Lecture #2:

Special elastic mismatch effects—the beta effect and definition of mode mix

Origins of mixed mode toughness dependence

Buckling delamination

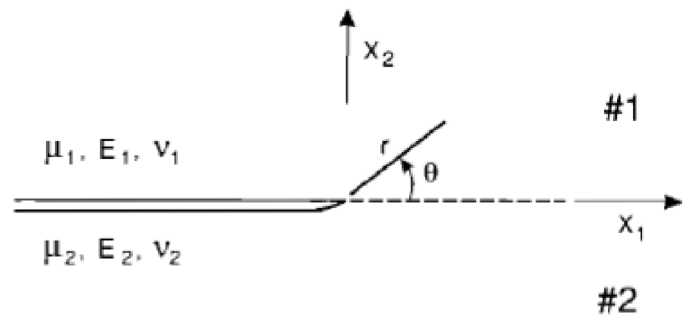
Thermal barrier coating delamination & specimens to measure interface toughness

From Lecture #1

Crack Tip Fields for Bilayer Interface Joining Isotropic Elastic Solids (1992-2; pg.72)

$$\sigma_{\alpha\beta} = \mathrm{Re}[Kr^{i\varepsilon}](2\pi r)^{-1/2}\sigma^{\mathrm{I}}_{\alpha\beta}(\theta,\varepsilon) + \mathrm{Im}[Kr^{i\varepsilon}](2\pi r)^{-1/2}\sigma^{\mathrm{II}}_{\alpha\beta}(\theta,\varepsilon)$$

$$K = K_1 + iK_2 \qquad \varepsilon = \frac{1}{2\pi}\ln\left(\frac{1-\beta}{1+\beta}\right)$$



On interface ahead of crack:

$$\sigma_{22} = \mathrm{Re}[Kr^{i\varepsilon}](2\pi r)^{-1/2}, \qquad \sigma_{12} = \mathrm{Im}[Kr^{i\varepsilon}](2\pi r)^{-1/2}$$

$$r^{i\varepsilon} = \cos(\varepsilon \ln r) + i\sin(\varepsilon \ln r)$$

Crack opening displacements :

$$\delta_2 + i\delta_1 = \frac{8}{(1+2i\varepsilon)\cosh(\pi\varepsilon)}\frac{(K_1 + iK_2)}{E_*}\left(\frac{r}{2\pi}\right)^{1/2} r^{i\varepsilon} \qquad \frac{1}{E_*} = \frac{1}{2}\left(\frac{1}{\bar{E}_1} + \frac{1}{\bar{E}_2}\right)$$

Energy release rate:

$$G = \frac{(1-\beta^2)}{E_*}(K_1^2 + K_2^2)$$

$$\bar{E} = E/(1-\nu^2) \ \text{plane strain}$$

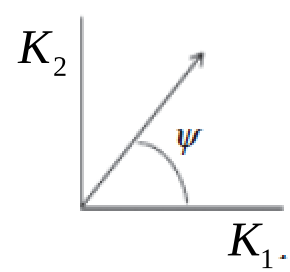
$$\bar{E} = E \qquad \text{plane stress}$$

To make life simpler, most of our discussion will take $\beta = 0 \Rightarrow \varepsilon = 0$ but $\alpha \neq 0$

For these cases, the singular stress fields at the tip are identical to those for a homogeneous solid

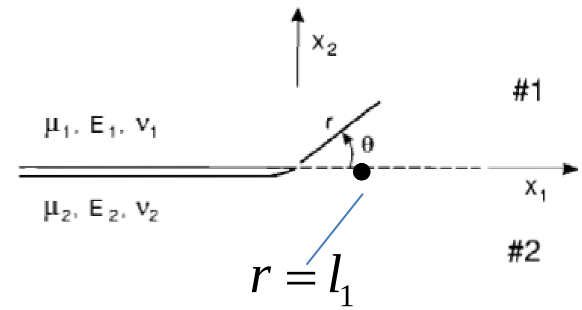
$$(\sigma_{22},\sigma_{12}) = (K_1,K_2)\frac{1}{\sqrt{2\pi r}}, \quad (\delta_2,\delta_1) = (K_1,K_2)\frac{8}{E_*}\sqrt{\frac{r}{2\pi}}$$

$$G = \frac{1}{E_*}\left(K_1^{\,2} + K_2^{\,2}\right) \ \ \& \qquad \tan\psi = \frac{K_2}{K_1}$$



Beta effects on interface toughness
(1992-2)

$$\varepsilon = \frac{1}{2\pi}\ln\left(\frac{1-\beta}{1+\beta}\right)$$



Ahead of crack tip:

$$K = K_1 + iK_2$$

$$\sigma_{22} = \mathrm{Re}[Kr^{i\varepsilon}](2\pi r)^{-1/2}, \qquad \sigma_{12} = \mathrm{Im}[Kr^{i\varepsilon}](2\pi r)^{-1/2}$$

Definition of ψ: $\psi(\ell_1) = \tan^{-1}\left(\frac{\sigma_{12}}{\sigma_{22}}\right)_{r=\ell_1} = \tan^{-1}\left(\frac{\mathrm{Im}\{K\ell_1{}^{i\varepsilon}\}}{\mathrm{Re}\{K\ell_1{}^{i\varepsilon}\}}\right)$

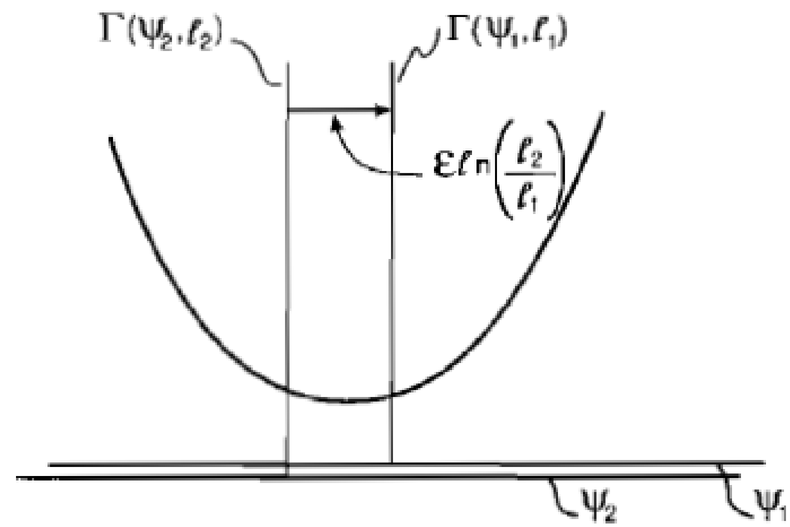
Crack propagation condition: $G = \Gamma(\psi(\ell_1))$ **depends on choice of ℓ_1 !!**

Note: with $\psi(\ell_2) = \tan^{-1}\left(\frac{\mathrm{Im}\{K\ell_2{}^{i\varepsilon}\}}{\mathrm{Re}\{K\ell_2{}^{i\varepsilon}\}}\right)$

$$\psi(\ell_2) = \psi(\ell_1) + \varepsilon\ln\left(\frac{\ell_2}{\ell_1}\right)$$

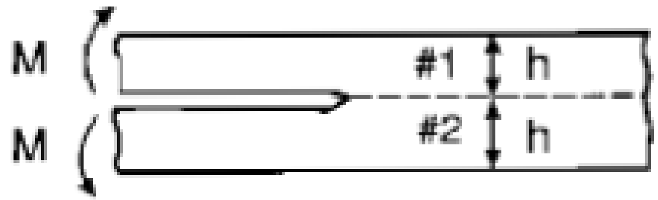
Thus: $G = \Gamma(\psi(\ell_1)) = \Gamma\left(\psi(\ell_2) - \varepsilon\ln\left(\frac{\ell_2}{\ell_1}\right)\right)$

$$\equiv \Gamma^*(\psi(\ell_2))$$



Schematic for shifting toughness function with different choice of reference length

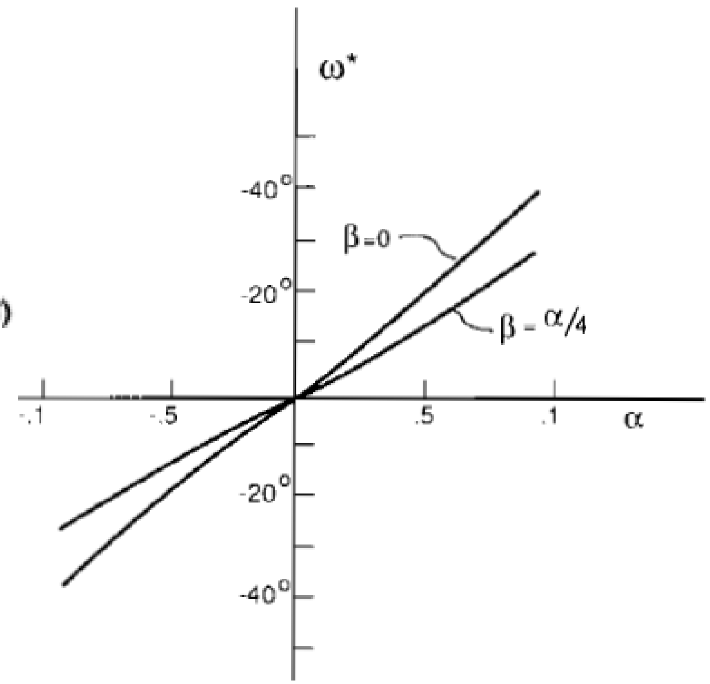
Crack on an interface between two materials of equal thickness (1992-2)



$$G = \frac{1}{2}\left(\frac{1}{\overline{E}_1} + \frac{1}{\overline{E}_2}\right)12M^2h^{-3}$$

$$K_1 + iK_2 = 2\sqrt{3}\,Mh^{-3/2-i\varepsilon}(1-\beta^2)^{-1/2}e^{i\omega^*(\alpha,\beta)}$$

$$\psi(\ell) = \tan^{-1}\left(\frac{\sigma_{12}}{\sigma_{22}}\right)_{r=\ell} = \tan^{-1}\left(\frac{\mathrm{Im}\{K\ell^{i\varepsilon}\}}{\mathrm{Re}\{K\ell^{i\varepsilon}\}}\right)$$



$$\Rightarrow \psi(\ell) = \omega^*(\alpha,\beta) + \varepsilon\ln(\ell/h)$$

Recall: $\varepsilon = \frac{1}{2\pi}\ln\left(\frac{1-\beta}{1+\beta}\right)$

epoxy/glass: $\varepsilon = 0.06$

rubber/steel: $\varepsilon \cong 0$

epoxy/plexiglass: $\varepsilon = 0.009$

Illustration of the beta effect on the Liechti-Chai toughness data for a epoxy/glass interface (1992-2)

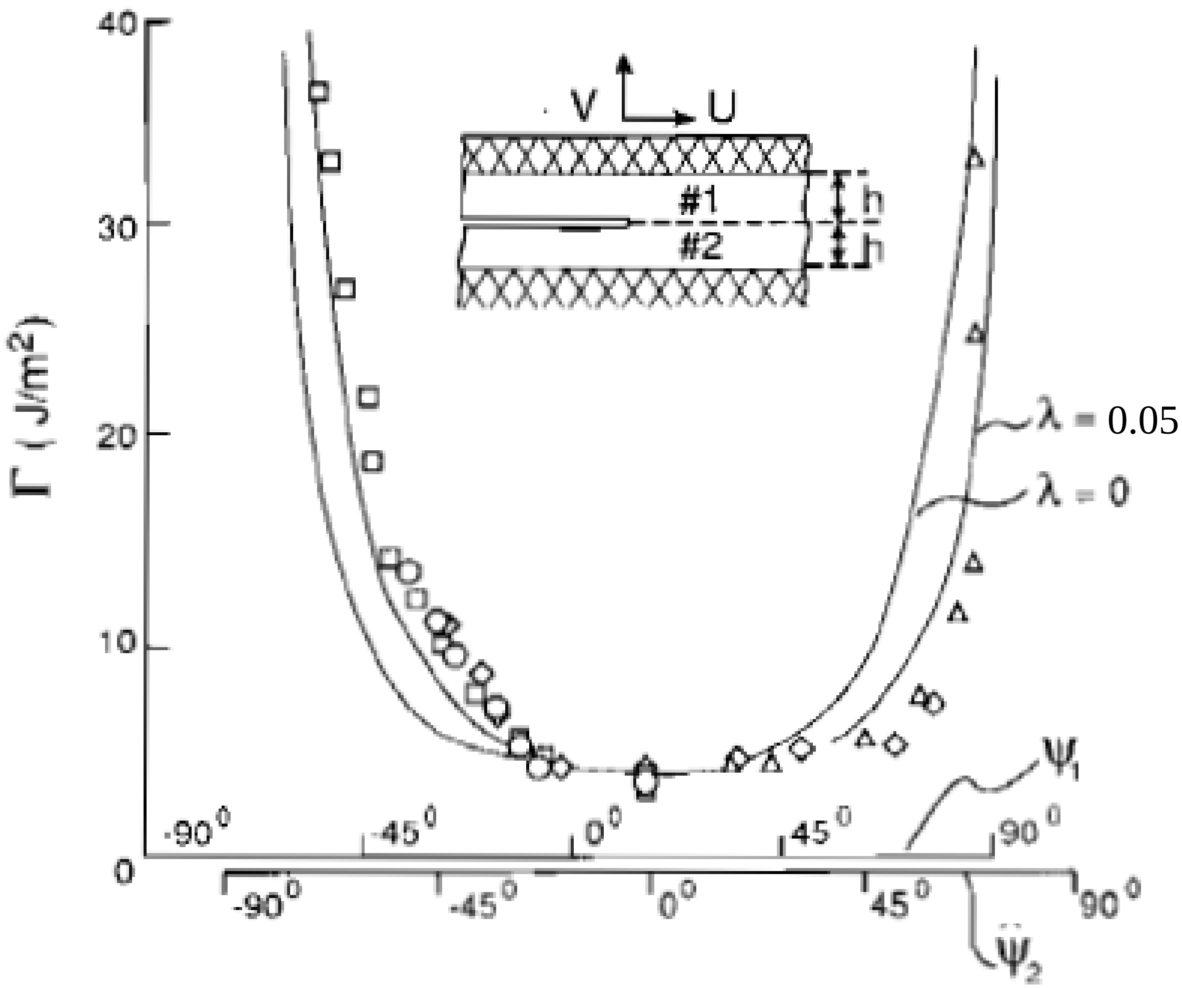
epoxy (#1)/glass (#2) interface

$E_1 = 2.07 GPa,\ \nu_1 = 0.37$
$E_2 = 68.9 GPa,\ \nu_2 = 0.20$
$h = 12.7 mm$

$\alpha = -0.935,\ \ \beta = -0.188,\ \ \varepsilon = 0.060$

Consider two choices for ℓ:
$\ell_1 = h = 12.7 mm$
$\ell_2 = h/100 = 127 \mu m$

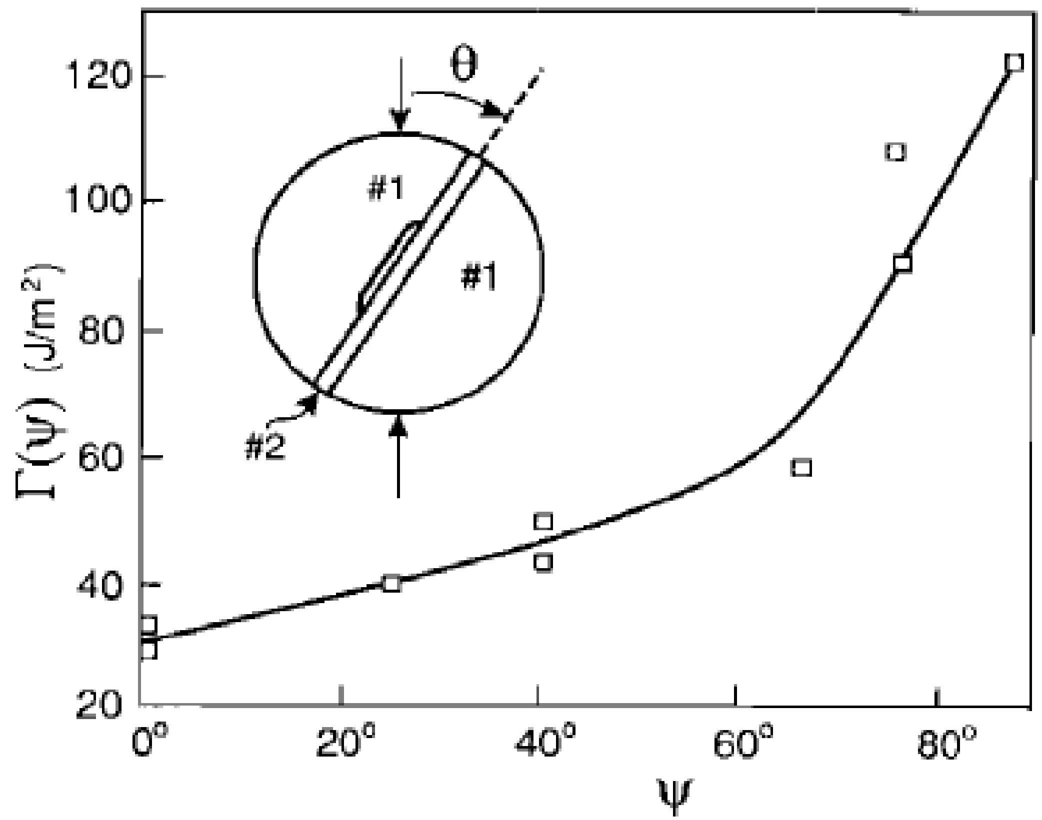
$$\Gamma_C(\psi_2) = \Gamma_{IC}\left(1 + \tan^2\left(1-\lambda\right)\psi_2\right)$$



Wang-Suo (1990) interface toughness data for plexiglass/epoxy obtained using a Brazil nut specimen (1992-2)

plexiglass (#1)
epoxy (#2)

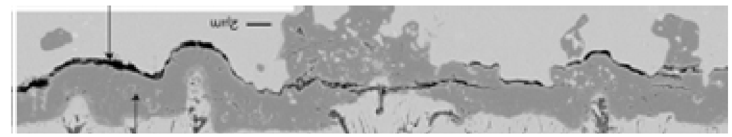
α=-0.15
β=-0.029
ε=0.009



I suspect this data is plotted using the thickness of the epoxy layer as the reference length, but epsilon is so small that the beta-effect can be ignored.

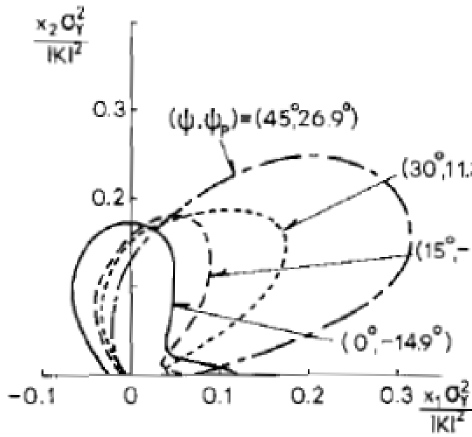
Micromechanical origins of mixed mode interface toughness

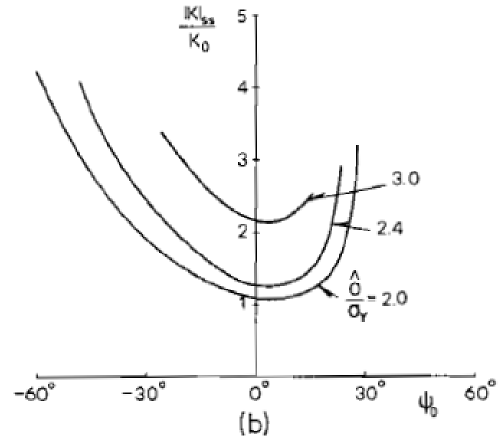
1. Non-planarity of interface (1989-2)



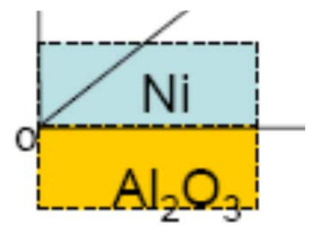
2. Plasticity (1993-1)

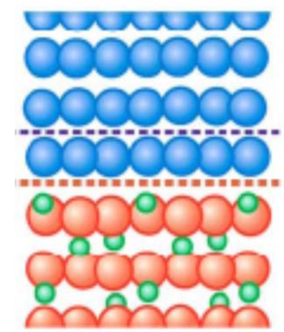
Liechti-Chai epoxy/glass interface has plastic zone in the epoxy on the order of several microns in and the extent depends on the mode mix.





3. Coupling between atomistic separation and plasticity at crack tip (2008-9)

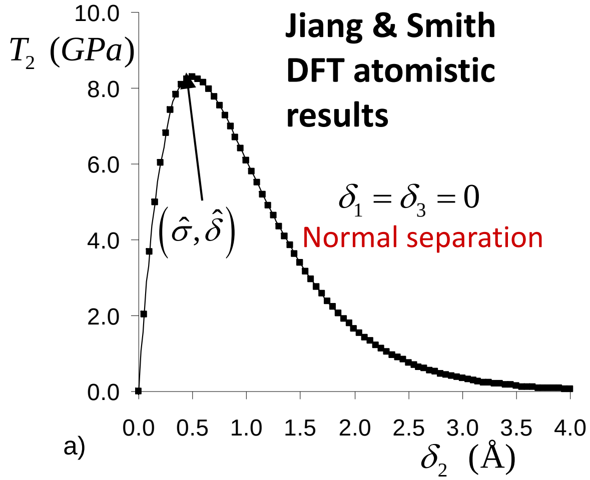


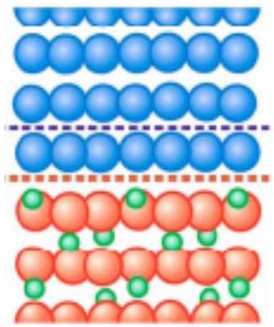


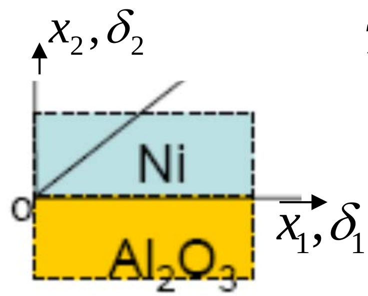
4. Recent experiments on adhesive (van der Vaals) debonding of elastomers from glass and metal substrates also reveals a significant mode dependence

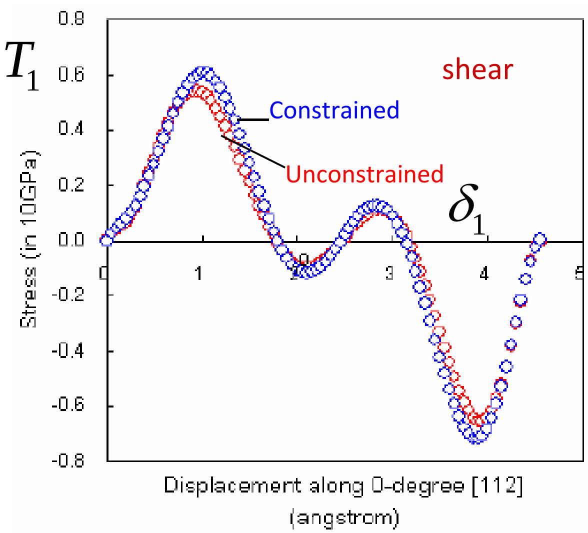
See (1995-4) & (1999-8) for reviews of various aspects

Interface Potential – Clean Stoichiometric Ni/Al_2O_3 Interface









Interface separation potential : $W(\delta_1,\delta_2)=$

$$=\Gamma_0\left[1-\left(1+\frac{\delta_2}{\hat{\delta}}\right)e^{-\frac{\delta_2}{\hat{\delta}}}+f(\delta_1)\left[1+(1+\beta)\frac{\delta_2}{\hat{\delta}}\right]e^{-\frac{\delta_2}{\hat{\delta}}}\right]$$

$$T_1=\frac{\partial W}{\partial\delta_1}=\Gamma_0\frac{df(\delta_1)}{d\delta_1}\left[1+(1+\beta)\frac{\delta_2}{\hat{\delta}}\right]e^{-\frac{\delta_2}{\hat{\delta}}}$$

$$T_2=\frac{\partial W}{\partial\delta_2}=\frac{\Gamma_0}{\hat{\delta}}\left[\frac{\delta_2}{\hat{\delta}}-\left((1+\beta)\frac{\delta_2}{\hat{\delta}}-\beta\right)f(\delta_1)\right]e^{-\frac{\delta_2}{\hat{\delta}}}$$

Normal separation :

$$T_2=\frac{\Gamma_0}{\hat{\delta}}\frac{\delta_2}{\hat{\delta}}e^{-\delta_2/\hat{\delta}},\quad T_1=0$$

Constrained shear $(\delta_2=0)$

$$T_1=\Gamma_0\frac{df(\delta_1)}{d\delta_1},\quad T_2=\beta\frac{\Gamma_0}{\hat{\delta}}f(\delta_1)$$

stoichiometric interface:

{0001} plane of α-Al_2O_3

{111} plane of γ-Ni

shear (δ_1) in [112] direction

Work of separation (all modes) : $\Gamma_0=1.13Jm^{-2}$

For normal separation :

Separation at peak stress ~ $\hat{\delta}=0.50$Å

peak stress ~ $\hat{\sigma}=\Gamma_0/(e\hat{\delta})=8.3GPa$

$f(\delta_1)$ is fit to **constrained shear** $(\delta_2=0)$

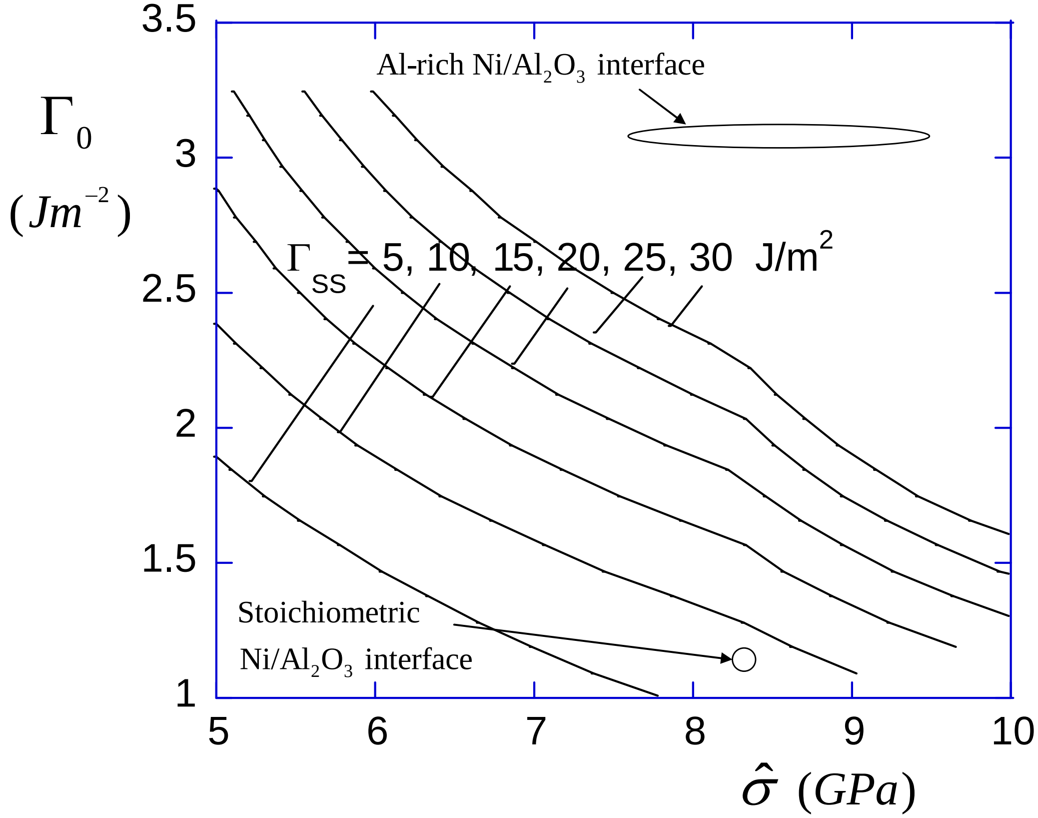
β is fit to T_2 in constrained shear (next slide)

References: (2008-9)
(2010-2)

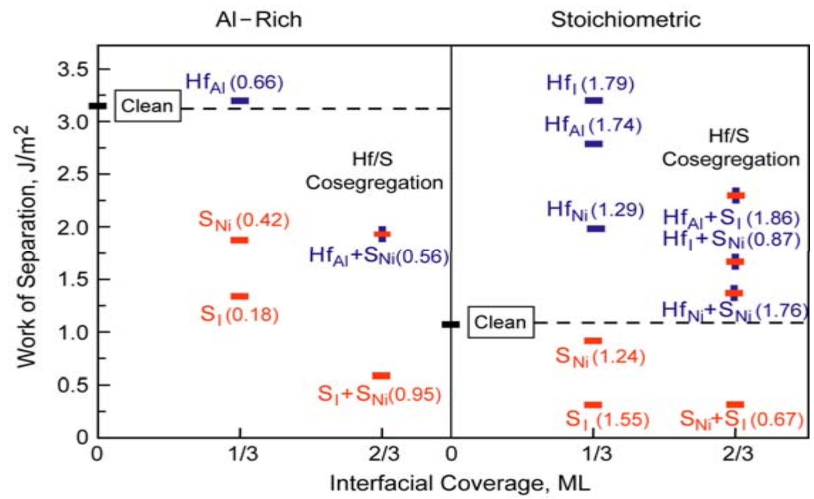
Dependence of Mode I Interface Toughness on Work of Separation and Strength of the Interface

Γ_{SS} ~ macroscopic mode I interface toughness

Work of separation



Interface strength

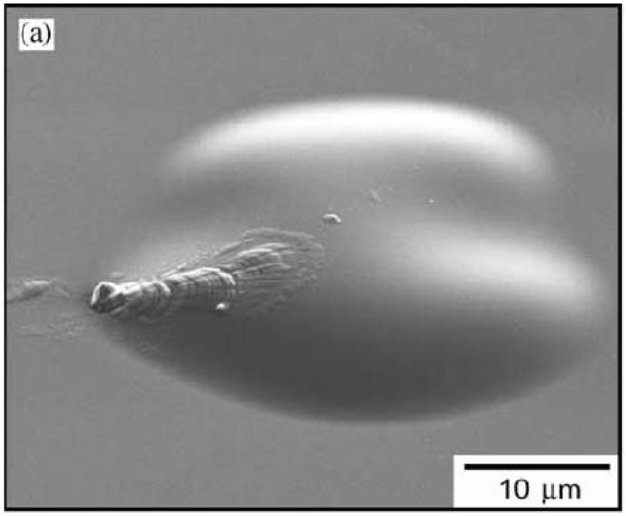


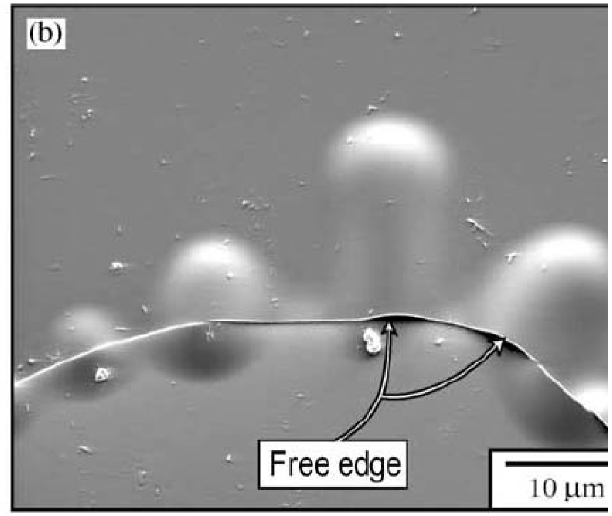
Smith, Jiang & Evans (2007) atomistic results for work of separation for various segregates at Ni Al interface

Atomistic separation energy of NiAl interface : $\Gamma_0 = 1.13 J/m^2$

Examples of buckle delaminations: Diamond-like carbon films on Silicon (2002-6)

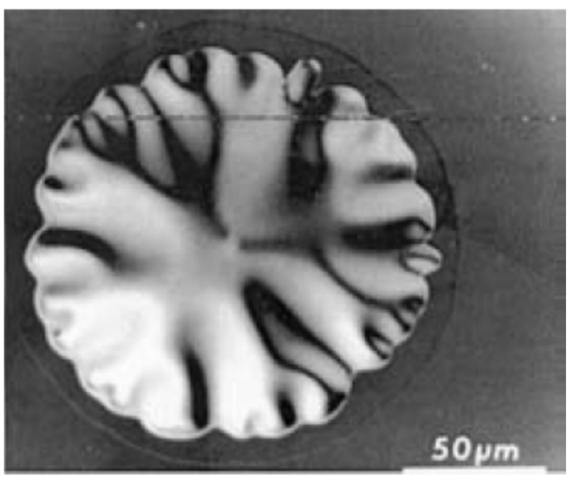
These films are all under equi-biaxial compression

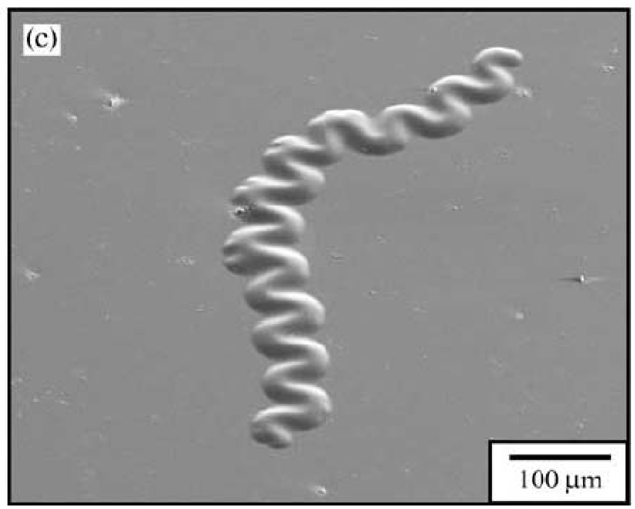




"circular"

"straight-sided"



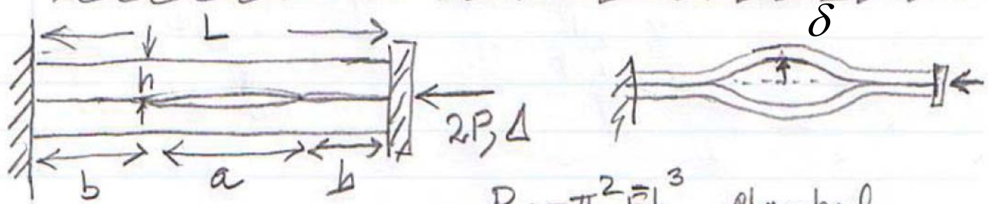


"telephone cord"

(Argon, 1989)

Fig. 1. Illustrations of straight-sided, circular, and telephone cord buckles (Moon et al., 2002).

A Simple Example of Buckling Delamination

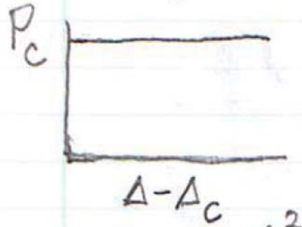


$$P_c = \frac{\pi^2}{12}\frac{E h^3}{a^2}$$ clamped flat plate

Symmetry ⇒ mode I

$$\Delta_c = \frac{P_c L}{E h} = \frac{\pi^2}{12}\frac{L h^2}{a^2}$$

Idealized buckling behavior:



For $\Delta \geq \Delta_c$ $\quad P = P_c$

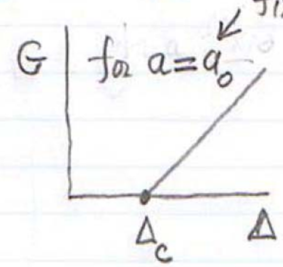
Strain energy = Work done on specimen

2 members

$$\Rightarrow SE = 2 \cdot \tfrac{1}{2} P_c \Delta_c + 2 P_c (\Delta - \Delta_c) = P_c (2\Delta - \Delta_c)$$

$$G = -\frac{1}{2}\left(\frac{\partial SE}{\partial a}\right)_\Delta = \frac{2 P_c}{a}(\Delta - \Delta_c)$$

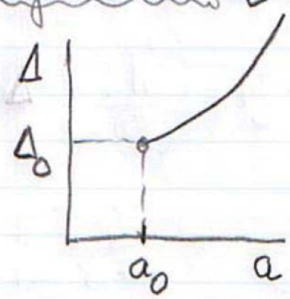
2 crack tips

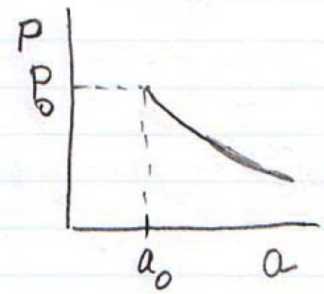


Consider brittle crack growth $G = \Gamma_c$

$\Rightarrow$ $a \geq a_o$

$$\Delta = \frac{6 \Gamma_c a^3}{\pi^2 E h^3} + \frac{\pi^2}{12}\frac{L h^2}{a^2}$$





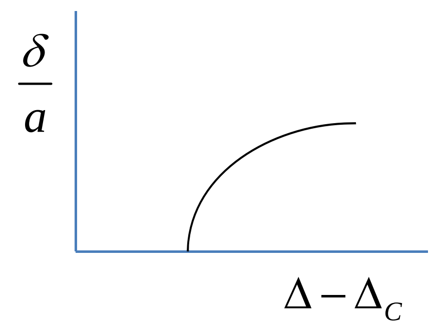
Buckling deflection:

$$w(x) = (\delta / 2)\left(1 + \cos(\pi x / a)\right)$$

Relation between buckling deflection and end shortening:

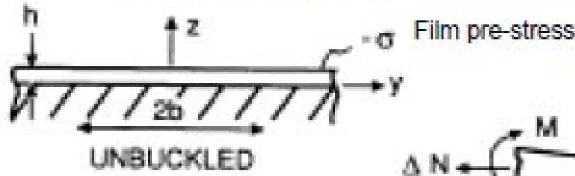
$$\Delta - \Delta_C = \frac{\pi^2}{8}\frac{\delta^2}{a}$$

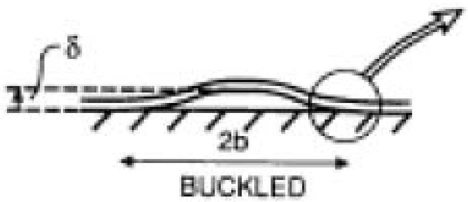
or, $$\frac{\delta}{a} = \frac{2\sqrt{2}}{\pi}\sqrt{\frac{\Delta - \Delta_C}{a}}$$

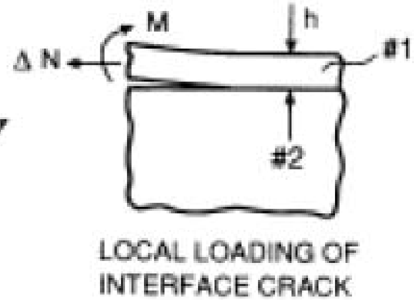


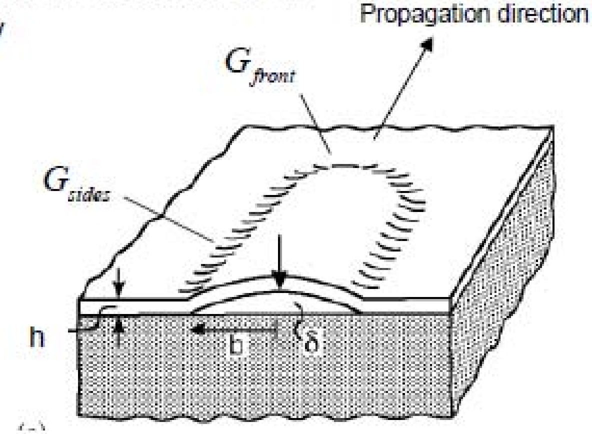
Abbreviated Analysis of the Straight-Sided Buckle Delamination

A 1D analysis based on vonKarman plate theory









Buckle deflection:

$$w(y)=\frac{1}{2}\delta\left(1+\cos(\pi y/b)\right)$$

Average stress in buckled film:

$$\sigma_C=\frac{\pi^2}{12}\bar{E}_1\left(\frac{h}{b}\right)^2$$

In-plane compatibility condition

$$\frac{1}{\bar{E}_1}(\sigma-\sigma_C)=\frac{1}{2}\int_{-b}^{b}w'^2dy=\frac{\pi^2}{8b}\delta^2$$

Buckle amplitude:

$$\frac{\delta}{h}=\sqrt{\frac{4}{3}\left(\frac{\sigma}{\sigma_C}-1\right)}$$

At edge of buckle:

$$\Delta N=(\sigma-\sigma_C)h,\;\; M=\frac{\pi^2\delta}{2b^2}$$

Energy release rate and mode mix along sides from basic solution:

$$G_{sides}=\frac{h}{\bar{E}_1}(\sigma-\sigma_C)(\sigma+3\sigma_C) \qquad \tan\psi=\frac{4+\sqrt{3}(\delta/h)\tan\omega}{-4\tan\omega+\sqrt{3}(\delta/h)}$$

Energy-release rate can also be obtained from direct energy change calculation

Mode mix depends on the amplitude of The buckle

Energy release rate along propagating front

$$G_{front}=\frac{1}{2b}\int_{-b}^{b}G_{sides}dy=\frac{h}{\bar{E}_1}(\sigma-\sigma_C)^2$$

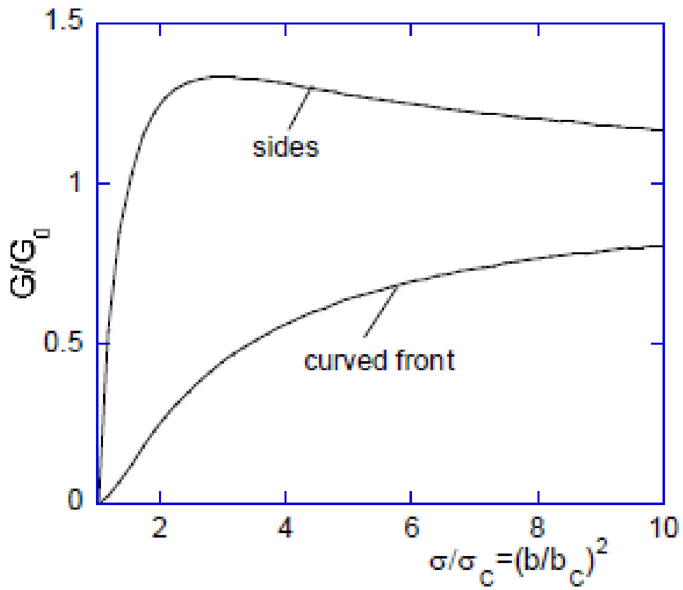
Plots are given on next overhead

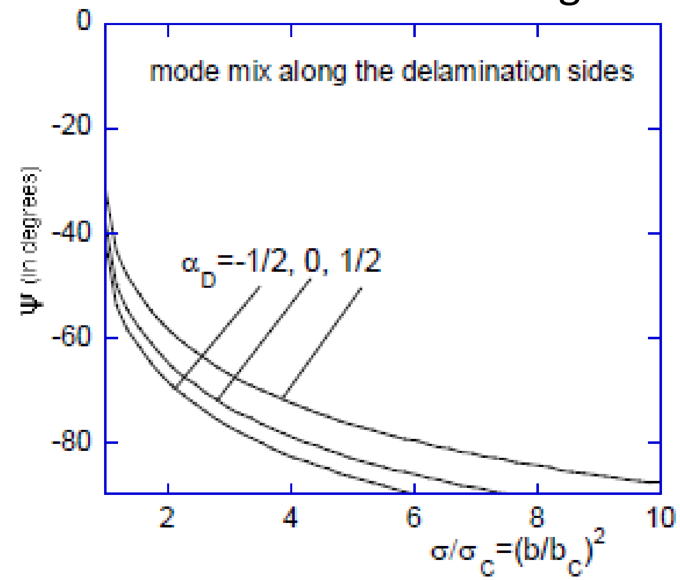
Energy release rate and mode mix on sides of Straight-sided buckle delamination

$$\sigma_C = \frac{\pi^2}{12}\bar{E}_1\left(\frac{h}{b}\right)^2$$ Stress at onset of buckling

$$\frac{b_C}{h} = \sqrt{\frac{\pi^2}{12}\frac{\bar{E}_1}{\sigma}}$$ Half-width at onset of buckling

$$G_0 = \frac{1}{2}\frac{\sigma^2 h}{\bar{E}_1}$$ Energy/area available for release in planes strain





Half-width of straight-sided delamination

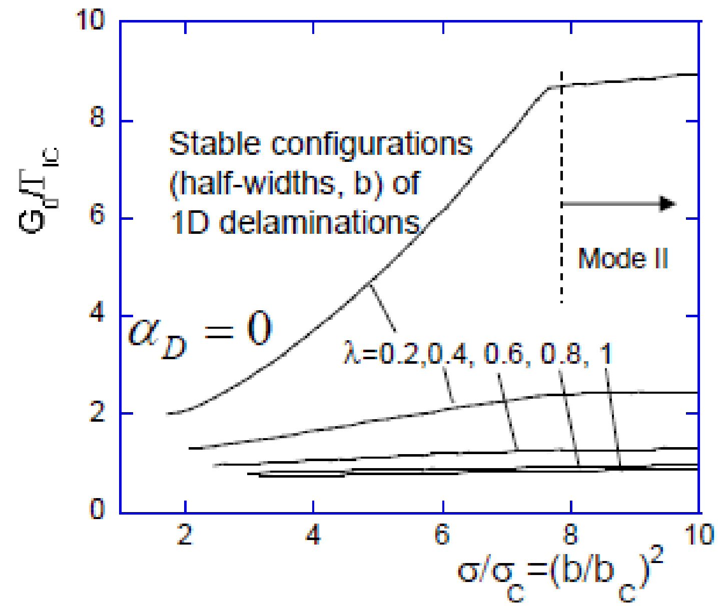
Impose: $G = \Gamma_{IC} f(\psi), \quad f(\psi) = 1 + \tan^2((1-\lambda)\psi)$

See earlier slide for interface toughness function

$$\Rightarrow \frac{G_0}{\Gamma_{IC}} = \frac{f(\psi)}{\left(1-\frac{\sigma_C}{\sigma}\right)\left(1+3\frac{\sigma_C}{\sigma}\right)}$$

Stability of crack front requires: $\frac{d}{db}\left(\frac{G}{f(\psi)}\right) < 0.$

i.e. if tip "accidentally" advances, it is no longer critical.



Caution! This plot is difficult to interpret because each axis depends on σ

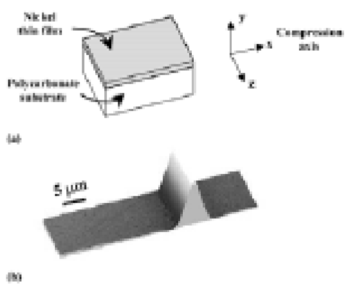
Metal or Ceramic Films on Compliant Substrates (Polymer or Elastomer)

Cotterell & Chen, 2000; Yu & Hutch, 2002; Parry, et al.,2005

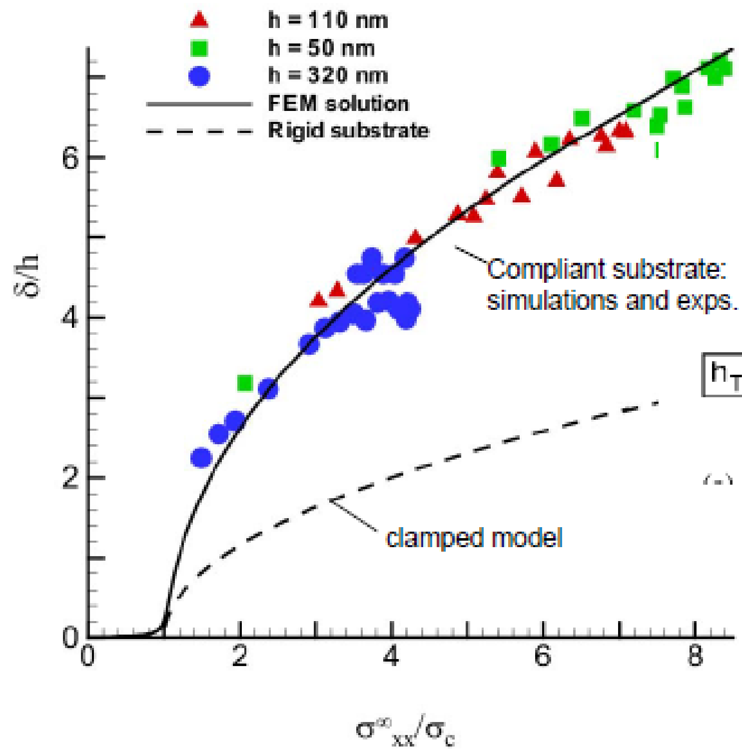
Analytical Fact: Edges of buckle delamination is effectively clamped if substrate modulus is larger than 1/3 of film modulus (i.e. clamped plate model is valid)

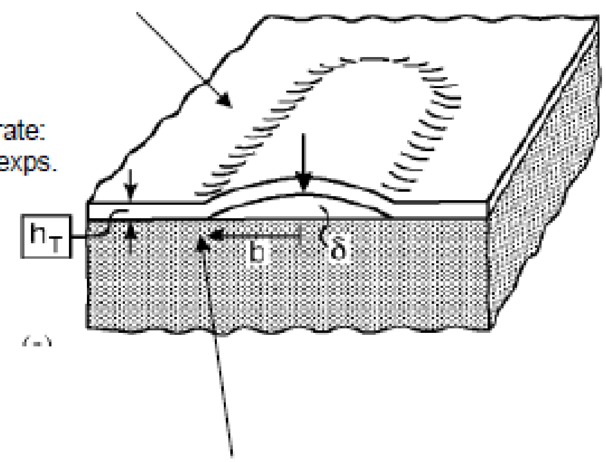
Highly compliant substrate has **three effects:**

1) Stabilizes straight-sided buckle delamination and tends to eliminate telephone cord morphology.
2) Significant film rotation occurs at edges of delamination and larger buckling deflections.
3) Relaxation of stress along bonded edges of delamination (shear lag effect) amplifies energy released.



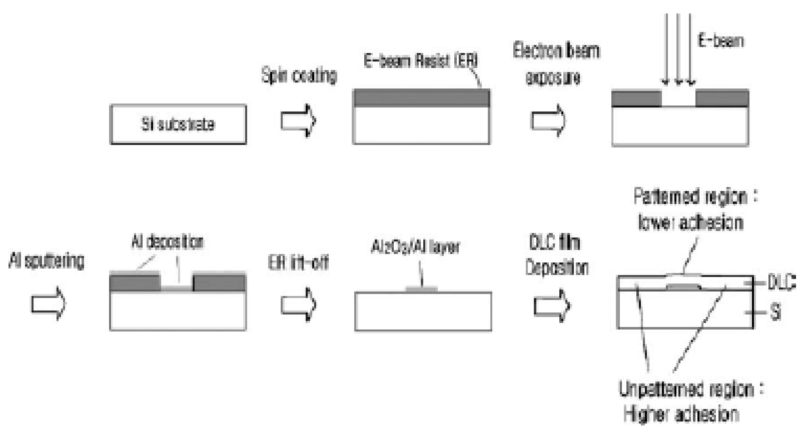
Ni films on polycarbonate substrates (Parry, et al.)

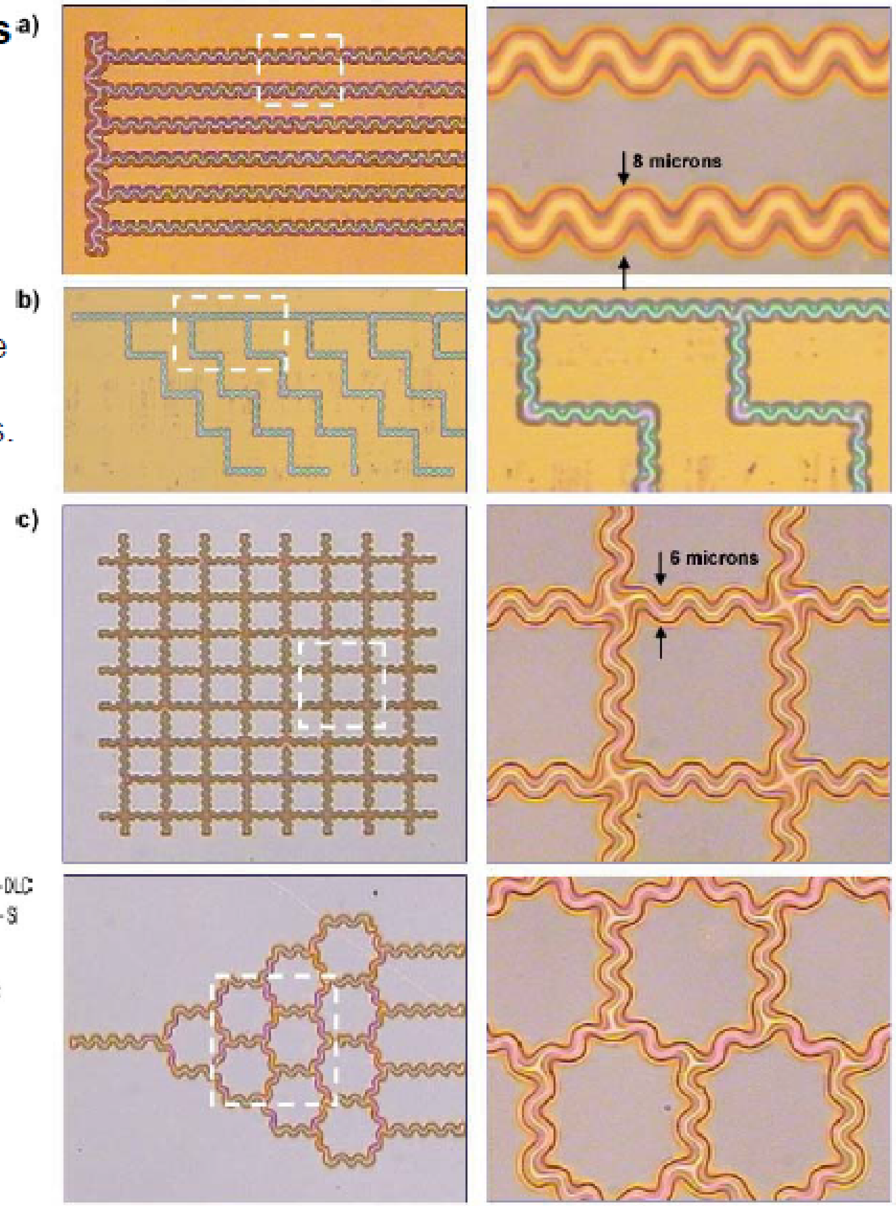




Harnessing Buckle Delaminations for the Good of Mankind! (2004-3)

Substrate pre-patterned with low adhesion channels or pathways. DLC coatings are then deposited onto the substrate.
Once initiated, buckle delaminations propagate down the low adhesion pathways creating Intricate networks of open micro/nano-channels.

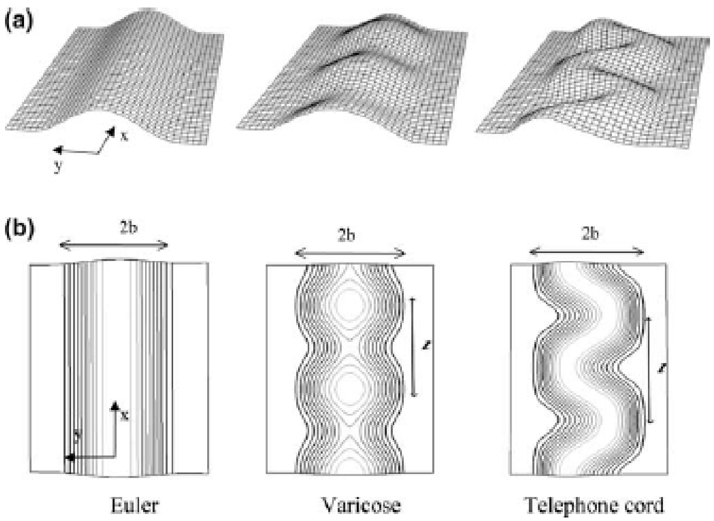


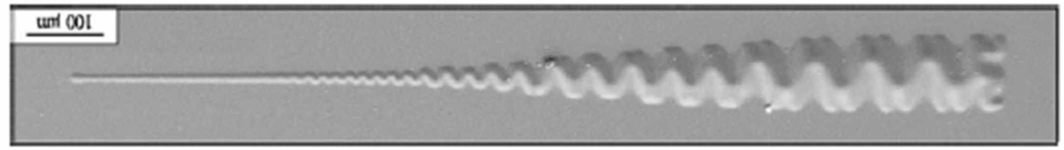


Moon, Lee, Oh & Hutch, 2004

Energy Released as a Function of Morphology (2004-3)

Three morphologies: B. Audoly (1999)





DLC on silicon—tapered low adhesion interface: propagates from right to left

Film under equi-biaxial stress

Energy/area: $$U_0 = \frac{\sigma^2 h}{E(1-\nu)}$$

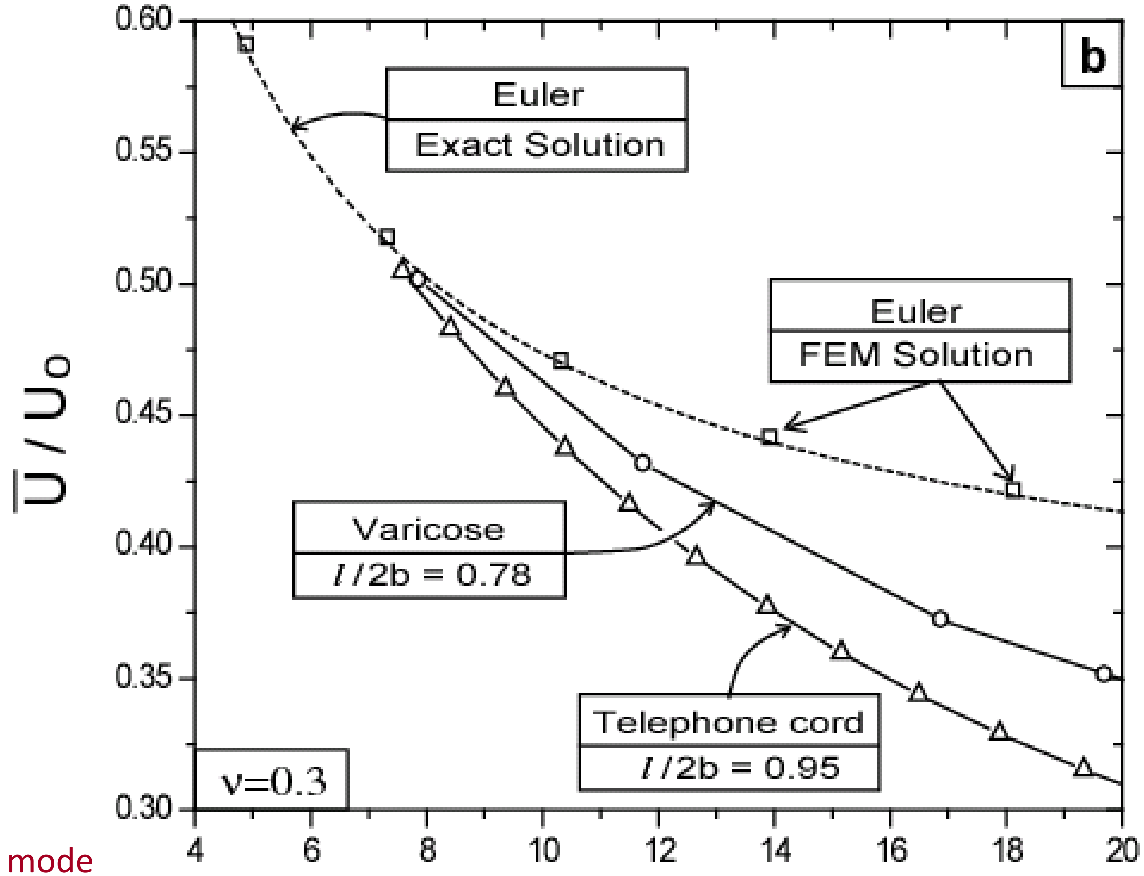
Energy/area in buckled film averaged over one full wavelength: $\bar{U}$

For $\sigma/\sigma_C < 6$:

Euler (straight-sides) mode is only possible mode

For $\sigma/\sigma_C > 7.5$:

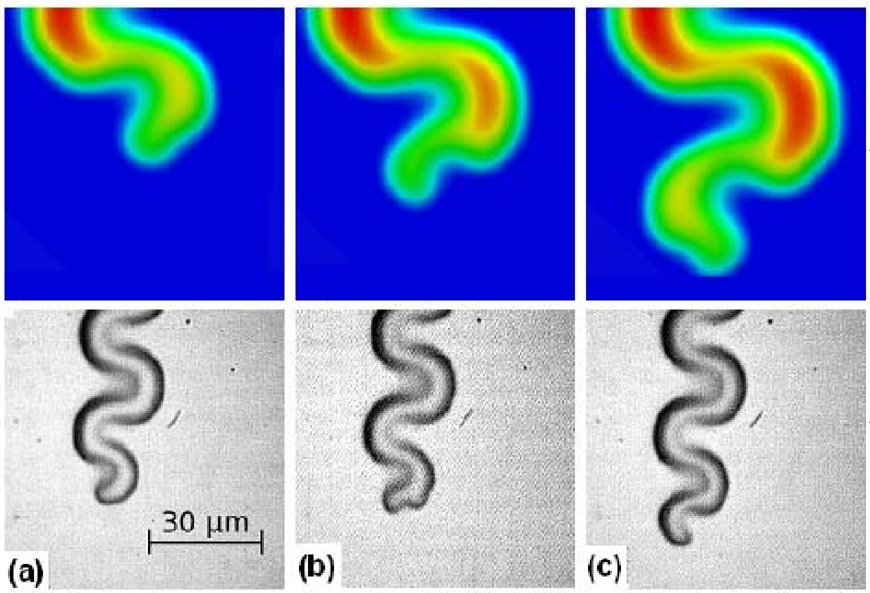
Telephone cord morphology has lowest energy and releases the most energy/area.



$$\sigma/\sigma_C = (b/b_C)^2$$

How does adhesion induce the formation of telephone cord buckles?

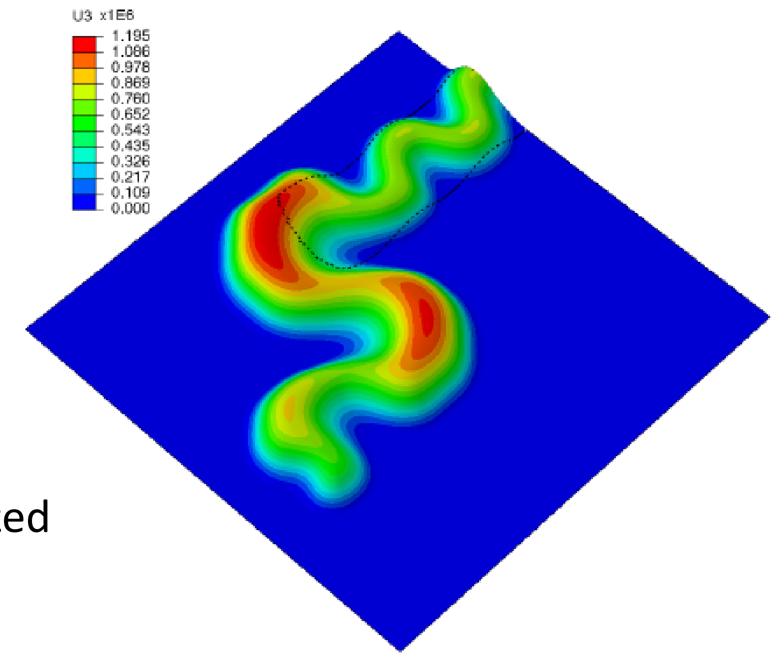
Jean-Yvon Faou, Guillaume Parry, Sergey Grachev, and Etienne Barthel (*EPL-2012)*



simulation

experimental

Equi-biaxial compression in the film



These numerical simulations account for the mixed mode dependence of the interface toughness—this is essential. If the toughness did not increase with increasing mode 2, the blisters would not be stabilized and the entire film would delaminate.

The following slides are selected from a talk in honor of Tony Evans in 2011

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

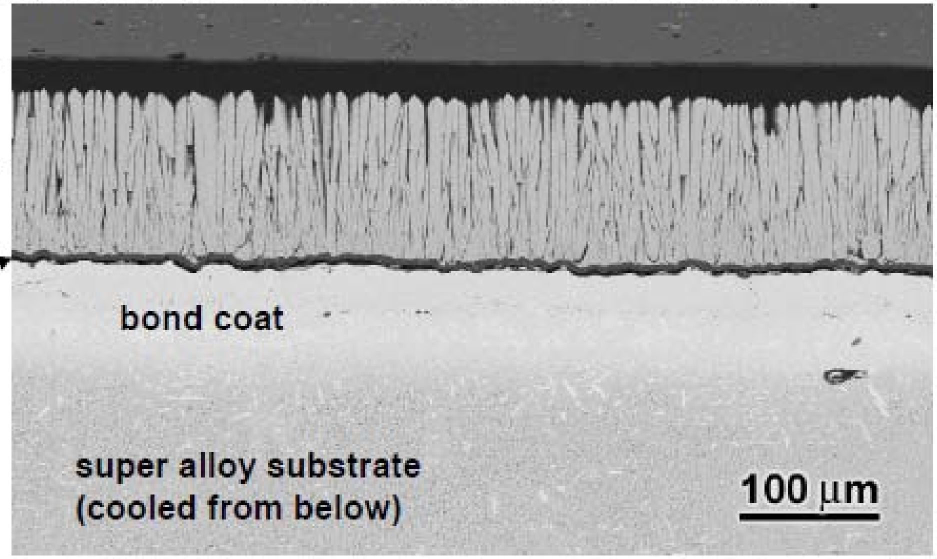
MODE I DELAMINATIONS WITHIN THERMAL BARRIER COATING

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.

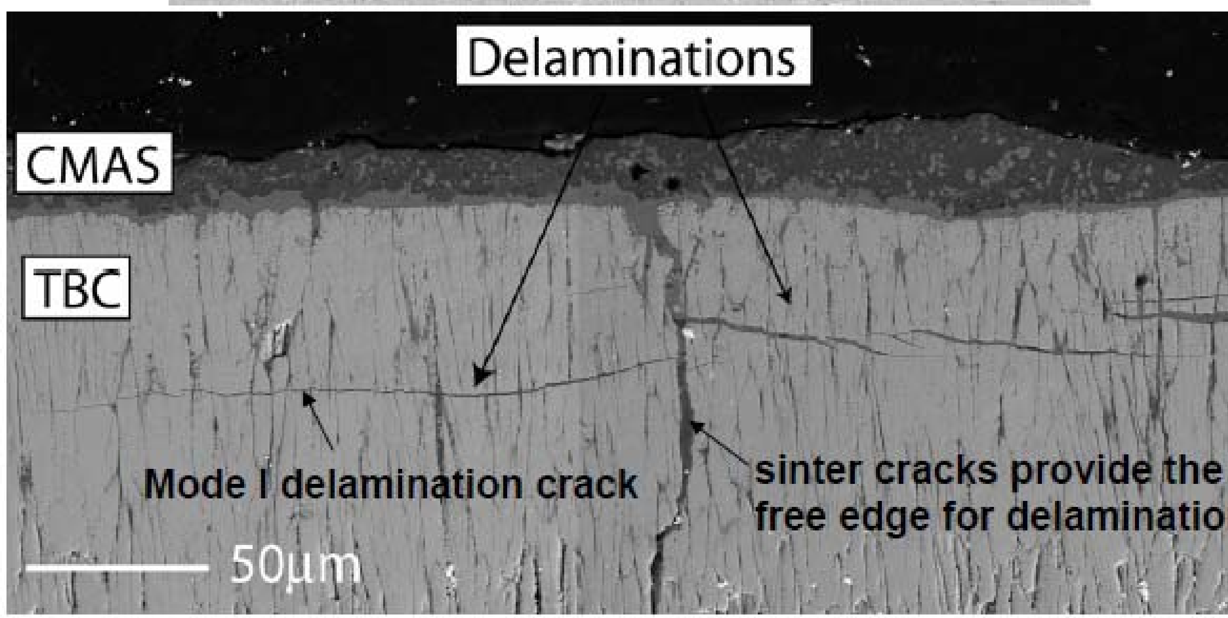


$\sim 1250 C^o$

$\sim 900 C^o$

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

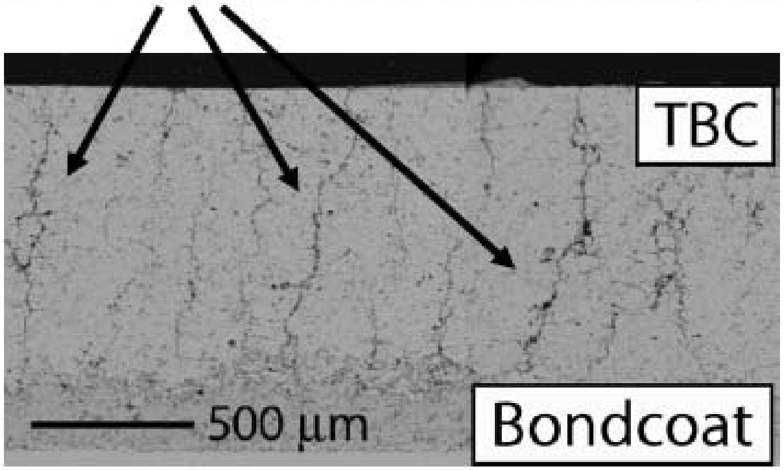
Blade showing spalled TBC

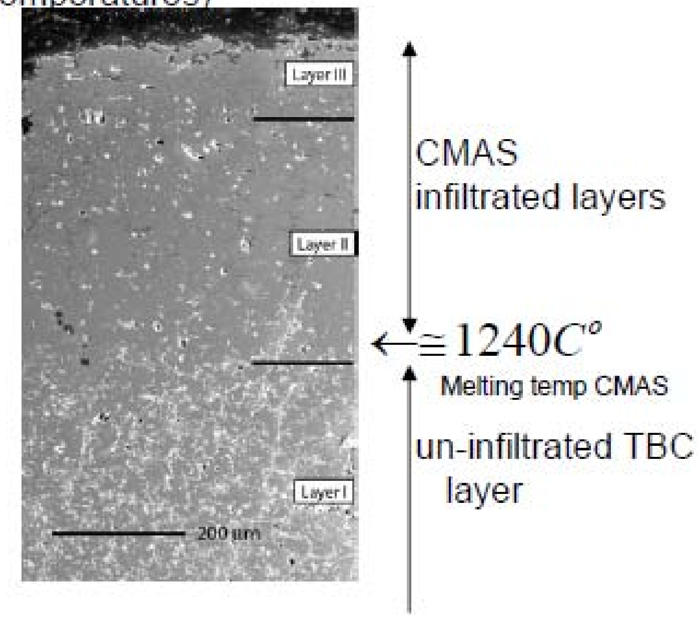


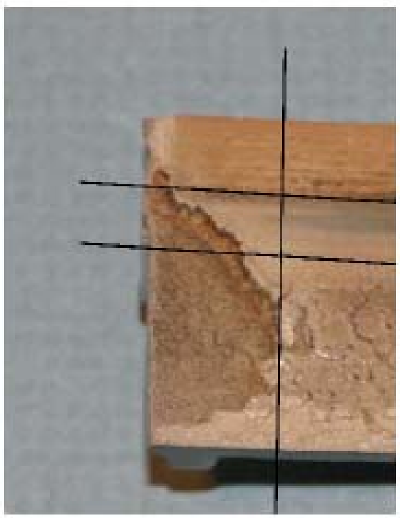
MODE I DELAMINATIONS WITHIN THERMAL BARRIER COATING

Plasma Spray TBC on engine shroud approximately 1mm thick

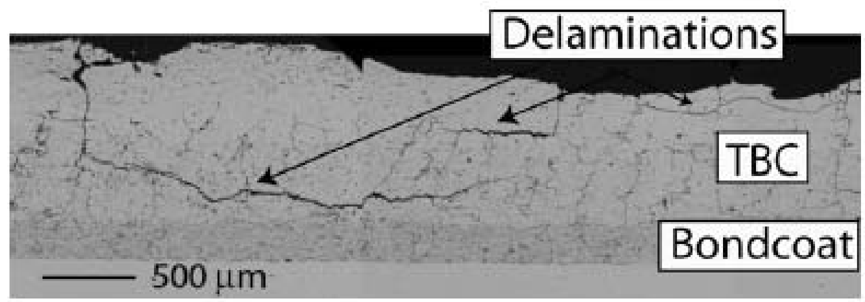
Vertical deposition cracks provide free edges for initiating delaminations
(They are essential for coating/substrate compatibility under cyclic temperatures)







Spalled region under CMAS

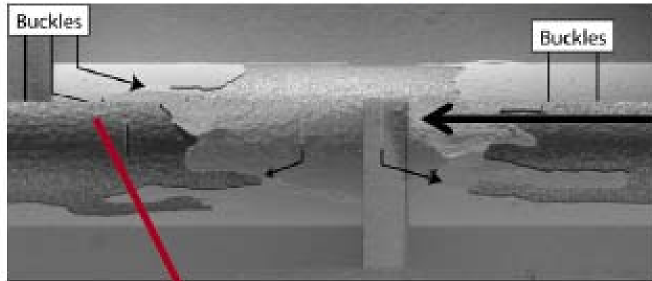


BUCKLE DELAMINATION OF THERMAL BARRIER COATING ON BURNER RIG SPECIMEN

Electron beam deposited TBC

(2006-6)

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

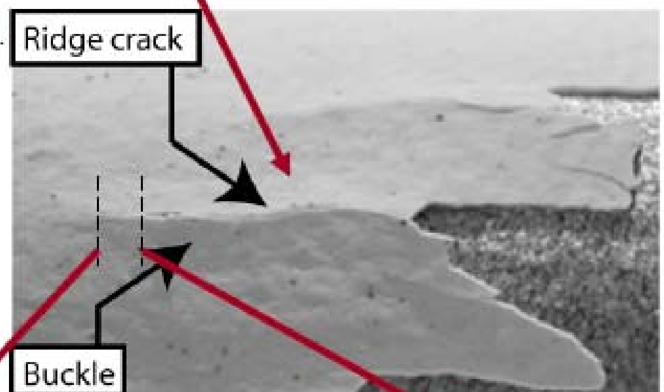


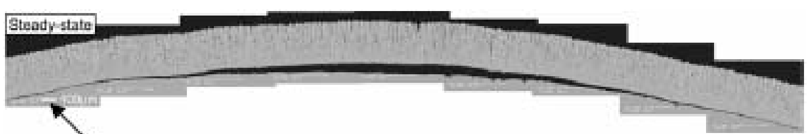
Wedge indentation to Initiate spall

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

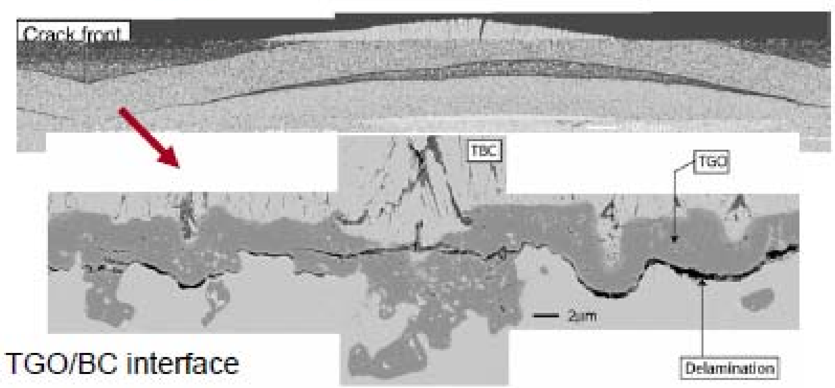
A wedge indentation at room temp. produces wide spread spalling with buckle delaminations.

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

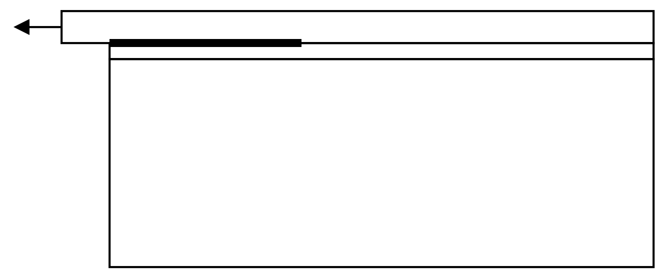
Blade showing spalled TBC

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).

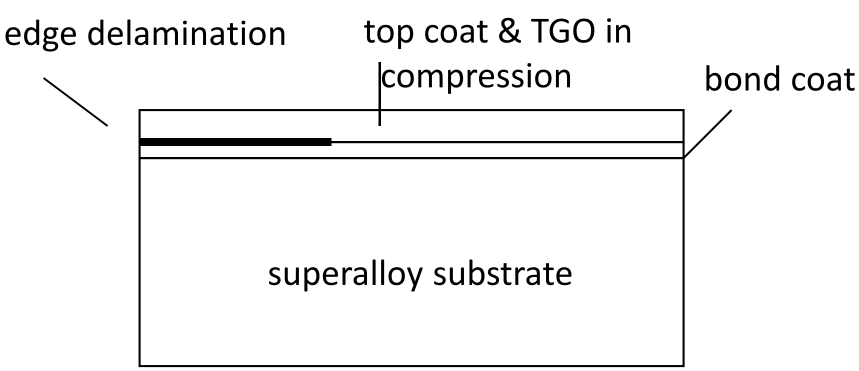
Mode II edge delaminations are the most likely culprit in controlling TBC lifetime.

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

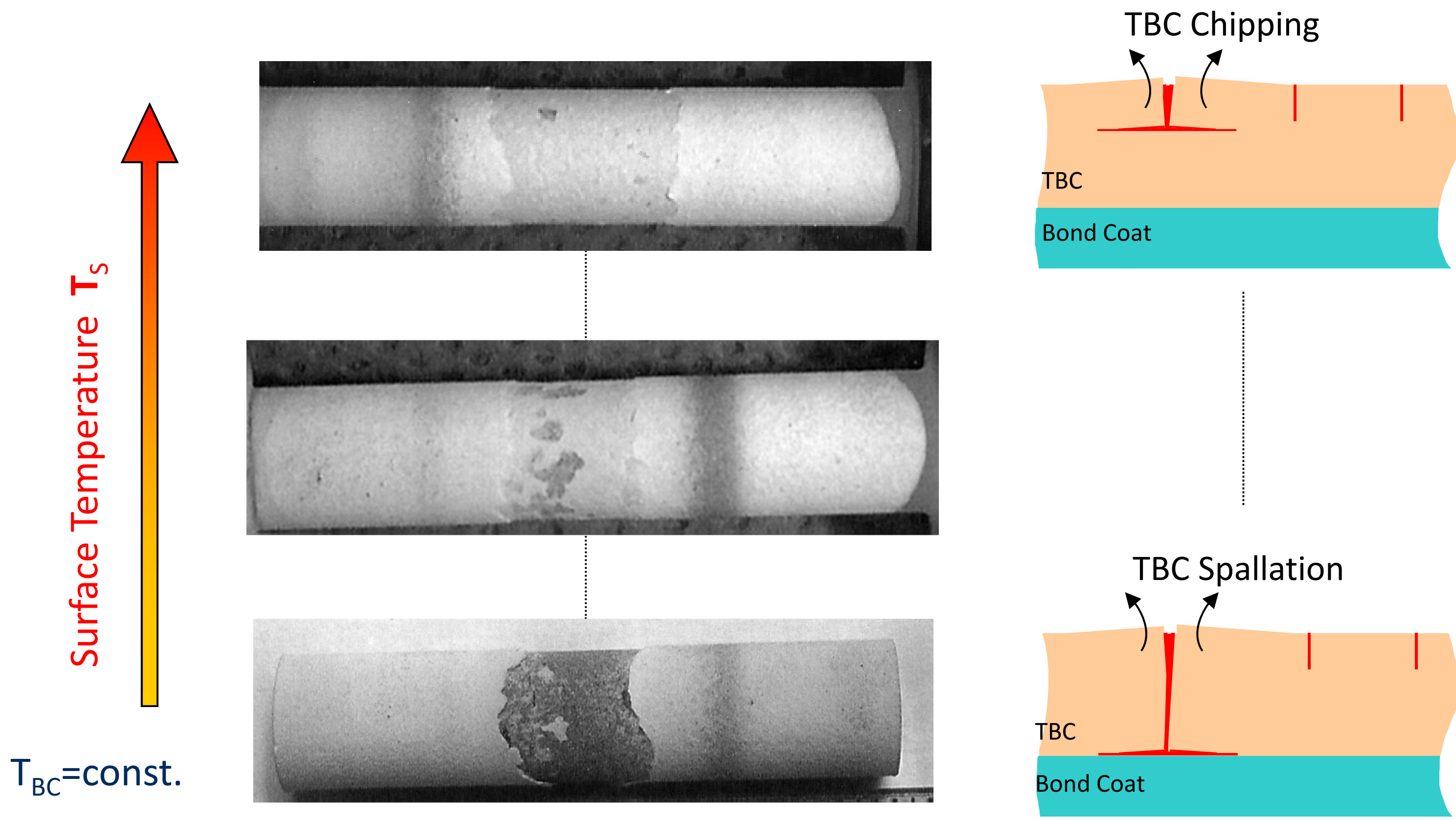


Mode II toughness data is the most relevant.
What tests can we use?

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

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

Life-Prediction Methodology for TBCs and other coatings

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

A. Experimentally measure mode II toughness,

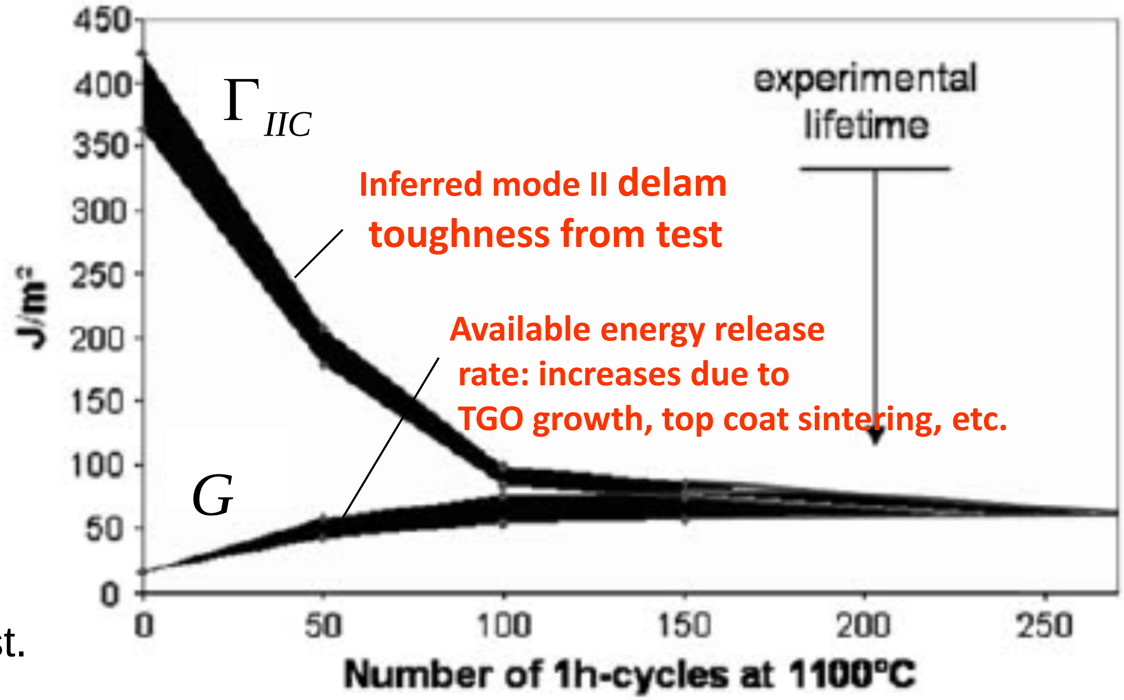
$$\Gamma_{IIC},$$

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

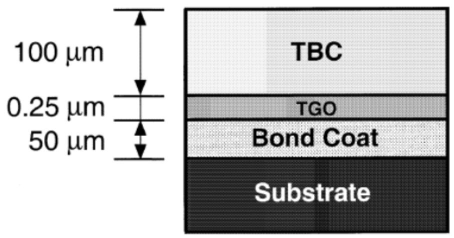
$$G \rightarrow \Gamma_{IIC}$$ (or equivalent for other mode mixes)

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

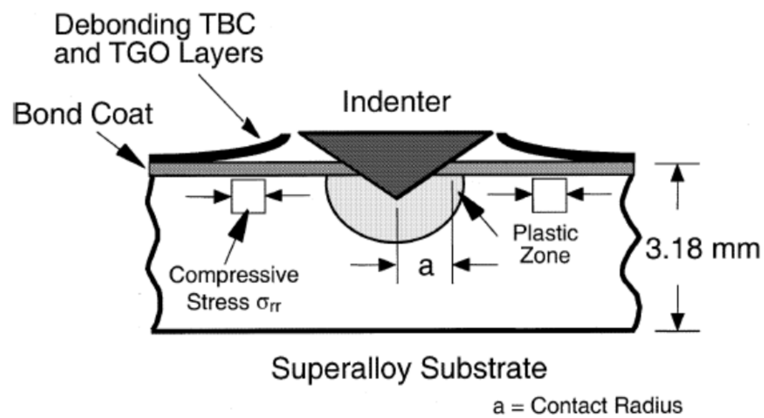
--Thermal stresses in top coat and TGO (**only** if the failure interface lies below the TGO)
-- Mechanical loads on substrate (e.g. bending)
-- Sintering and/or CMAS infiltration of top coat (increases top coat modulus)
-- Thermal (and stress) gradients, both through thickness and in-plane

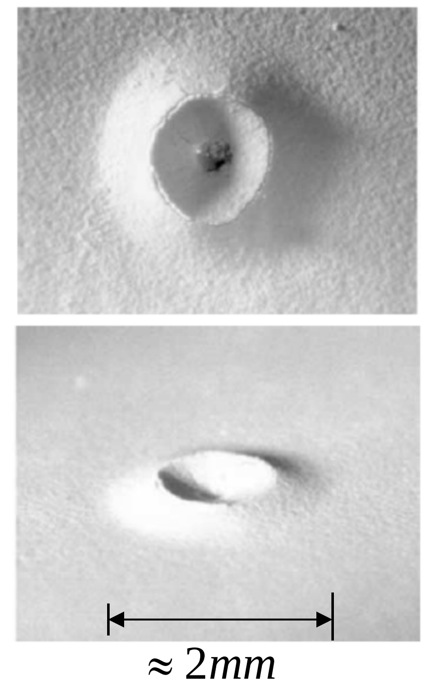
Measuring TBC Interface Toughness by Indentation-induced Delamination

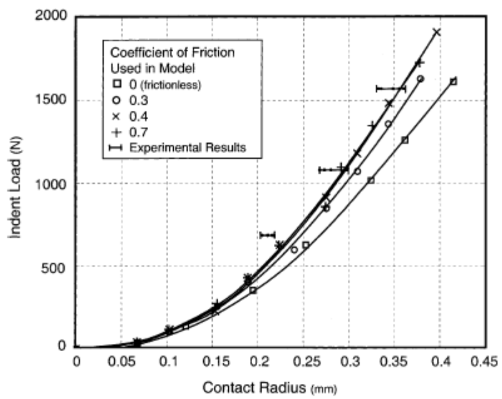
– A. Vasinonta & J.L. Beuth

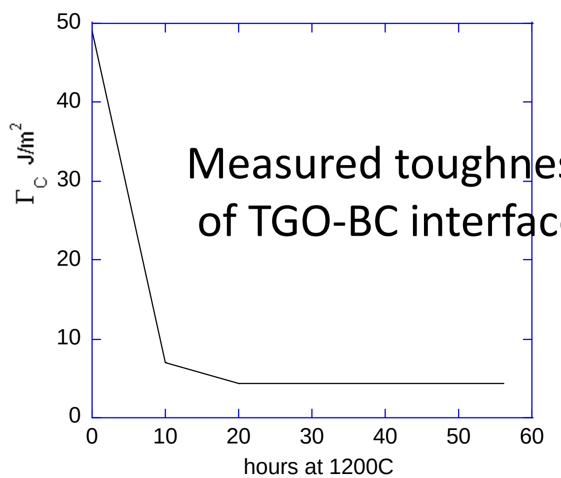


EBPVD Top Coat, Pt Aluminide Bond Coat









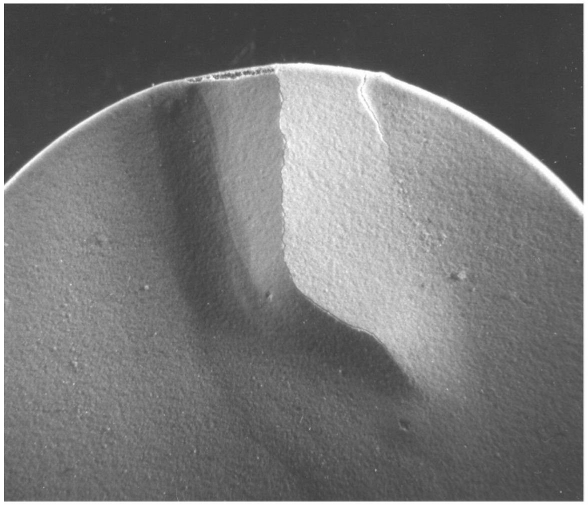
Measured toughness of TGO-BC interface

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.

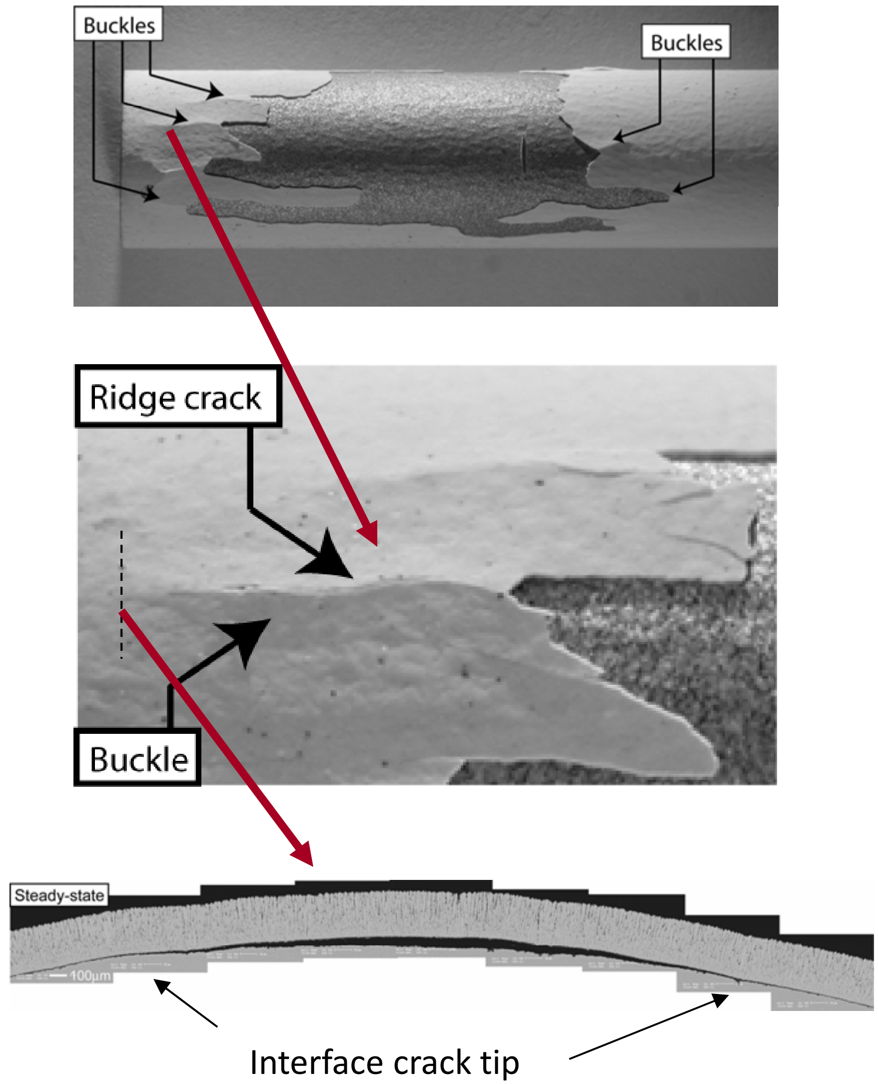
Interface toughness (TGO-Bond coat interface) after burner rig exposure and inferred from extent of the buckle delamination.:

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

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

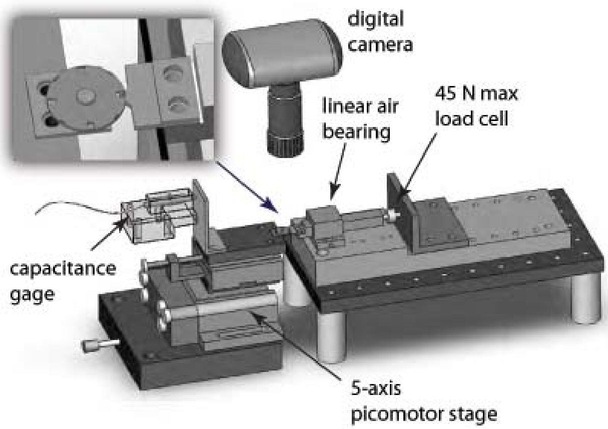
BUCKLE DELAMINATION OF THERMAL BARRIER COATING ON BURNER RIG SPECIMEN

Delamination precipitated by a wedge indentation



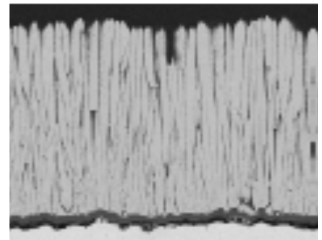
Insitu measurement of modulus of TBC and fracture toughness of interface

K. Hemker & colleagues at JHU



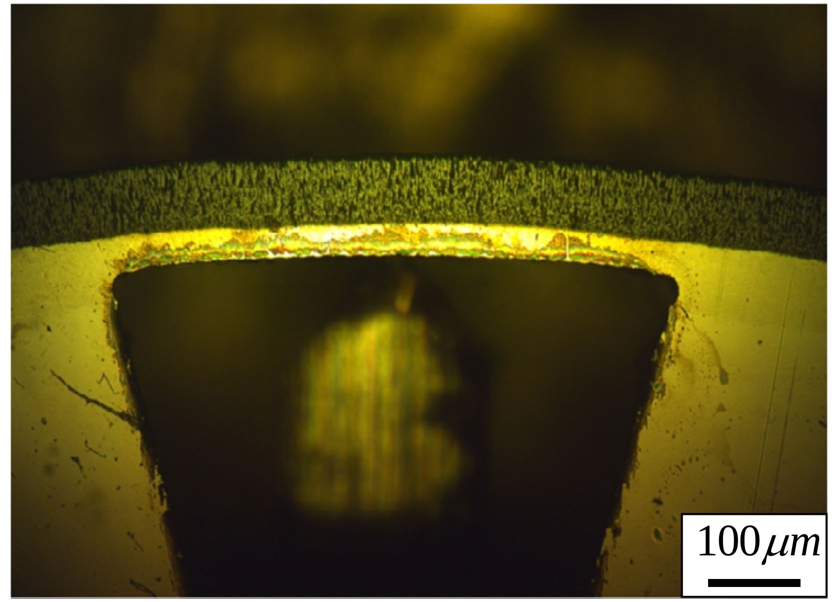
JHU Micro-bend tester

↑ $E_y \approx E_{bulk} = 130GPa$



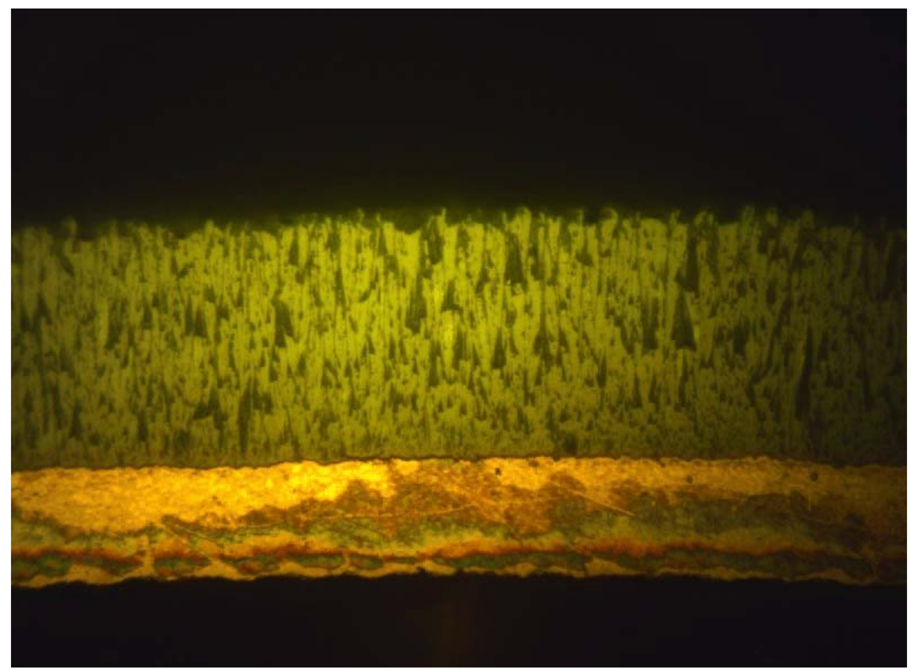
$E_x << E_{bulk}$ →

$E_x \approx 20 - 30GPa$

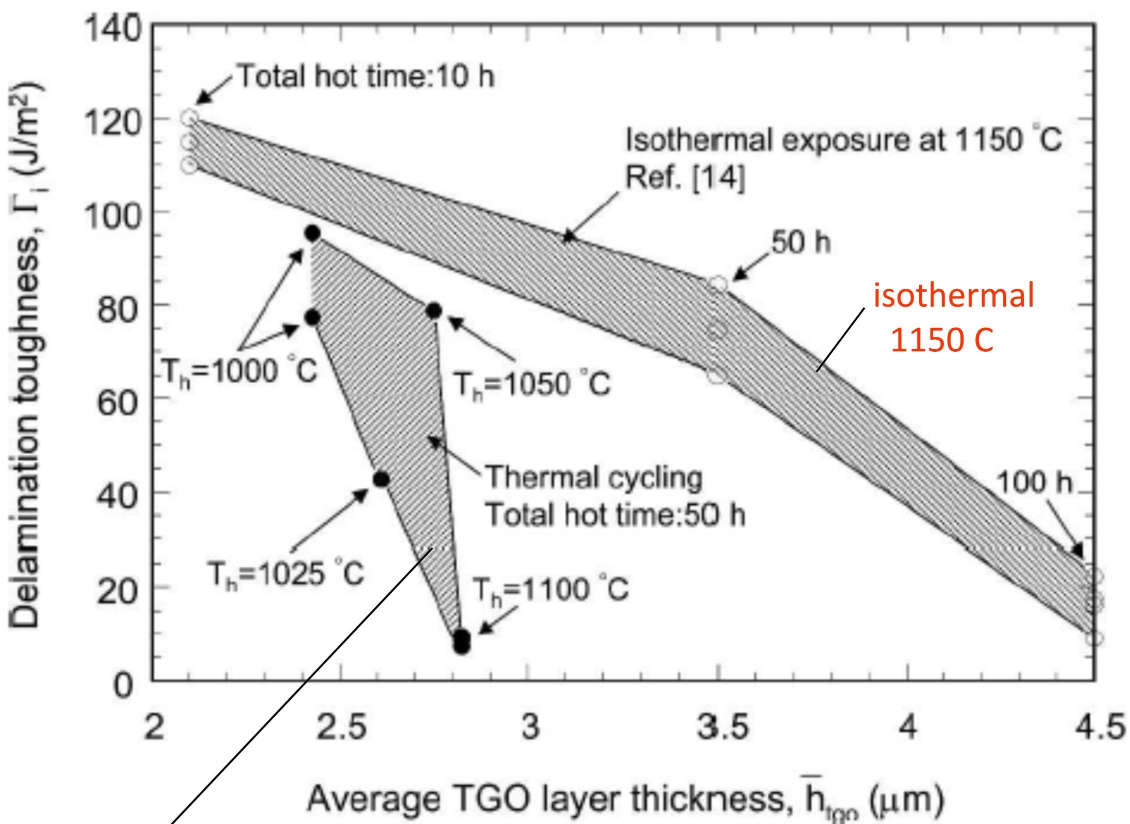


Advantages and disadvantages of test

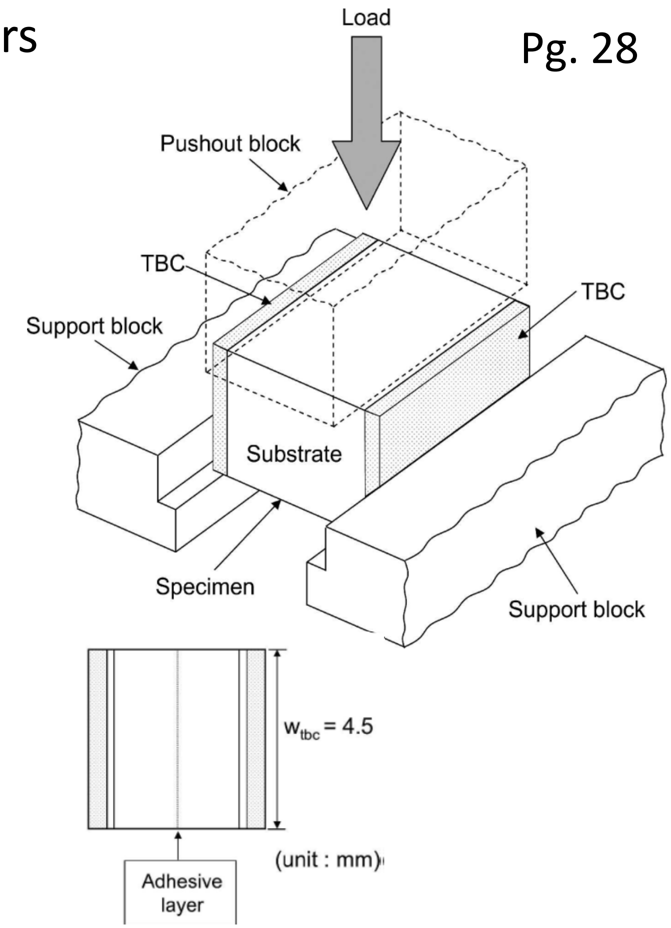
- difficult to carry out--a high end test!
- also provides top coat modulus information
- requires detailed FEM analysis
- mixed mode loading
- residual stress must be taken into account and play a significant role



The Barb Test: Kagawa and co-workers



50 thermal cycles 1hr hold.
at various temperatures

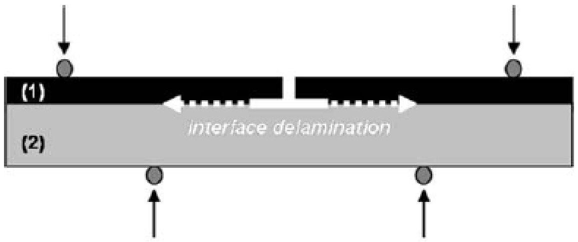


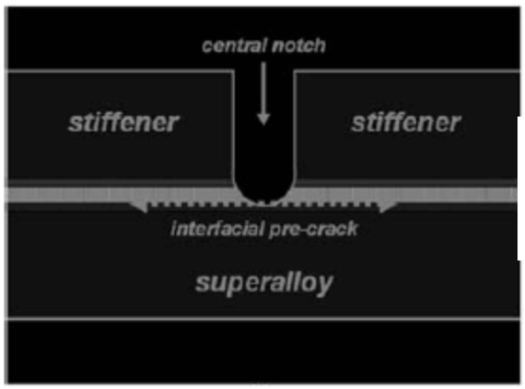
Advantages and disadvantages of test

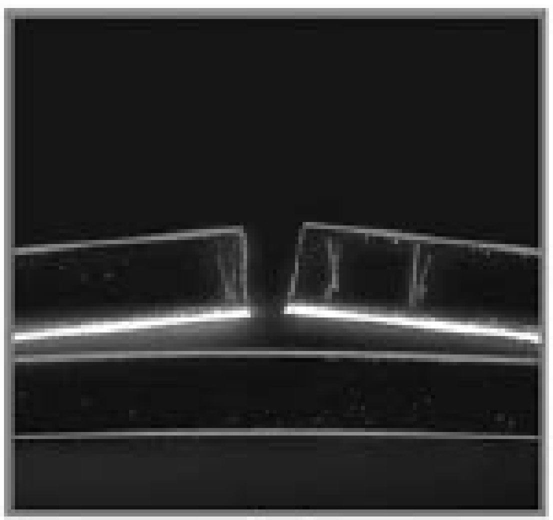
- difficult test--requires great expertise
- stable steady-state delam propagation--mixed mode
- requires detailed FEM analysis
- loads coating in opposite manner as delaminations in service
- residual stress must be taken into account

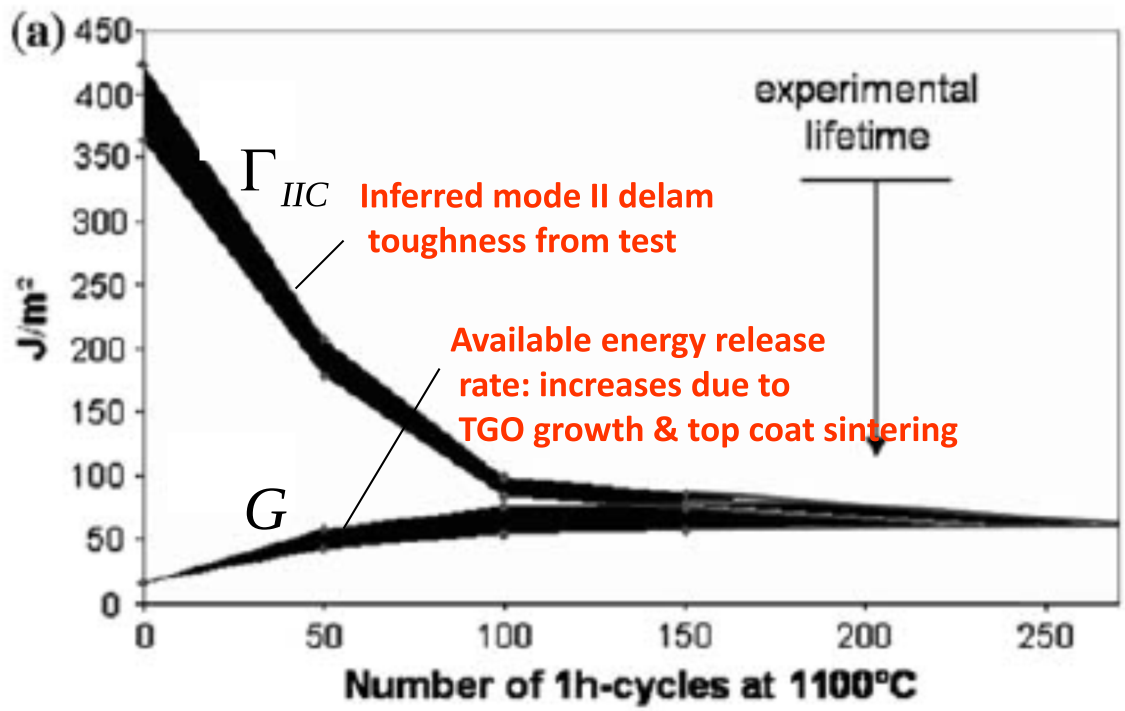
ONERA siffener-enhanced 4-point UCSB bend test

(Thery, Poulain, Dupeux, Braccini, 2009)







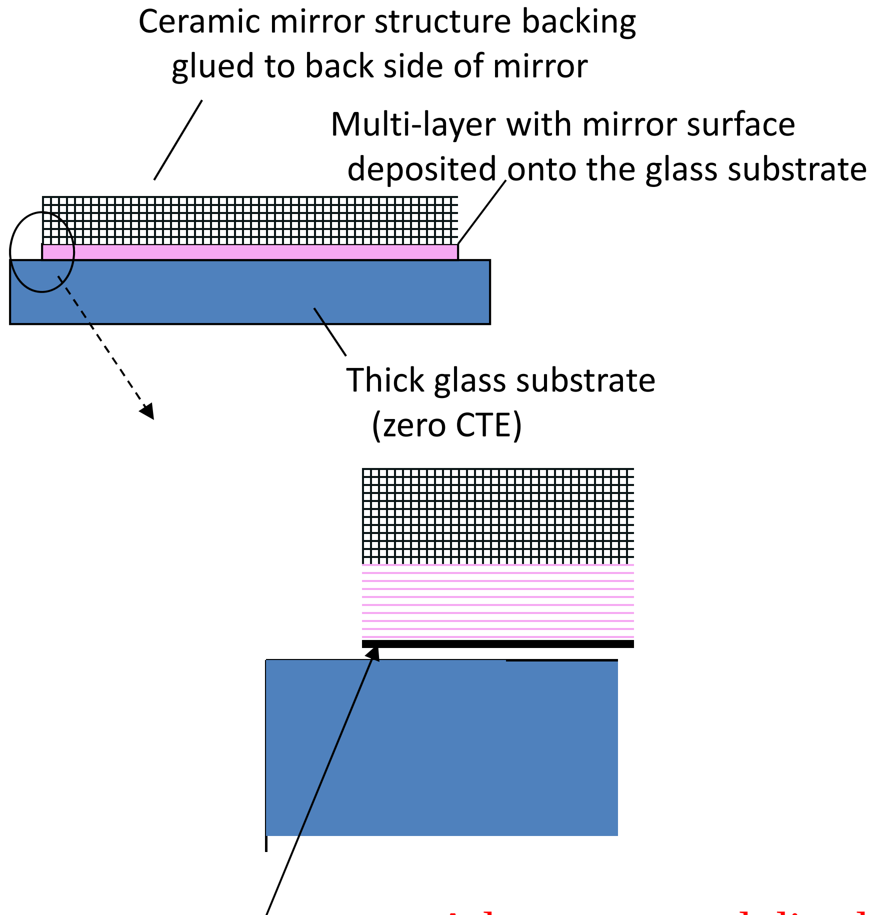


Advantages and disadvantages of test

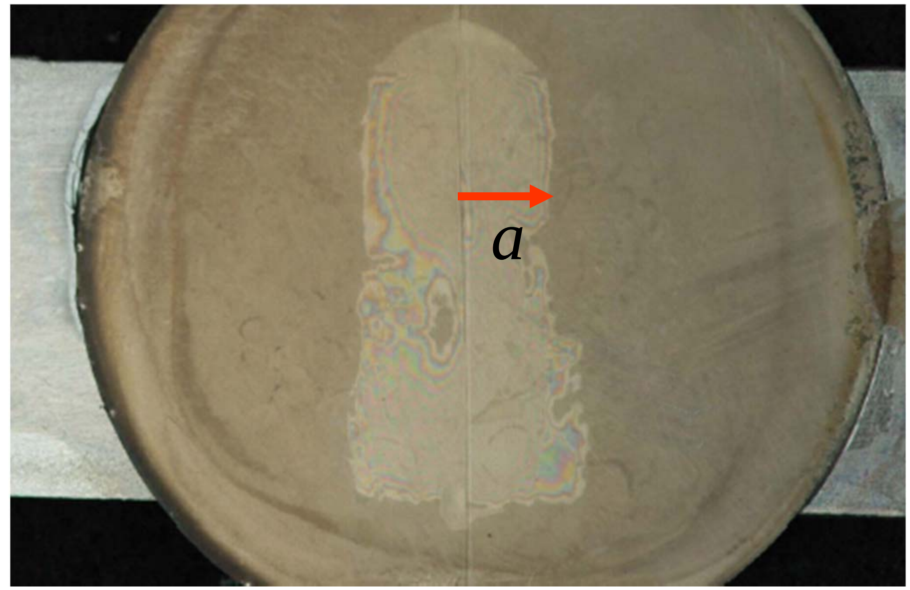
- well established test--variation of UCSB bend test
- stable steady-state delam propagation--mixed mode ($\psi \cong 40^o$)
- requires analysis but straightforward
- loads coating in opposite manner as delaminations in service
- residual stress must be taken into account but little is released if coating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

DIGRESSION: Delamination mechanics applied to manufacture of high fidelity mirrors

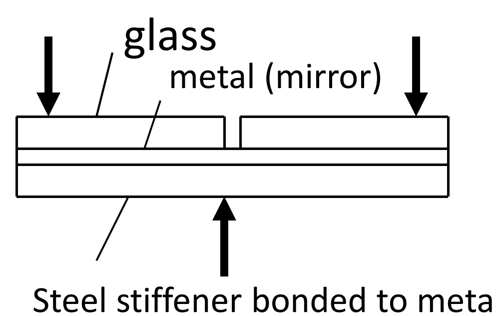
Evans-Phillips 3-point bend test to measure toughness of a glass/metal interface



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



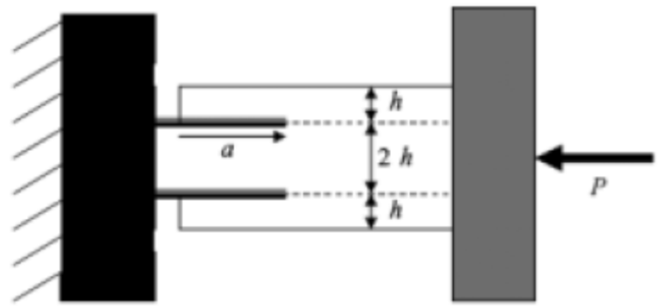
3-point bend test developed to measure interface toughness

Advantages and disadvantages of test

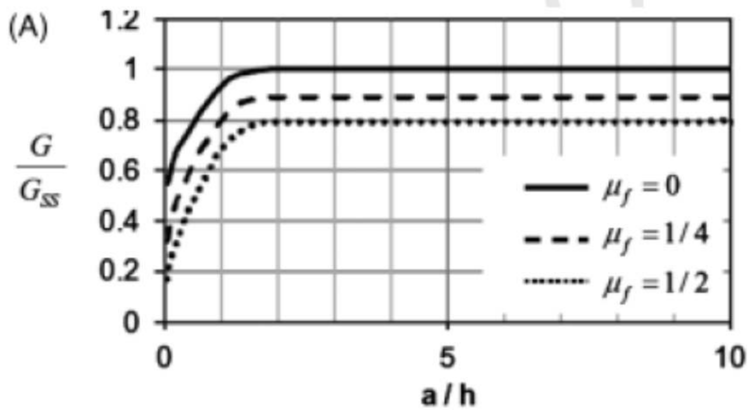
- straightforward test, easily analyzed
- stable mixed mode delam propagation
- test loading closely mimics the application
- Only effective for special interface systems

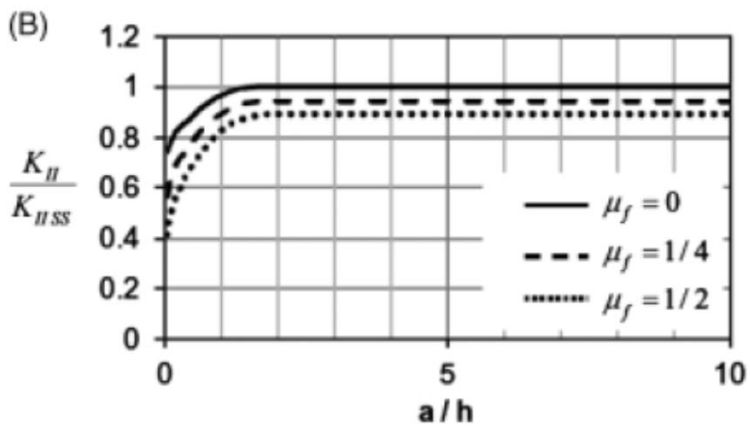
Mode II Shear Test (2011-4)

Closely mimics in-service edge-delamination



compression edge delamination specimen





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

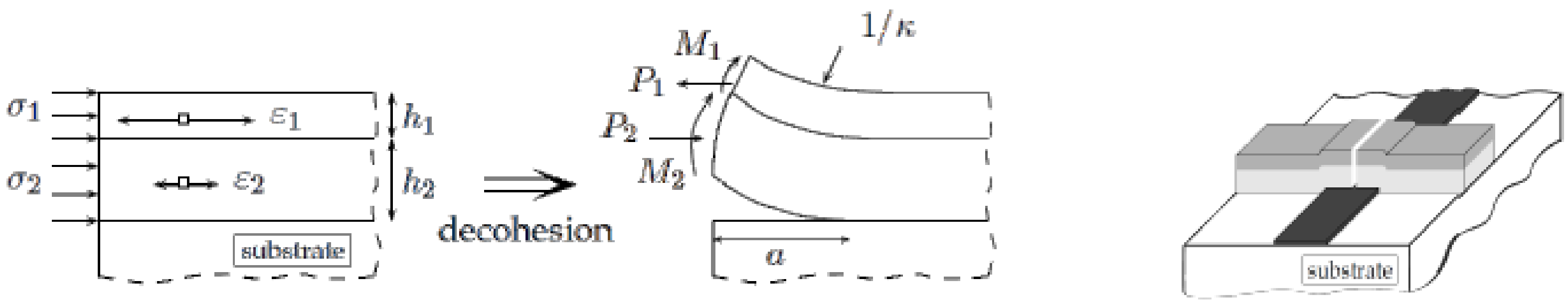
$$G_{SS} = \frac{\sigma^2 h}{\bar{E}}, \;\; \psi = -90^o \;\; (\sigma = -P/4h)$$

A method specific for thin film / coating delamination

Superlayer test

A. Bagchi, G.E. Lucas, Z. Suo, and A.G. Evans, *A new procedure for measuring the decohesion energy for thin ductile films on substrates*, Journal of material research 9 (1994), no. 7, 1734–1741.

Highly stressed *superlayer* deposited on top of the film



No external loading is applied $\mathcal{G} = -\dfrac{\partial W_e}{\partial A} = Z\dfrac{\sigma^2 h}{E}$.

$\Rightarrow$ Variation of W_e

$\Rightarrow$ Variation of A

Life-Prediction Methodology for TBCs and other coatings

A. Experimentally measure mode II toughness,

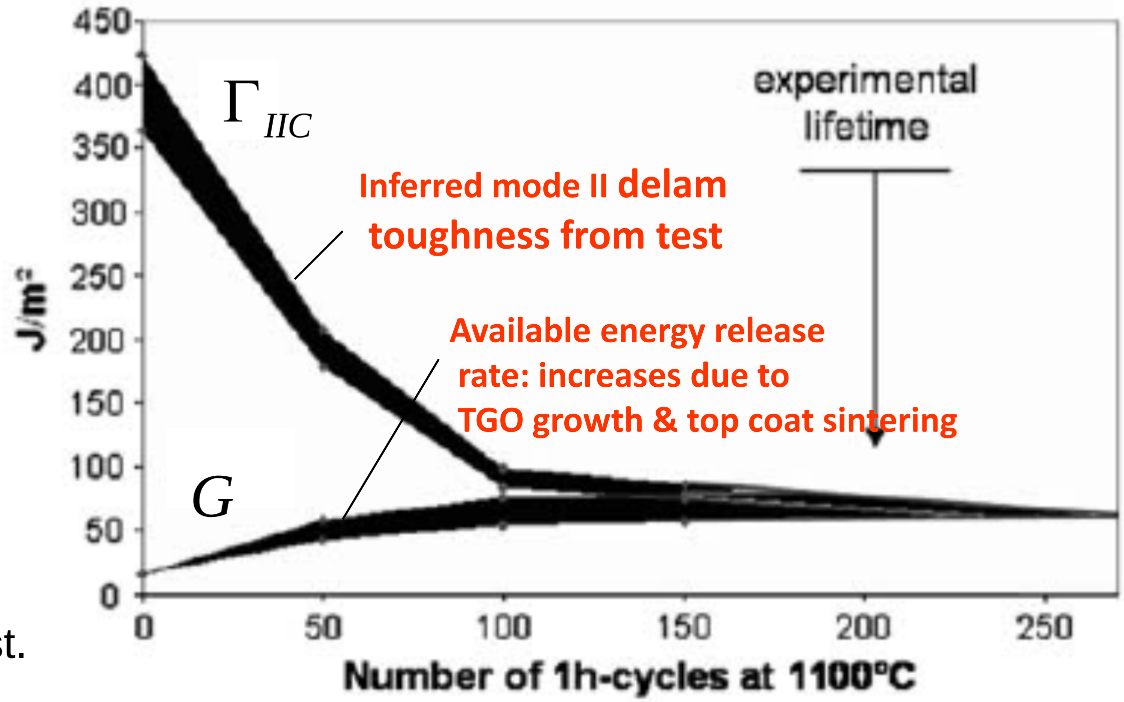
$$\Gamma_{IIC},$$

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
(Thery, Poulain, Dupeux, Braccini, 2009)

C. Lifetime of coating is determined by condition

$$G \rightarrow \Gamma_{IIC}$$

or equivalent for other mode mixes. (Using Γ_{IIC} is always conservative.)

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