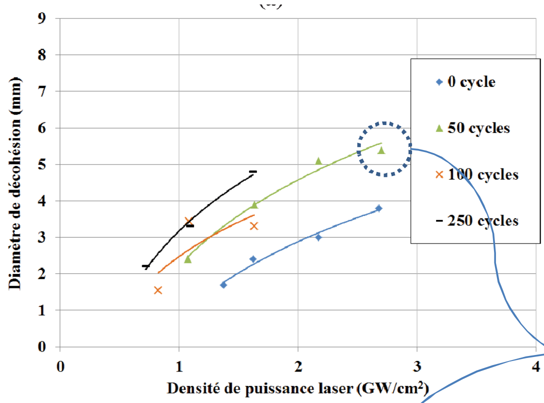
Stereocorrelation technique



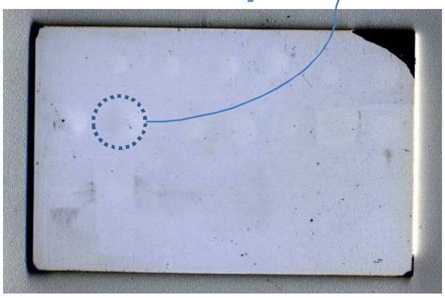
- **Buckling precedes delamination up to ceramic coating failure**
- **Influence of shear loading on crack propagation by FEA (mode I and II)**
- **H. Sapardanis et al., *Surf Coat Technol*, 2016**

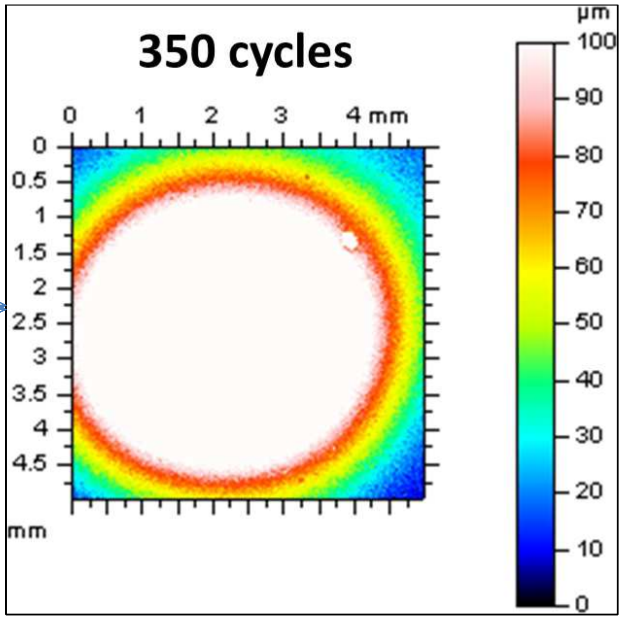
Ex situ blister analysis with thermal cycling

- P2 sample: LASAT at 0, 50 , 100, 250 cycles



- P2 after 250 cycles



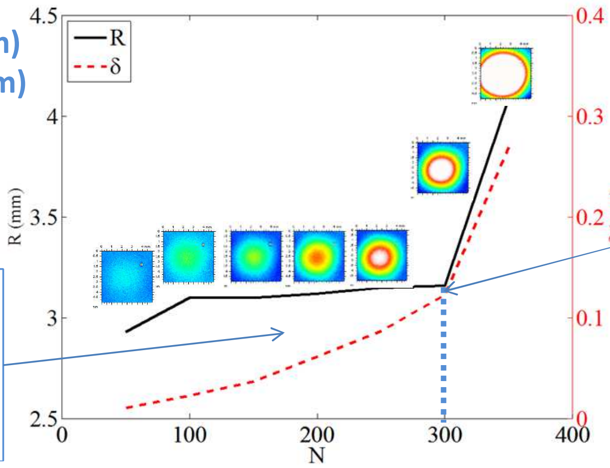


- P2 sample failed at 400 cycles

Single blister evolution with thermal cycling

R: blister radius (mm)
D: Blister height (mm)

Buckling is activated while delamination is not (effect of rumpling?)



Beginning of significant delamination and buckling: G=Gc critical energy release rate

Assuming blister perfectly clamped on edges [Hutchinson 1992, Mc Donald 2010]

$$\sigma_C = 1.2235 \frac{E}{1-\nu^2}\left(\frac{h}{R}\right)^2$$

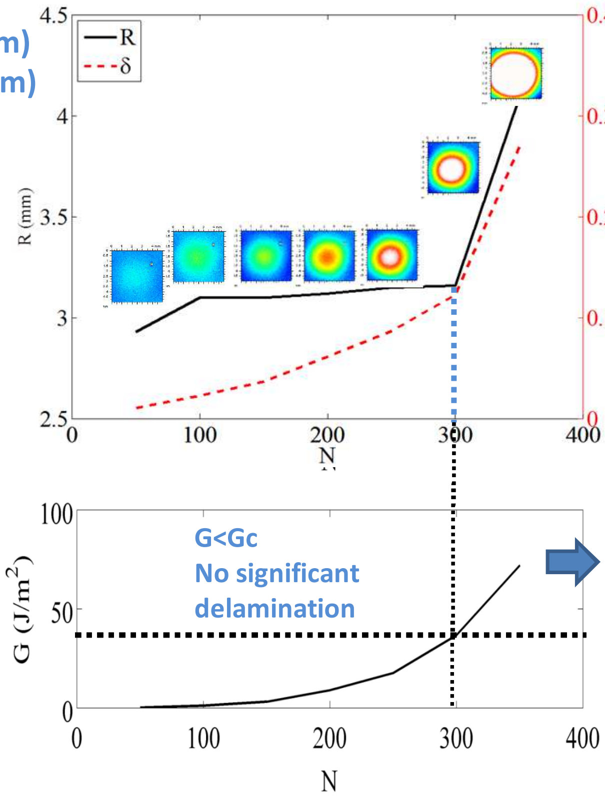
- Blister elastic properties and coating thickness yields critical stress at buckling and available energy
- Buckling height yields stress in buckled configuration and energy release rate at delamination

$$\sigma_0 = \sigma_c\left[c_1\left(\frac{\delta}{h}\right)^2 + 1\right]$$

$$\frac{\mathcal{G}}{\mathcal{G}_0} = c_2\left[1-\left(\frac{\sigma_c}{\sigma_0}\right)^2\right]$$

Single blister evolution with thermal cycling

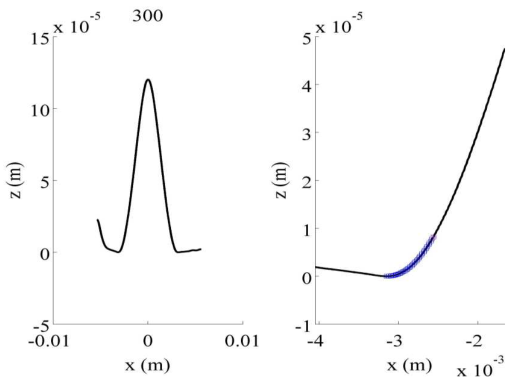
R: blister radius (mm)
D: Blister height (mm)



critical energy release rate
Gc=36 J/m²
After 300 cycles
[Hutchinson 1992, Mc Donald 2010]

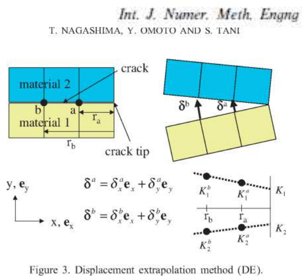
Single blister evolution with thermal cycling

Experimental local deflection of the blister
→ Mode I crack tip opening with N

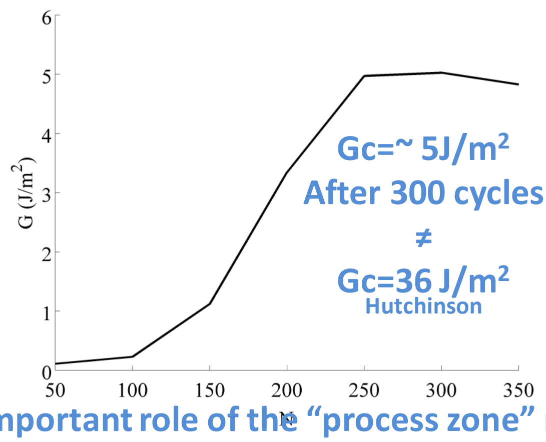


$(\delta y) \rightarrow (K_I) \rightarrow G \rightarrow Gc$

critical energy release rate Gc
Calculated by
Displacement Extrapolation method
[Nagashima 2003]



Material 2: YSZ
Material 1: TGO



Gc=~ 5J/m²
After 300 cycles
≠
Gc=36 J/m²
Hutchinson

Important role of the "process zone" near the crack tip on macroscopic deformation behaviour

Conclusions

- LASAT:
  - to test as-deposited or aged TBC (conv. and last generation),
  - to compare designs of interface (surface prep., pre-oxidation, bond coat),
  - to detect low toughness regions within the ceramic.
- Thick ceramic coatings can be envisaged but the IR diagnostic might be limited.
- Non destructive LASAT on coated part (not shown here).
- FCT combined to LASAT to achieve a much faster and more reliable control of TBCs interface strength.
- Samples with initial blisters created by LASAT open for new studies to investigate the damaging behaviour under controlled thermo-mechanical loadings.
- Through this new methodology, the role of the process zone and local critical energy release rate Gc on macroscopic buckling might be further investigated to improve predictive models for TBC lifetime.

- Thank you for your attention

Acknowledgments and collaborations (LASAT on TBCs)

Barradas S[1], Berthe L[3], Boustie M[2], Cuq-Lelandais JP[2], Fabre G[1], Jeandin M[1], Nivard M[3], Bégué G[1], Barhli S[1], Sapardanis H[1], Maurel V[1,], Koster A[1], Sampath S[4], Bartsch M[5], Dennstedt A[1].

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Industrial support

literature

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G. Fabre, V. Guipont, M. Jeandin, M. Boustie, J.P. Cuq-Lelandais, L. Berthe, A. Pasquet, and J.Y. Guédou, Laser Shock Adhesion Test (LASAT) of Electron Beam Physical Vapor Deposited Thermal Barrier Coatings (EB-PVD TBCs), *Advanced Materials Research*, 2011, 278, p 509–514.