5-6 Juin 2019

Apport de la méthode LASAT (choc laser) pour l'étude de systèmes revêtus métal/céramique en présence d'une couche d'oxyde

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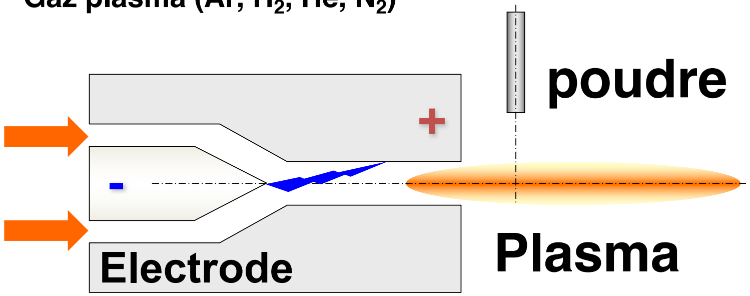
Coll: V.Maurel, C.Duhamel

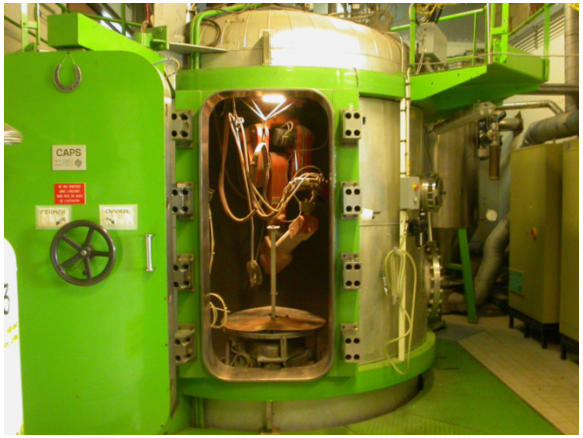
Journées « Couplage Mécanique/Diffusion/Oxydation », UTC

Revêtements particulaires par projection

Projection Plasma CAPS

Gaz plasma (Ar, H_2, He, N_2)

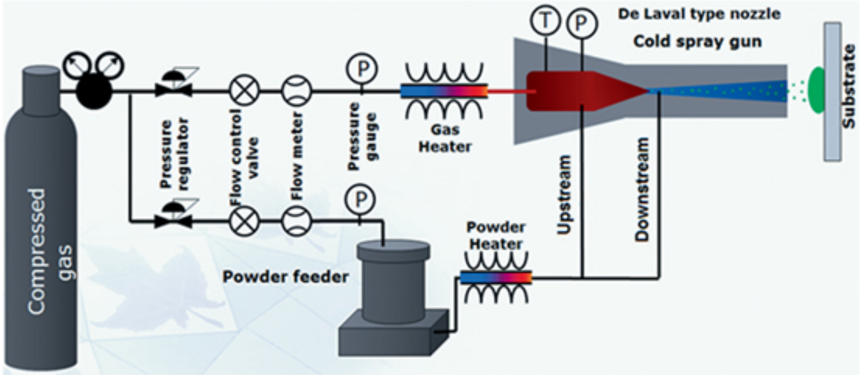




- APS
- VPS

CAPS enceinte multiprocédés
(plasma, cold spray,…)

Projection Dynamique par Gaz Froid 'Cold Spray'



Modern Cold Spray: Materials, Process, and Applications," 2015, Springer

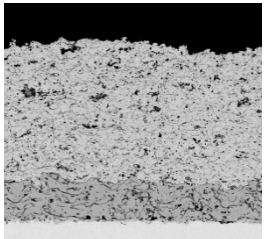
CGT - Kinetiks 3000

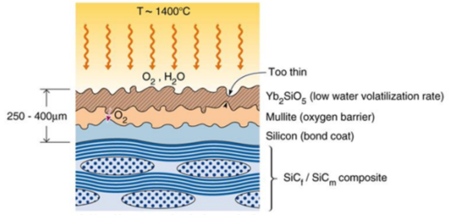
P: 0,5-3,0 Mpa/ Gaz: Azote, Hélium /T: 200-600° C
Buse De-Laval / Injection axiale

Revêtements particulaires par projection

Versalité des solutions de dépôt

- **Multicouches / Systèmes fonctionnels**

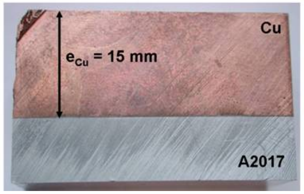




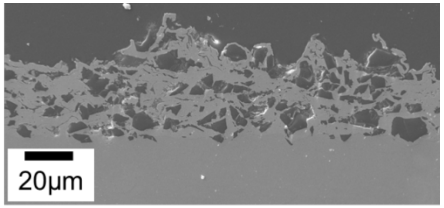
http://www.virginia.edu/

ex.: Barrière thermique (TBC) Barrière Environnementale (EBC) par plasma

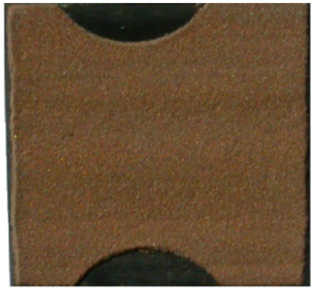
- **Fabrication additive/Réparation (cold spray)**



- **Composites / multimatériaux**



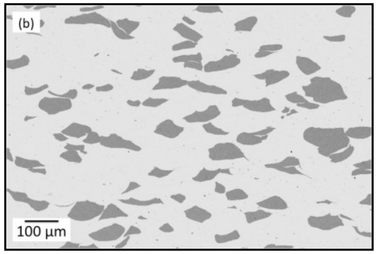
B_4C/Ni cold spray



Dépôt de mélange 70/30

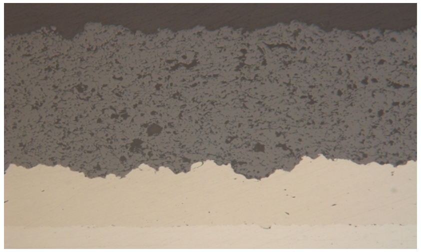
25mm

Cu/PEEK sur CMO

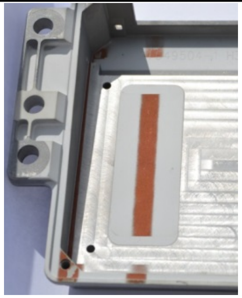


Ag/Cu cold spray

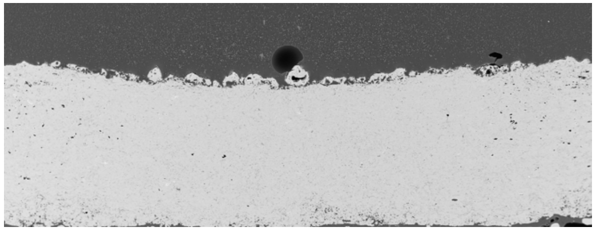
Combinaison des procédés



YSZ **plasma** / MCrAlY **Cold Spray**



Cold Spray Cu / plasma Al_2O_3



Plasma Al + **Choc laser**

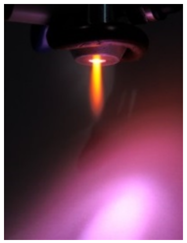
Dépôt particulaires état liquide ou vapeur

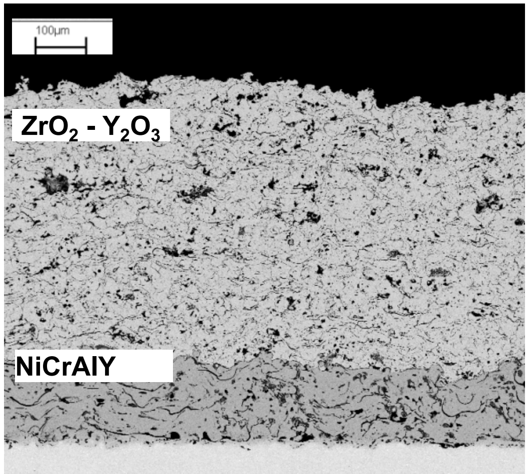
Dépôts céramiques poreux type BT « barrière thermique »

SOUS AIR

SOUS VIDE

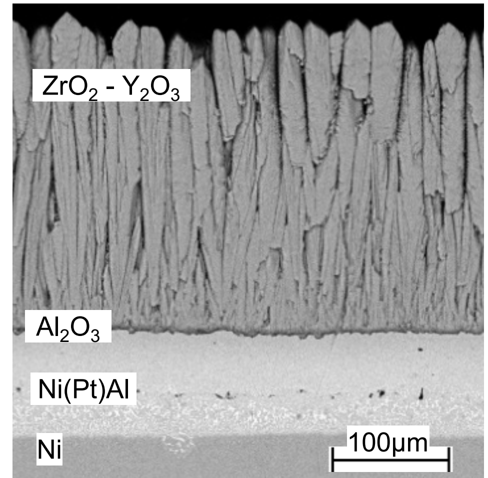
APS





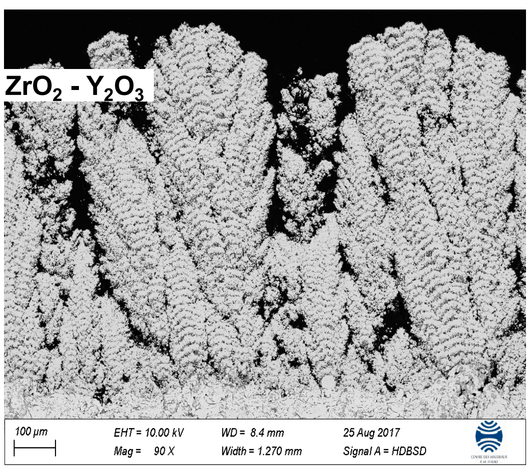
Lamellaire (conv. ou segmenté)

EB-PVD



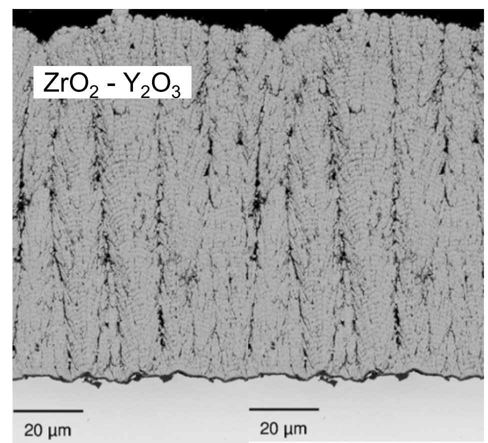
Colonnaire (cible)

SPS



Colonnaire, suspension liquide poudre <1µm)
(S.Sampath, Stony Brook U.)

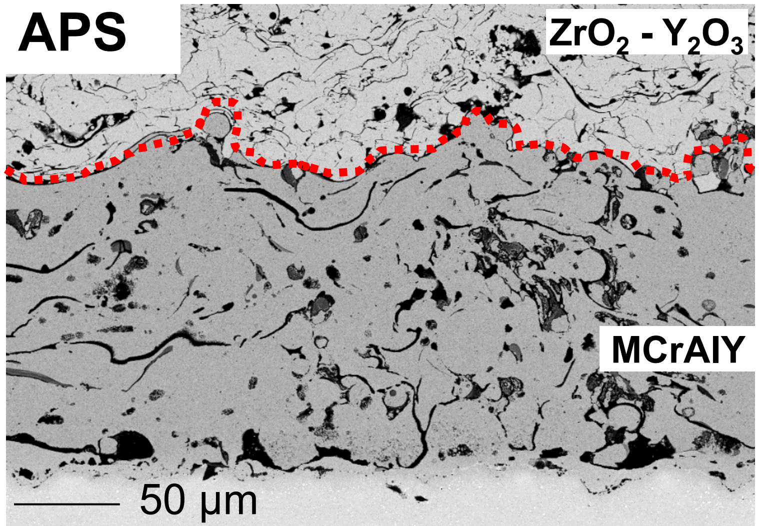
PS-PVD

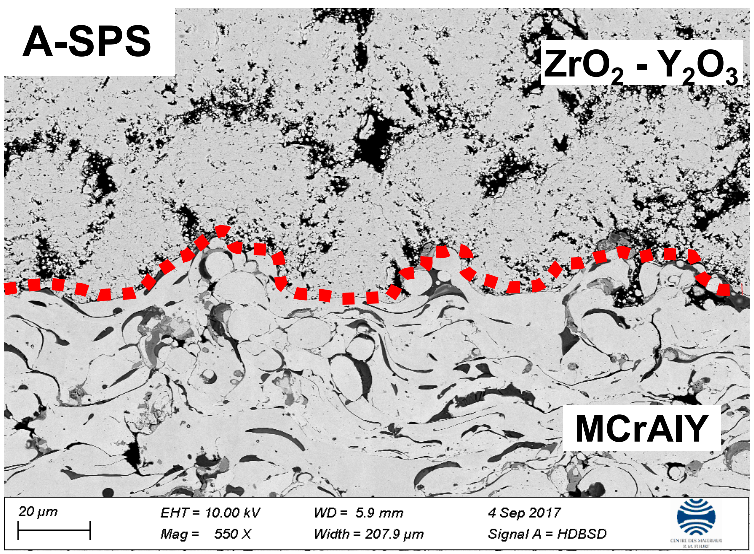


Colonnaire par PS-PVD (poudre fine voie sèche)
(Oerlikon Metco; Malko Gindrat)

“Design” d’interfaces : cas des BT

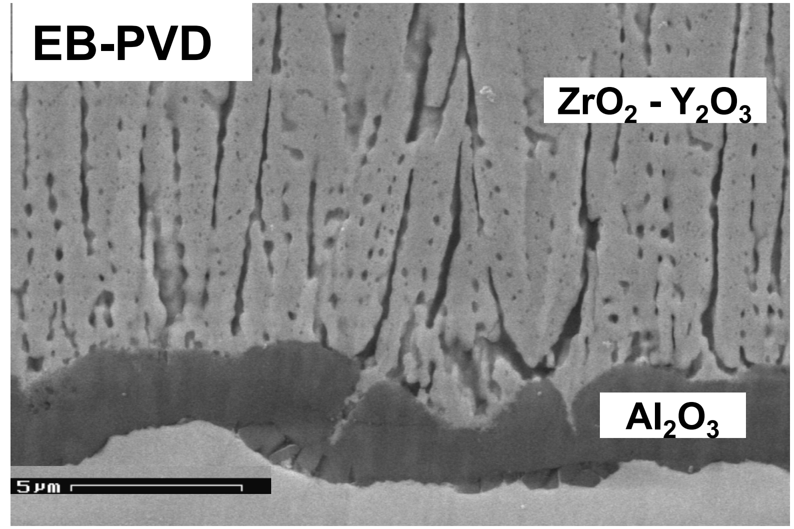
SOUS AIR

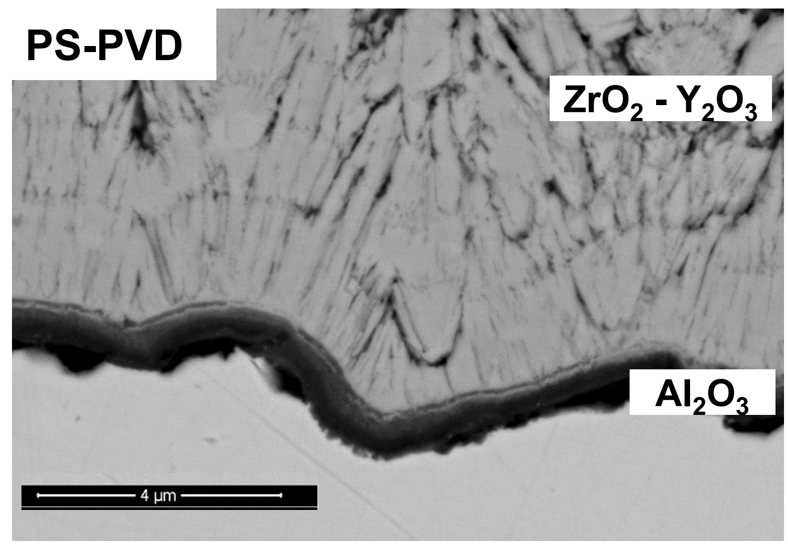




(coll. S.Sampath, Stony Brook U.)

SOUS VIDE



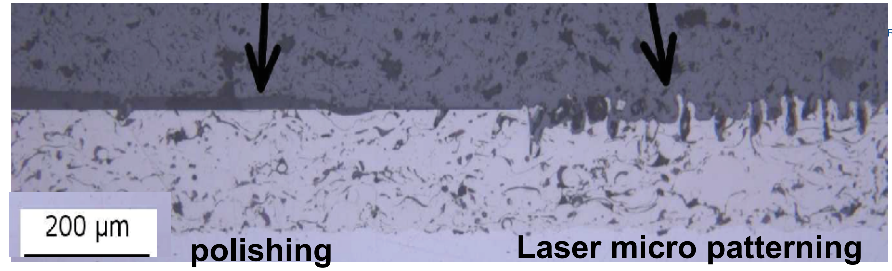


(fourni par Oerlikon Metco; Malko Gindrat)

Design d'interface: adhérence, tenue fissuration

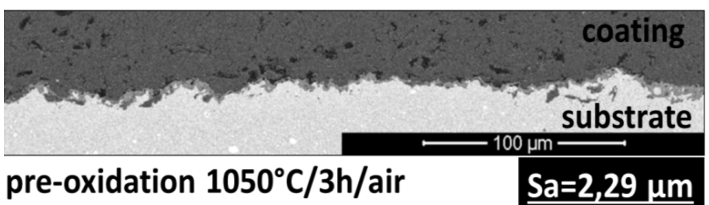
A l'état initial:

1- Aspects morphologiques

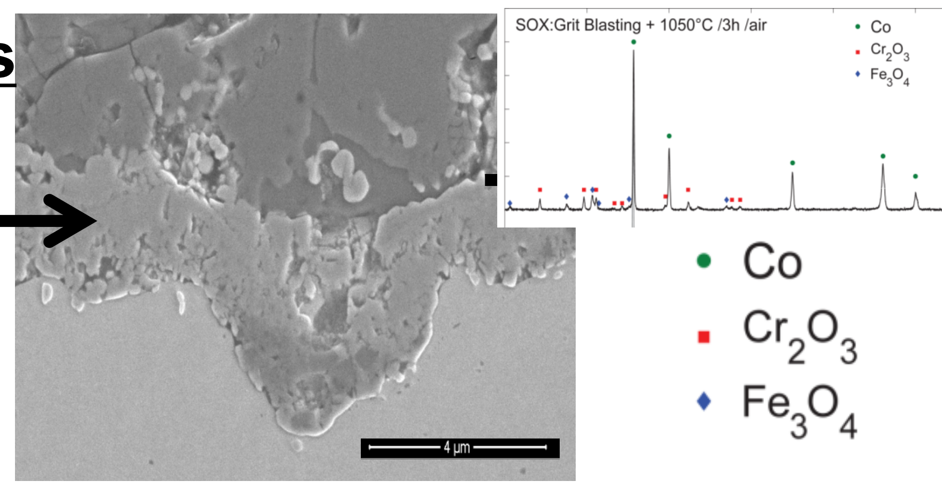


MICRO	MACRO	GRADIENTS
• Rugosification (aléatoire) • Structuration (motif)	• Rugosification (aléatoire) • Structuration (motif)	Mélange de deux constituants

2- Aspects physico-chimiques



pre-oxidation 1050°C/3h/air
Base Co HAYNES 188



3- Aspects mécaniques: Coefficient de dilatation

Contraintes résiduelles

Microstructure du dépôt (proche interface)

Problématiques du design des interfaces

Comment améliorer les designs d'interface à notamment ceux relatifs aux nouveaux systèmes revêtus?

→Evaluer facilement, de manière robuste et répétable la tenue mécanique initiale de l'interface la plus faible et représentative de l'endommagement en service

→Contrôler l'évolution de cette tenue mécanique:

- **sur échantillons en conditions de vieillissement** → LASAT
- **sur pièce réelle, si possible de manière non destructive**

Appréhender les modes d'endommagement prépondérant en relation avec les aspects morphologiques, physico-chimiques et mécaniques initiaux (macro/micro)

Aide à la prévision de durée de vie

Retour sur les procédés

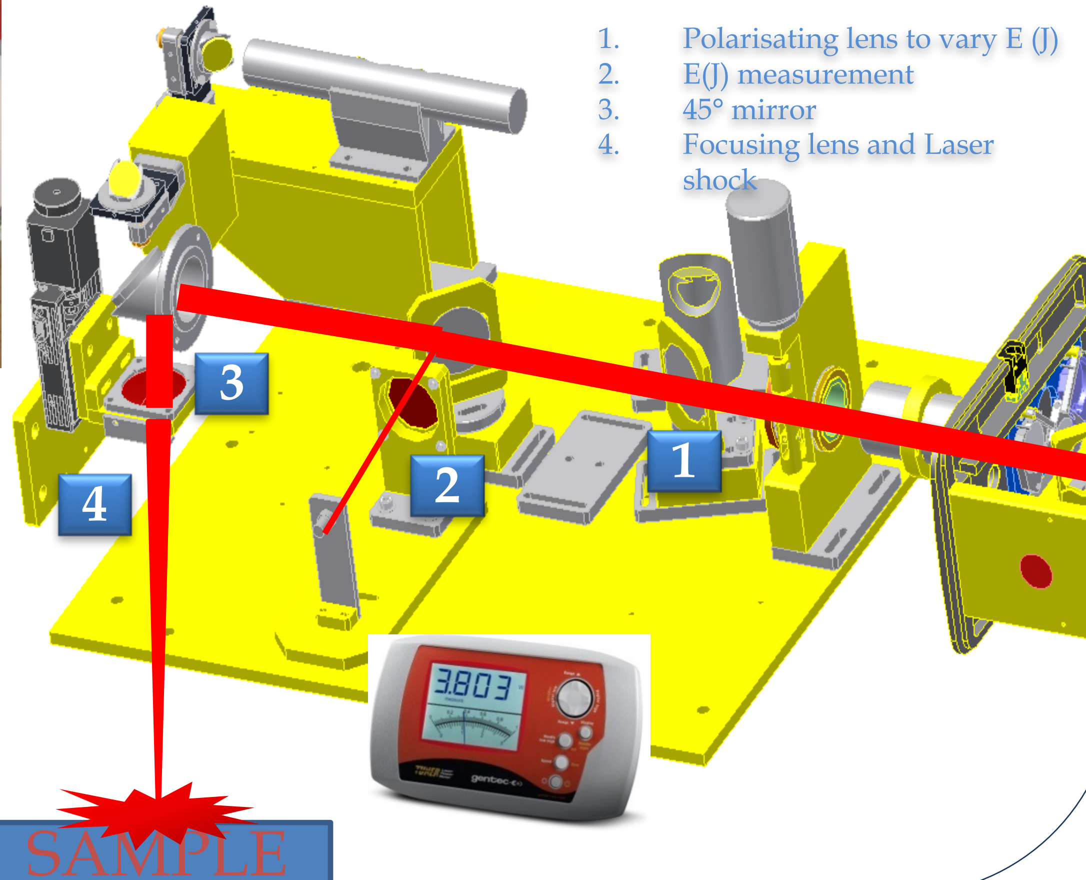
LASAT (Laser Shock Adhesion Test)

PSL

CENTRE DES MATERIAUX P.M FOURT

Etude des interfaces de dépôts et mesure de l'adhérence par choc laser (LASAT)

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



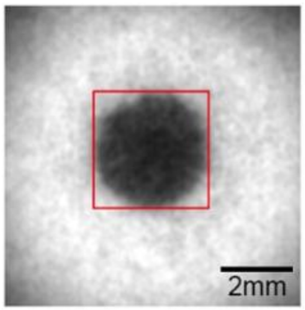
- ~ GPa , $\dot{\varepsilon}$ >10^4 s^{-1}
- No specific geometry
- No contact
- Local assessment
- Debonding threshold

Travaux amorcés en 2000
projet LASAT MNRT MINES (M. Jeandin)-ENSMA (M. Boustie)-ENSAM (L. Berthe)

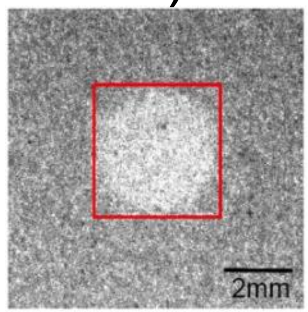
Choc laser sur dépôts céramiques

Caracterisation non destructive de la fissure

Fissure (Diamètre)



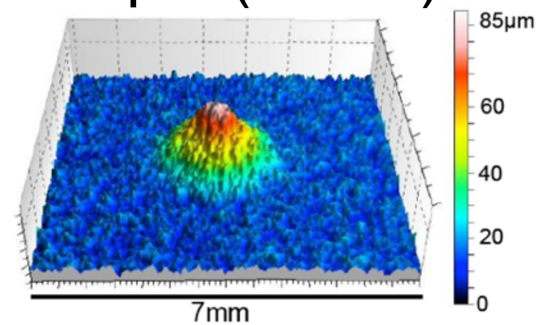
IR Thermography
(+/-30µm)



Optical observation
(+/-59µm)

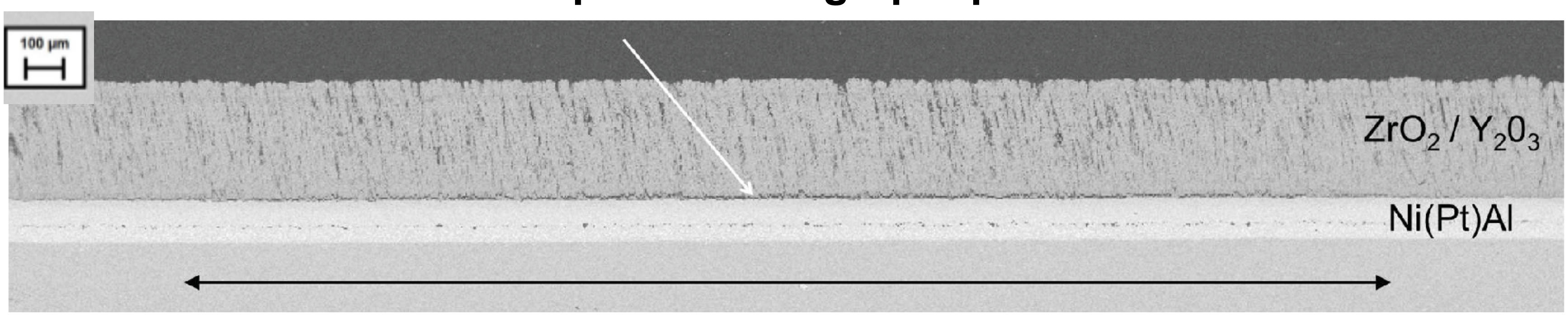
+

Cloque (Hmax)



Profilometry

Coupes métallographiques

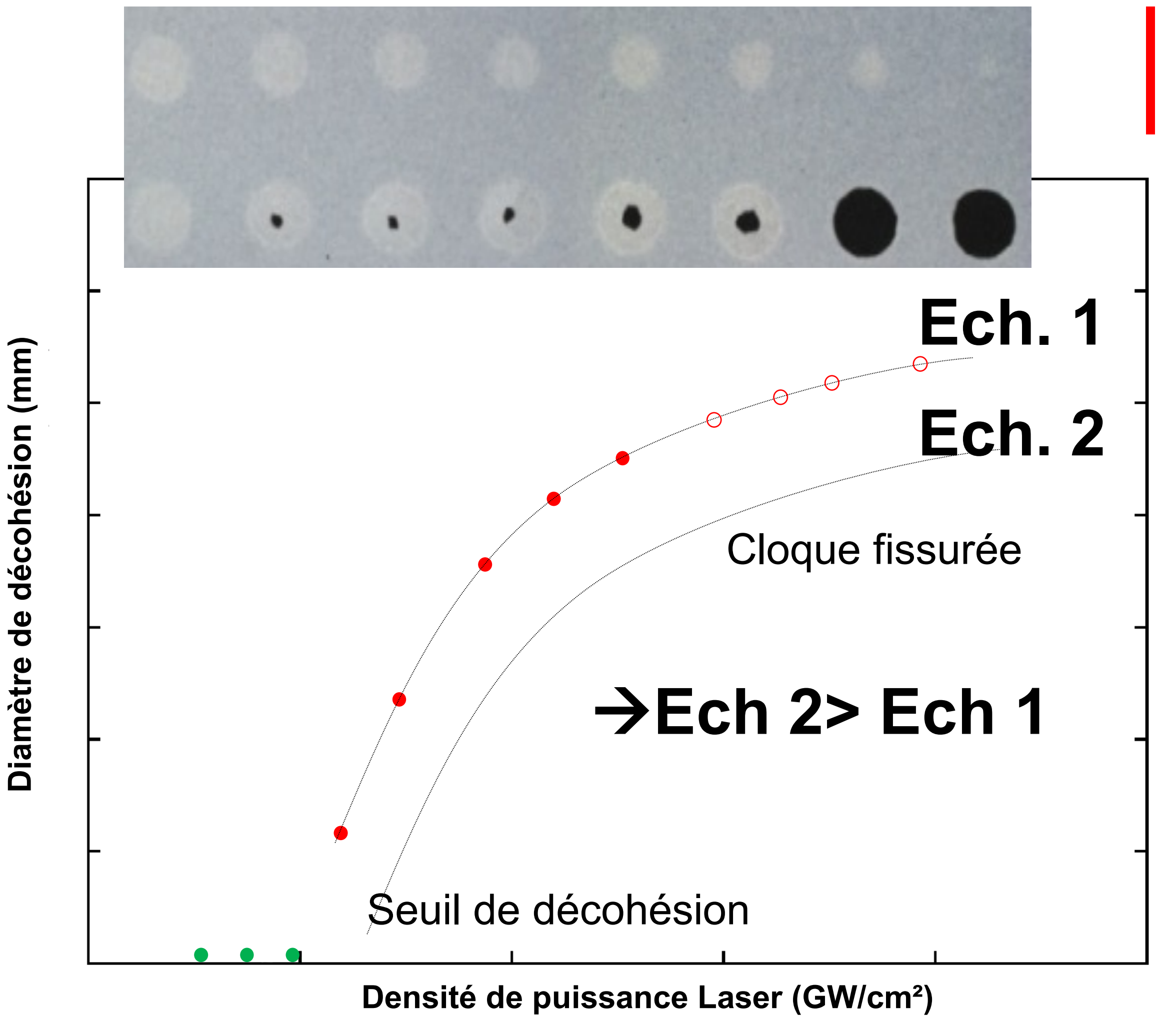


→ Plasma (HAP, Alumine, YSZ) , EB-PVD YSZ, Plasma DSY EBC

→ Adhérence par LASAT, t=0 et au cours du vieillissement

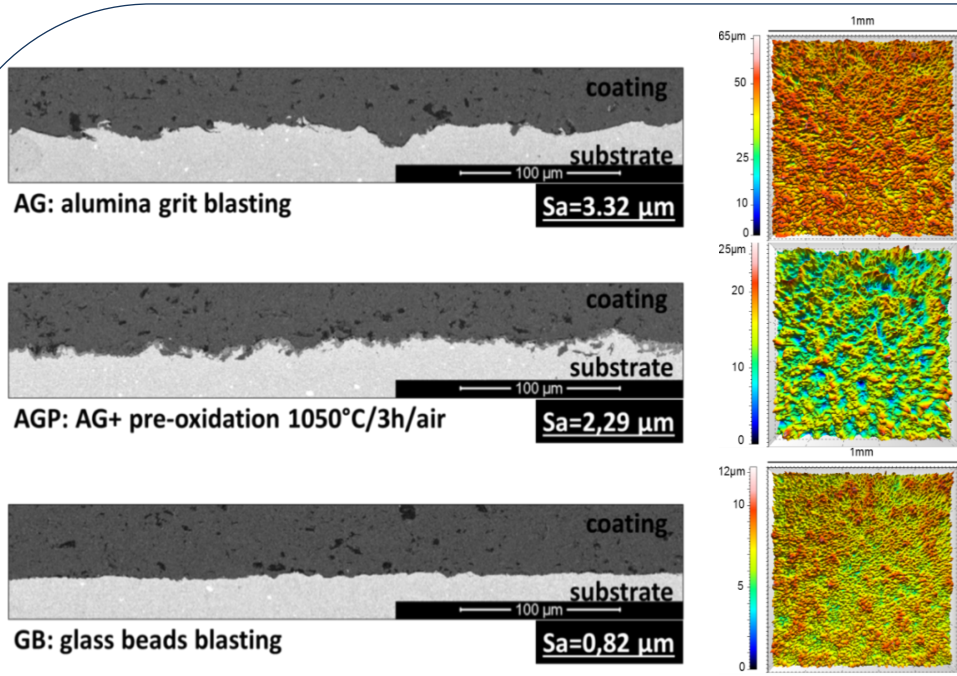
→Propagation de pré-fissures provoquées par choc laser

Méthode des courbes LASAT-2D



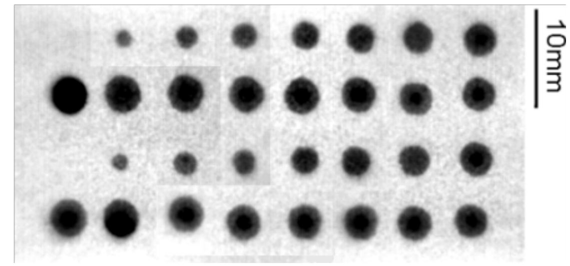
- Taille de fissure augmente avec E_{laser}
- Position des courbes → comparaison directe de l'adhérence

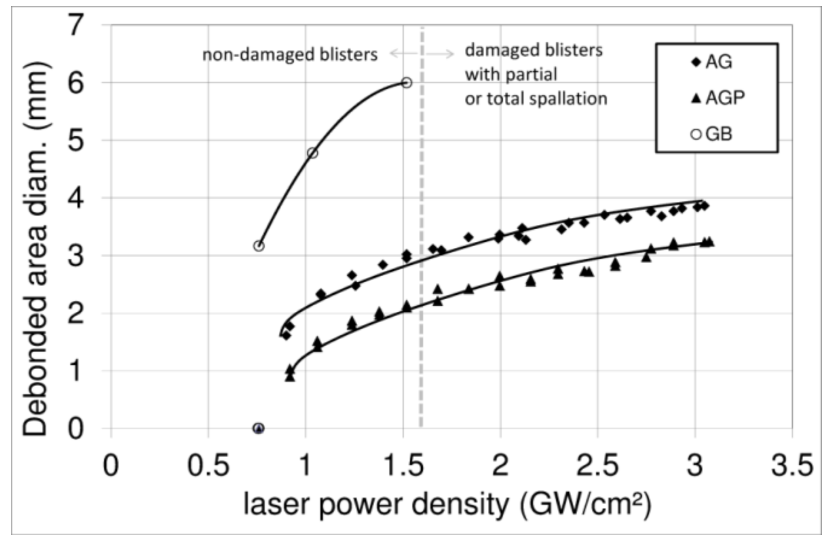
LASAT-2D (Alumine plasma)



$Ø_{laser}$=2.2mm

e.g. AG, IR Imaging





S parameters	*AG*	*AGP*	*GB*
S_a, Average roughness (µm)	*3.32*	*2.29*	*0.82*
S_{Sk}, Skewness	*-1.11*	*-.015*	*0.22*
S_{Ku}, Kurtosis	*8.48*	*3.85*	*3.66*
$S\Delta_q$, Root mean square slope	*0.86*	*0.35*	*0.19*
S_{dr}, Developed area ratio (%)	*31.5*	*3.9*	*1.8*

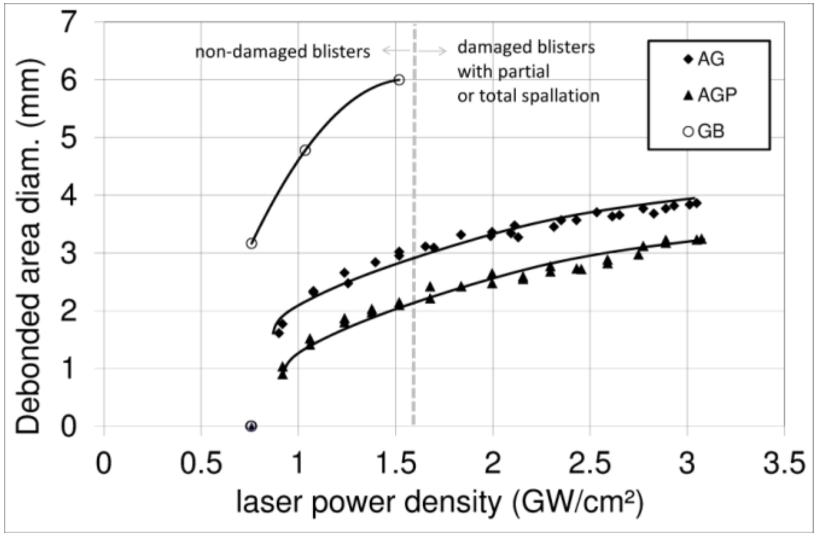
<u>Adhérence</u>

<u>AG+Pre-Ox.>AG>>GB</u>

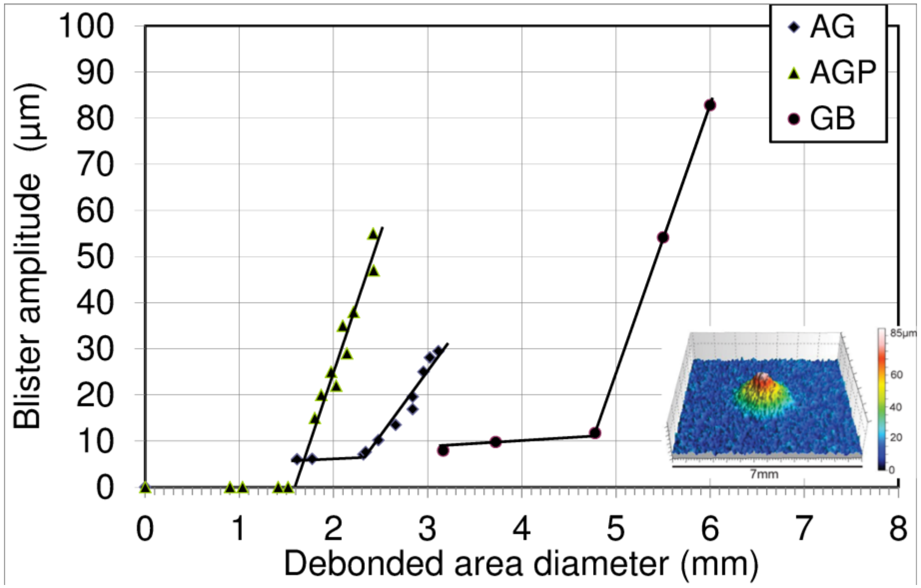
Seuil de rupture GW/cm² → MPa (calculs onde de choc, calibration interférométrie VISAR)

LASAT-2D (Alumine plasma)

COURBES LASAT-2D



Evolution du cloquage $\delta = f(\text{Ø}_{fissure})$



Adhérence (décohésion)

Relaxation Contraintes résiduelles (cloquage)

AG+Pré-Ox>AG>>GB

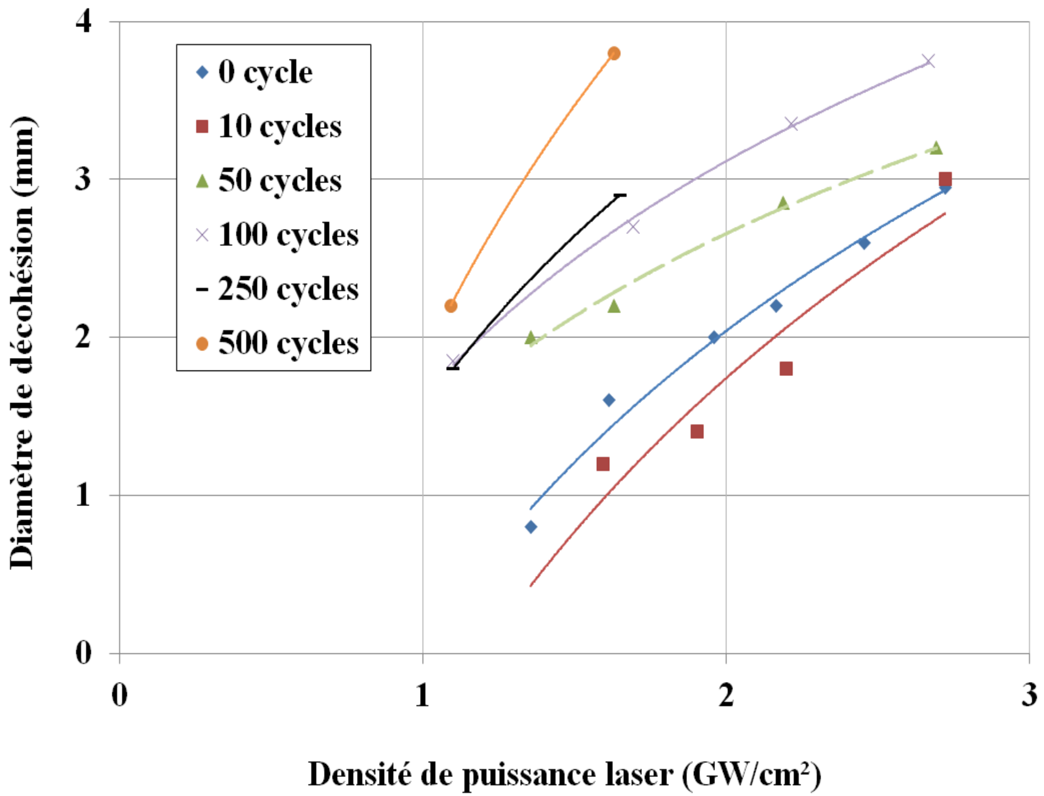
compression AG+Pré-Ox>AG>>GB

LASAT sur BT EB-PVD + cyclage thermique

Courbes LASAT 2D après N cycles sur le même éch.

<u>Après 500 cycles</u>

EX: Ech. >500cycles (1100C/1H)

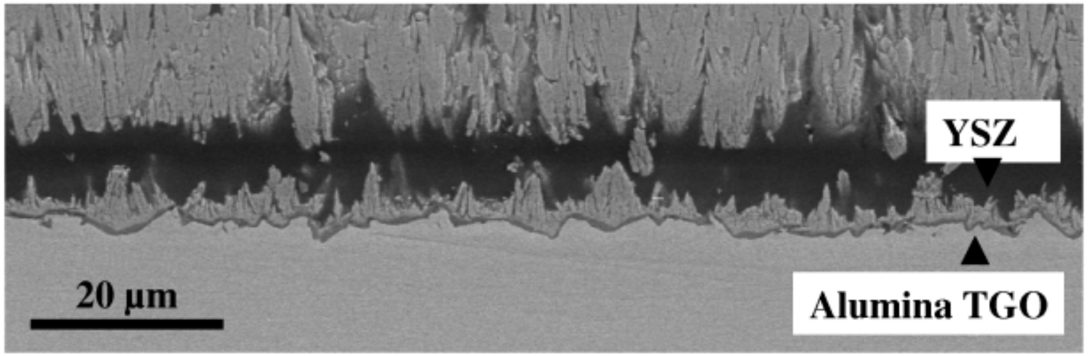


G. Bégué, PHD Thesis MINES ParisTech 2023

Adhérence augmente après 10 cycles (rupture au dessus TGO) puis décroit

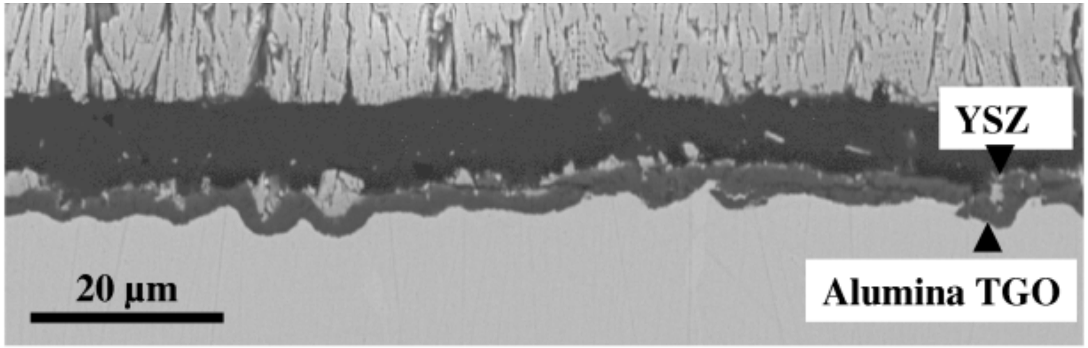
Fissure interfaciale induite par choc laser

Après dépôt → fissure dans la céramique



Mise en évidence de la zone de ténacité plus faible

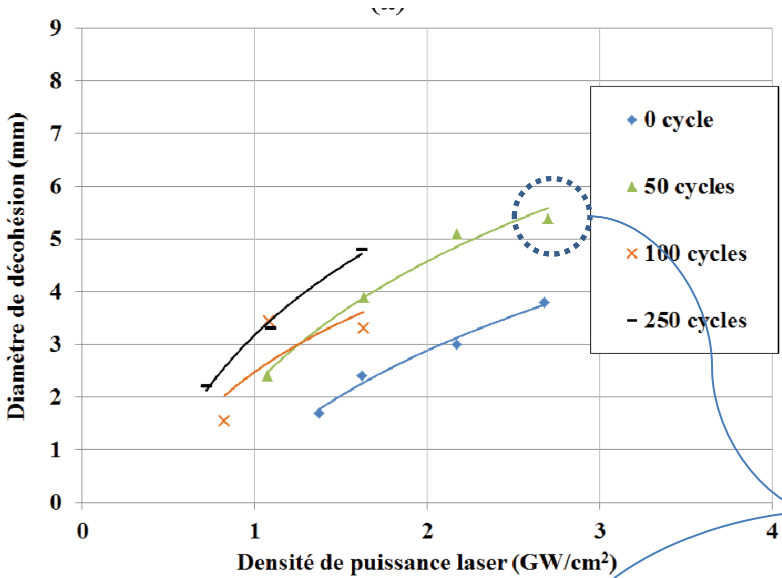
Après cyclage → fissure TGO/céramique



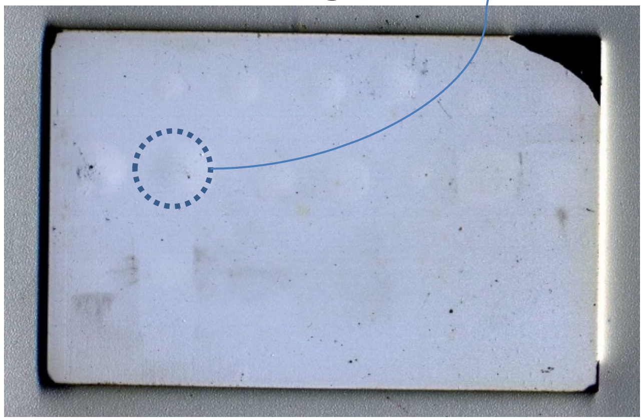
Comportement similaire lors d'un écaillage provoqué uniquement par le cyclage thermique

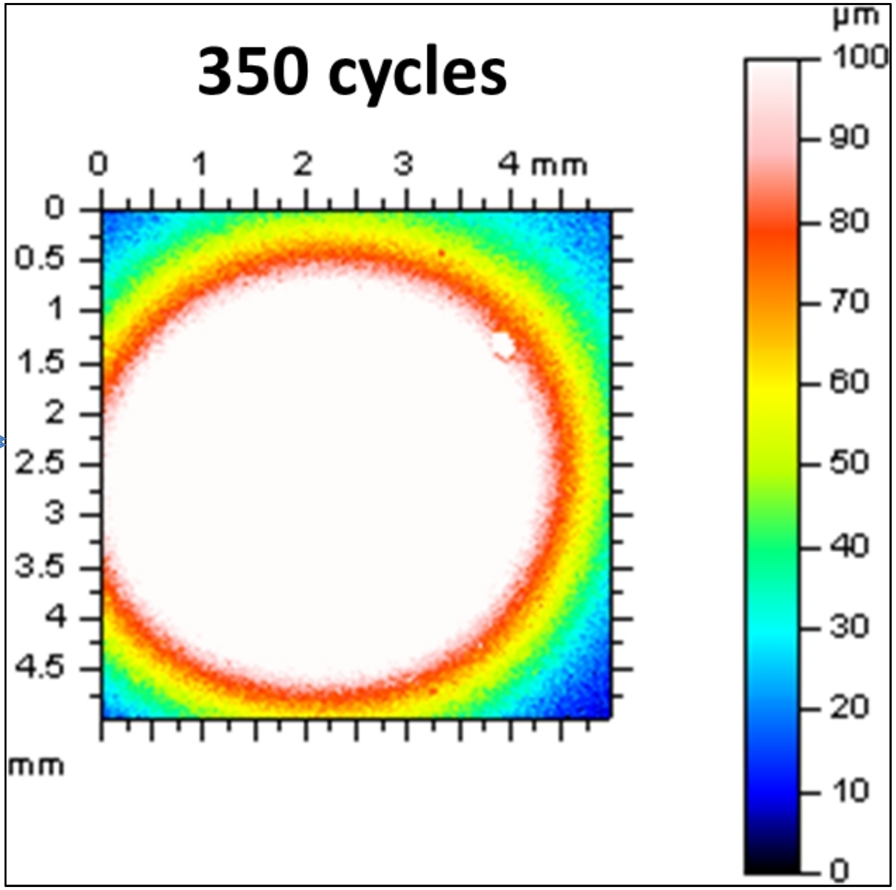
Analyse *Ex situ* du cloquage / cyclage thermique

- **Ech BT EB-PVD: LASAT à 0, 50 , 100, 250 cycles à 1100C/1H**



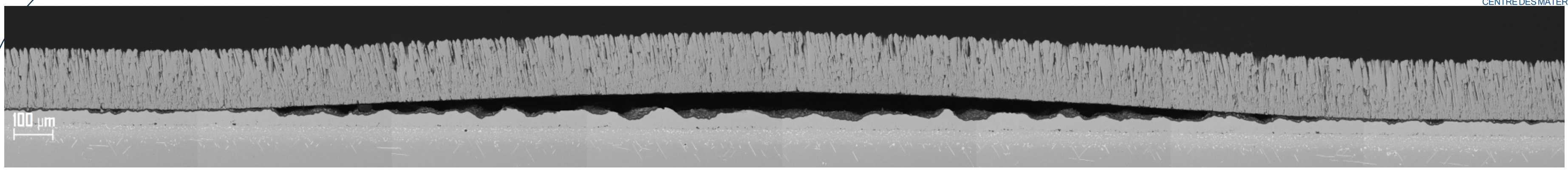
- **après 250 cycles**

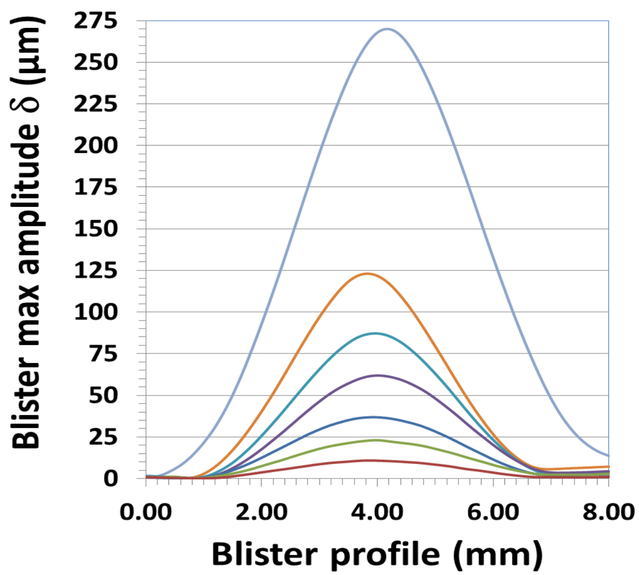


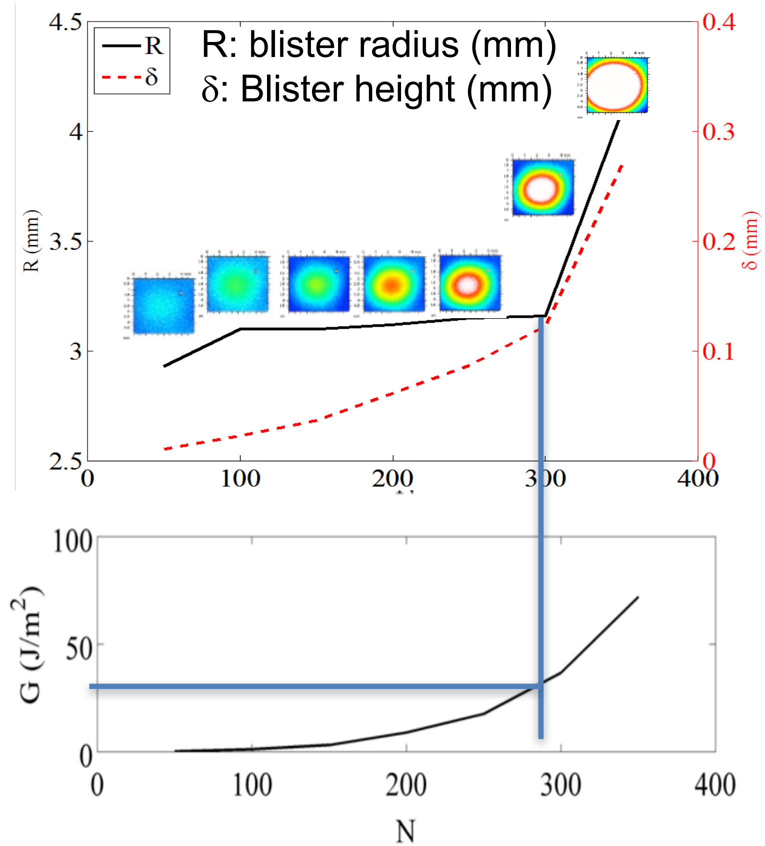


- **Ecaillage à 400 cycles**

Analyse *Ex situ* du cloquage / cyclage thermique







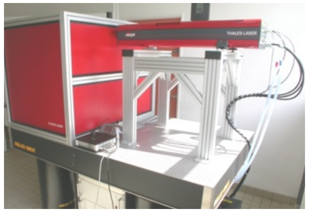
- Buckling is activated while delamination is not: effect of “rumpling”?
- At N=300, delamination G=Gc

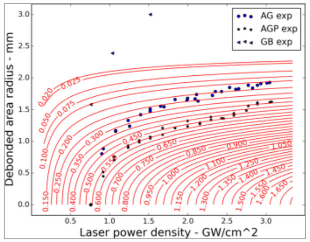
[Guipont, Fabre, Begue and Maurel, SCT under review]

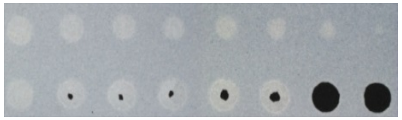
Gc at 300 cycles = 36 J/m2

LASAT-aided studies of coating's interface strength

LASAT Laser Shock Adhesion Test







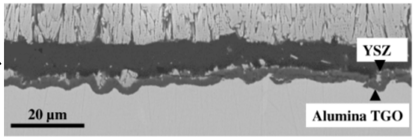
Adhesion

- **Laser shock faciltity**
  - ~ 1-5 GPa , $\dot{\varepsilon} > 10^4\ s^{-1}$
  - No specific geometry
  - No contact, Local
- **Failure threshold**
- **LASAT 2D**
- **Non-destructive LASAT on parts**
- **Towards normalization (Biomed.)**
- **Modelling (Hydro, CZM)**

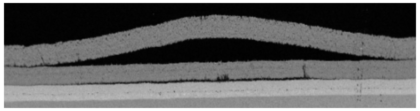
Damage and mechanical properties

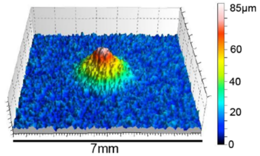
Post-mortem crack analyses

Interface→



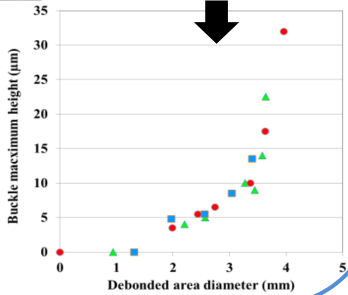
Coating→



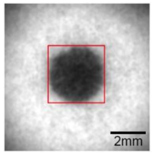


Residual stress release

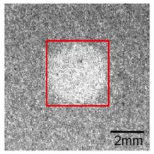
Blister height vs. crack diameter



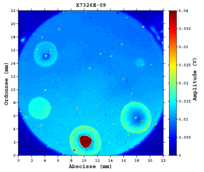
Laser Shock experiments with controlled debonding of coatings



IR Thermography



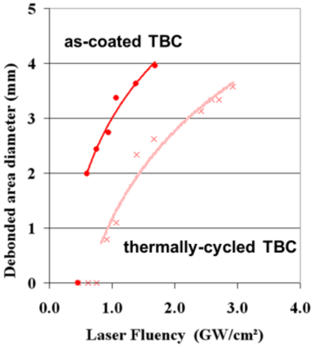
Optical



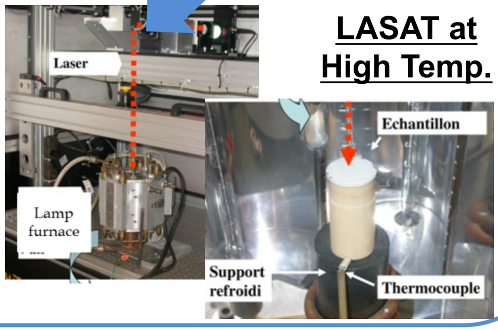
PLPS (ONERA)

e.g. : debonding of ceramic coatings
Non destructive evaluation

LASAT after thermal cycling



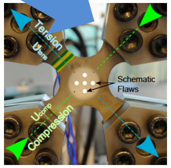
LASAT at High Temp.

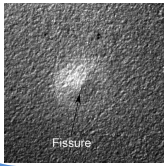


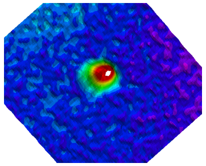
Pre-crack by LASAT

(Coll. V.Maurel, A. Koster)

- *Crack and blister analyses under shear loading at room T*







- *Crack and blister analyses during thermal cycling*