Lecture #3:

Initiation of delamination vs. steady-state delamination in thin films

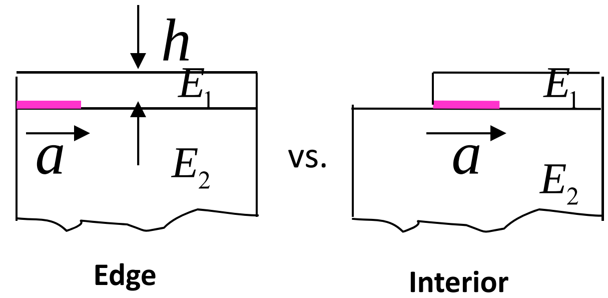
Kinking of a crack out of an interface

Cracks approaching an interface: penetration vs. kinking

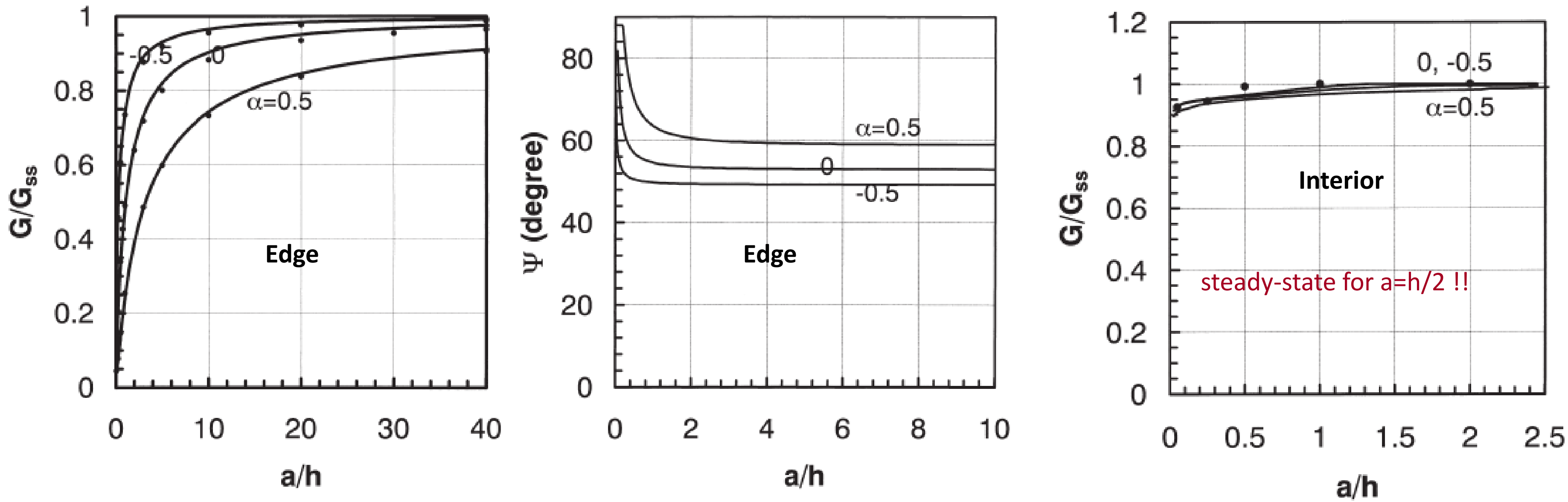
Thermal Barrier Coatings (TBCs):

Illustrations of delamination & current issues

Delamination edge effects in plane strain: The approach to steady-state

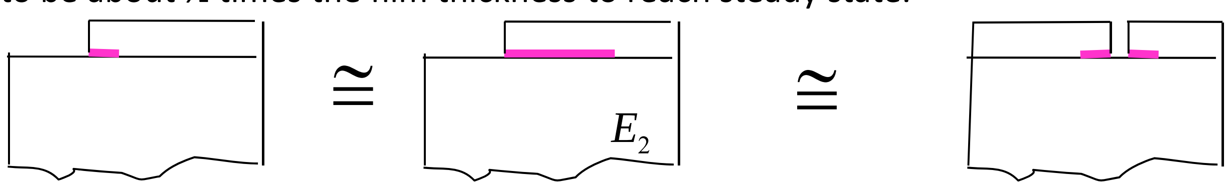


$$G_{SS} = \frac{1}{2}\frac{\sigma^2 h}{\bar{E}_1}$$



Conclusion: A compliant substrate (or even one with no mismatch) reduces the possibility of delamination initiating at the edge when a film extends to the edge of a substrate. The crack has to be ten times the film thickness, depending on the elastic mismatch, to attain steady-state.

If the film terminates in the interior of the substrate, there is no protection—the crack only has to be about ½ times the film thickness to reach steady state.



Competition between crack advance in interface and kinking out of interface: continued

KINKING IN A HOMOGENEOUS MATERIAL UNDER MIXED MODE LOADING

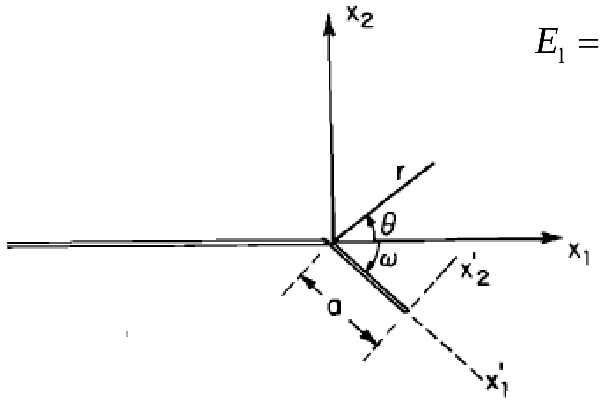


Fig. 1 Geometry of kinked crack

$E_1 = E_2 = E, \quad \nu_1 = \nu_2 = \nu; \quad K_1$ & K_2 are prescribed.

Contending criteria for advance of the kinked crack in a material with isotropic and homogenerous elastic and fracture properties.

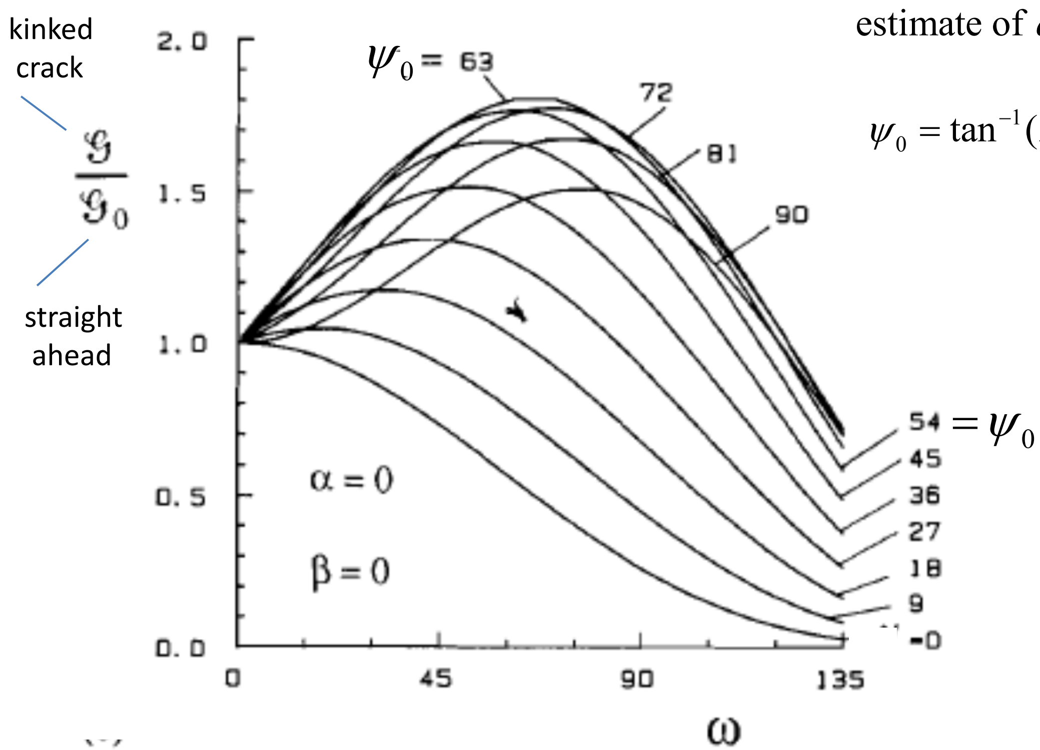
A) ω is determined by $K_{II} = 0$; advance requires $K_I = K_{IC}$

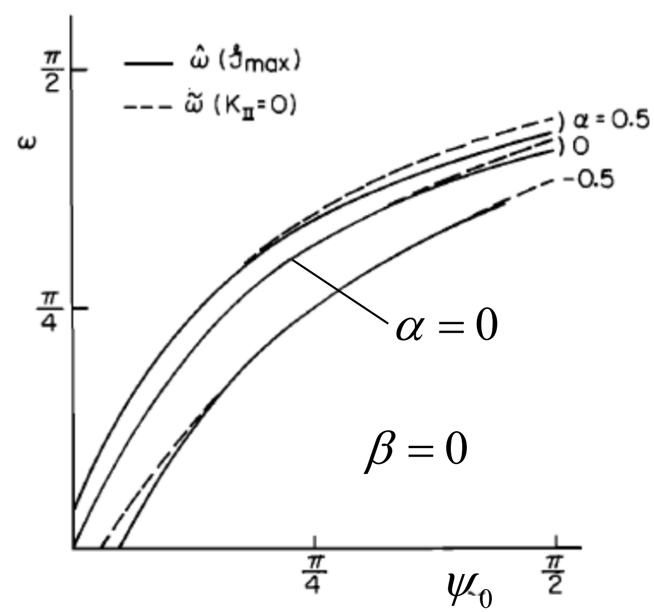
B) ω is determined by maximizing G; advance requires $G = \Gamma_{IC}$

C) ω is determined by maximizing $\sigma_{\theta\theta}$ associated with K_1 & K_2

Criterion C was set as a homework problem. It give a reasonable estimate of ω (compared to A or B) as long as $\psi_0 < 45^o$

$\psi_0 = \tan^{-1}(K_2 / K_1)$





There is very little difference between A & B

Competition between crack advance in interface and kinking out of interface: continued (1989-3)

Bi-material case

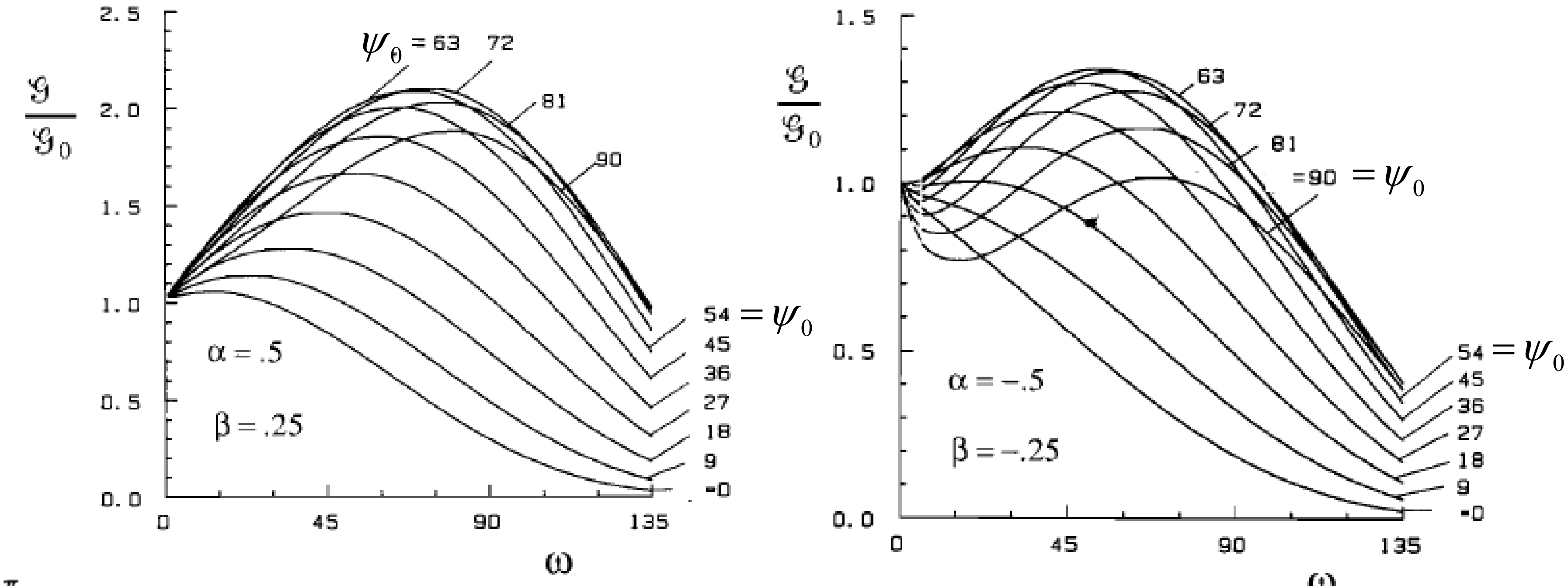
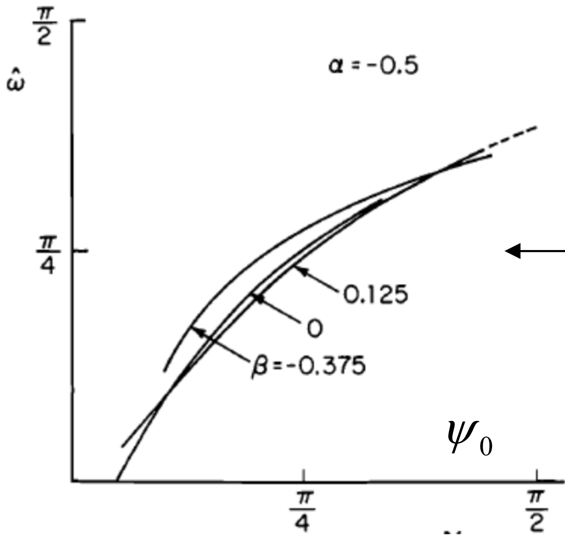
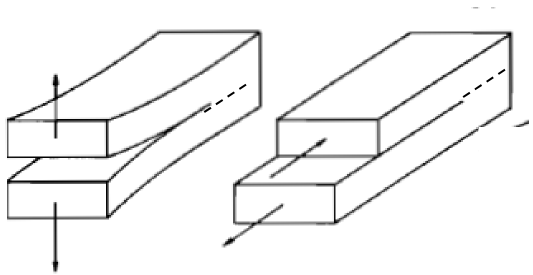


Fig. 8 $\mathcal{G}^*/\mathcal{G}_0$ versus ω for two cases in which $\beta \neq 0$



Kink angle associated with K2=0

Competition between interface delamination and substrate cracking



Mode I

$$\sigma = \frac{K_I}{\sqrt{2\pi x}}$$

Mode II

$$\tau = \frac{K_{II}}{\sqrt{2\pi x}}$$

$$\frac{G^{\text{interface}}}{(G^{\text{substrate}})_{\max}}$$

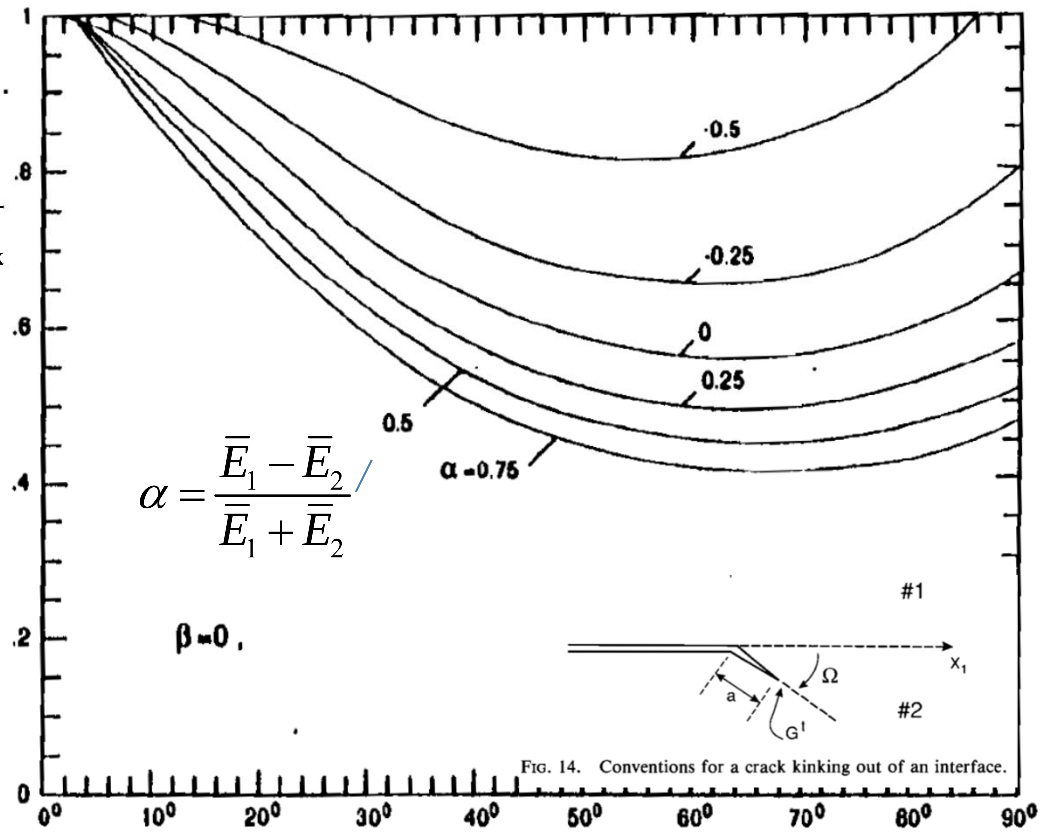


FIG. 14. Conventions for a crack kinking out of an interface.

$$\alpha = \frac{\bar{E}_1 - \bar{E}_2}{\bar{E}_1 + \bar{E}_2}$$

$$\psi = \tan^{-1}\left(K_{II} / K_I\right)$$

Energy release rate & stress intensity factors:

$$G^{\text{interface}} = \frac{1}{2}\left(\frac{1-\nu_1^{\,2}}{E_1} + \frac{1-\nu_2^{\,2}}{E_2}\right)\left(K_I^{\,2} + K_{II}^{\,2}\right) \quad \text{(interface)}$$

$$G^{\text{substrate}} \cong \frac{1}{2}\left(\frac{1-\nu_2^{\,2}}{E_2}\right)(K_I^{substrate})^2 \quad \text{(substrate)}$$

Conditions governing kinking into substrate :

with $\psi = \tan^{-1}(K_{II} / K_I) > 0,$

$$G^{\text{interface}} < \Gamma_{\text{interface}}(\psi), \qquad \left(G^{\text{substrate}}\right)_{\max} \geq \Gamma_{IC}$$

which requires:

$$G^{\text{interface}} / \left(G^{\text{substrate}}\right)_{\max} < \Gamma_{\text{interface}}(\psi) / \Gamma_{IC}$$

Conditions governing propagation in interface:

With $\psi = \tan^{-1}(K_{II} / K_I) > 0.$

$$G^{\text{interface}} \geq \Gamma_{\text{interface}}(\psi), \qquad \left(G^{\text{substrate}}\right)_{\max} < \Gamma_{IC}$$

which requires:

$$G^{\text{interface}} / \left(G^{\text{substrate}}\right)_{\max} > \Gamma_{\text{interface}}(\psi) / \Gamma_{IC}$$

Competition between crack advance in interface and kinking out of interface

Reference: He & Hutchinson, J. Appl. Mech. 1989, 270-278.

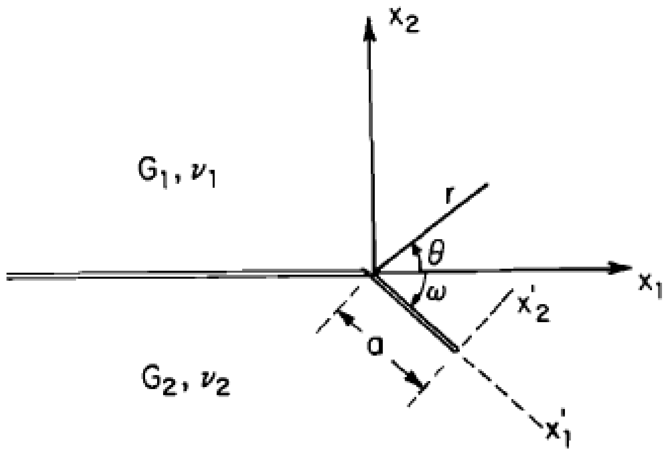


Fig. 1 Geometry of kinked crack

Crack in the interface:

Stress intensity factors & energy release for **crack on interface**:

$$K_1 \ \& \ K_2, \ \ \tan\psi_0 = \frac{K_2}{K_1}, \ \ G_0 = \frac{1}{\bar{E}^*}\left(K_1^{\,2} + K_2^{\,2}\right), \ \ \frac{1}{\bar{E}^*} = \frac{1}{2}\left(\frac{1}{\bar{E}_1} + \frac{1}{\bar{E}_2}\right)$$

Crack kinking out of the interface:

Stress intensity factors & energy release for **kinked crack** $(\beta = 0)$:

$$K_I \ \& \ K_{II}, \ \ \tan\psi = \frac{K_{II}}{K_I}, \ \ G_{kink} = \frac{1}{\bar{E}_2}\left(K_I^{\,2} + K_{II}^{\,2}\right)$$

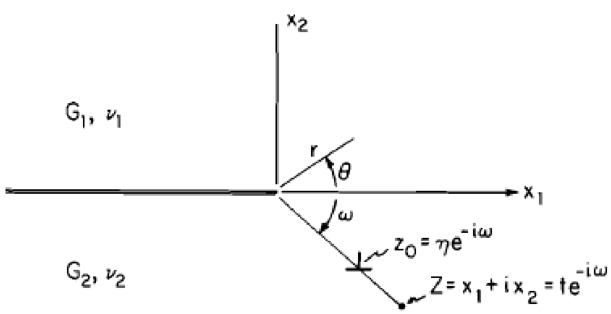
Assume $\psi_0 > 0$ so kinked crack propagates into material #2.

K_I & K_{II} are linear functions of K_1 & K_2. Dimensional analysis implies:

$$K_I = a_{11}K_1 + a_{12}K_2, \quad K_{II} = a_{21}K_1 + a_{22}K_2$$

where the $a_{ij}(\omega,\alpha)$ depend on ω and the first Dundurs' parameter α, but independent of a.

Brief sketch of solution procedures to determine KI & KII based on integral equation methods.



Let $b_r(\eta)$ & $b_\theta(\eta)$ be components of an edge dislocation at z_0. The problem noted in the figure where the dislocation interacts with a semi-infinite crack can be solved in closed form. The tractions acting on the plane at angle ω at a point $z = te^{-i\omega}$ are given by (see He & Hutch, 1989)

$$\sigma_{\theta\theta}(t) = \bar{E}\left(\left(\frac{1}{4\pi}\frac{1}{t-\eta} + H_{\theta\theta}(t,\eta,\omega)\right)b_\theta(\eta) + H_{\theta r}(t,\eta,\omega)b_r(\eta)\right)$$

$$\sigma_{r\theta}(t) = \bar{E}\left(\left(\frac{1}{4\pi}\frac{1}{t-\eta} + H_{r\theta}(t,\eta,\omega)\right)b_r(\eta) + H_{r\theta}(t,\eta,\omega)b_\theta(\eta)\right)$$

Competition between crack advance in interface and kinking out of interface: continued

The stress on the plane at z due to the applied intensity factors is (classic crack tip fields)

$$\sigma_{\theta\theta}(t)=\frac{K_1}{\sqrt{2\pi t}}f_{\theta\theta}^{(1)}(-\omega)+\frac{K_2}{\sqrt{2\pi t}}f_{\theta\theta}^{(2)}(-\omega),\quad \sigma_{r\theta}(t)=\frac{K_1}{\sqrt{2\pi t}}f_{r\theta}^{(1)}(-\omega)+\frac{K_2}{\sqrt{2\pi t}}f_{r\theta}^{(2)}(-\omega),$$

The integral equations for the distributions $b_r(\eta)$ & $b_\theta(\eta)$ are

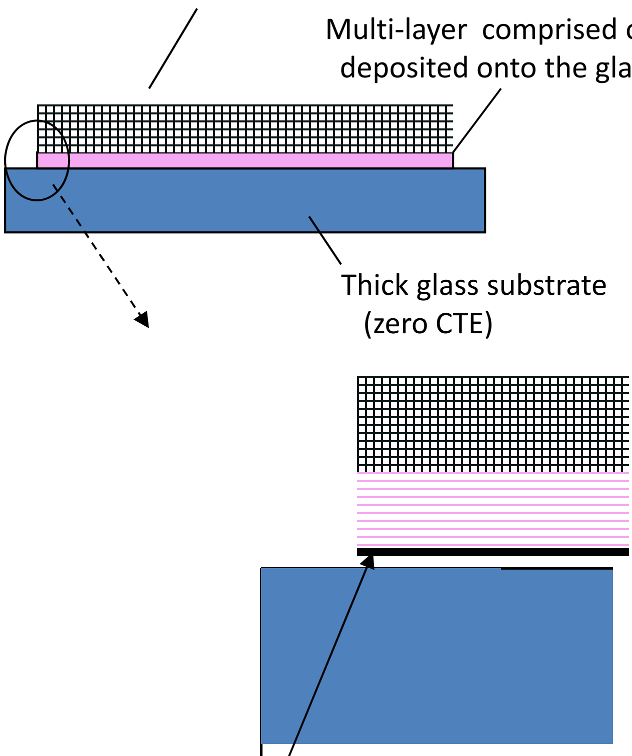
$$\bar{E}\int_0^a\left(\left(\frac{1}{4\pi}\frac{1}{t-\eta}+H_{\theta\theta}(t,\eta,\omega)\right)b_\theta(\eta)+H_{\theta r}(t,\eta,\omega)b_r(\eta)\right)d\eta=-\frac{K_1}{\sqrt{2\pi t}}f_{\theta\theta}^{(1)}(-\omega)-\frac{K_2}{\sqrt{2\pi t}}f_{\theta\theta}^{(2)}(-\omega)$$

$$\bar{E}\int_0^a\left(\left(\frac{1}{4\pi}\frac{1}{t-\eta}+H_{r\theta}(t,\eta,\omega)\right)b_r(\eta)+H_{r\theta}(t,\eta,\omega)b_\theta(\eta)\right)d\eta=-\frac{K_1}{\sqrt{2\pi t}}f_{r\theta}^{(1)}(-\omega)-\frac{K_2}{\sqrt{2\pi t}}f_{r\theta}^{(2)}(-\omega)$$

These are called Cauchy-type integral equations. There are powerful numerial methods for solving these equations (Erdogan and Gupta, 1972, Q. Appl. Math. 29, 525-534). The desired stress intensity factors, K_I and K_{II}, and thus the coefficients, a_{ij}, are simply related to the distribution of the dislocations as $t \to a$.

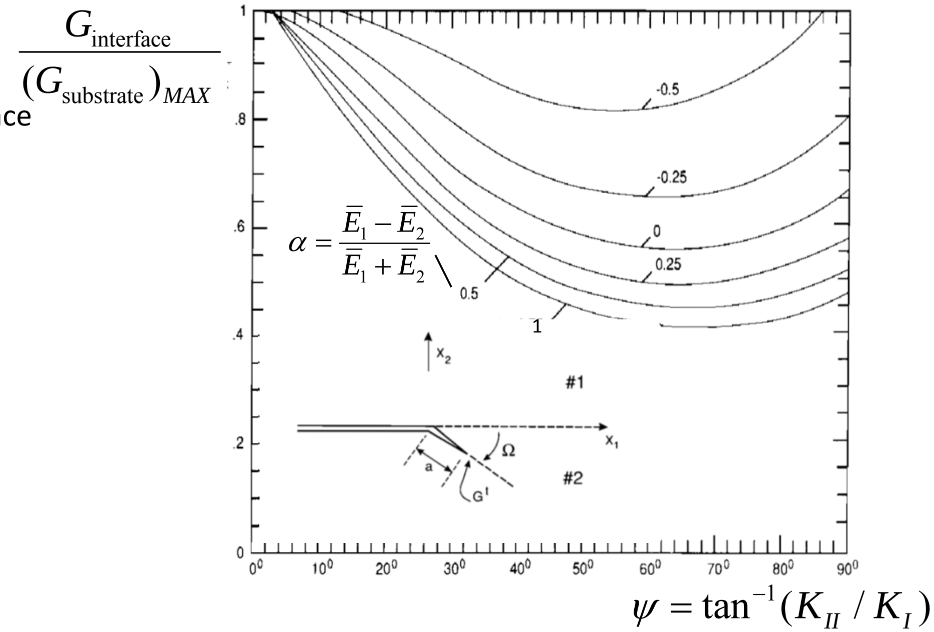
Alternatively, finite element methods could be used to obtain the intensity factors and coefficients. However, given the interest in all orientations ω, integral equation methods are probably more efficient and somewhat more accurate.

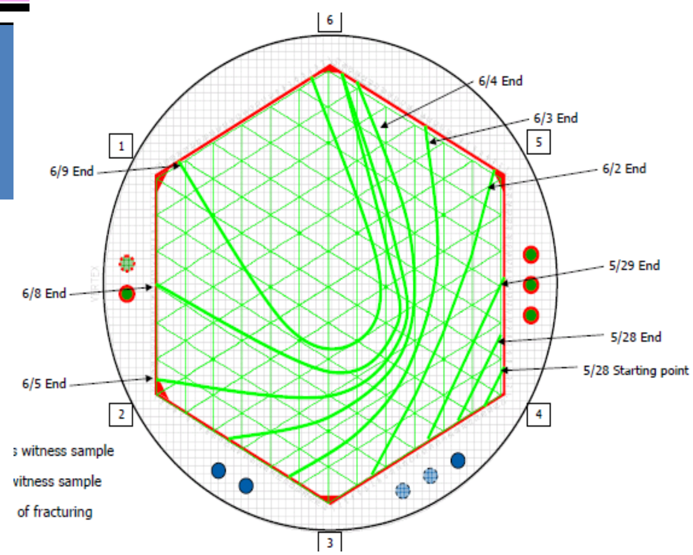
Elastic fracture mechanics applied to manufacture of high fidelity surfaces



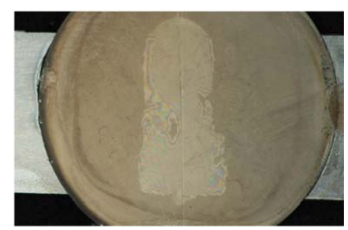
Assembled curved surface is separated from substrate by delamination along mirror/glass interface by temperature drop and/or wedging

Competition between interface separation & cracking of glass



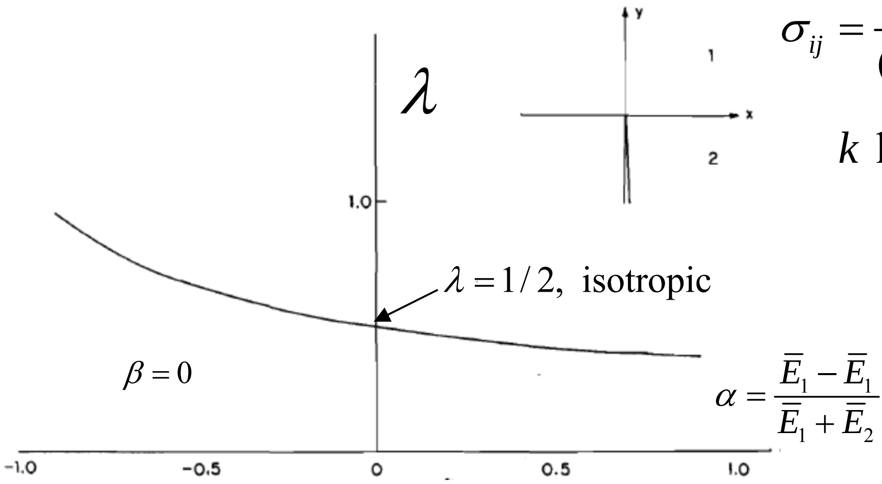


Week-long separation of a curve surface



3-point bend test developed to measure interface toughness

Competition between crack penetration and deflection at an interface (1989-7; 1991-3)



$$\sigma_{ij} = \frac{k}{(2\pi r)^{\lambda}} f_{ij}(\theta)$$

k has units $Pa{\bullet}m^{\lambda}$

Consider a short crack of length a in B1.

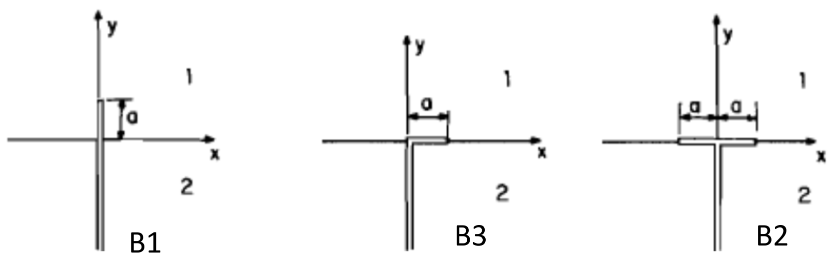
The stress intensity factor K of this crack depends linearly on k. Dimensional arguments require:

$$K_1 = c_1 k a^{-\lambda+1/2}$$

$$G_{penetration} = (c_1 k)^2 a^{1-2\lambda} / \overline{E}_1$$

where c_1 is a dimensionless function of α and β.

Note! $G \to \infty$ as $a \to 0$ if $\lambda > 1/2$ ($\alpha<0$).



Now consider a short crack of length a in B2 & B3.

The stress intensity factors K1 & K2 of this crack depends linearly on k. For each case, dimensional arguments require:

$$K_1 = d_1 k a^{-\lambda+1/2}, K_2 = d_2 k a^{-\lambda+1/2},$$

$$G_{deflection} = \left[(d_1 k)^2 + (d_2 k)^2\right] a^{1-2\lambda} / \overline{E}^*$$

$$\text{for } \beta\text{=0 and } \frac{1}{\overline{E}^*} = \frac{1}{2}\left(\frac{1}{\overline{E}_1} + \frac{1}{\overline{E}_2}\right)$$

where d_1 and d_2 are dimensionless functions of α ($\beta = 0$).

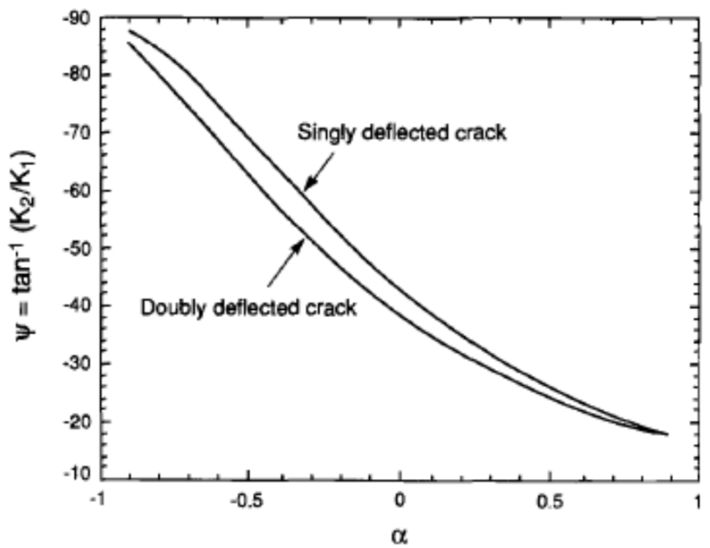
$$\Leftarrow$$

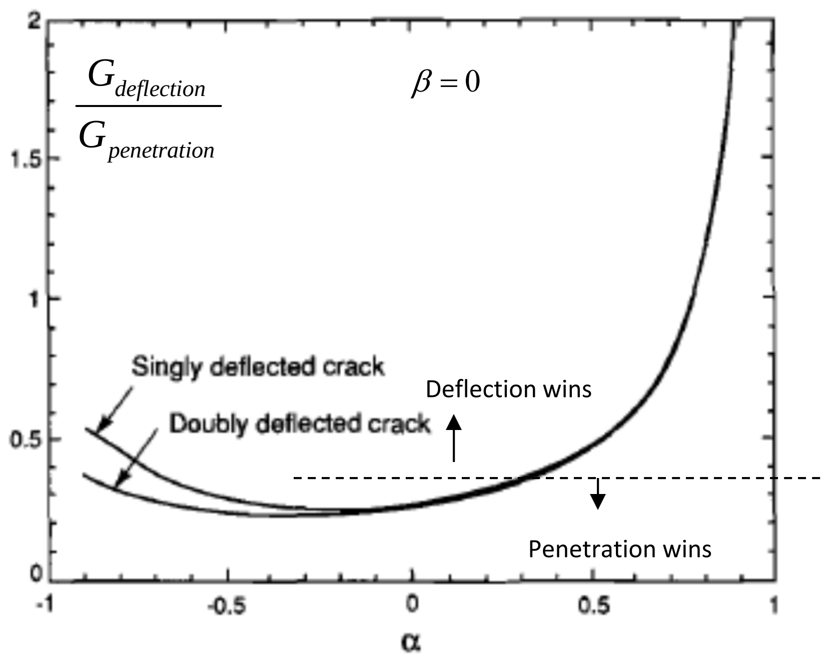
$$\frac{G_{deflection}}{G_{penetration}} = \frac{\left[d_1^{\,2} + d_2^{\,2}\right]}{c_1^{\,2}} \frac{\overline{E}_1}{\overline{E}^*}$$

$$\tan\Psi_{deflection} \equiv \frac{K_2}{K_1} = \frac{d_2}{d_1}$$

Note that the above ratios are independent of load!

Competition between crack penetration and deflection at an interface, continued (1991-3)





$$\frac{(\Gamma_C(\psi))_{\text{interface}}}{(\Gamma_{IC})_{\text{material1}}}$$

Crack Advance Criteria:

Penetration $\Rightarrow\ G_{penetration} = (\Gamma_{IC})_{\text{material1}}$

Deflection $\Rightarrow\ G_{deflection} = (\Gamma_C(\psi))_{\text{interface}}$

Assuming roughly the same flaw size, a,
for both the interface and the penetrating crack,

$$\frac{(\Gamma_C(\psi))_{\text{interface}}}{(\Gamma_{IC})_{\text{material1}}} < \frac{G_{deflection}}{G_{penetration}} \quad \Rightarrow \textbf{Deflection wins}$$

$$\frac{(\Gamma_C(\psi))_{\text{interface}}}{(\Gamma_{IC})_{\text{material1}}} > \frac{G_{deflection}}{G_{penetration}} \quad \Rightarrow \textbf{Penetration wins}$$

See plot. Of course the load must be sufficient such that

$$G_{deflection} \geq (\Gamma_C(\psi))_{\text{interface}} \quad or \quad G_{penetration} \geq (\Gamma_{IC})_{\text{material1}}$$

When the **elastic mismatch is small**,

$$\frac{G_{deflection}}{G_{penetration}} \cong \frac{1}{4}$$

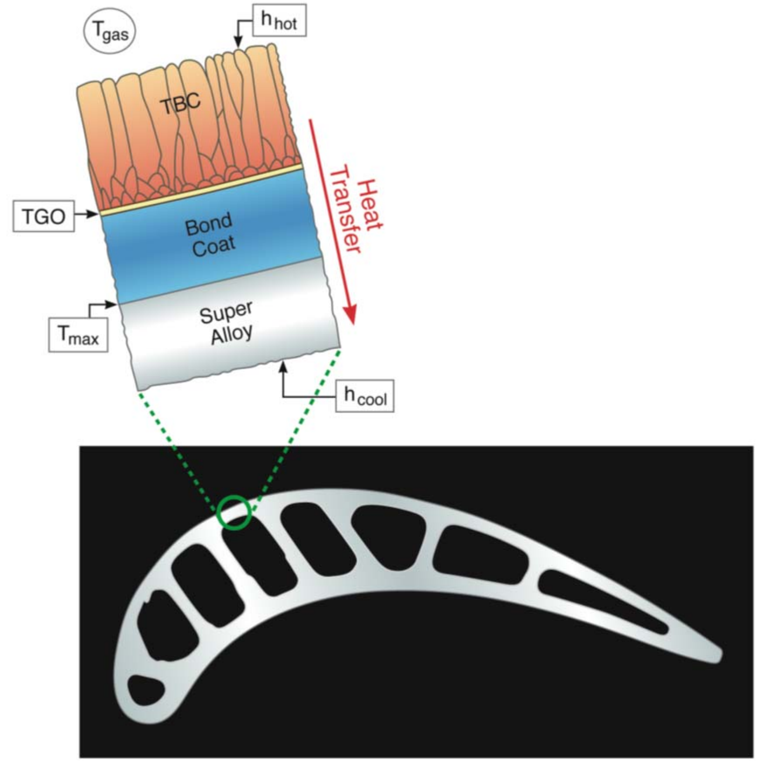
Examples of TBC delamination failures—from service and from lab tests

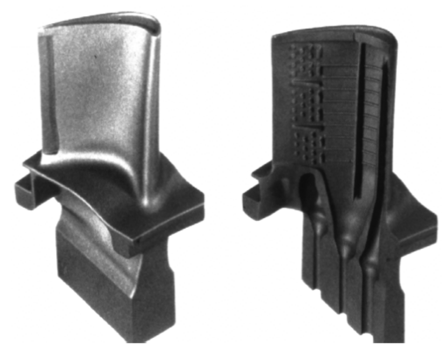
A practical fracture mechanics approach to lifetime assessment of TBCs given the complexity and unpredictability of the intrinsic failure processes

Measurement of TBC delamination toughness as a function of thermal history—new tests are needed!

References: (2007-5), (2008-6), (2011-4)
See also October 2012 Issue of MRS Bulletin < www.mrs.org/bulletin> for an overview of TBC development efforts, including issues related to delamination

Airfoil Technology

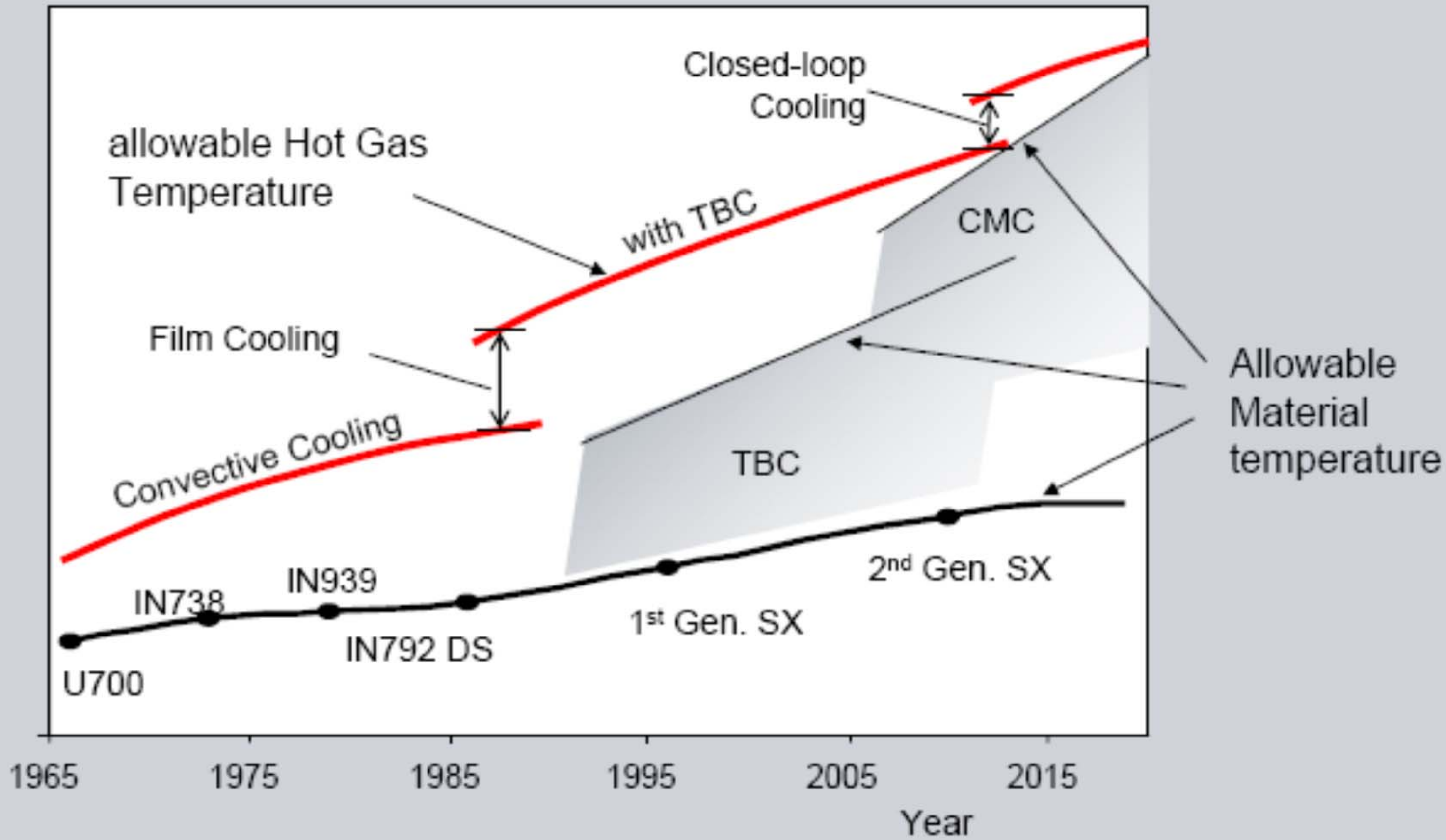




High Performance Coating Systems:
Enabling technology for advanced gas turbines

Advanced Material Systems are a key technology to advance Gas Turbine Technology

SIEMENS



TBCs are today the Materials technology with the highest pay-off

TBC challenges — Thermal cycles, stresses, failures

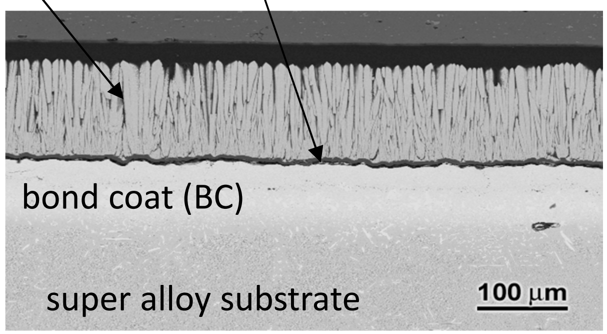
Temperature range of TBC surface: $20^{o}C \le T \le 1100^{o}C$; **Temperature Drop across TBC:** $\Delta T \approx 150^{o}C$

Coefficients of thermal expansion: $\alpha_{Superalloy} \sim 15\times10^{-6}\,/^{o}C,\ \ \alpha_{NiCoCrAlY} \sim 16\times10^{-6}\,/^{o}C,$

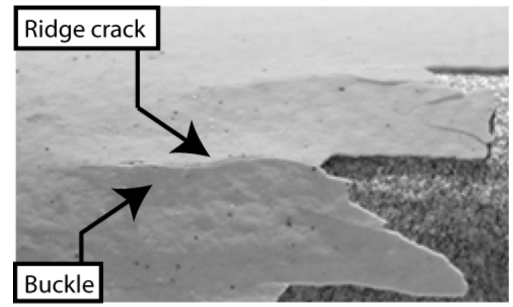
$$\alpha_{Al_2O_3} \sim 8\times10^{-6}\,/^{o}C,\ \ \alpha_{TBC} \sim 11\times10^{-6}\,/^{o}C\quad (all\ T-dependent)$$

Stress in TGO (Al_2O_3): $\sigma \sim 0\,GPa\ (T=1100^{o}C),\ \ \sigma \sim -4\,GPa\ (T=20^{o}C)$

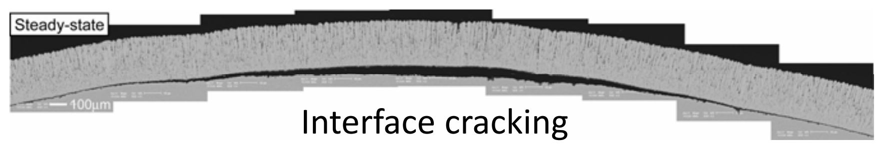
Blades after approx. 3 years of service



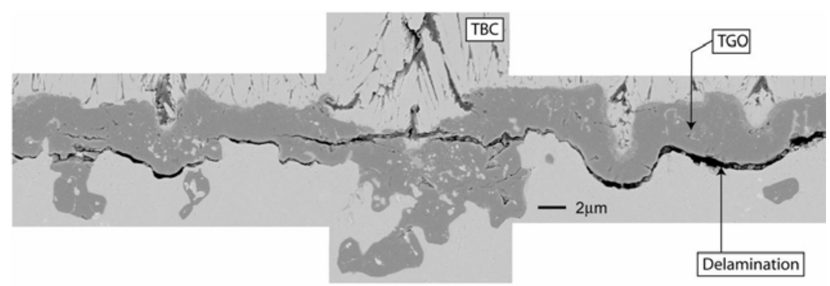
Multilayer coating



Spalling of TBC



Interface cracking



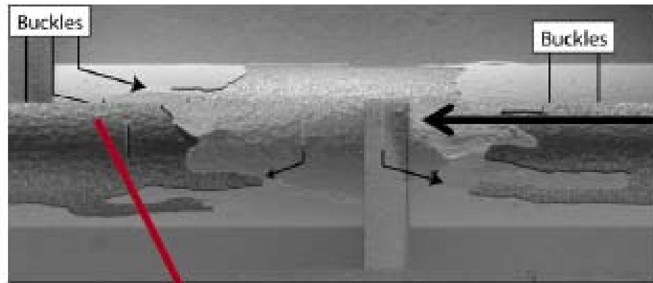
Delamination along ceramic (Al2O3)/ metal (Ni) BC interface

BUCKLE DELAMINATION OF THERMAL BARRIER COATING ON BURNER RIG SPECIMEN

Electron beam deposited TBC

(2006-6)

Faulhaber, Mercer, Moon, Hutchinson and Evans, JMPS 2006.

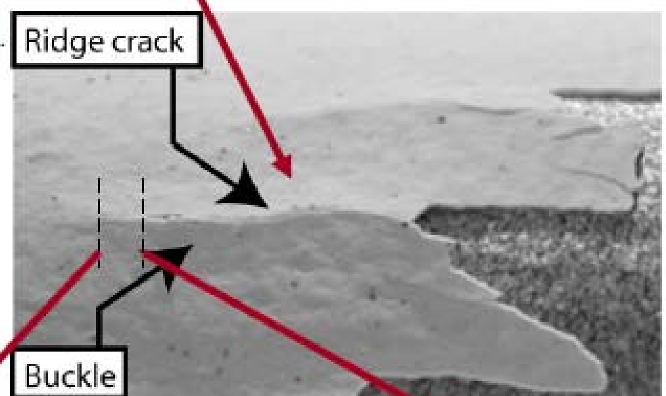


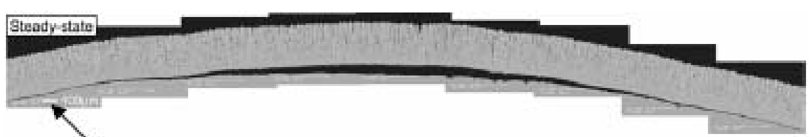
Wedge indentation to Initiate spall

Specimen exposed to 100 cycles between room temp. and 1150C with no visible damage.

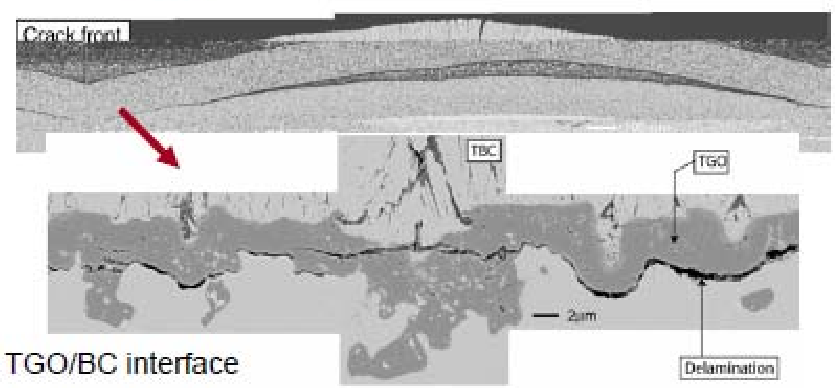
A wedge indentation at room temp. produces wide spread spalling with buckle delaminations.

Stress in TGO is approx. -4GPa
Stress in TBC is approx. -1GPa





Mixed mode (Modes I & II) interface cracking



Delamination on TGO/BC interface

Most TBC Delamination Failures are Mode II (or near-Mode II) Edge Delaminations

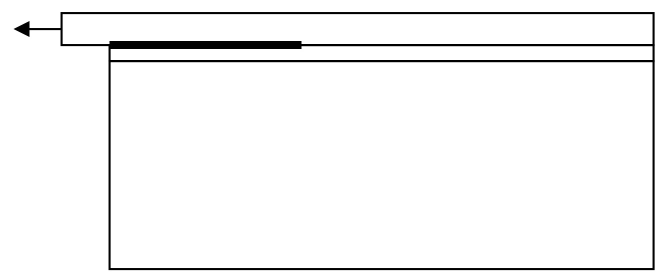
Blade showing spalled TBC

Coatings under compression primarily fail by edge delamination or buckling delamination. Buckling delamination can only occur after a very large interface separation has occurred (typically more than 15 times the coating thickness).

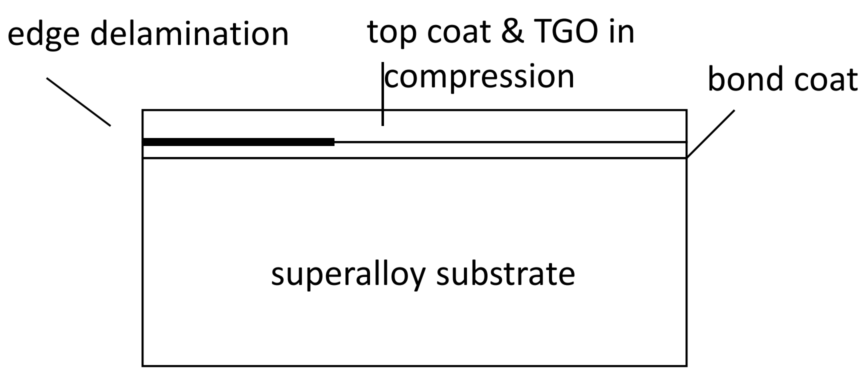
Mode II edge delaminations are the most likely culprit in controlling TBC lifetime.

Compressive stresses in TGO and Top Coat upon cool-down create susceptibility to edge delamination at **edges, holes and open sinter cracks**.

Maximum susceptibility is upon cool down: Room temperature toughness is relevant



top coat and TGO are in compression on cool down



The relevant mechanics

The edge delamination releases the compression in the top coat and the TGO (if the crack is below the TGO). The mechanics problem is depicted above. This is a **mode II delamination crack**— the crack is closed

Mode II toughness data is the most relevant. What tests can we use?

Life-Prediction Methodology for TBCs and other coatings

Premise: Toughness cannot be predicted, it must be measured.

A. Experimentally measure mode II toughness,

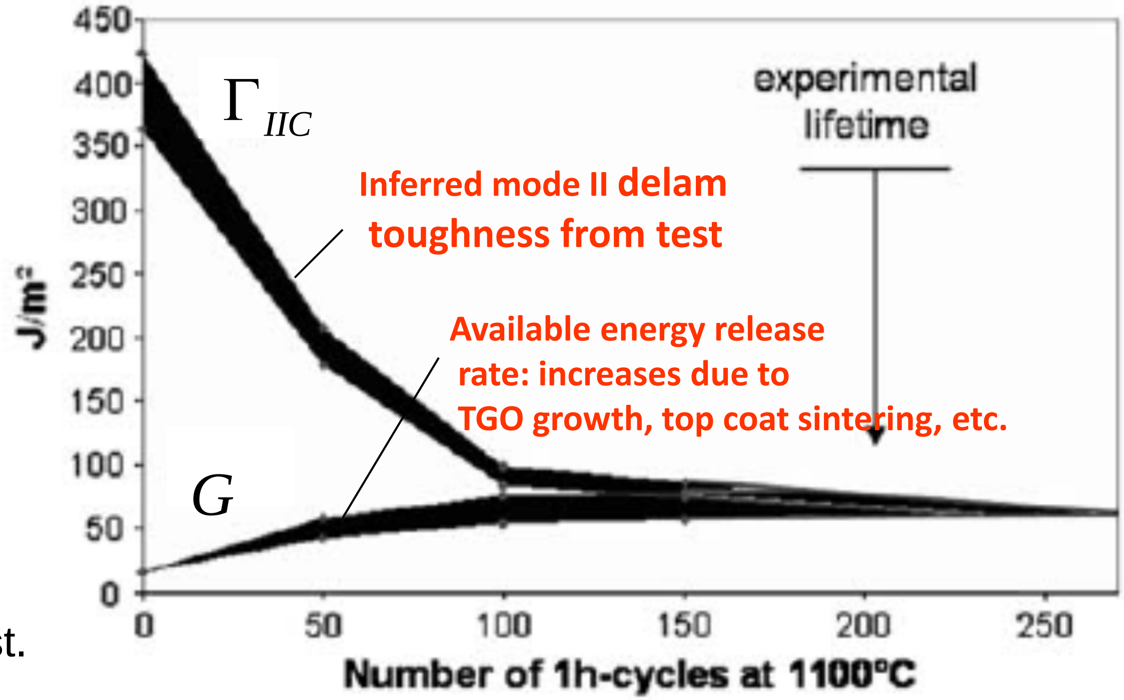
$$\Gamma_{IIC},$$

as a function of relevant thermal history.

B. Determine energy release rate,

$$G,$$

(and mode mix) as a function of time for the application of interest.



ONERA data (test described later)
(Thery, Poulain, Dupeux, Braccini, 2009)

C. Lifetime of coating is determined by condition

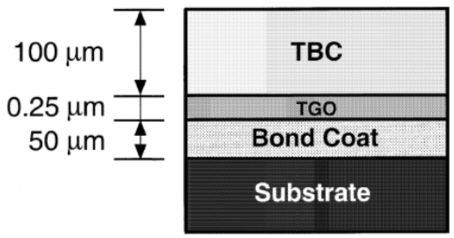
$$G \to \Gamma_{IIC}$$ (or equivalent for other mode mixes)

What determines G ? **Extrinsic effects such as:**

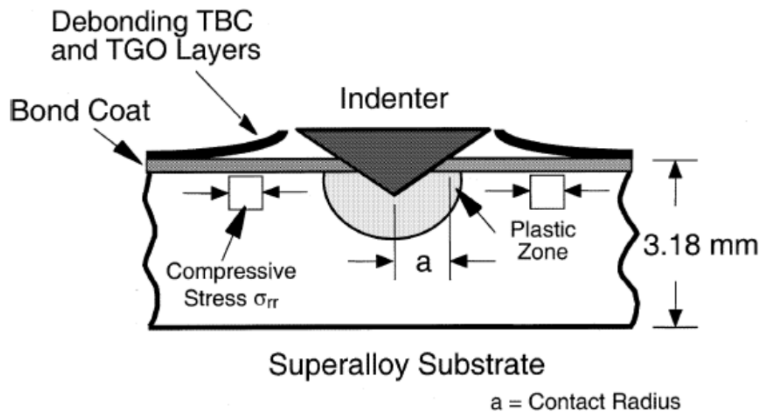
--Thermal stresses in top coat and TGO (**only** if the failure interface lies below the TGO)
-- Mechanical loads on substrate (e.g. bending)
-- Sintering and/or CMAS infiltration of top coat (increases top coat modulus)
-- Thermal (and stress) gradients, both through thickness and in-plane

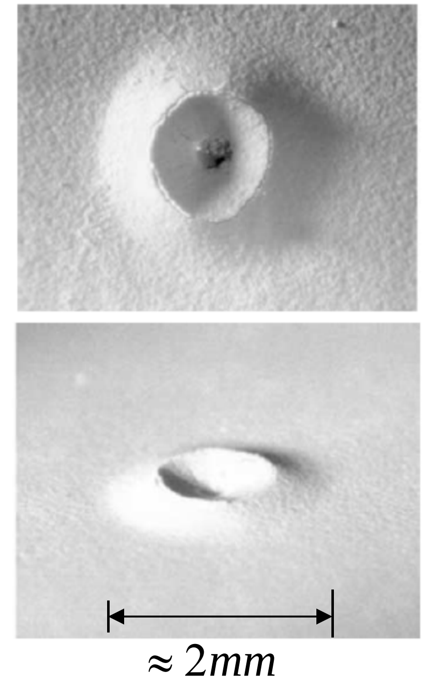
Measuring TBC Interface Toughness by Indentation-induced Delamination

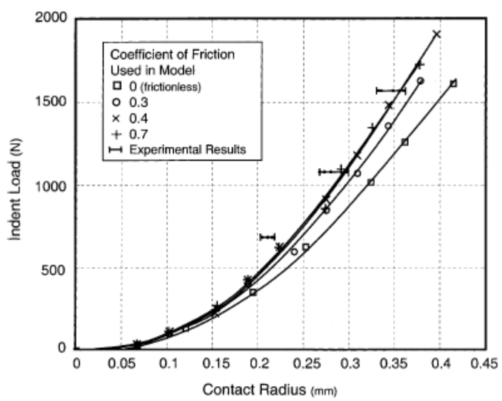
– A. Vasinonta & J.L. Beuth

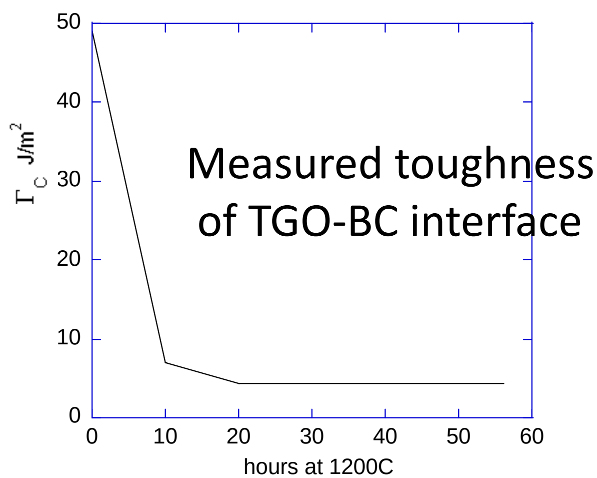


EBPVD Top Coat, Pt Aluminide Bond Coat







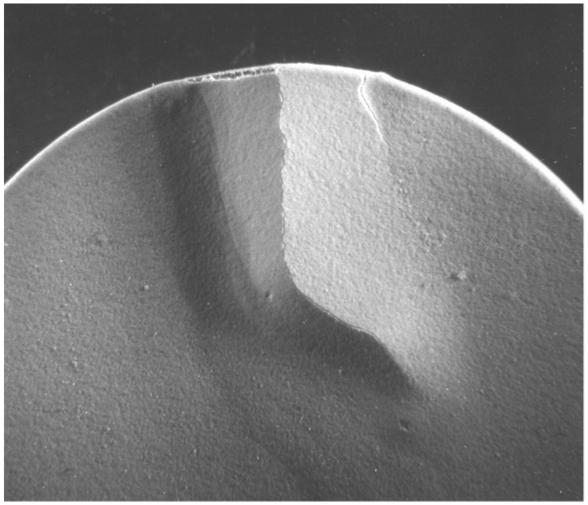


Advantages and disadvantages of test

- indentation is straightforward
- can be carried out directly on components
- requires detailed FEM analysis of elastic-plastic indentation & coating stresses & possibly buckling
- role of residual stress difficult to quantify
- Mixed mode with ψ depending on size of delam & buckling

Fracture toughness of interface: UCSB experiments on burner rig specimens

Faulhaber, Evans, et al (2006-6)



Typical buckle delamination of TBC starting from the edge of a flat test coupon.
(courtesy of D. Clarke)

Delamination occurs at room temperature when compressive stresses in TBC and TGO are the largest.

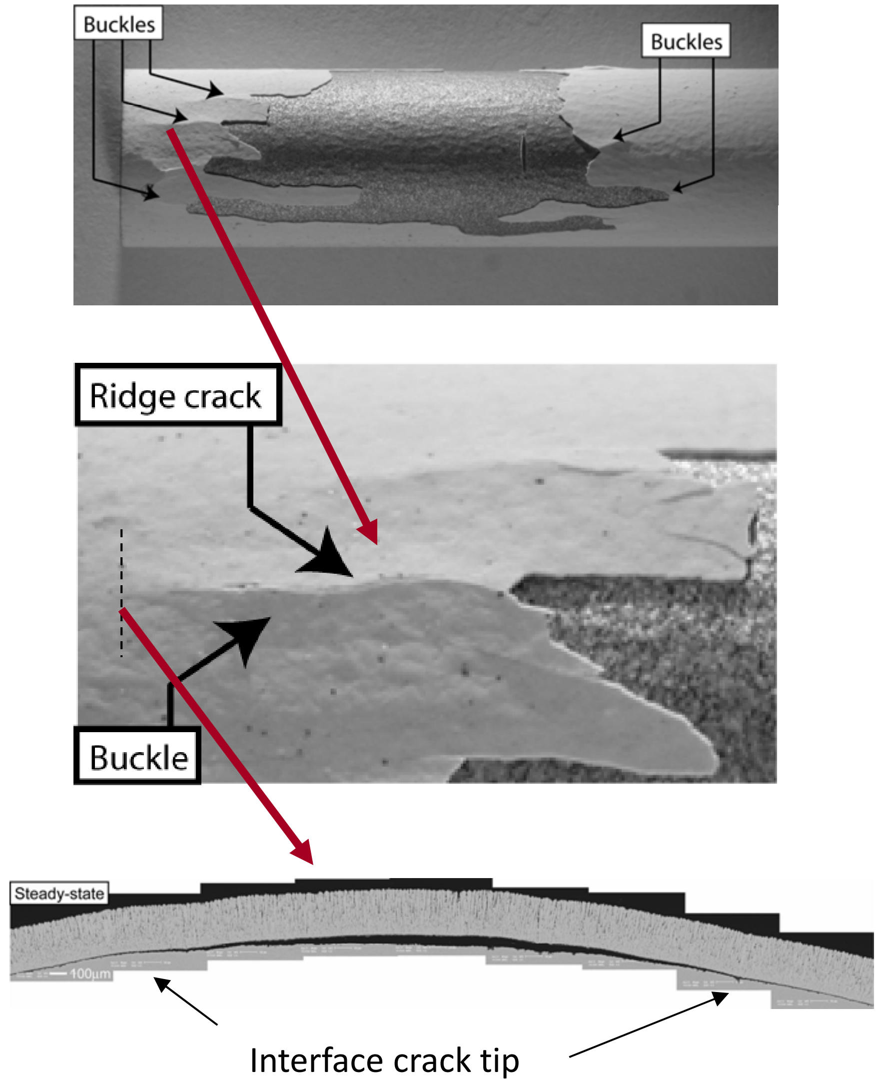
Interface toughness (TGO-Bond coat interface) after burner rig exposure and inferred from extent of the buckle delamination.:

$$\text{mixed mode:} \quad \Gamma_C^I \approx 20-30\ J/m^2$$

$$\text{mode II:} \quad \Gamma_C^{II} \geq 60\ J/m^2$$

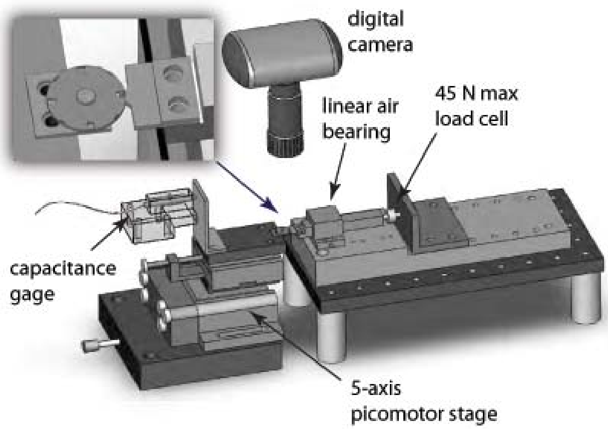
BUCKLE DELAMINATION OF THERMAL BARRIER COATING ON BURNER RIG SPECIMEN

Delamination precipitated by a wedge indentation



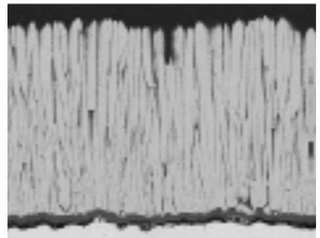
Insitu measurement of modulus of TBC and fracture toughness of interface

K. Hemker & colleagues at JHU



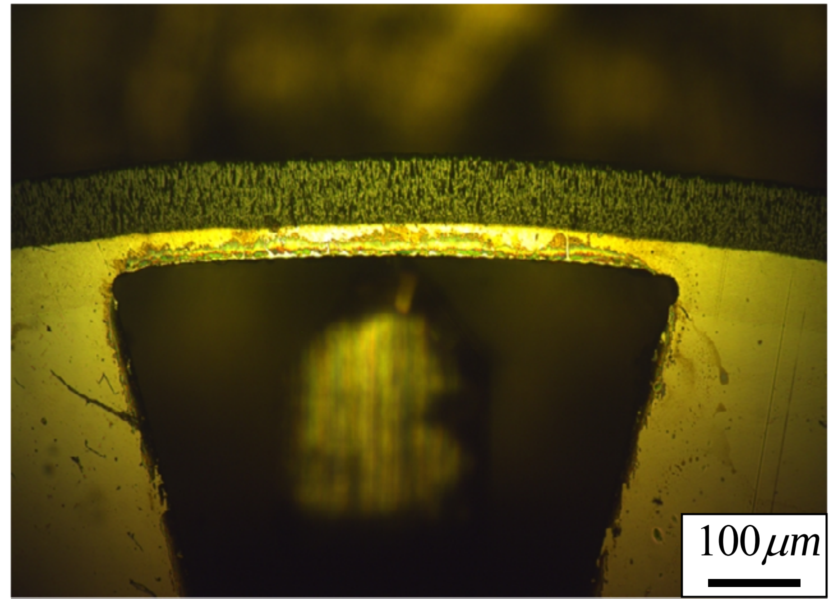
JHU Micro-bend tester

$\uparrow E_y \approx E_{bulk} = 130 GPa$



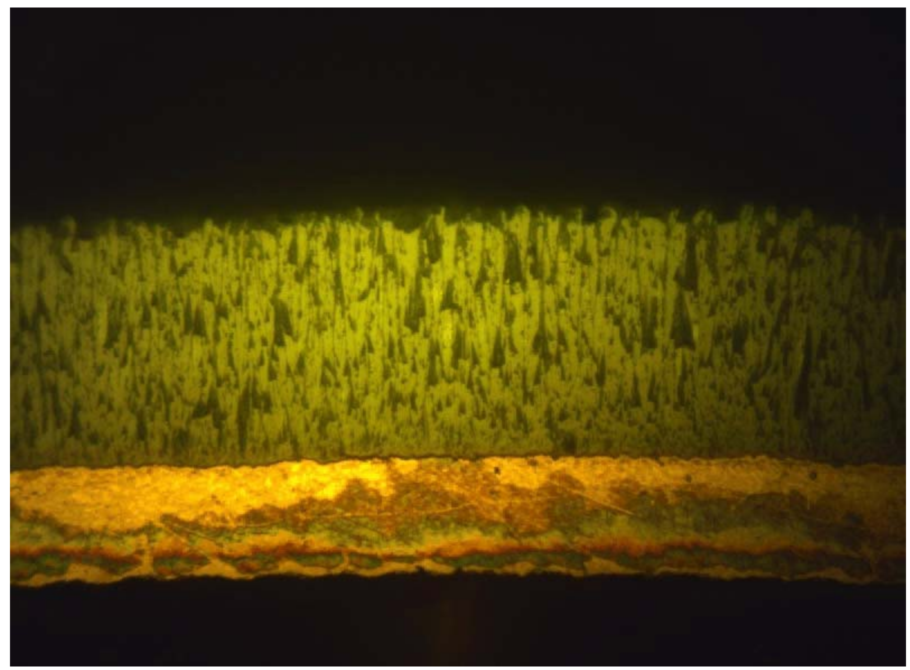
$E_x << E_{bulk}$ $\longrightarrow$

$E_x \approx 20 - 30 GPa$

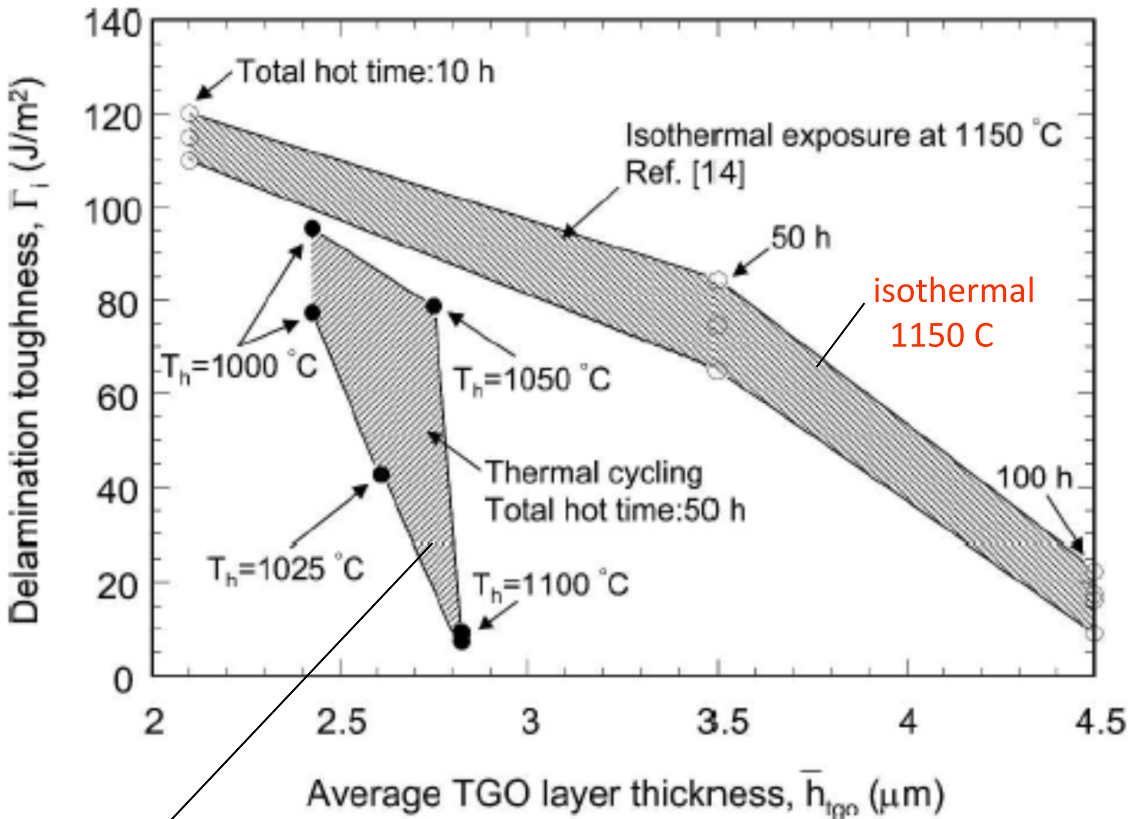


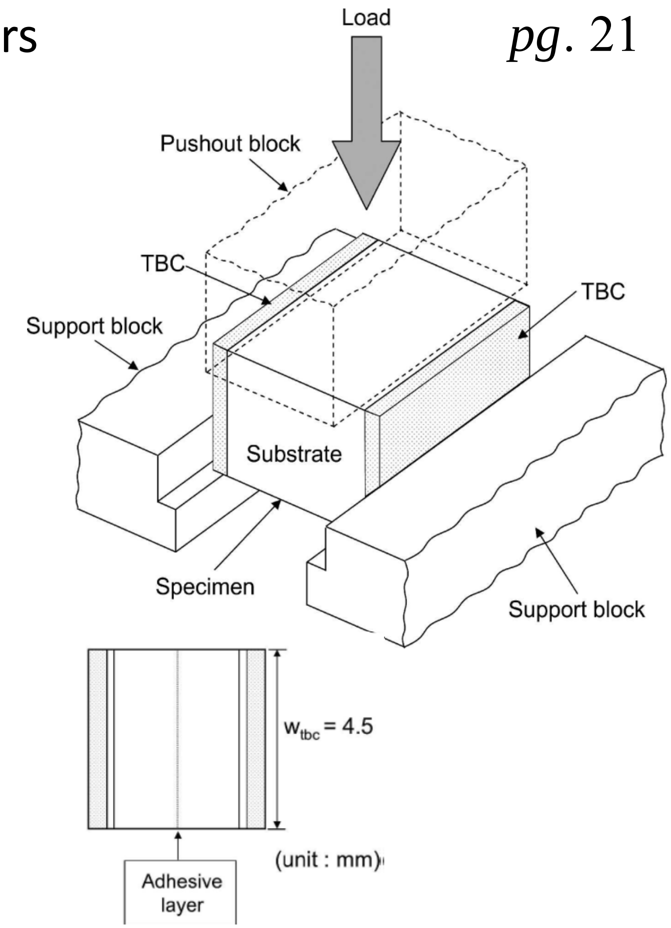
Advantages and disadvantages of test

- difficult to carry out--a high end test!
- also provides top coat modulus information
- requires detailed FEM analysis
- mixed mode loading
- residual stress must be taken into account and play a significant role



The Barb Test: Kagawa and co-workers





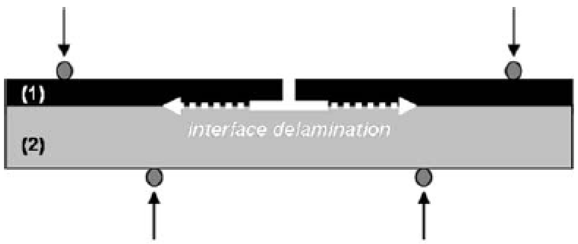
50 thermal cycles 1hr hold.
at various temperatures

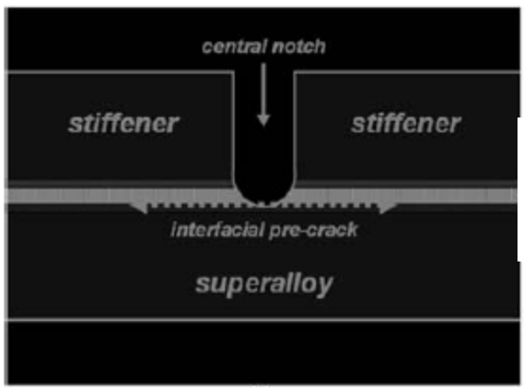
Advantages and disadvantages of test

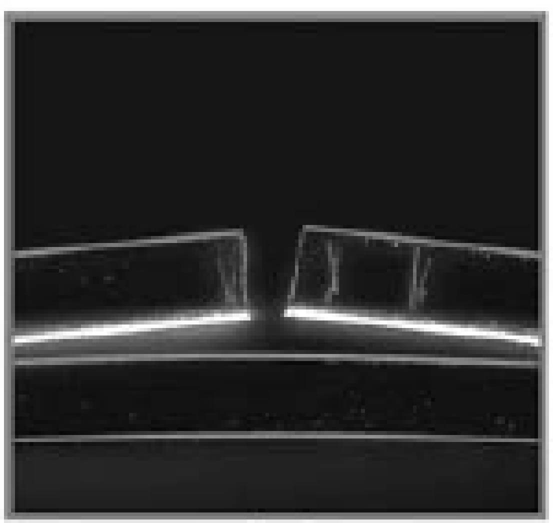
- difficult test--requires great expertise
- stable steady-state delam propagation--mixed mode
- requires detailed FEM analysis
- loads coating in opposite manner as delaminations in service
- residual stress must be taken into account

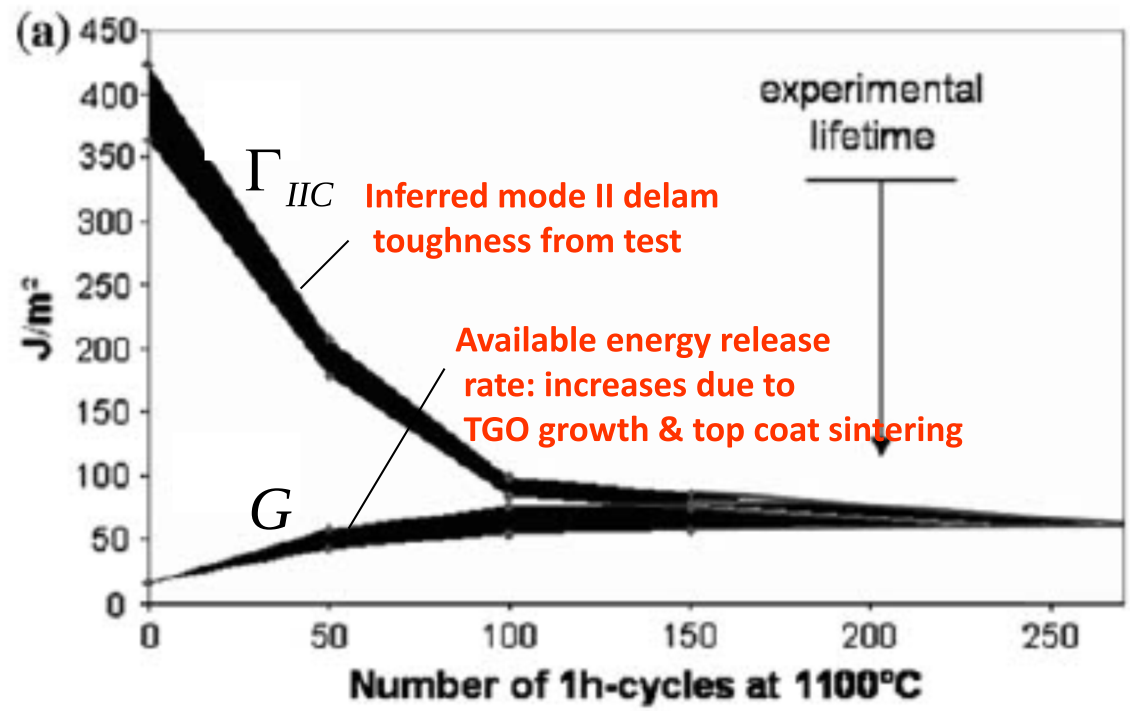
ONERA siffener-enhanced 4-point UCSB bend test

(Thery, Poulain, Dupeux, Braccini, 2009)







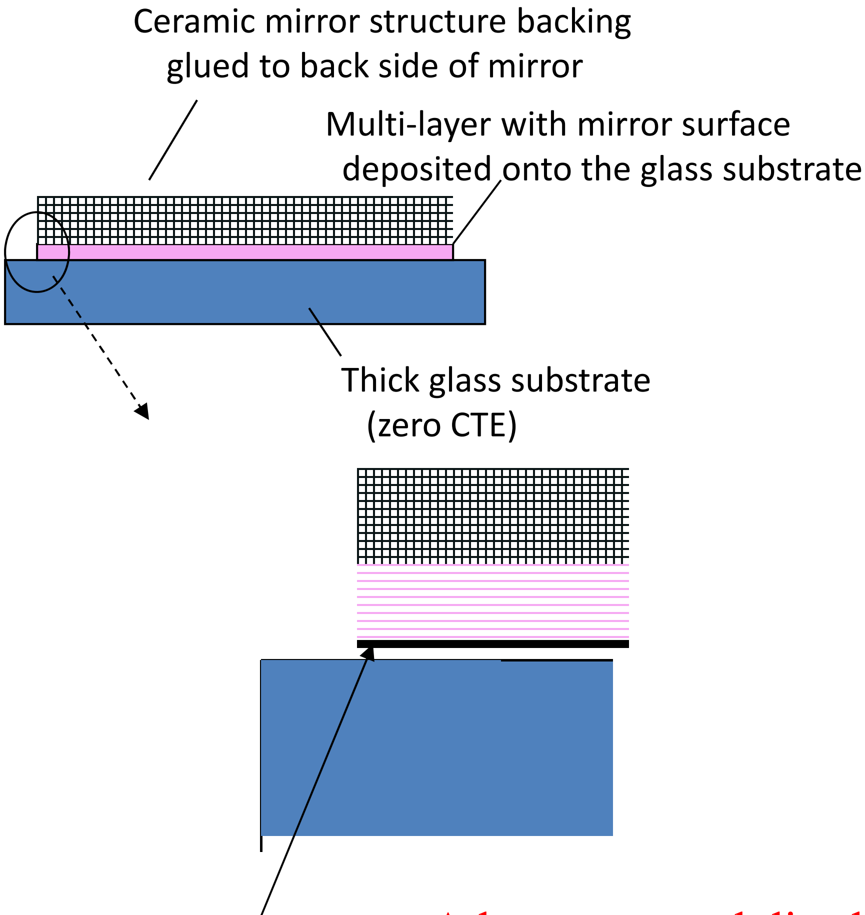


Advantages and disadvantages of test

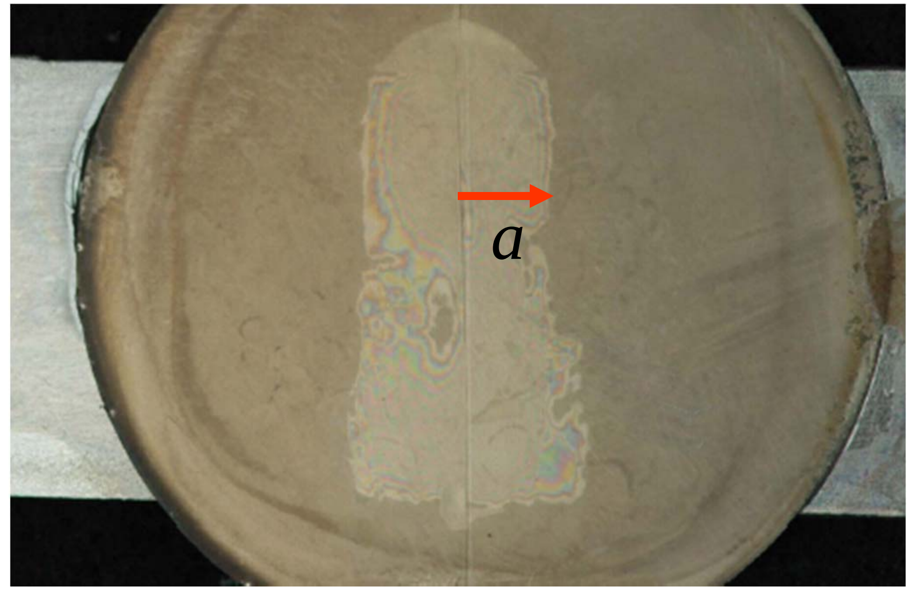
- well established test--variation of UCSB bend test
- stable steady-state delam propagation--mixed mode ($\psi \cong 40^o$)
- requires analysis but straightforward
- loads coating in opposite manner as delaminations in service
- residual stress must be taken into account but little
  is released if coating is thin compared to stiffener

DIGRESSION: Delamination mechanics applied to manufacture of high fidelity mirrors

Evans-Phillips 3-point bend test to measure toughness of a glass/metal interface



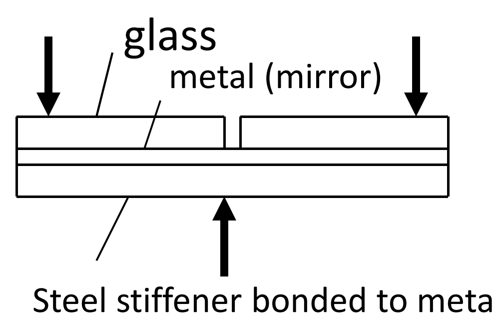
Assembled mirror is separated from substrate by delamination along mirror/glass interface by temperature drop and/or wedging



Looking through glass at delamination —glass is scribed to create through- crack

Advantages and disadvantages of test

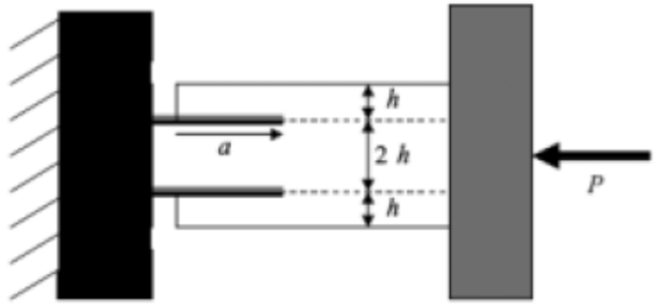
- straightforward test, easily analyzed
- stable mixed mode delam propagation
- test loading closely mimics the application
- Only effective for special interface systems



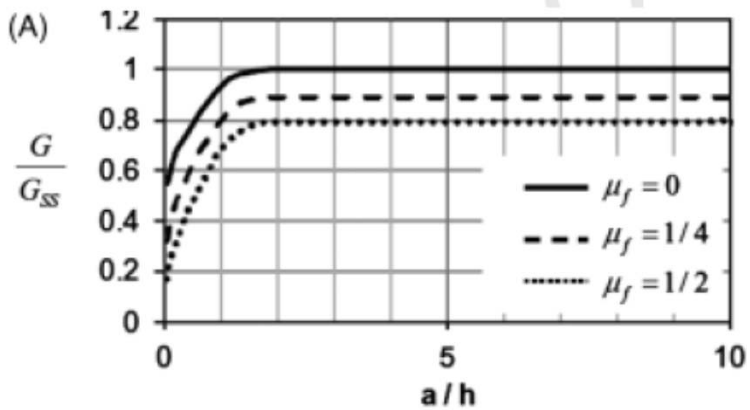
3-point bend test developed to measure interface toughness

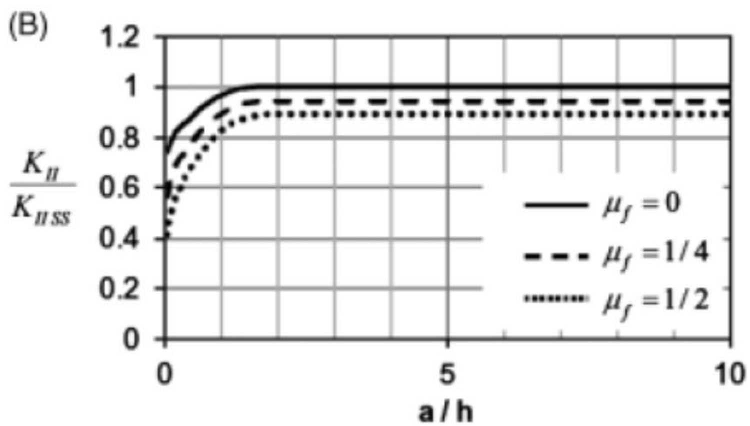
Mode II Shear Test (2011-4)

Closely mimics in-service edge-delamination



compression edge delamination specimen





Steady-state energy release rate for no friction and no elastic mismatch:

$$G_{SS} = \frac{\sigma^2 h}{\bar{E}}, \;\; \psi = -90^o \;\; (\sigma = -P/4h)$$

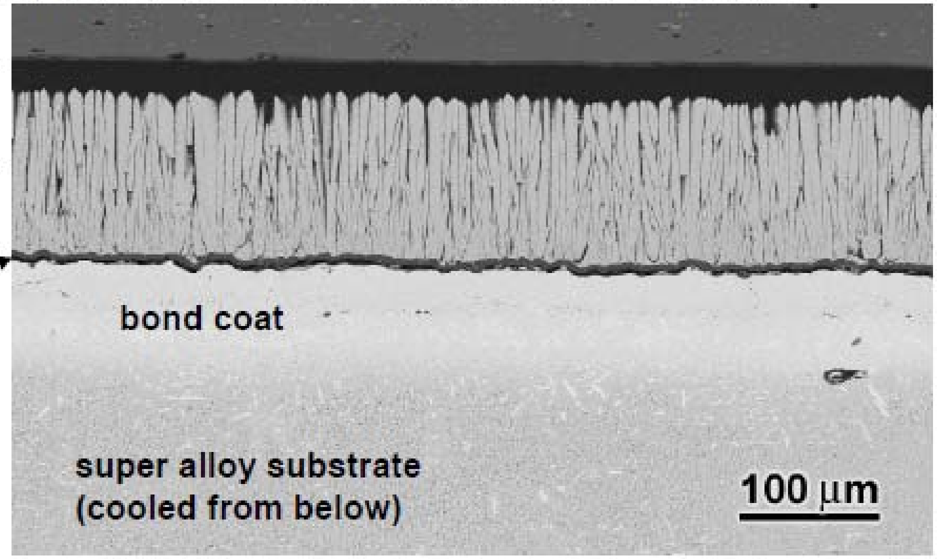
MODE I DELAMINATIONS WITHIN THERMAL BARRIER COATING

Electron Beam Deposited TBC with Columnar Micro-Structure

CMAS (undesirable)
see below

Zirconia top coat (TBC)--
The thermal barrier supporting
a steep temperature drop from
gas to substrate (100 microns)

Thermally grown oxide (TGO)
Alumina (Al_2O_3) which grows
in use from 1 to 10 microns.
It provides oxidation protection.

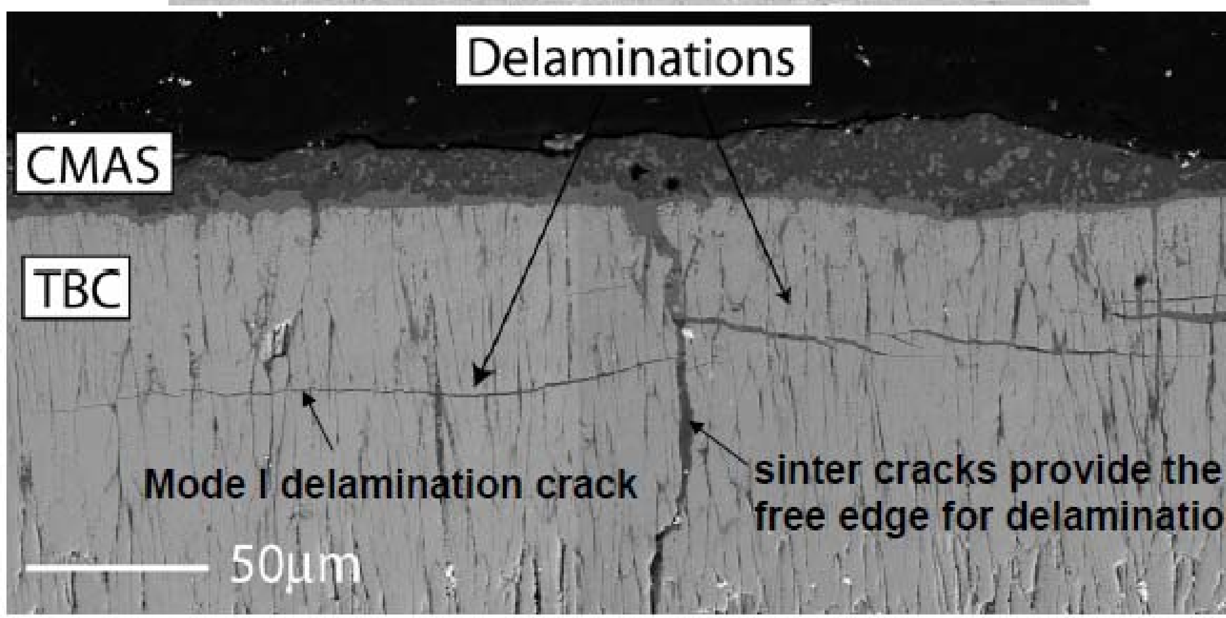


~1250C°

~900C°

CMAS is air borne dirt that melts and accumulates on TBC surfaces. (Calcium, Metallic, Aluminum Silicates)

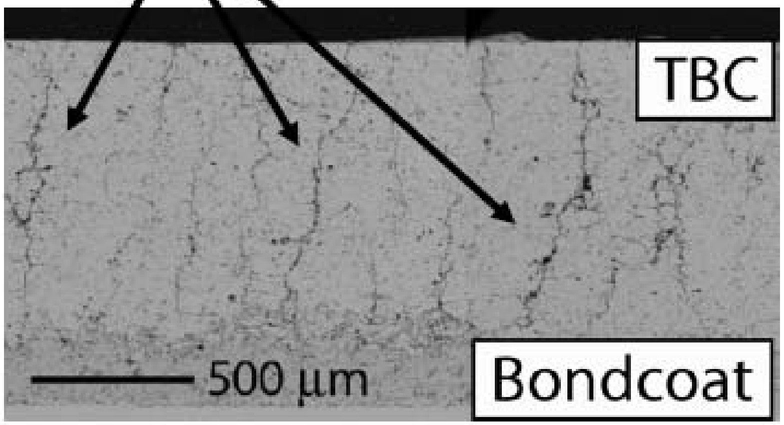
Blade showing spalled TBC

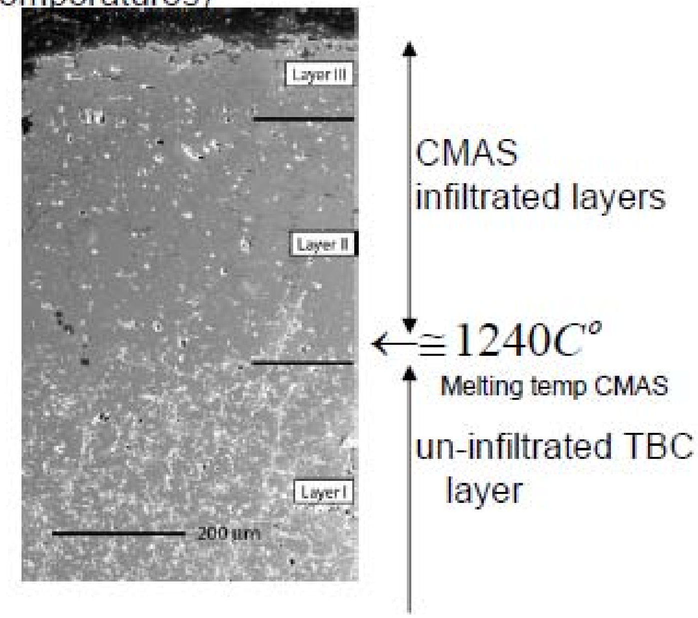


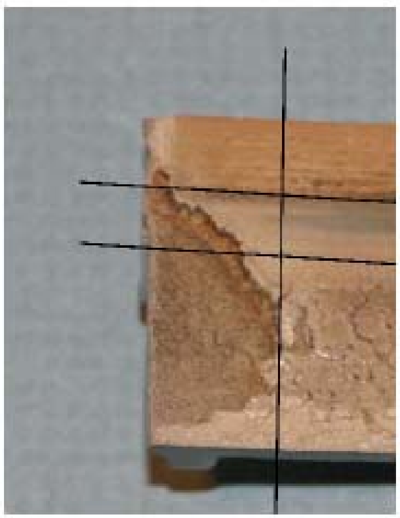
MODE I DELAMINATIONS WITHIN THERMAL BARRIER COATING

Plasma Spray TBC on engine shroud approximately 1mm thick

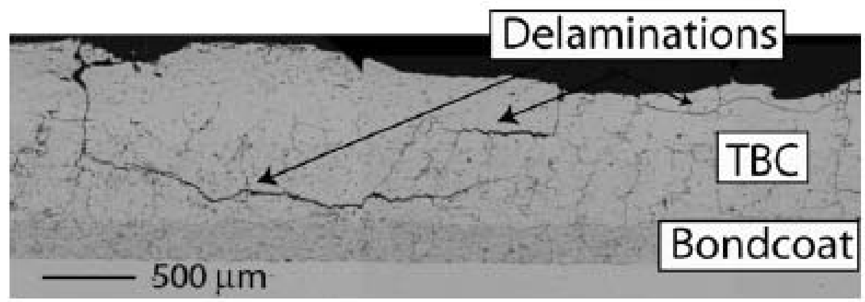
Vertical deposition cracks provide free edges for initiating delaminations
(They are essential for coating/substrate compatibility under cyclic temperatures)



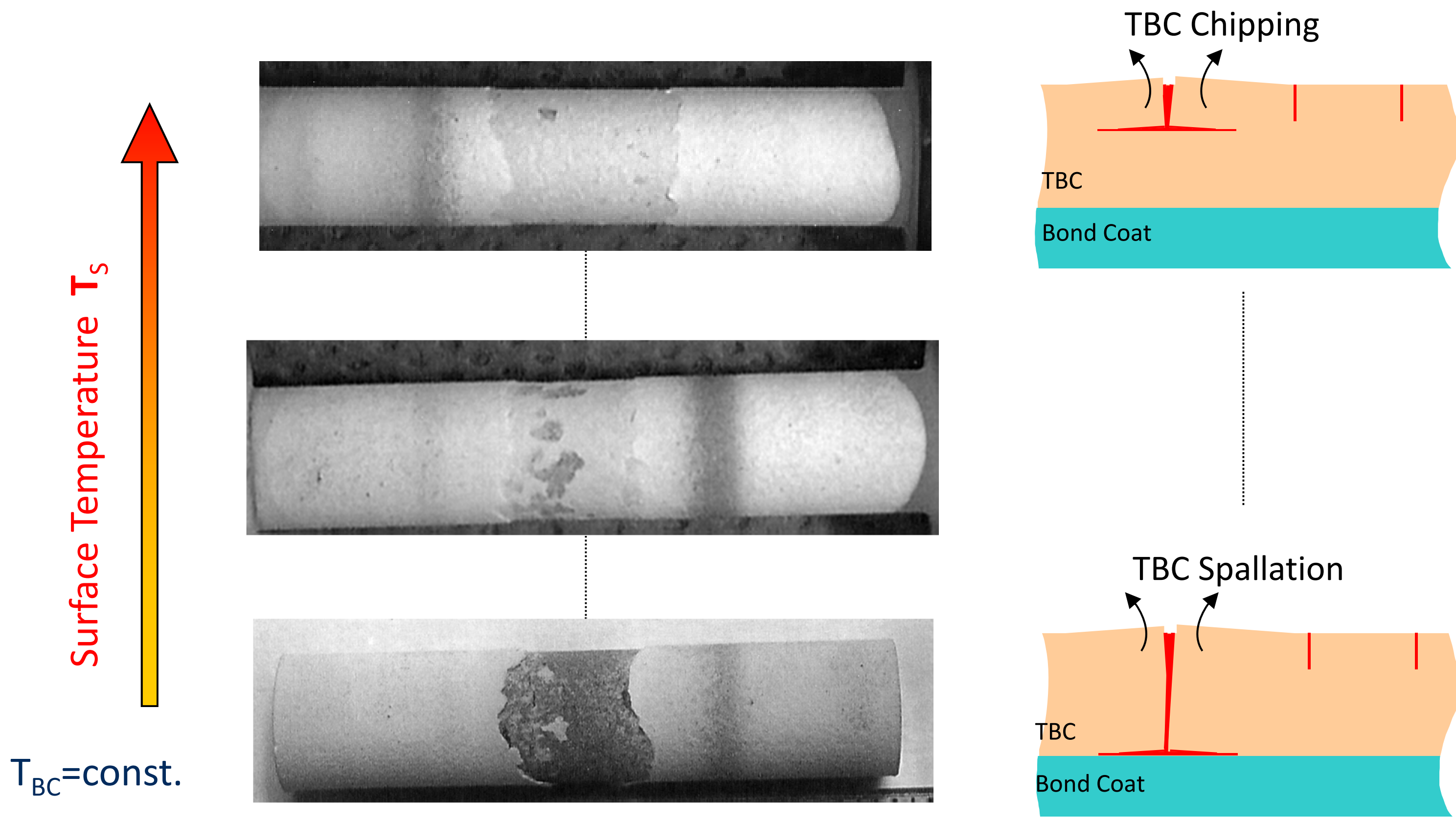




Spalled region under CMAS



High Heat Flux Test
Plasma spray TBC on a hollow tube cooled on inside
Siemens's High Gradient Test—courtesy of S. Lampenscherf



HHF results suggest a temperature dependent failure mechanism:

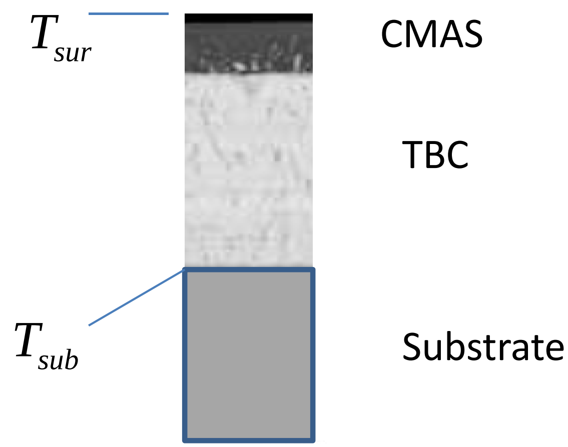
- complete TBC lift-off at low temperature gradients
- layer-by-layer TBC failure at high temperature gradients (mode I delamination)

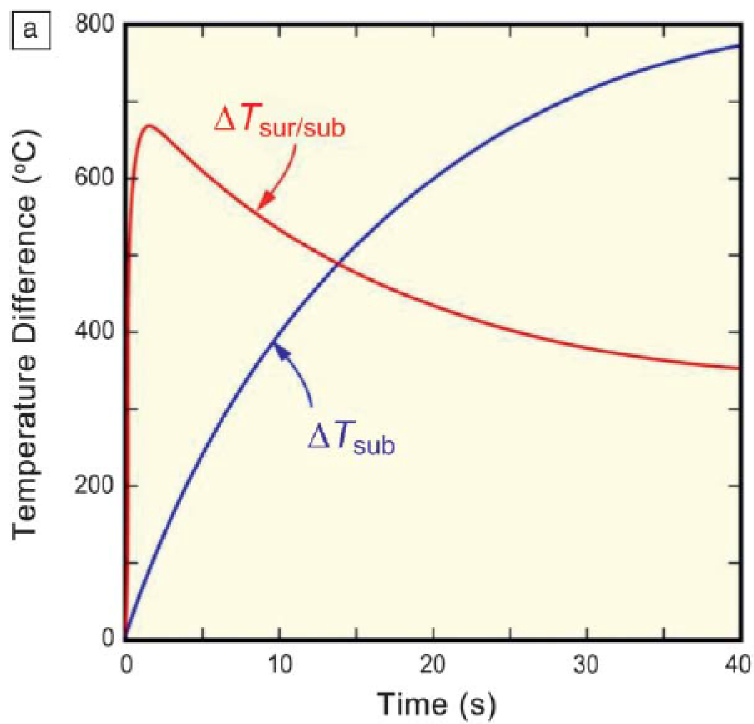
Simulations for rapid cooling of an experimental coating/substrate system with an initial thermal gradient (October 2012 issue of MRS Bulletin).

Stress in coating is zero at highest temperatures due to creep in coating

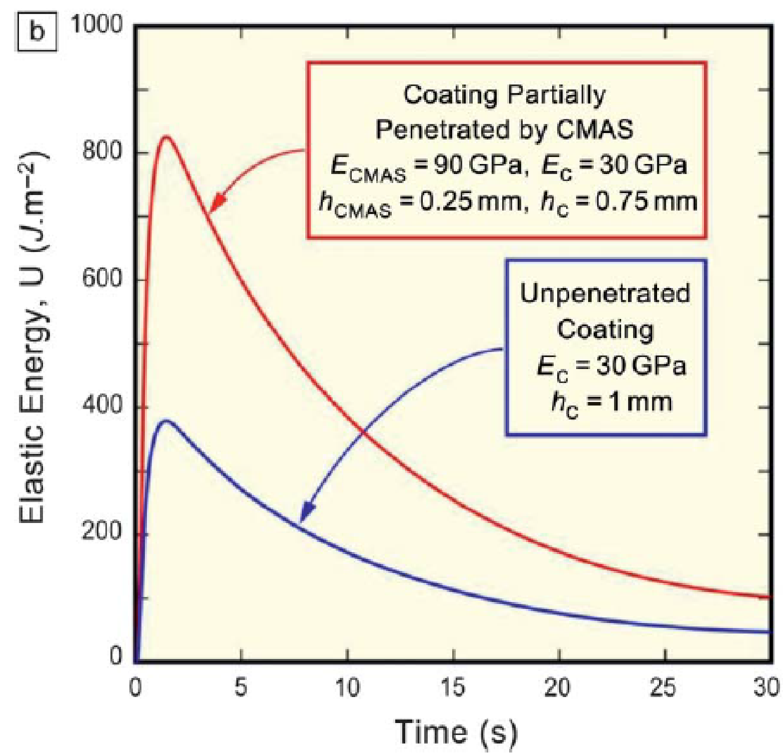
$$\Delta T_{sur/sub} = (T_{sur}^{0} - T_{sur}) - \Delta T_{sub}$$

$$\Delta T_{sub} = T_{sub}^{0} - T_{sub}$$





Temperature drops



Elastic energy in coating

UCSB Tests: Rapid cooling of hot surface vs. slow cooling (Oct. Issue of MRS Bulletin, 2012)