Thermal and Environmental Barrier Coatings VI Proceedings

6-21-2022

Thermo-mechanical Analysis of Blister Damage in Eb-pvd Tbc System: Experiments and Modeling

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See next page for additional authors

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Irsee - TBC VI
19-24 june 2022

THERMO-MECHANICAL ANALYSIS OF BLISTER DAMAGE IN EB-PVD TBC SYSTEM: EXPERIMENTS AND MODELING

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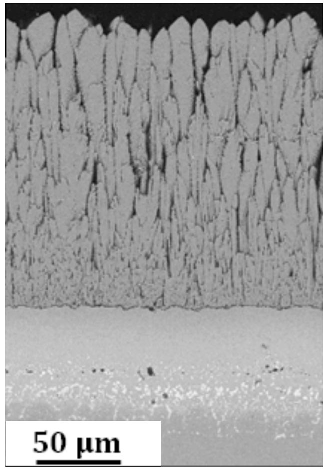
Mines Paris, PSL University, Centre des Matériaux, UMR CNRS 7633

Florent Coudon, Mark Harvey, Safran Group

in memory of Alain Köster (1964/2021)

COMMON PRACTICE IN TBC LIFE ASSESSMENT

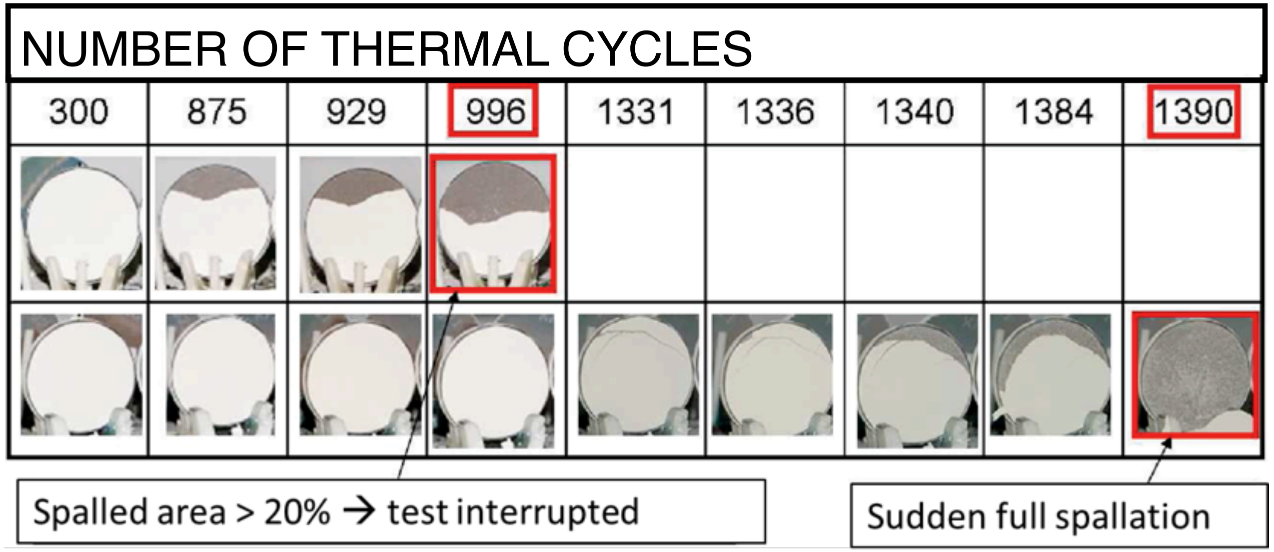


TC EB-PVD
BC (Ni,Pt)Al
substrate AM1

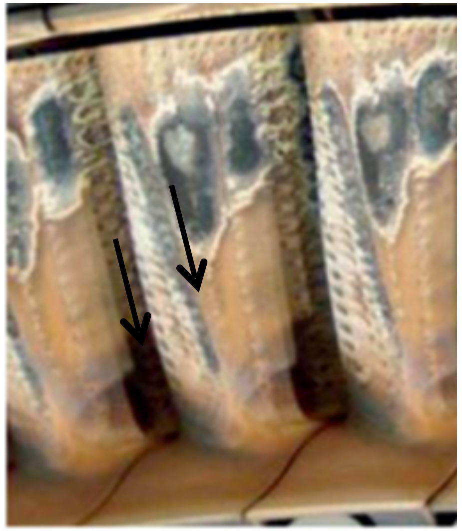
Initiation driven by edge effect on button shape specimens?

Continuous delamination on HP Turbine Blade

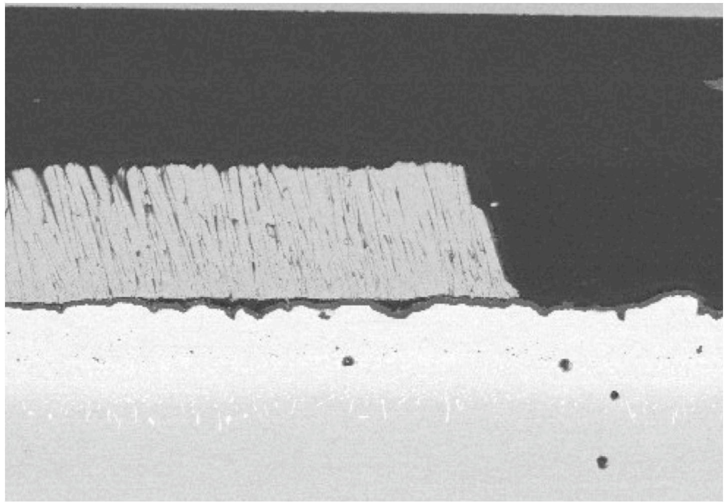
- Temperature gradient?
- Blister driven edge-delamination?



[Fabre, PHD Thesis, MINES ParisTech, 2014]



[Levi et al, MRS 2012]

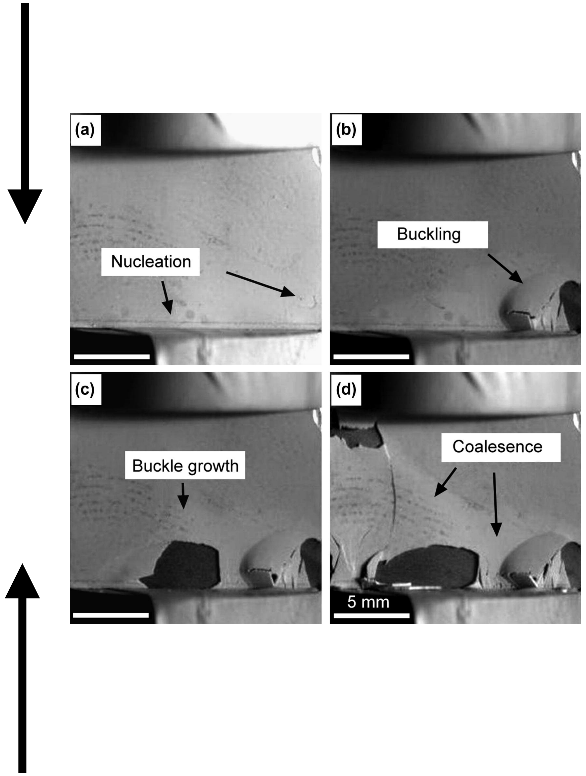


[Courcier et al, SCT 2011]

COMMON PRACTICE IN TBC LIFE ASSESSMENT

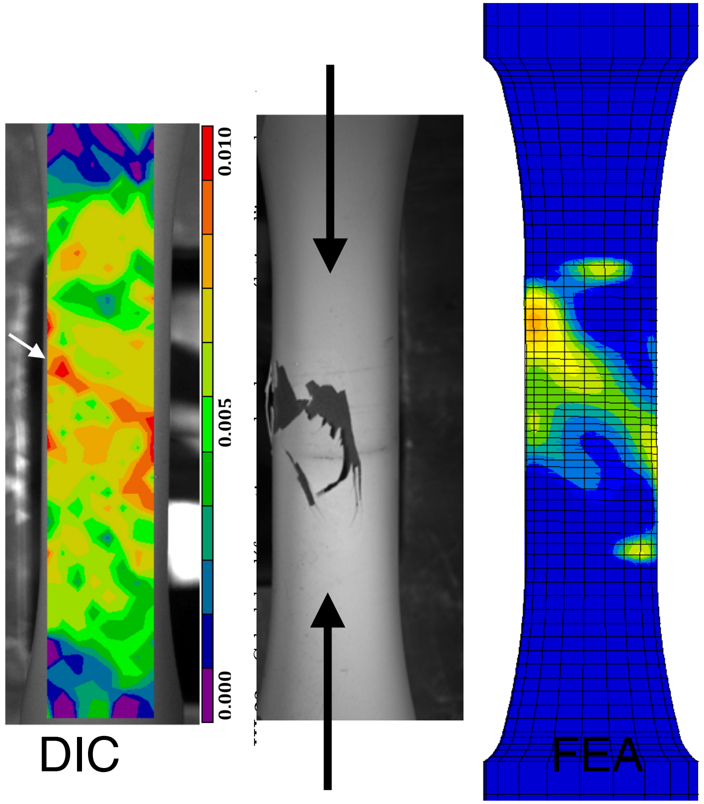
Compressive testing

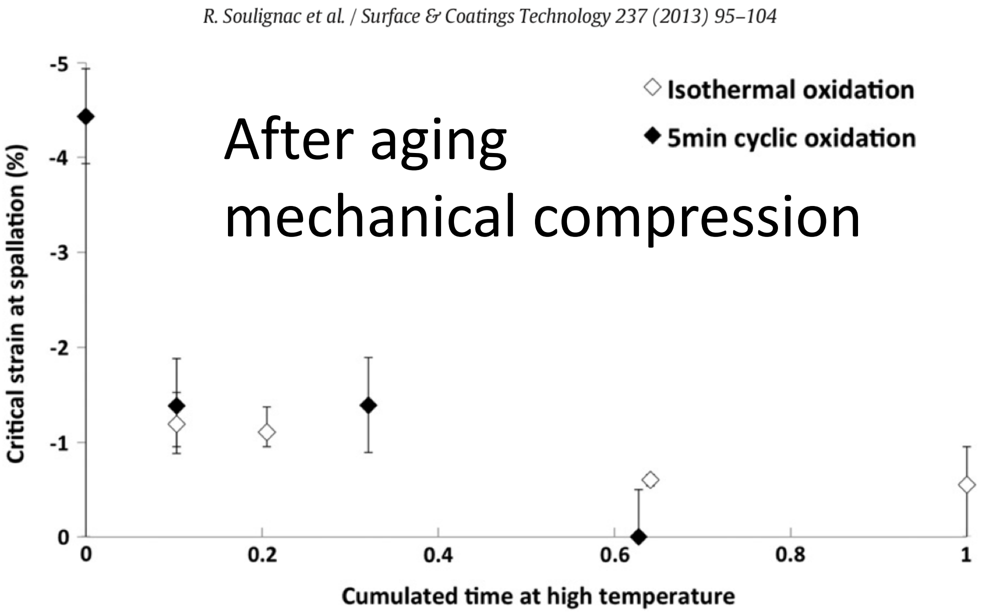
Edge effect



X. Zhao et al. / Acta Materialia 59 (2011) 6401–6411

Specimen designed to avoid edge effect





A. Bickard / PhD Thesis, 1998
M. Harvey et al. / Surface & Coatings Technology 203 (2008) 432–436
V. Maurel, P. De Bodman, and L. Rémy. "Influence of substrate strain anisotropy in TBC system failure." Surface and Coatings Technology 206.7 (2011): 1634-1639.
R. Soulignac et al. / Surface & Coatings Technology 237 (2013) 95–104 99

OUTLINE

Toward robust modelling of TBC model to spallation
How to test TBC adhesion in a robust manner?
How to gain in damage mechanisms analysis to assess TBC lifetime?

LASER ADHESION TEST (LASAT)

THERMAL CYCLING

BLISTERING

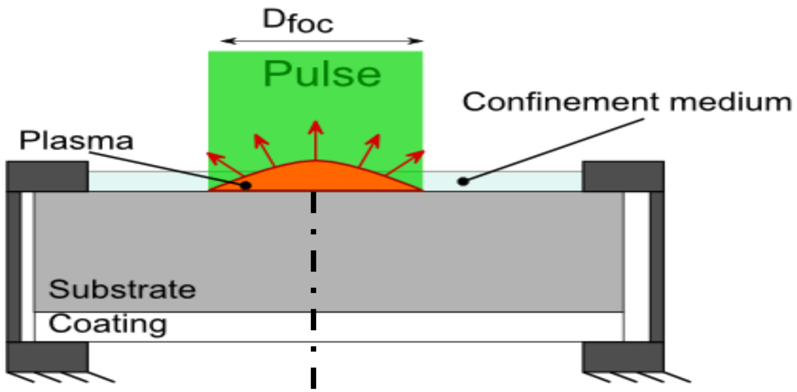
FEA

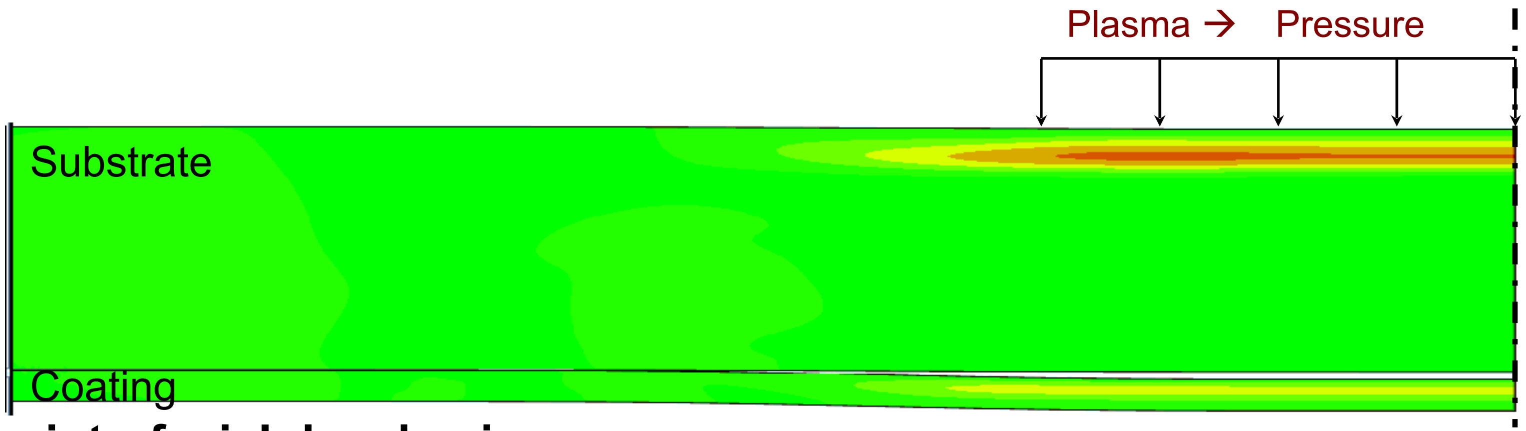
OUTLOOK

LASER ADHESION TEST : LASAT

- Contactless method
- Circular debonded area induced by wave shock
- LAser Shock Adhesion Test (LASAT)

$$\Phi\ (\mathrm{GW/cm^2}) = \frac{4.E}{\pi.\tau.D_{foc}^2}$$





Laser Source
E = 1,8J
λ = 532nm
τ = 5-6ns

If $\Phi > \Phi c$: interfacial decohesion

If $\Phi < \Phi c$: no interfacial damage = Non-Destructive Technique

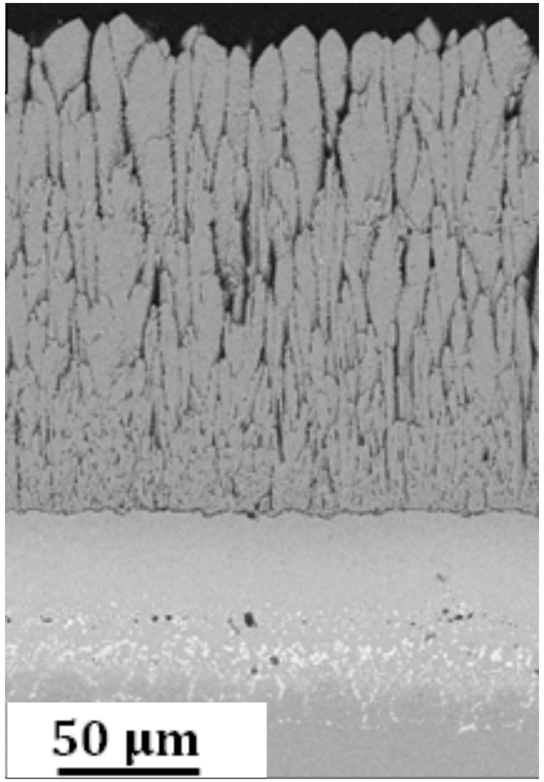
Mainly mode I

Extremely high strain rate (10^6/s)

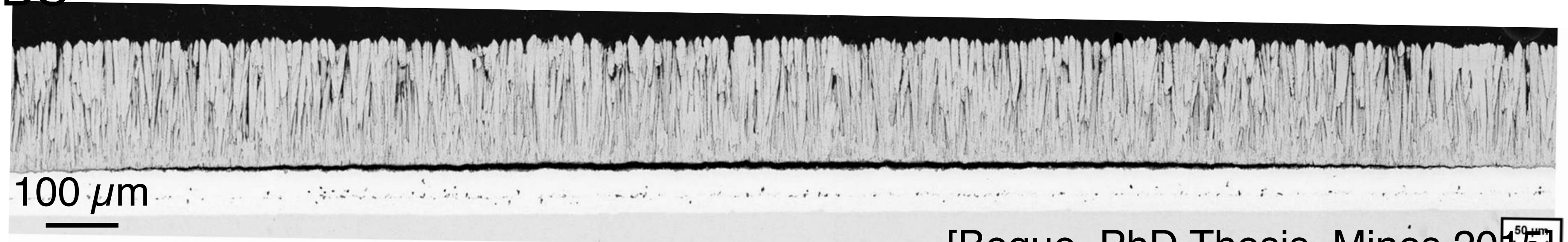
APS - SPS - EB-PVD [Guipont et al, IRSEE V]
EBC [Guipont et al, IRSEE VI] poster

CHARACTERIZATION OF A LASER SHOCK FLAW

Application to EB-PVD TBC

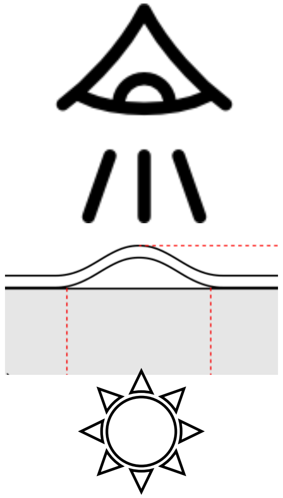


TC: YSZ EB-PVD
BC : NiAlPt
Substrate: AM1 first generation Ni Base SX superalloy



[Begue, PhD Thesis, Mines 2015]

- Using button shape specimen



25 mm

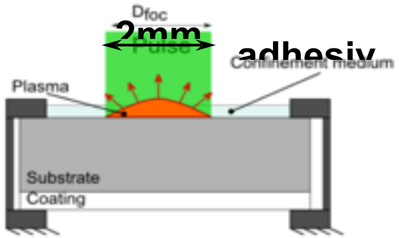
13 shocks

optic

Infra red thermography (IRT)

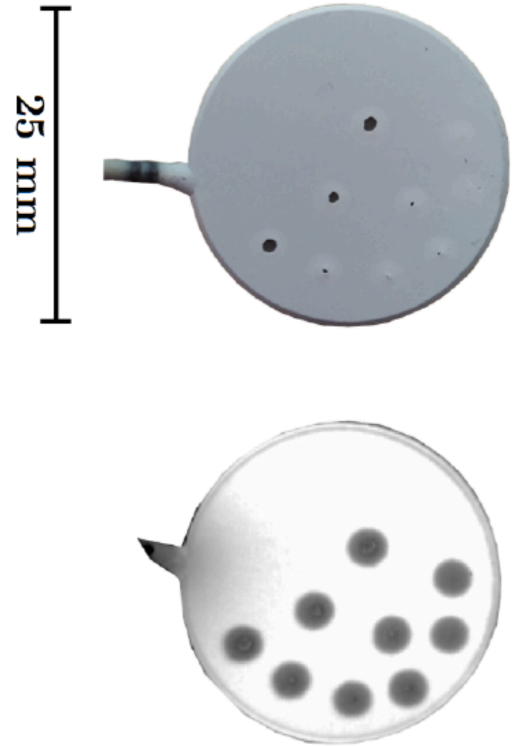
50 °C

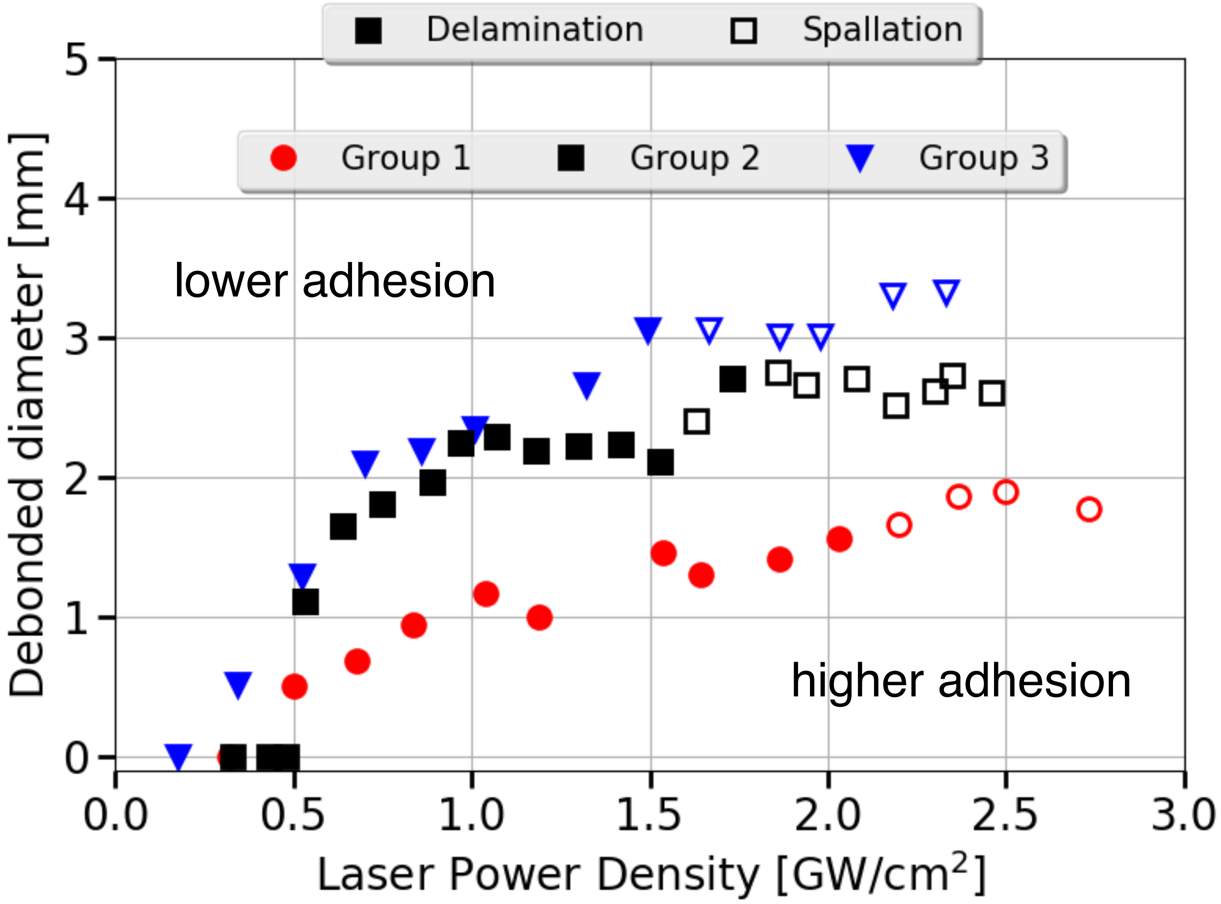
[Theveneau-Prost, Guipont, Coudon SAFRAN Tech]



LASAT CURVE

Measurement of debonding as function of laser intensity

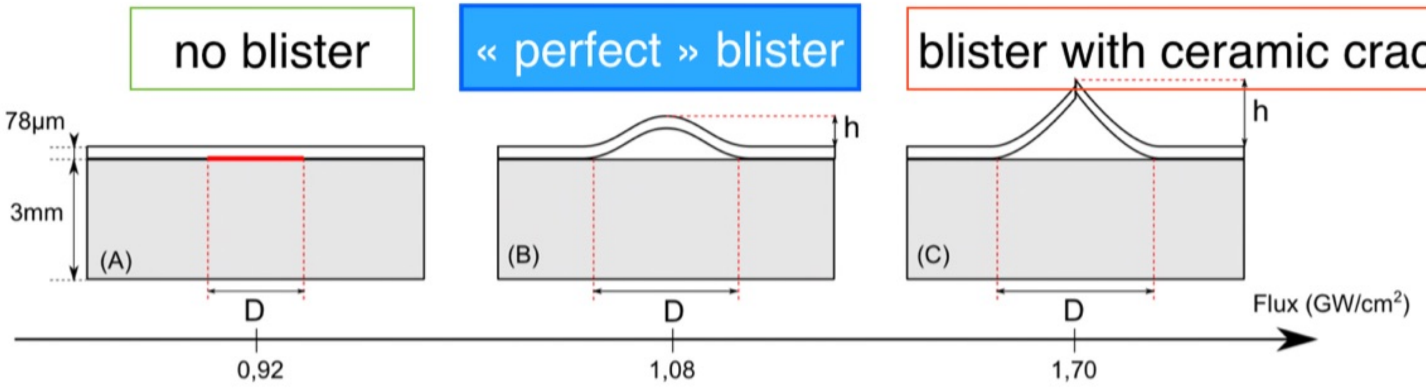


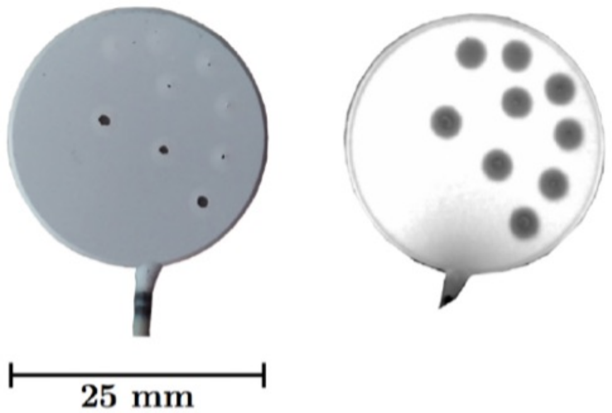


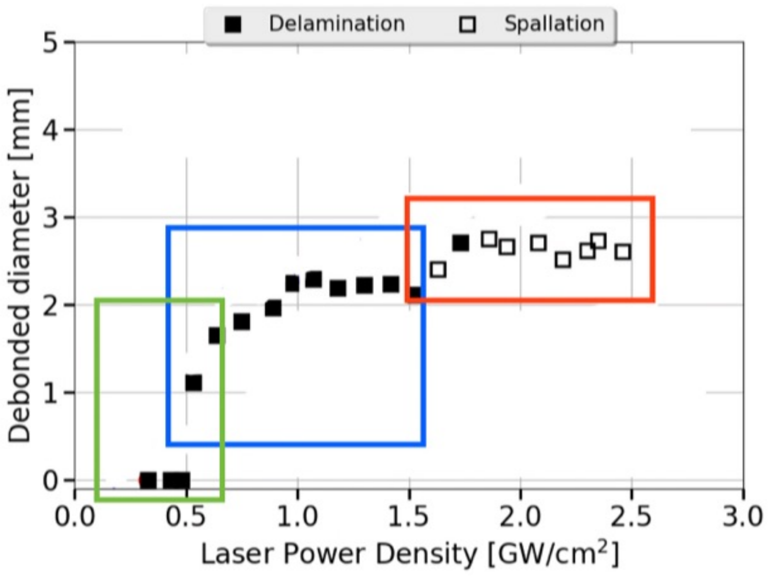
$$\Phi\ (\mathrm{GW/cm^2}) = \frac{4.E}{\pi.\tau.D_{foc}^{2}}$$

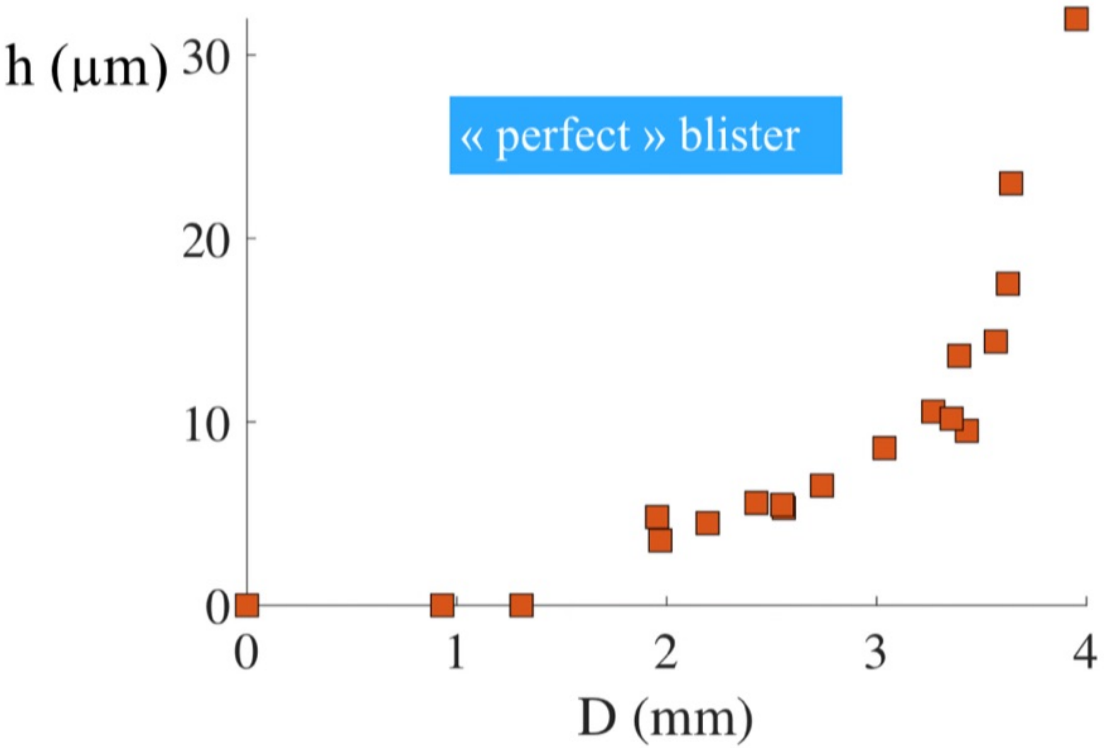
- Easiness of debonding evaluation
- Low level of experimental scatter (*i.e.* laser intensity → flaw diameter)

LASAT TO DESIGN A BLISTER / EB-PVD







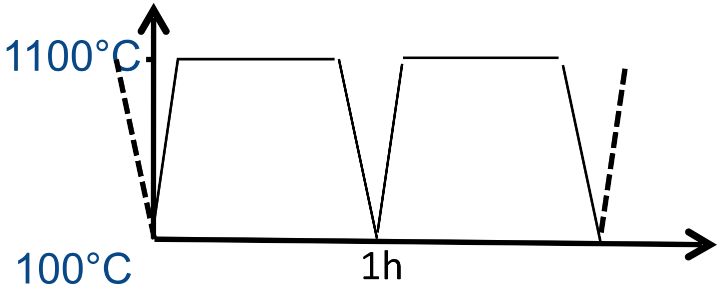


choose your blister!

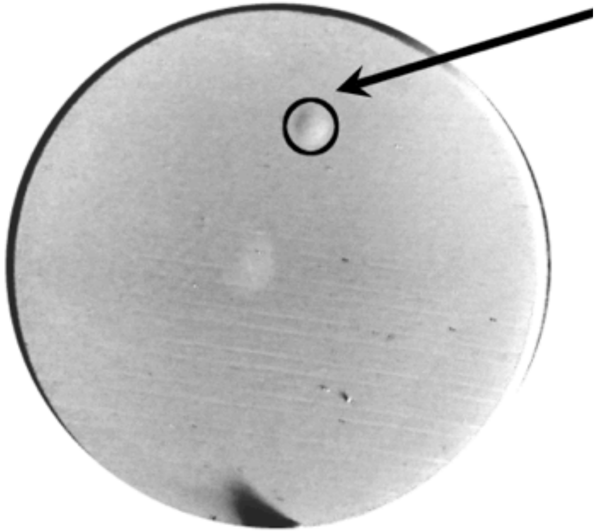
[Sapardanis & Begue G PhD Thesis]

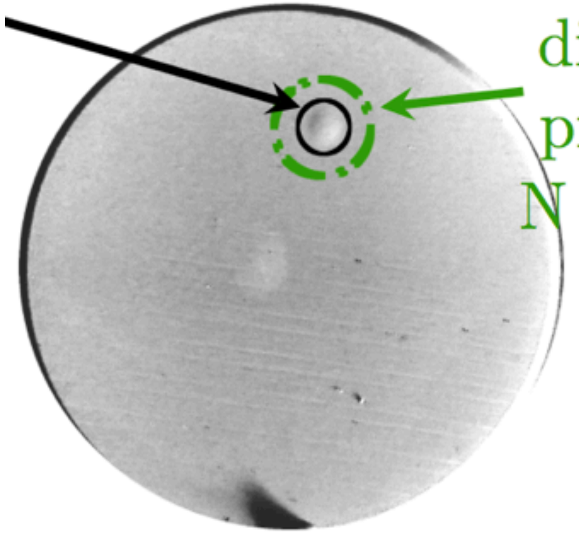
LASAT PRE-DEFECT AND THERMAL CYCLING

To assess impact of aging



Debonded Area in the as-processed condition

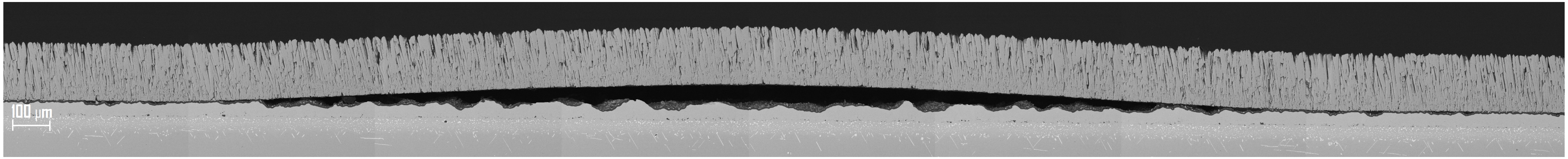




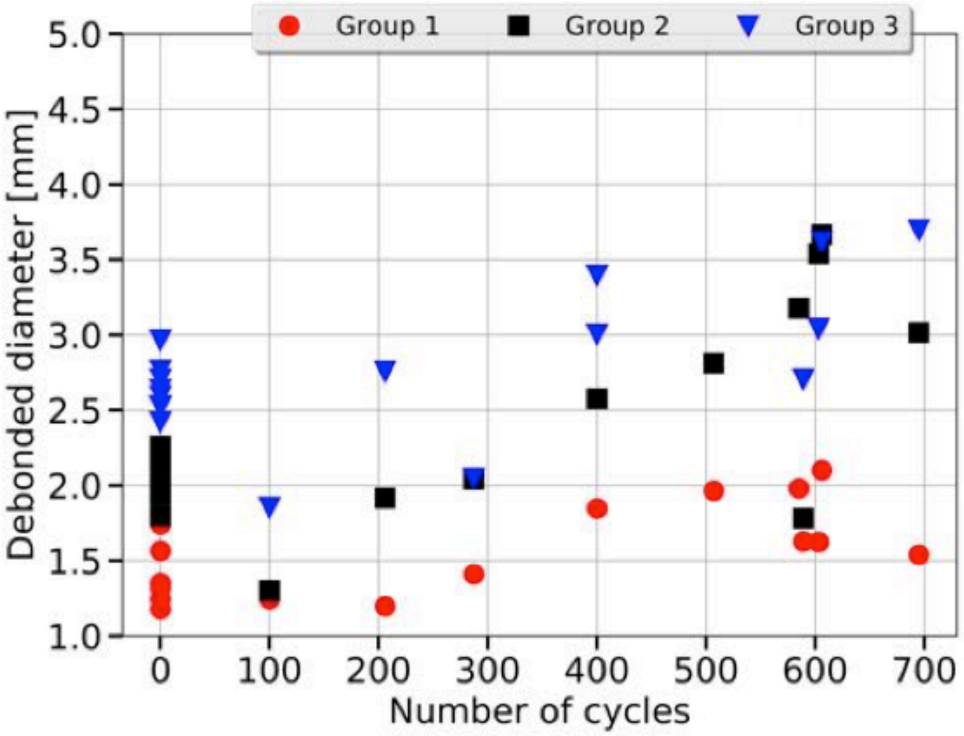
Evolution of the debonded diameter made in the as-processed condition after N thermal cycles → $D(N)$

? ? ? ? ?

LASAT PROPAGATION



- strong evolution of the TBC
  - higher height of the blister
  - rumpling in initial debonded area
  - “natural” damage beyond the crack tip
- **Progressive delamination from initial defect**
- Group ranking is consistent from AR to aged condition
- progressive evolution of debonded area with the number of cycles : D=D(N)



MINES PARIS | PSL | Centre des Matériaux

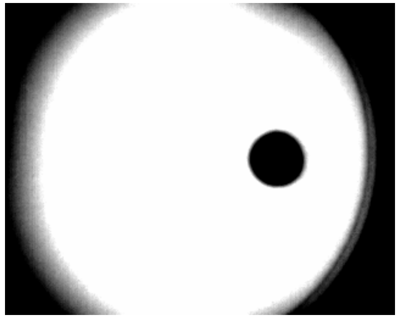
[V. Guipont, et al, SCT 19, V. Maurel et al SCT 19] / M Prost - F Coudon

INFLUENCE OF THERMAL CYCLING PARAMETERS

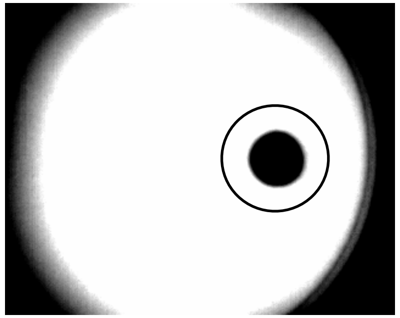
interfacial crack propagation analysis

- **IRT measurement of debonding**

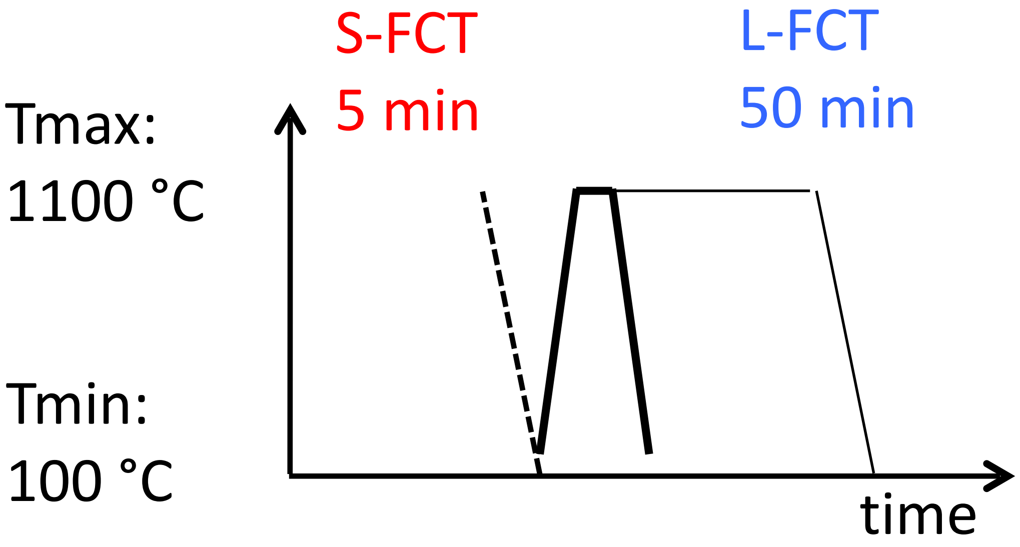
Long versus Short Furnace Cycling Test

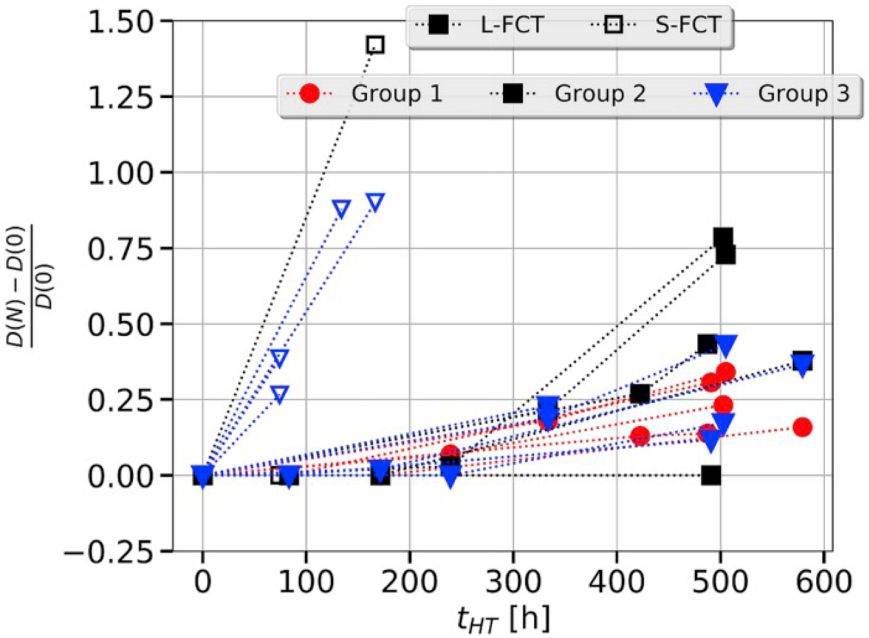


As received



Evolution of delamination





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INFLUENCE OF THERMAL CYCLING PARAMETERS

interfacial crack propagation analysis

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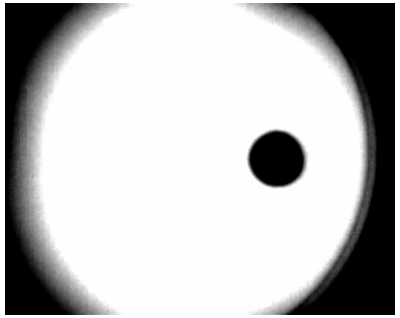
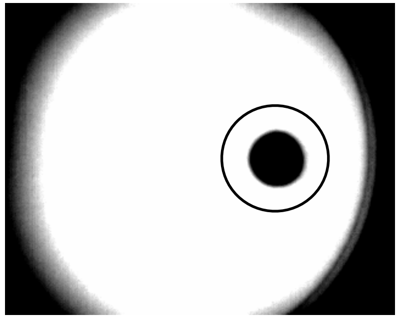


As received



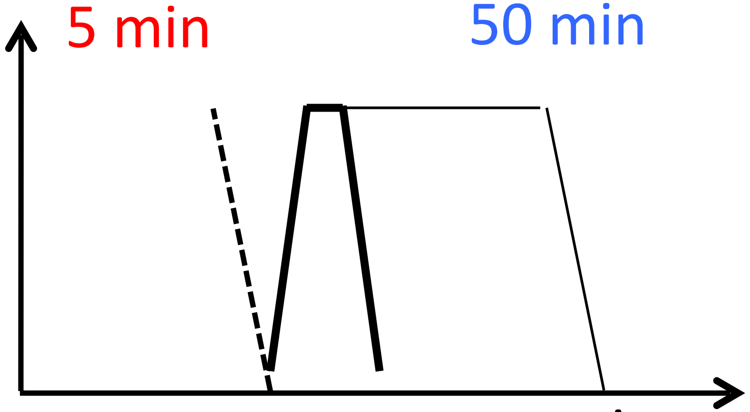
Evolution of delamination

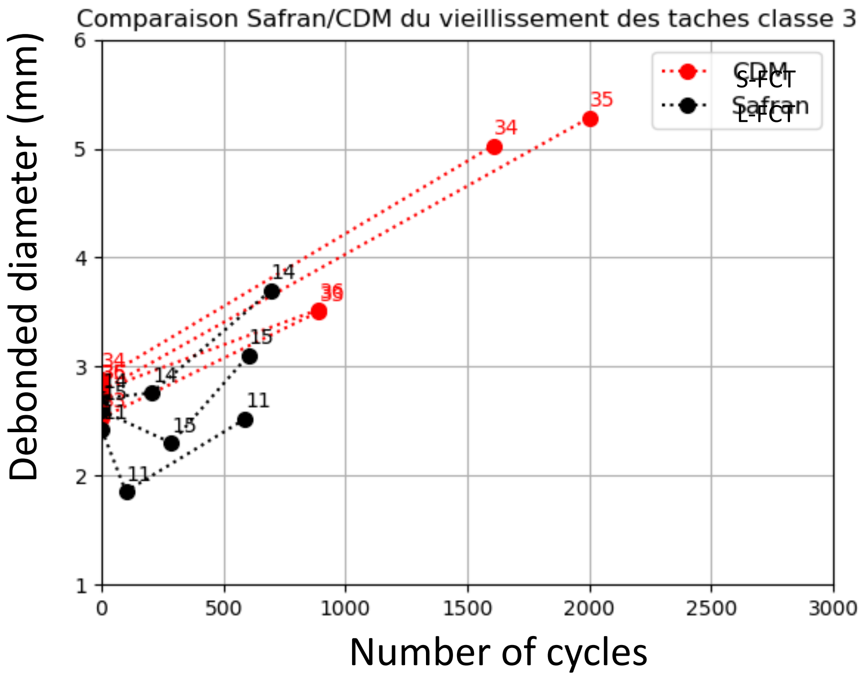
S-FCT
5 min

L-FCT
50 min

Tmax:
1100 °C

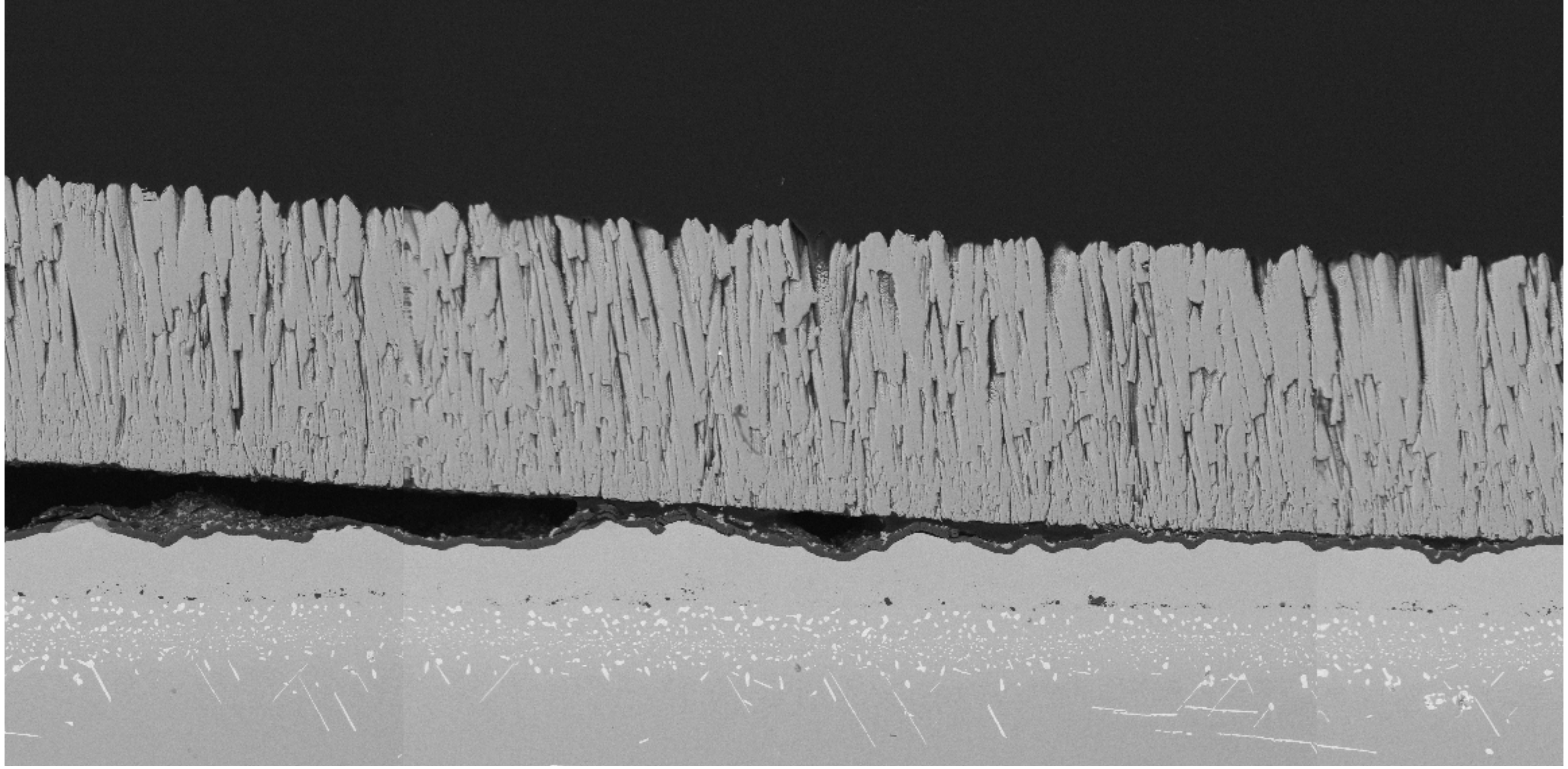
Tmin:
100 °C





LASAT to introduce artificial defect to test TBC adhesion in a robust manner

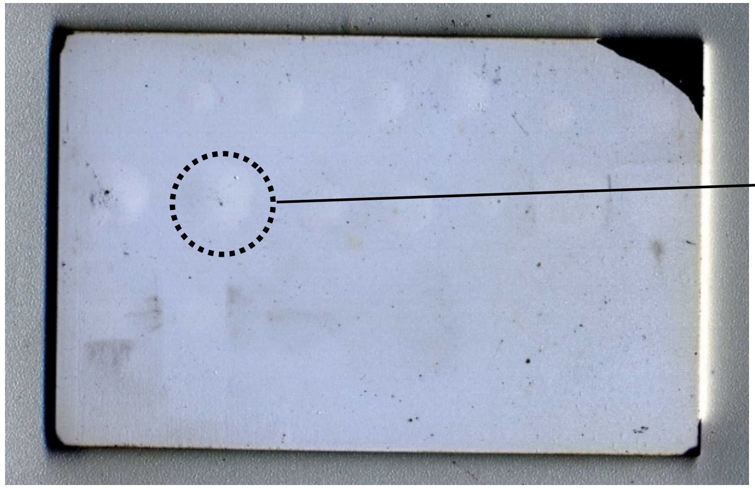
Nf = f(fatigue crack growth rate) => what are the driving forces ?



BLISTERING WITH THERMAL CYCLING

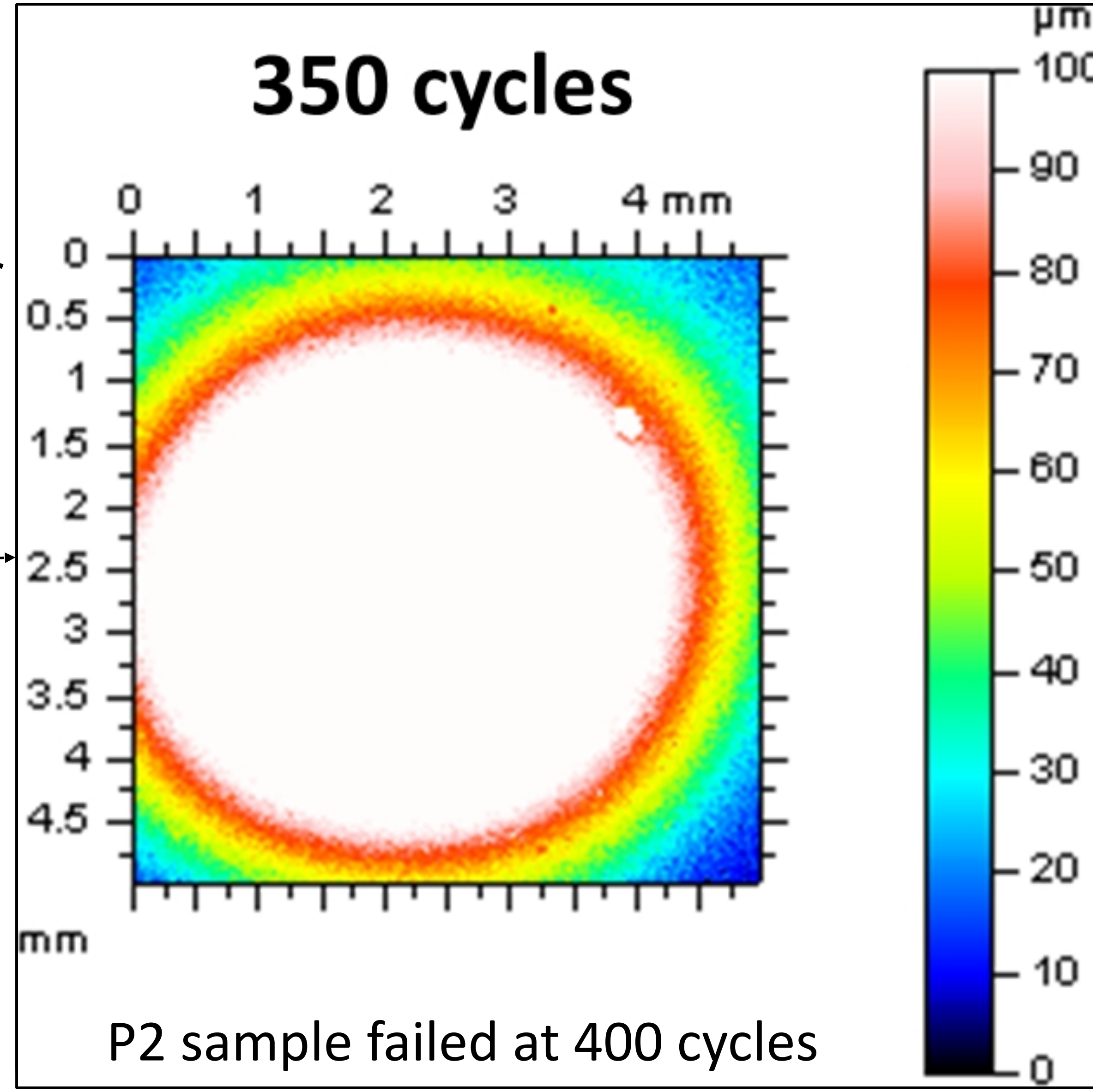
THERMAL CYCLING ANALYSIS FROM LASAT DEFECT

- One single specimen, following one single blister
- Measurement of 3D morphology of the blister



- P2 after 250 cycles

[PhD Begue]



[Guipont et al, Surf Coat Techn 2019]

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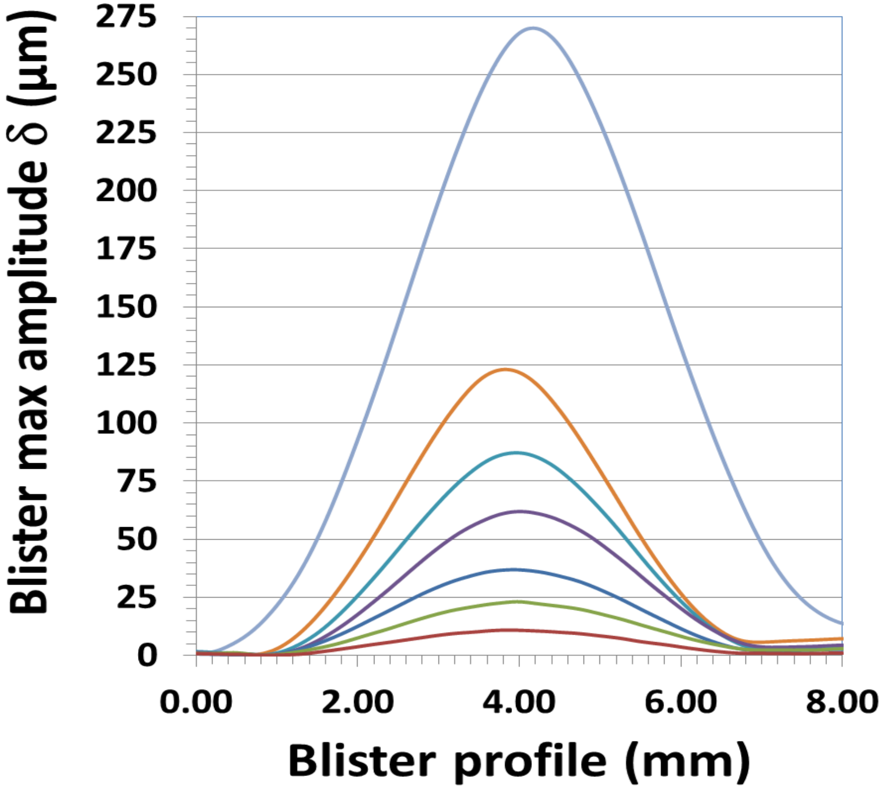
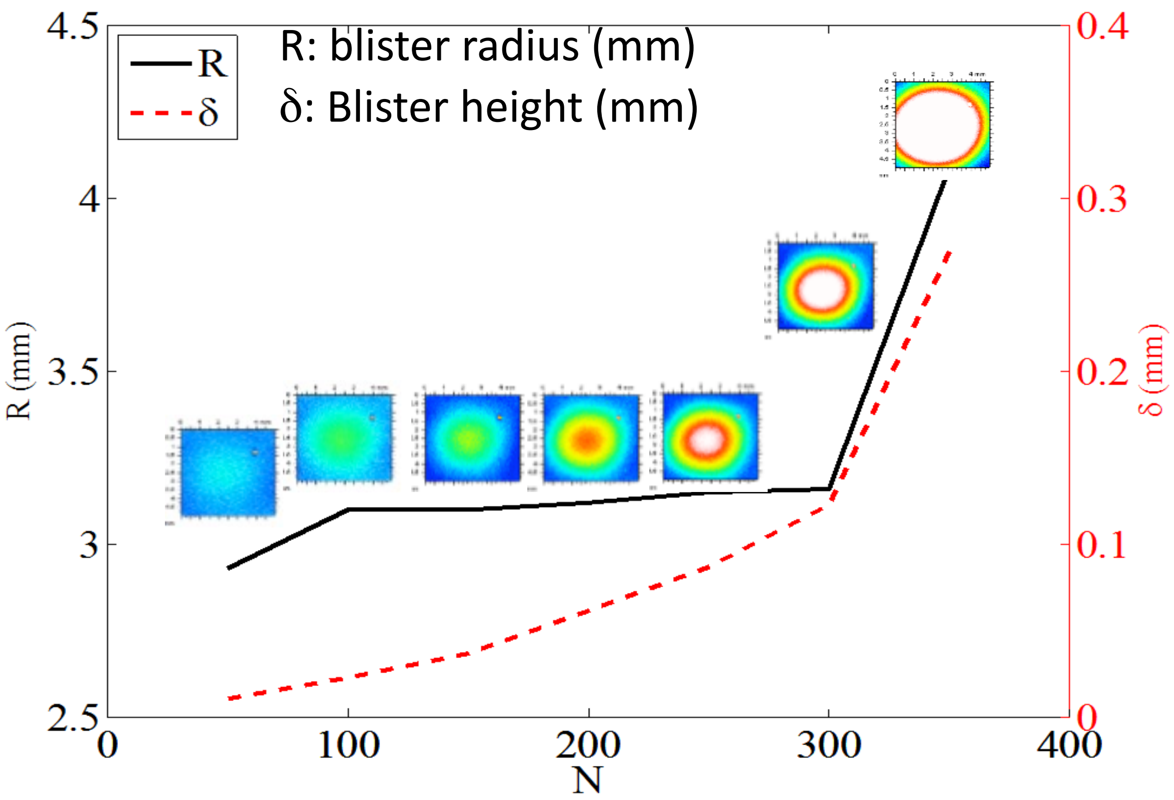
SINGLE BLISTER EVOLUTION WITH THERMAL CYCLING





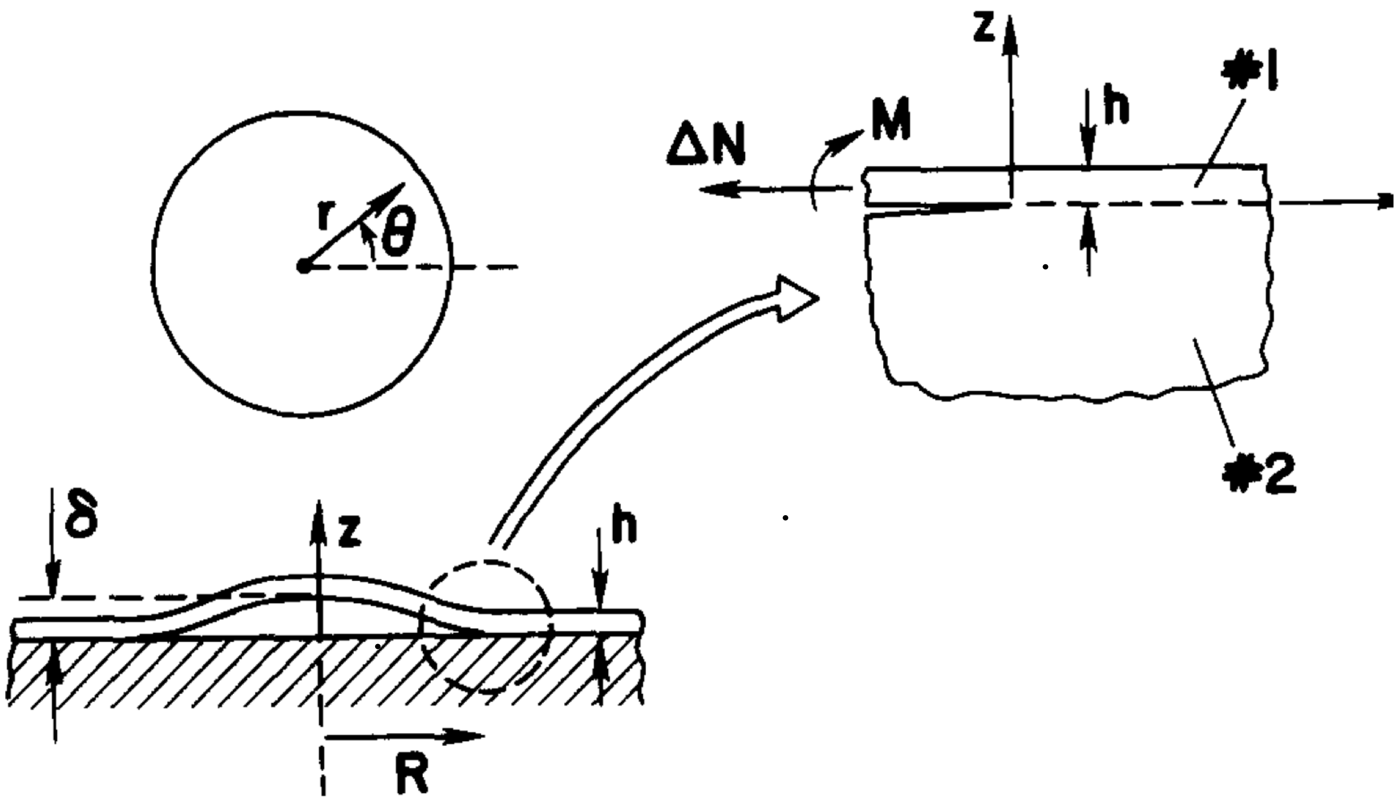
- Buckling is activated while delamination is not

[Guipont et al, Surf Coat Techn 2019]

BLISTERING WITH THERMAL CYCLING

mechanical governing equations

J. Hutchinson, M. Thouless, E. Liniger / ActaMetallurgica et Materialia 40 (2) (1992) 295 – 308



critical stress at buckling

$$\sigma_c = 1.2235 \frac{E_1}{1-\nu_1^2}\left(\frac{h}{R}\right)^2.$$

buckling height

$$\frac{\delta}{h} \cong \left[\frac{1}{c_1}\left(\frac{\sigma}{\sigma_c}-1\right)\right]^{1/2}$$

energy release rate

$$G = \frac{6(1-\nu_1^2)}{E_1 h^3}\left(M^2 + \frac{1}{12}h^2 \Delta N^2\right)$$

FEA OF THERMAL CYCLING

Frachon, Julien, PhD Thesis, Mines Paris, 2009

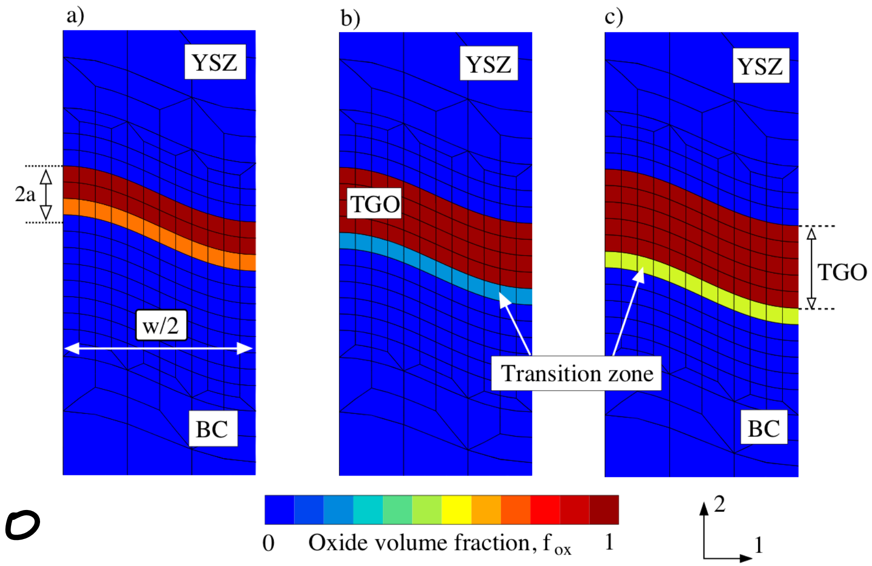
explicit model of

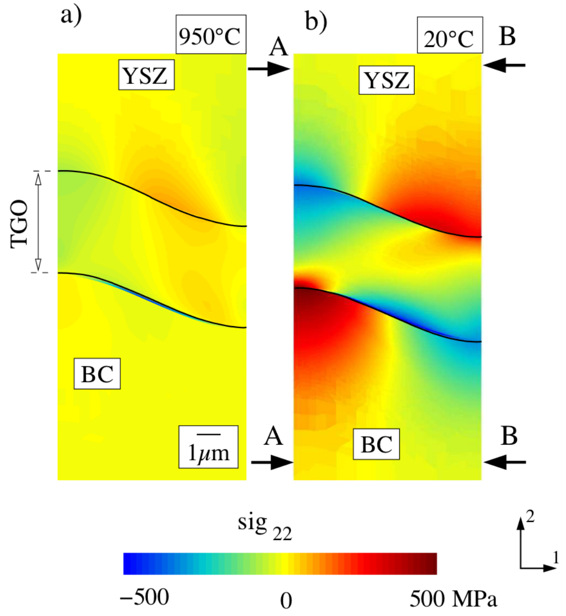
- interfacial roughness
- oxidation kinetic
- **growth strain from BC to TGO**

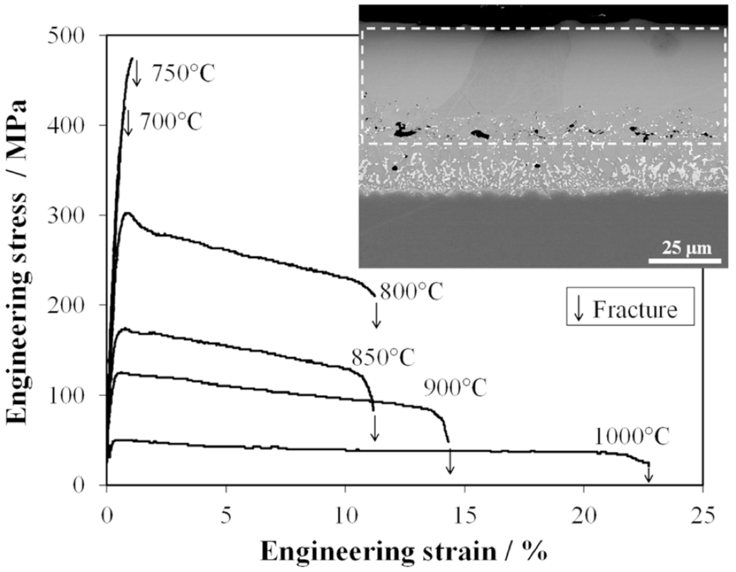
$$\varepsilon_{tot}^{TGO} = \varepsilon_{m}^{TGO} + \varepsilon_{th}^{TGO} + \varepsilon_{gr}^{TGO}$$

- **strain compatibility**

$$\varepsilon_{tot}^{TGO} = \varepsilon_{tot}^{BC} = \varepsilon_{tot}^{substrate}$$







BC behavior from free standing specimens :

0.035x2x35 mm^3

Texier, Damien, et al. *Met. Mat. Trans. A* 51.4 (2020): 1475-1480.

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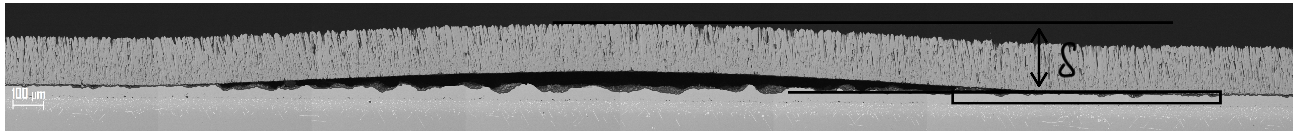
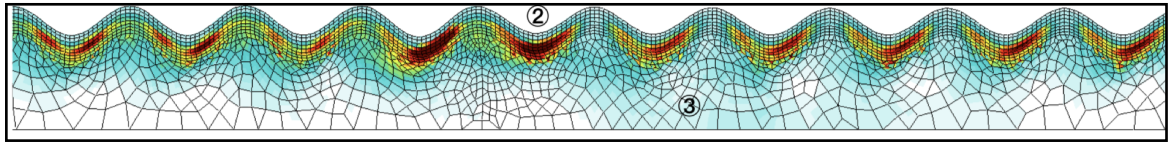
PLASTIC HINGE : STRONG MODIFICATION OF BOUNDARY CONDITIONS

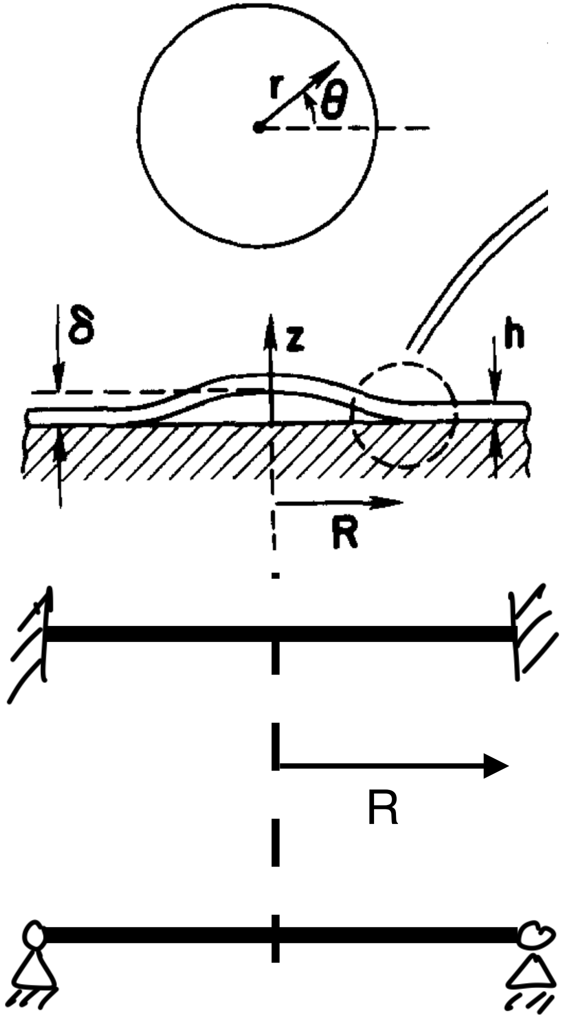




strain localization

plasticity decreases the apparent stiffness of the BC

modifies the boundary conditions for buckling



critical stress at buckling

$$\sigma_c = 1.2235 \frac{E_1}{1-\nu_1^2}\left(\frac{h}{R_{eff}}\right)^2.$$

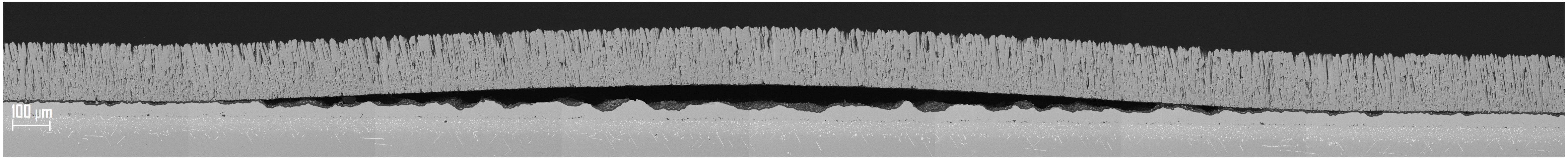
buckling height

$$\frac{\delta}{h} \cong \left[\frac{1}{c_1}\left(\frac{\sigma}{\sigma_c} - 1\right)\right]^{1/2}$$

$R_{eff} = R$

$R_{eff} = 2R$ → $\sigma_c / 4$, $\delta \times 2$

CONCLUSIONS



LASAT predefect is fantastic

= a methodology to assess interfacial damage evolution and driving forces for cracking

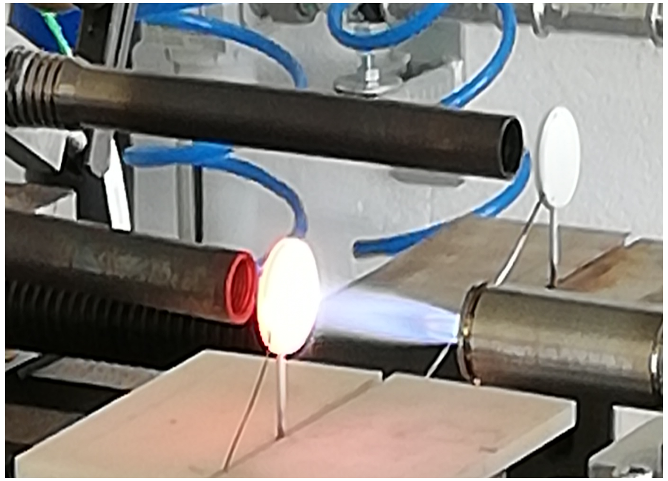
increase of blister height precedes debonding due to crack closure

blister height increase is associated to strain localization in the BC

driving forces for blistering and damage are confirmed by FEA to be the same as for rumpling but

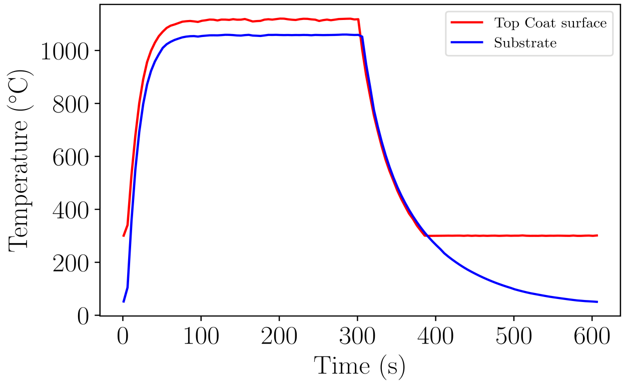
- increase in available energy for blistering precedes crack growth
- because of crack closure : top of roughness is a stable configuration for crack
- damage is promoted beyond the crack tip : valley of roughness triggers damage

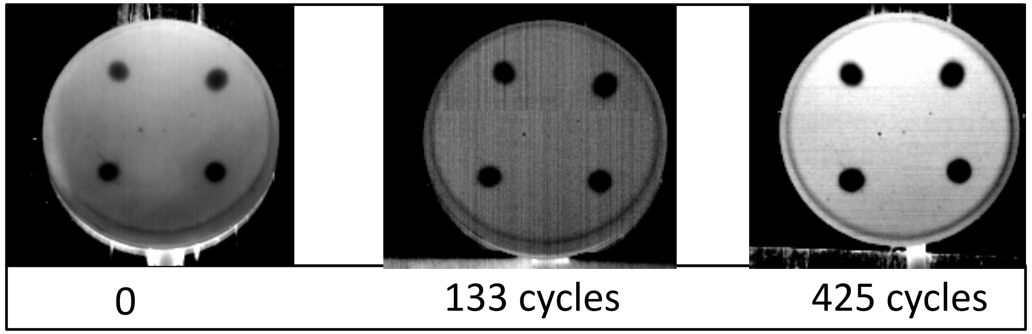
OUTLOOK : THERMAL GRADIENT IN BURNER RIG



Thermal cycling test configuration

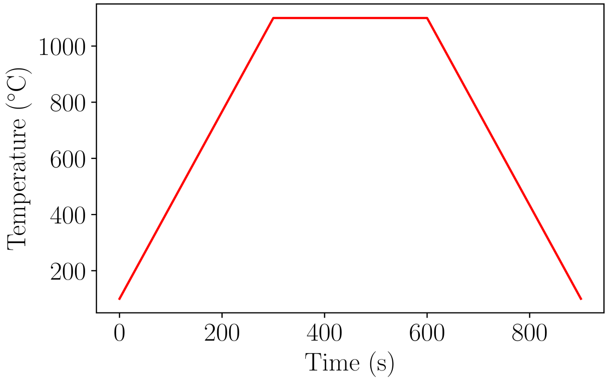
Burner rig cycle

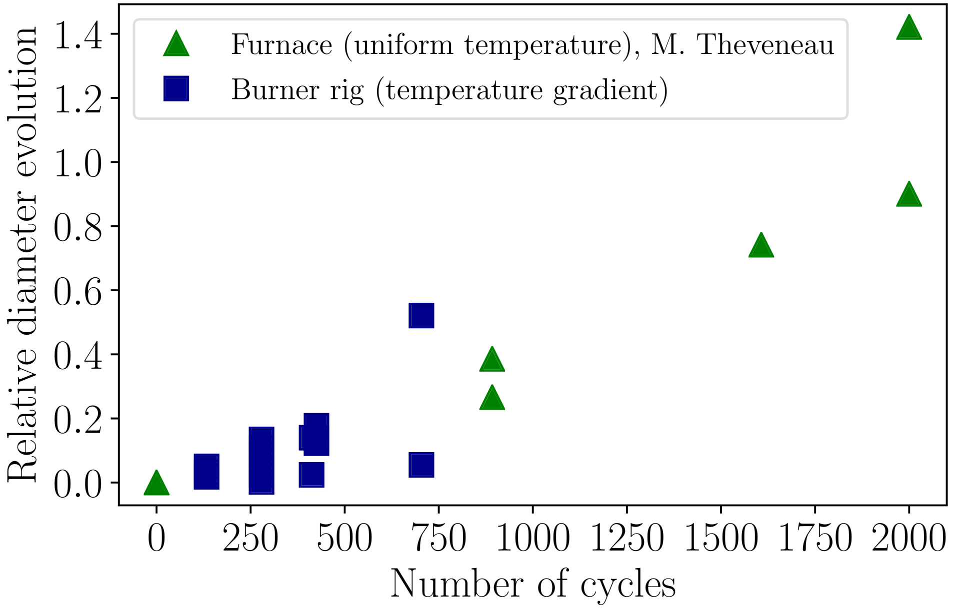




Progressive delamination measurement by infrared thermography

Furnace cycle





stability of the blister in the flame (no direct failure)

in situ monitoring of debonding by image analysis

[L. Mahfouz, PhD Safran]

LABEGA PROJECT : THERMAL GRADIENT IN BURNER RIG

LABEGA German/French project

Julich IEK1 R Vaßen D Mack

=> PhD Thesis Jens Igel

Oerlikon Metco

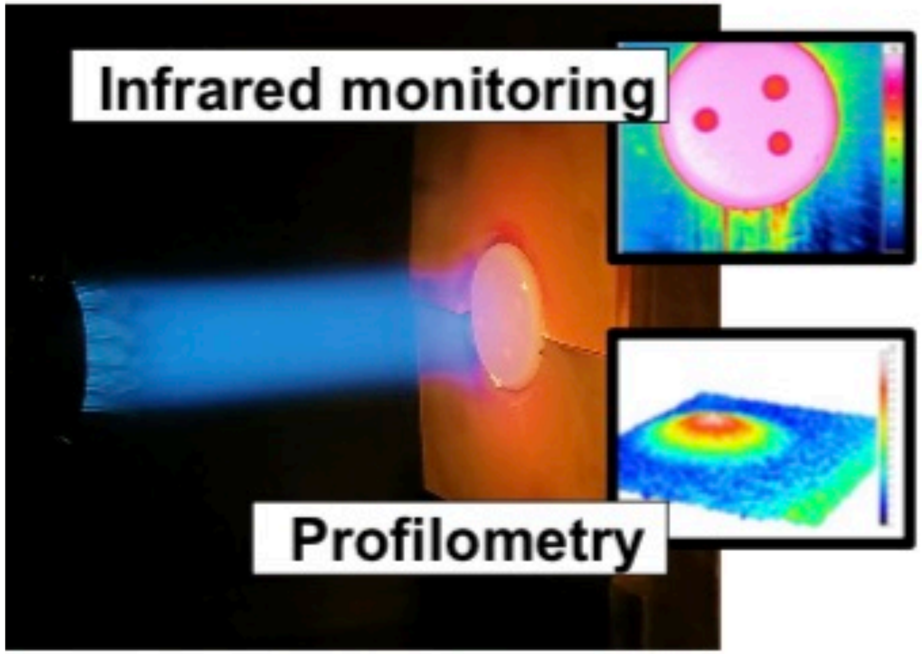
Mines Paris

=>PhD Thesis Lara Mahfouz

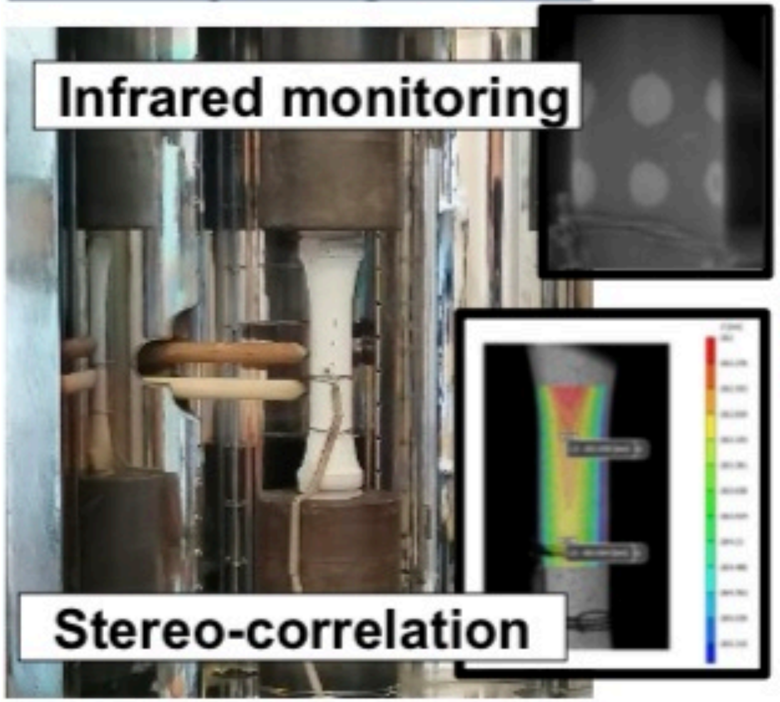
Safran

Florent Coudon, Mark Harvey

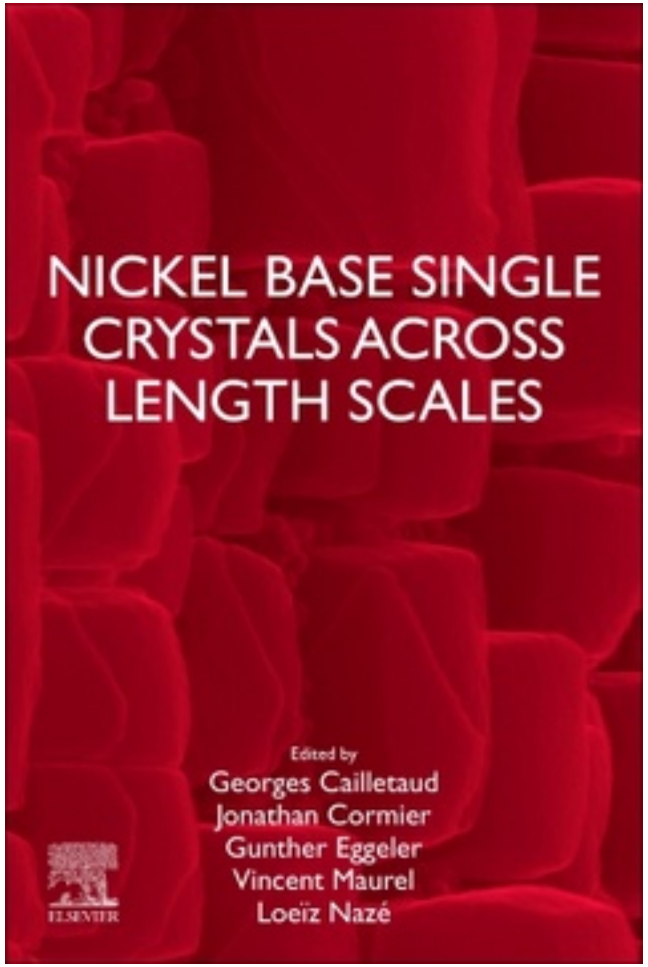
Burner Rig Cycling - Jülich



TMF Cycling - CdM



Thank you for your attention



webinar series

online next Septembre, 9th, at 3 pm (Paris Time).

Microstructure characterization (in Ni base single crystal superalloys)
Pr. Cathie M.F. Rae from the University of Cambridge (UK) and Pr. Florence Pettinari-Sturmel from CEMES/University of Toulouse (France).

online next October, 6th(*), at 2 pm (Paris Time).
Coated single crystal superalloys: processing, characterization, and modeling of protective coatings.
Pr R Vaßen from Jülich IEK1 (Germany) and V. Maurel from Mines Paris (France)

(*) TBC

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