Fracture of Brittle Thin Films on Compliant Substrates:

Effect of substrate constraint and loss of the constraint

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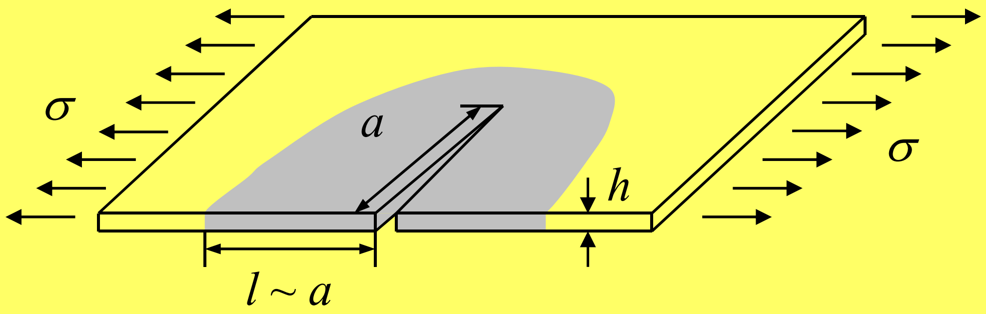
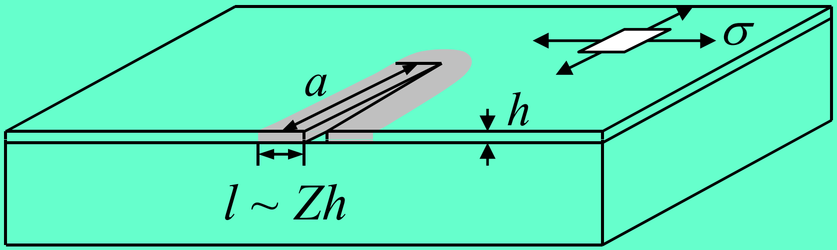
Fracture without and with constraint



Free-standing film

$$G \sim \frac{\sigma^2}{E} a \qquad K \sim \sigma\sqrt{a}$$



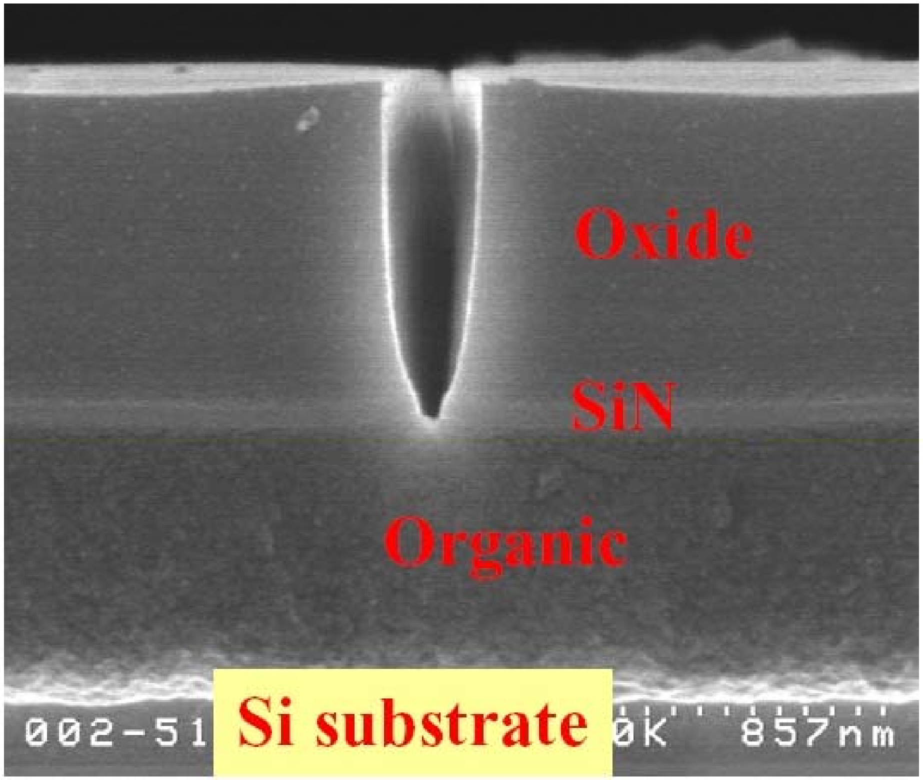
Film on elastic substrate

$$G \sim \frac{\sigma^2}{E} h \qquad K \sim \sigma\sqrt{h}$$

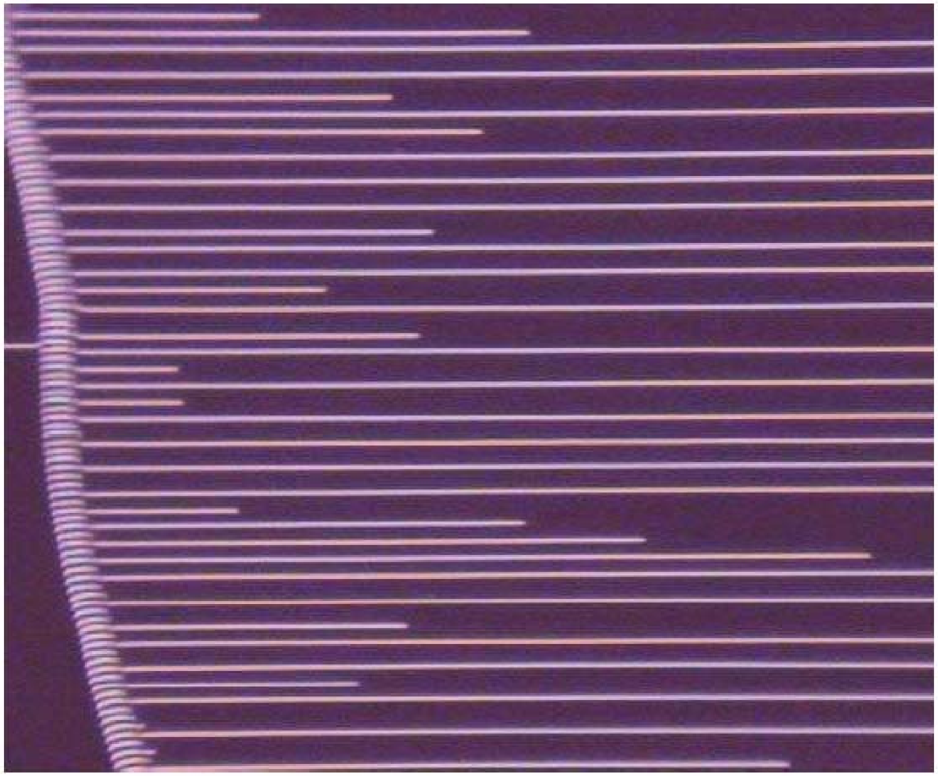
- Without constraint, the energy release rate as the driving force for crack growth scales with the crack length and is unbounded;
- Constrained by an elastic substrate, the energy release rate scales with the film thickness and is bounded for a long crack (steady state).

Channel cracks in thin films

Cross section:



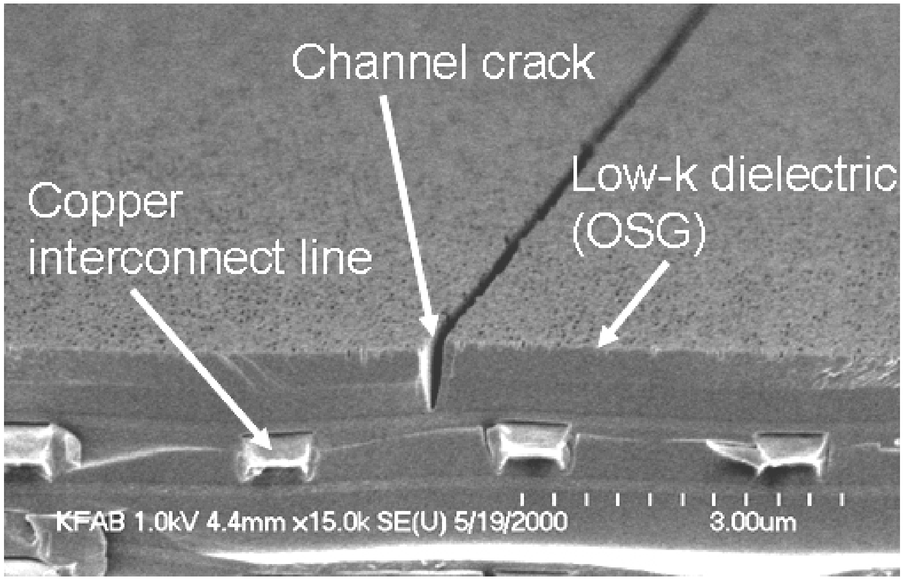
Top view:

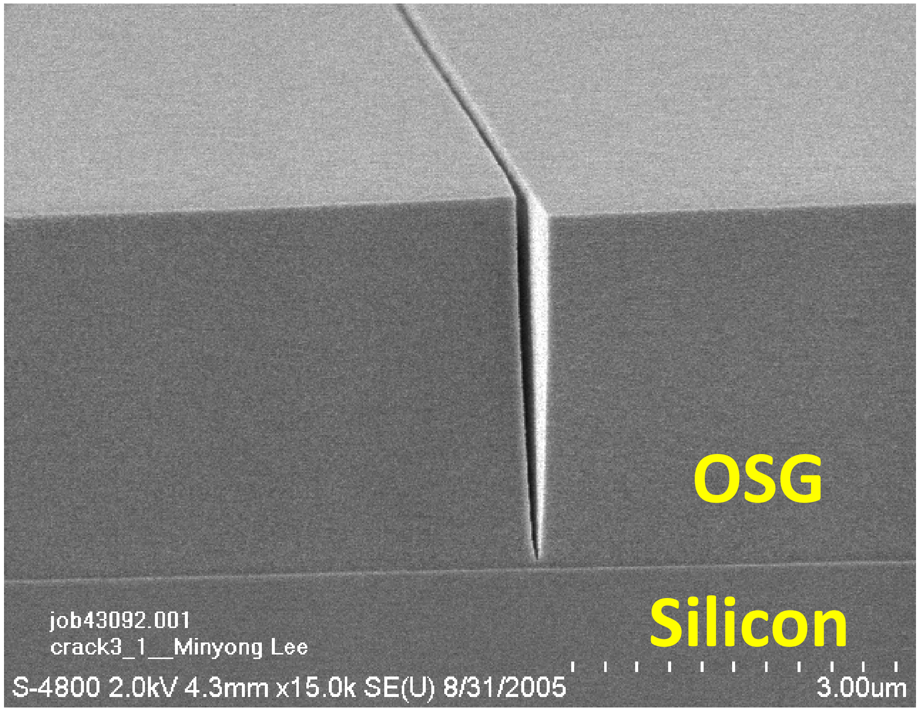


Courtesy of Jun He of Intel Corp.

He et al., *Proc. of the 7th Int. Workshop on Stress-Induced Phenomena in Metallization* (2004), pp. 3-14.

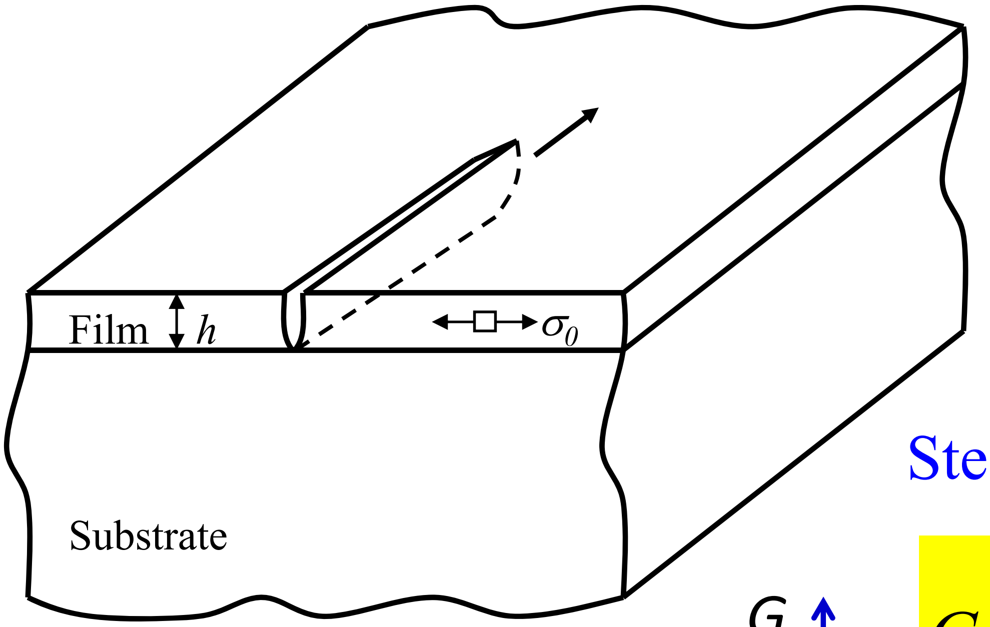
Fracture of low-k dielectrics





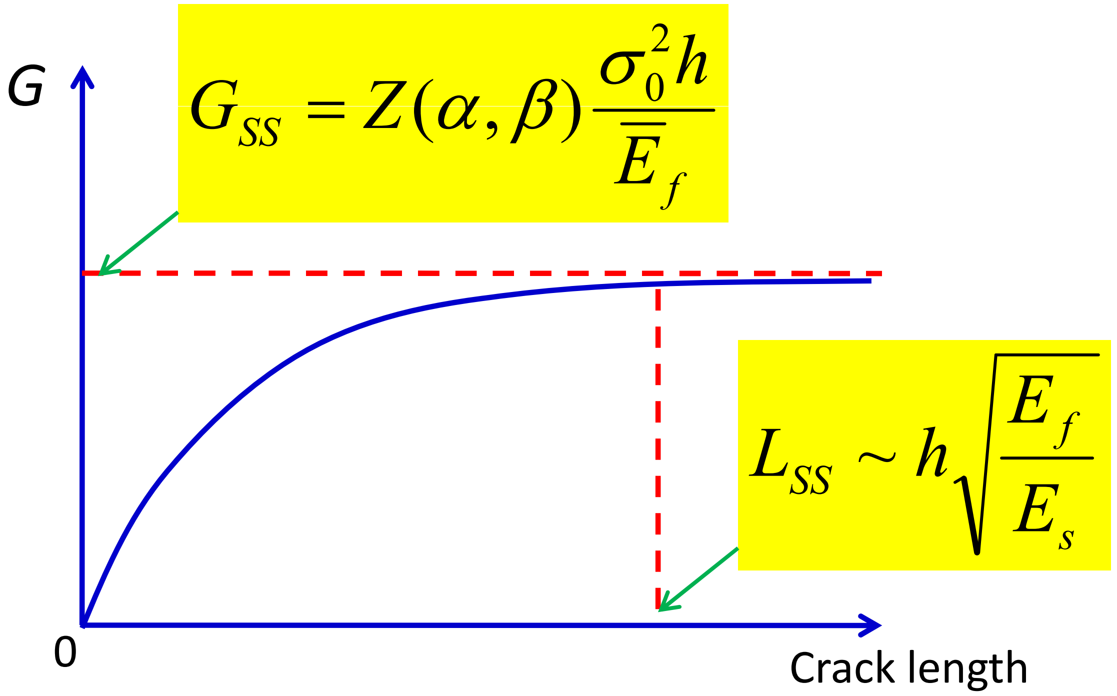
Tsui et al., *J. Mater. Res.* **20** , 2266-2273 (2005).

Mechanics of channel cracking



The crack reaches a **steady state** when the crack length exceeds a few times the film thickness.

Steady-state energy Release Rate:



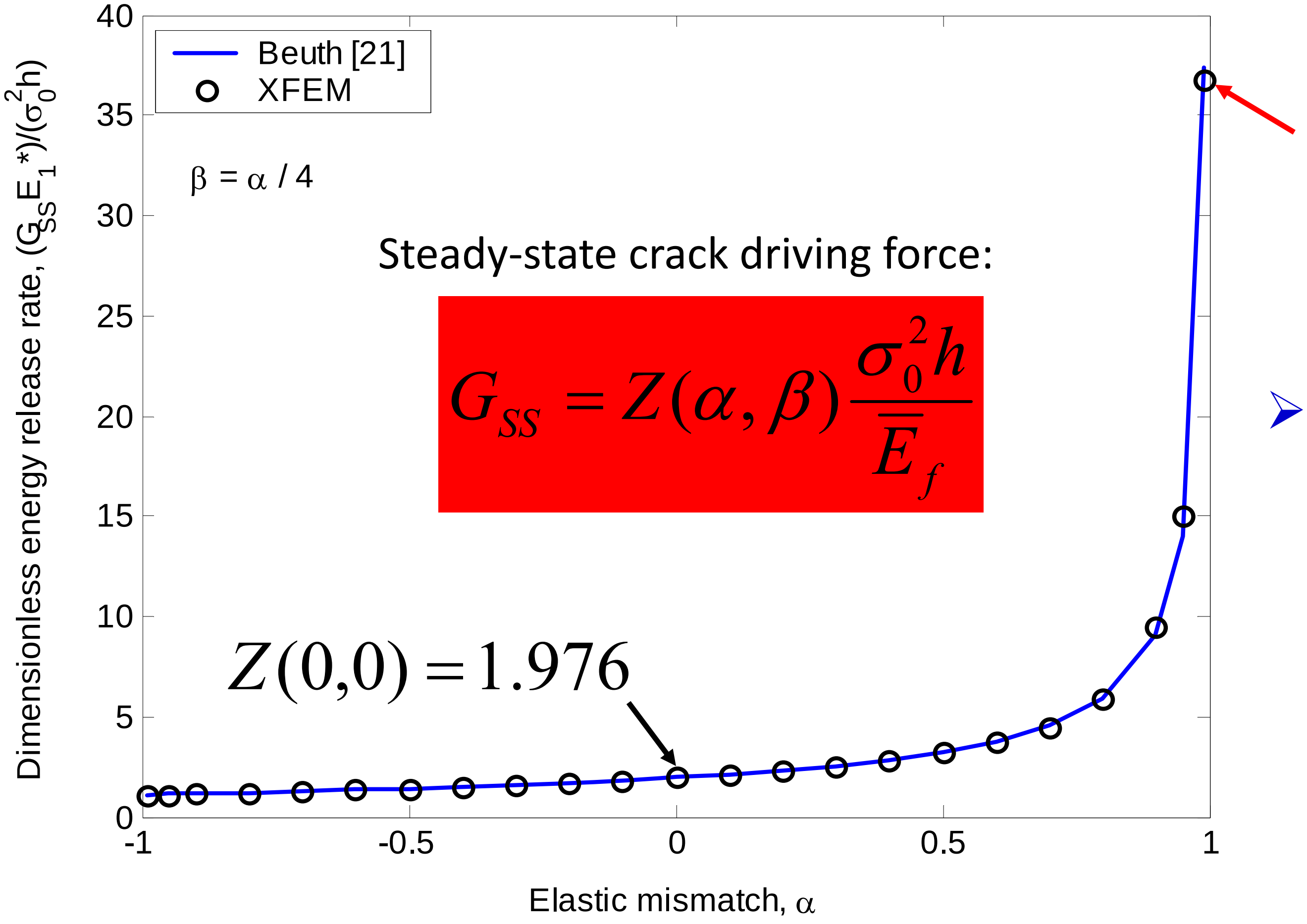
$$G_{SS} = Z(\alpha, \beta)\frac{\sigma_0^2 h}{\bar{E}_f}$$

$$L_{SS} \sim h\sqrt{\frac{\bar{E}_f}{\bar{E}_s}}$$

Hutchinson and Suo, 1992.
Nakamura and Kamath, 1992.
Xia and Hutchinson, 2000.
Ambrico and Begley, 2002.
Liang et al., 2003.

Effect of Elastic Mismatch

Beuth, IJSS 29, 1657-1675 (1992).
Huang et al., Engineering Fracture Mech. 70, 2513-2526 (2003).



Steady-state crack driving force:

$$G_{SS} = Z(\alpha,\beta)\frac{\sigma_0^2 h}{\overline{E}_f}$$

$$Z(0,0) = 1.976$$

Very large crack driving force on compliant substrates!

- The more compliant the substrate, the weaker the constraint effect.

$$\alpha = \frac{\overline{E}_f - \overline{E}_s}{\overline{E}_f + \overline{E}_s} \qquad \beta = \frac{\overline{E}_f(1-\nu_f)(1-2\nu_s) - \overline{E}_s(1-\nu_s)(1-2\nu_f)}{2(1-\nu_f)(1-\nu_s)\left(\overline{E}_f + \overline{E}_s\right)}$$

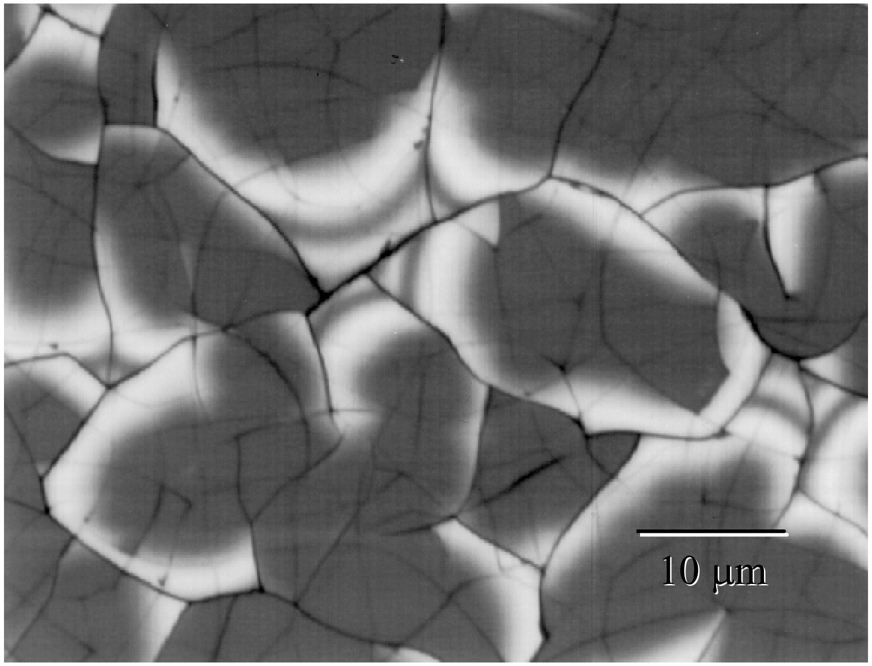
Loss of constraint on film cracking

- On *elastic* substrates:
  - Interfacial delamination
  - Substrate cracking

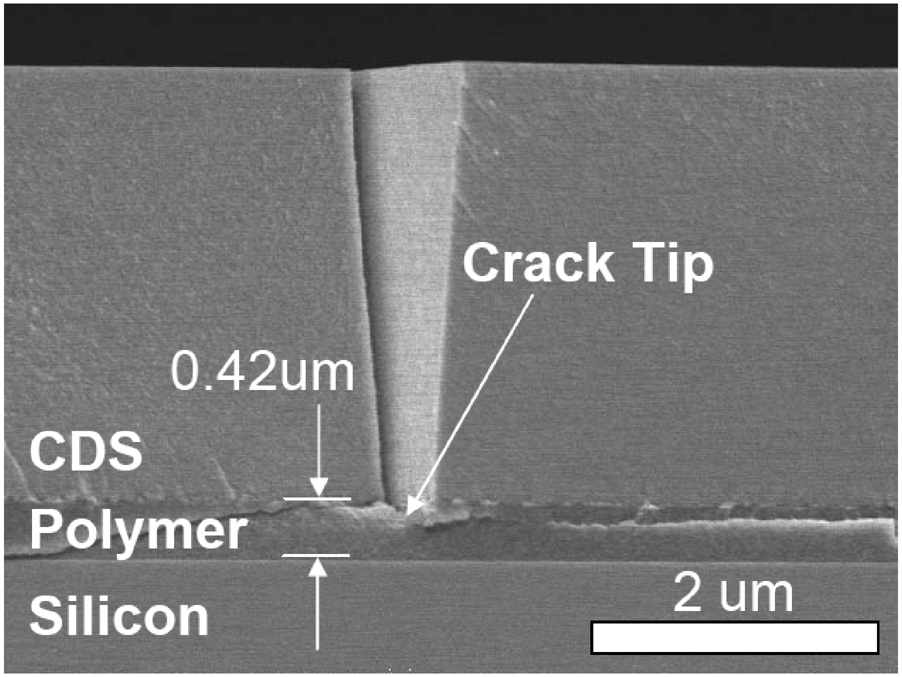
- On *viscoelastic* substrates:
  - Substrate creep

- On *elastoplastic* substrates:
  - Substrate plasticity
  - Substrate ratcheting under cyclic temperatures

Film cracking with delamination



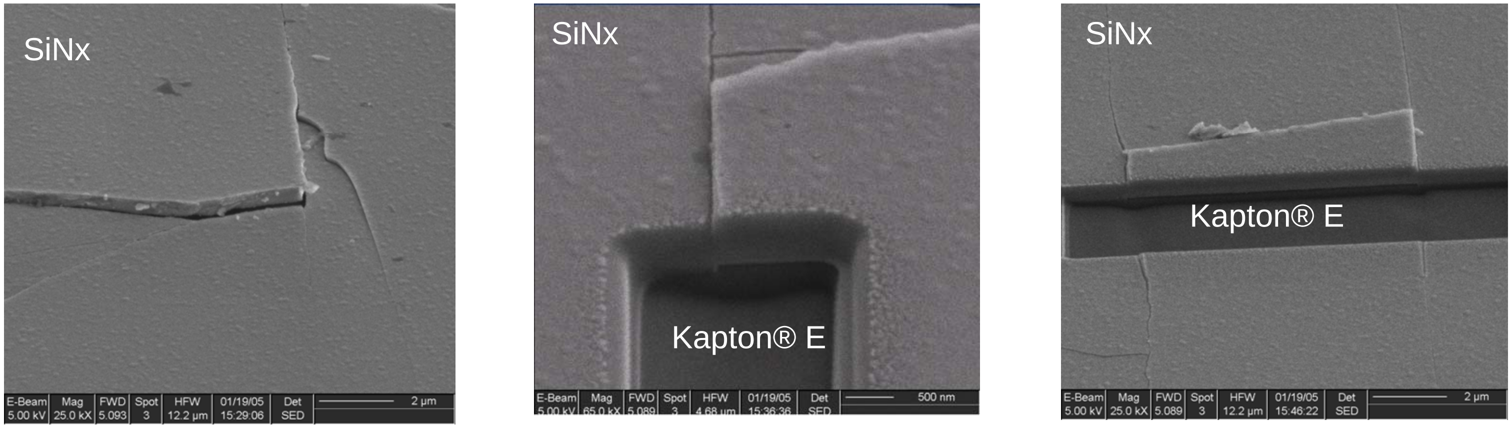
1μm SiN on Si (Courtesy of Q. Ma, Intel Corp.)



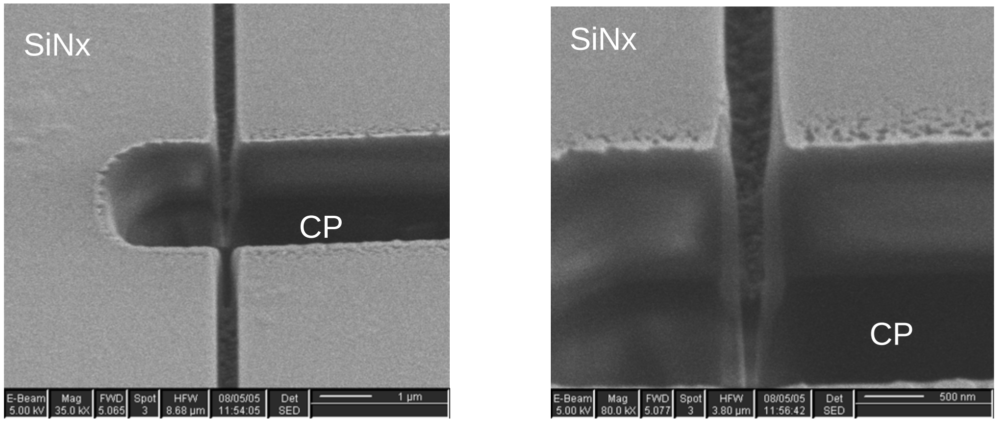
Tsui et al., JMR, 20, 2266 (2005).

- Under what conditions would interfacial delamination occur?
- If it occurs, how would interfacial delamination affect the fracture driving force?

Fracture of SiN thin films on compliant substrates



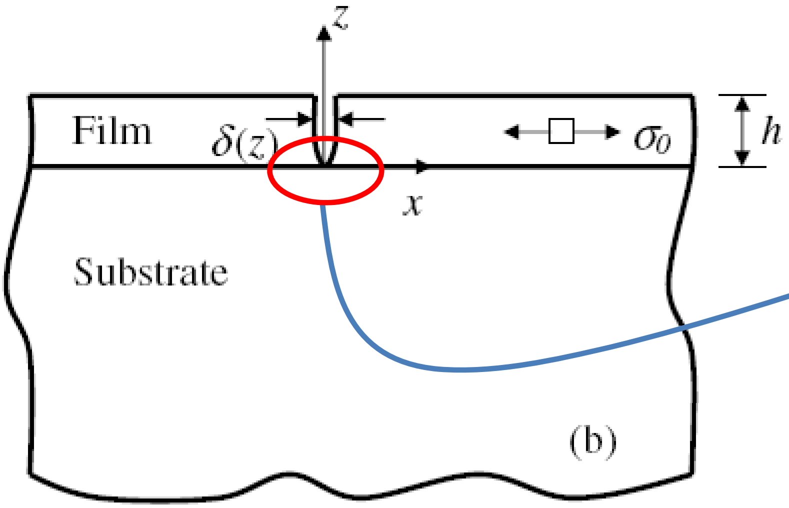
On Kapton: SiN film cracks with interfacial delamination.



On clear plastic: SiN film cracks with substrate fracture.

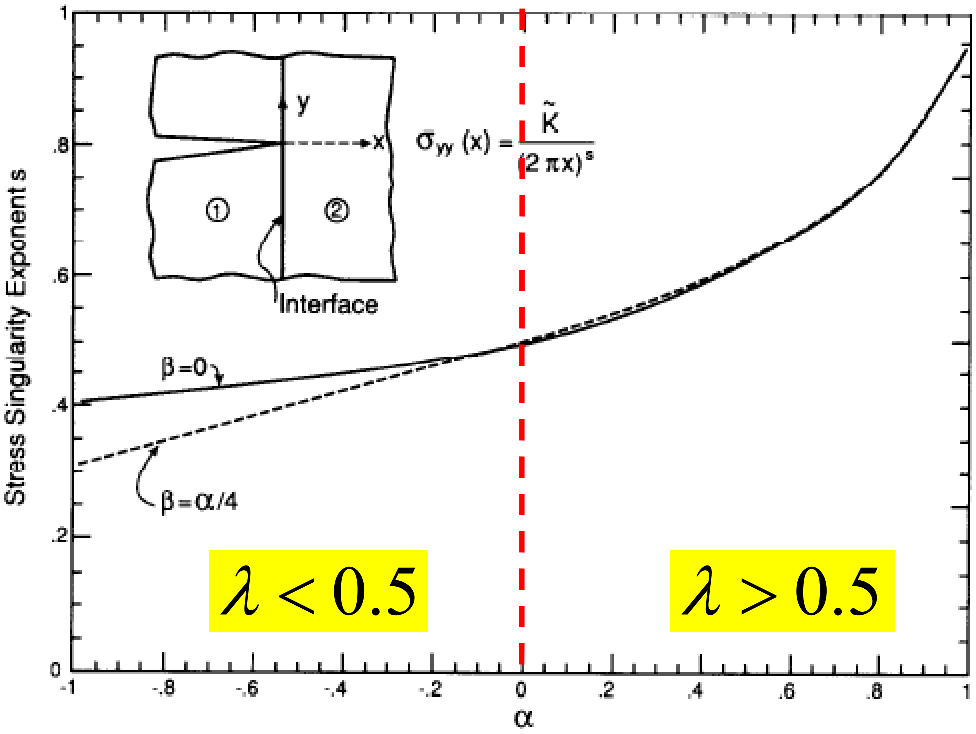
Kattamis et al., Mat. Res. Soc. Sym. Proc. 2008.

Stress singularity at the channel root



$$\sigma \sim \sigma_0 \left(\frac{h}{r} \right)^{\lambda}$$

Zak and Williams, 1963.
Hutchinson and Suo, 1992.
Beuth, 1992.
Vlassak, 2003.
Huang et al., 2003.

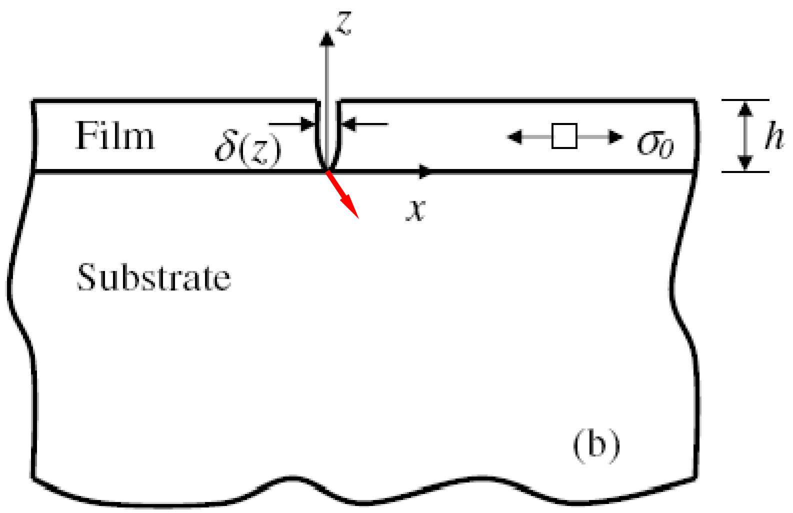


$\sigma_{yy}(x) = \frac{\tilde{K}}{(2\pi x)^s}$

$\lambda < 0.5$

$\lambda > 0.5$

A power law for crack deflection

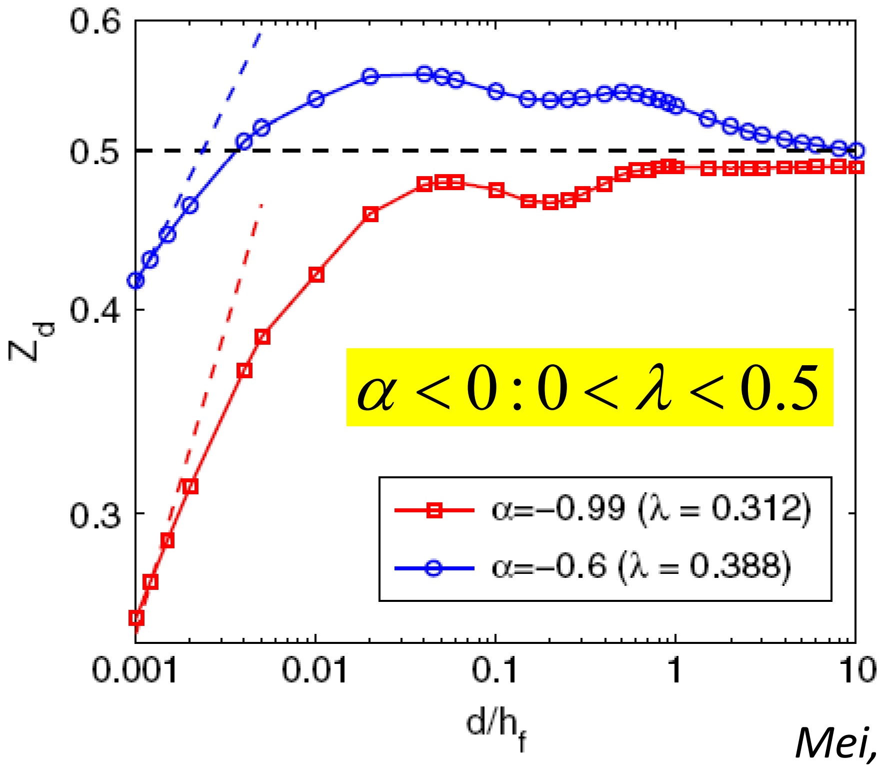


$$G_d = Z_d\left(\frac{d}{h},\alpha,\beta\right)\frac{\sigma_0^2 h}{\bar{E}_f}$$

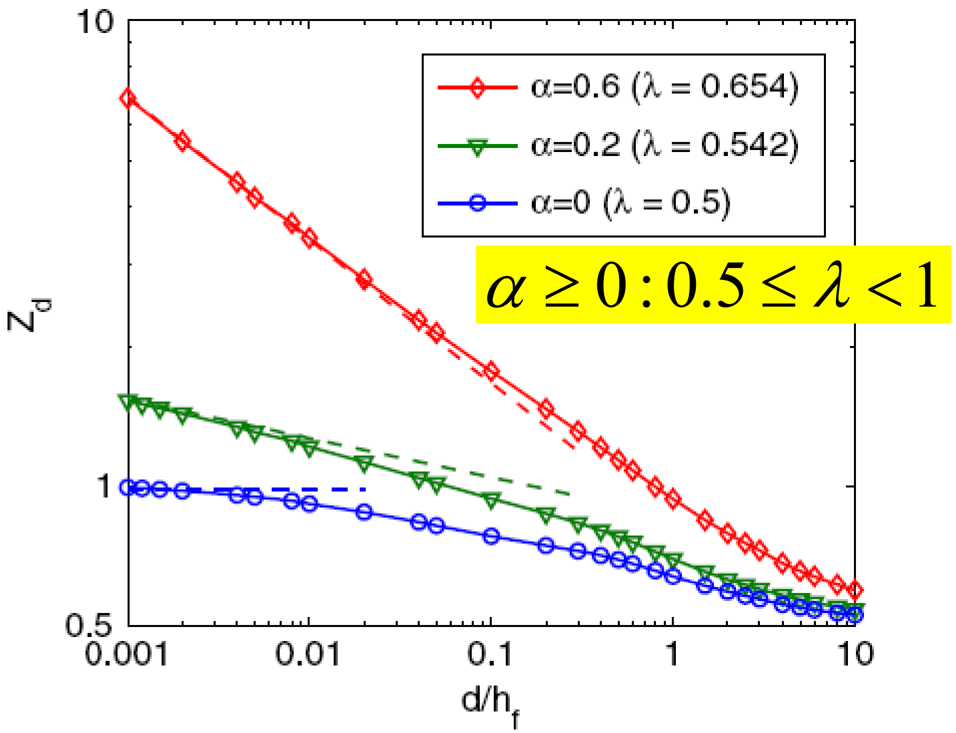
$$\boxed{Z_d \sim \left(\frac{d}{h}\right)^{1-2\lambda}}$$

For an emanating crack (d/h → 0)

He and Hutchinson, 1989;
Ye, Suo, and Evans, 1992.



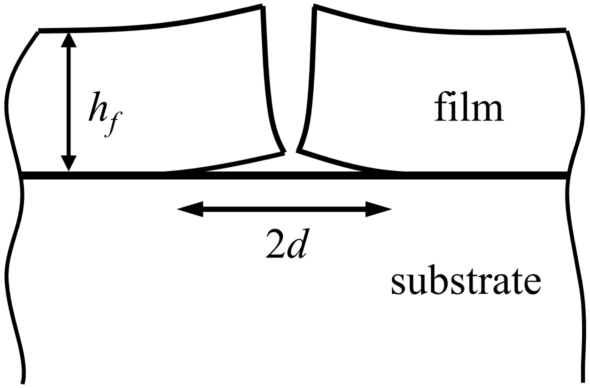
$$\alpha < 0 : 0 < \lambda < 0.5$$



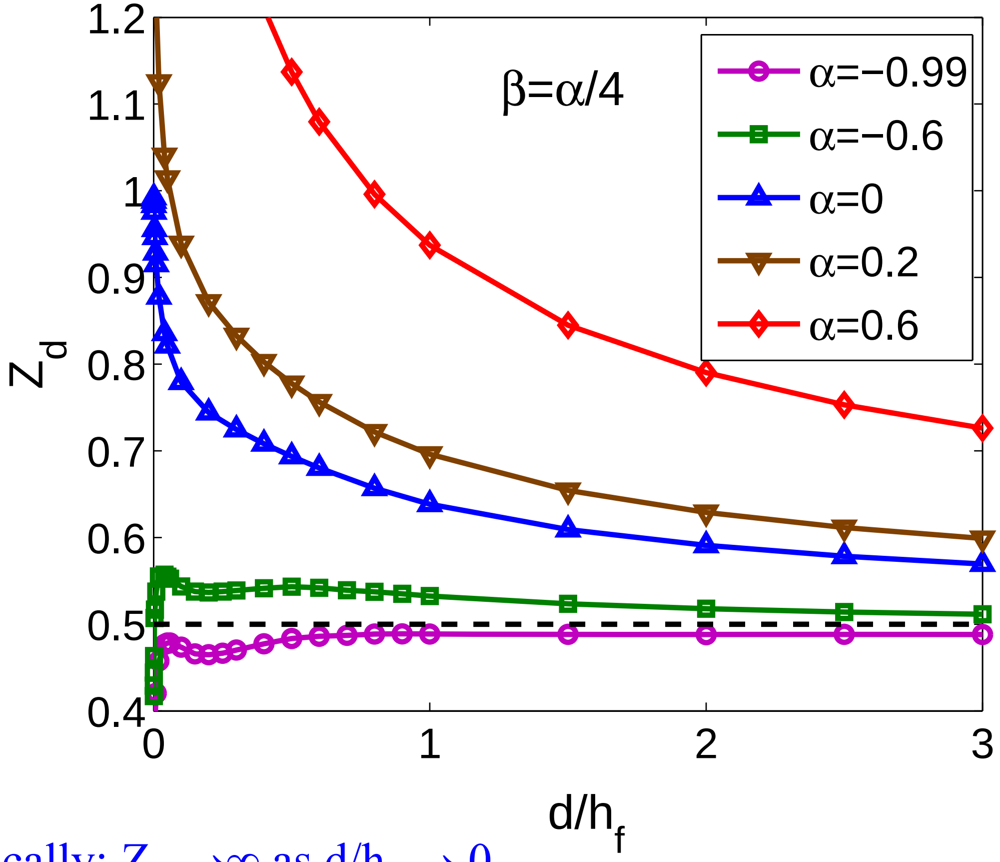
$$\alpha \geq 0 : 0.5 \leq \lambda < 1$$

Mei, Pang, and Huang, Int. J. Fracture 148, 331 (2007).

Delamination driving force



$$G_d = Z_d\left(\frac{d}{h},\alpha,\beta\right)\frac{\sigma_0^2 h}{\overline{E}_f}$$



(i) $\alpha > 0$: Z_d decreases monotonically; $Z_d \rightarrow \infty$ as $d/h_f \rightarrow 0$.

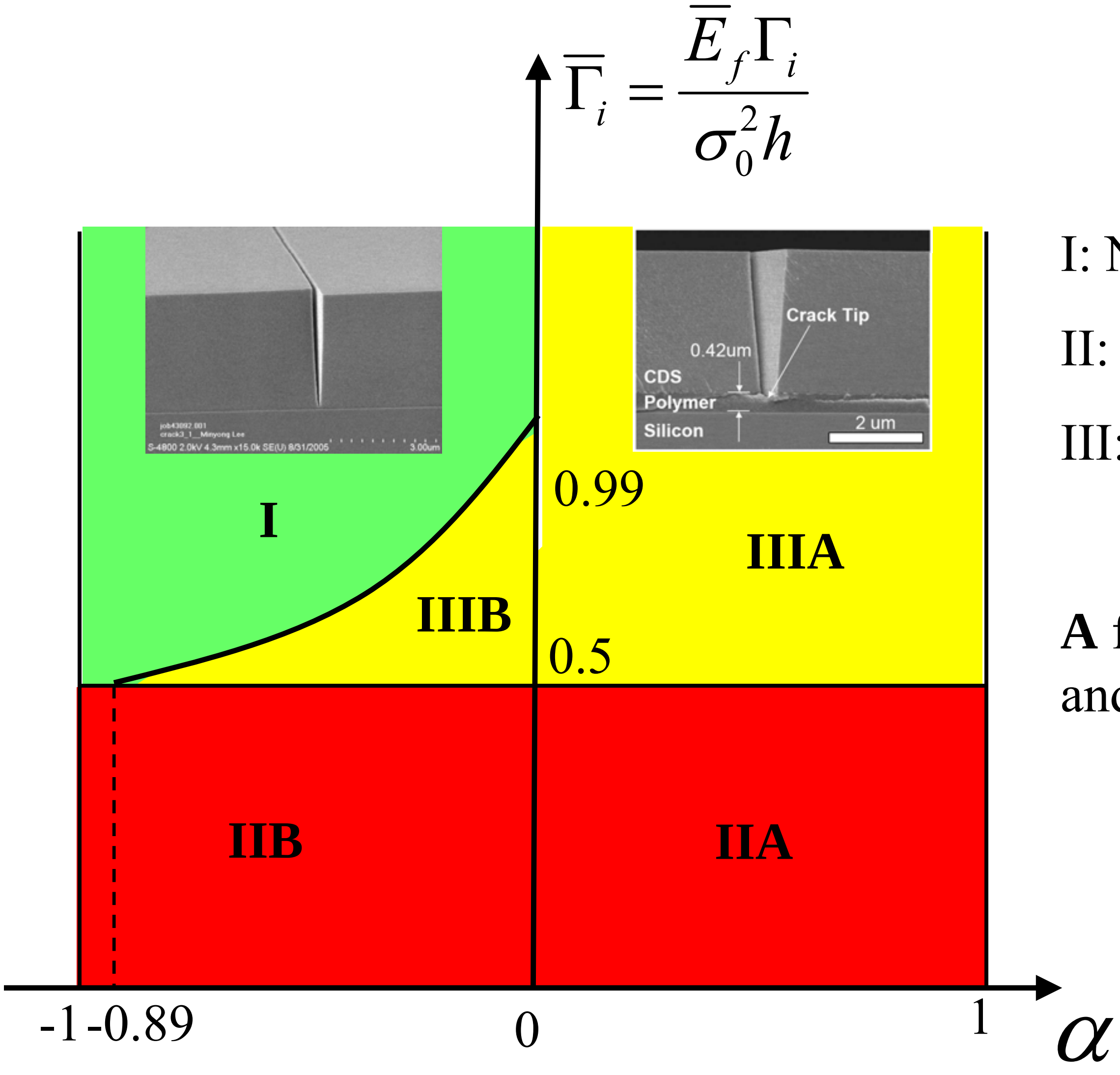
(ii) $\alpha = 0$: Z_d decreases monotonically; $Z_d \rightarrow 0.99$ as $d/h_f \rightarrow 0$.

(iii) $0 > \alpha > -0.89$: $\max(Z_d) > 0.5$; $Z_d \rightarrow 0$ as $d/h_f \rightarrow 0$.

(iv) $\alpha < -0.89$: $\max(Z_d) < 0.5$; $Z_d \rightarrow 0$ as $d/h_f \rightarrow 0$.

Mei, Pang, and Huang, Int. J. Fracture 148, 331 (2007).

A “phase diagram” for delamination



compliant film
stiff substrate

stiff film
compliant substrate

I: No delamination

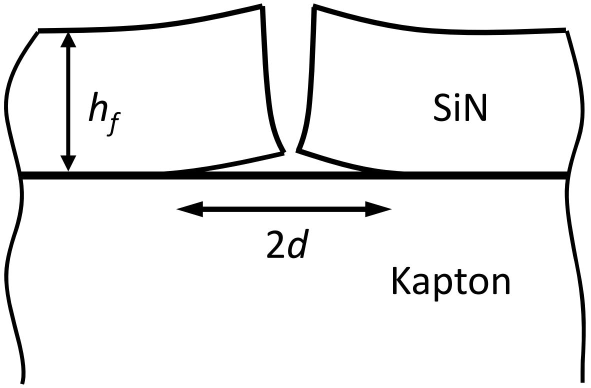
II: Spontaneous delamination

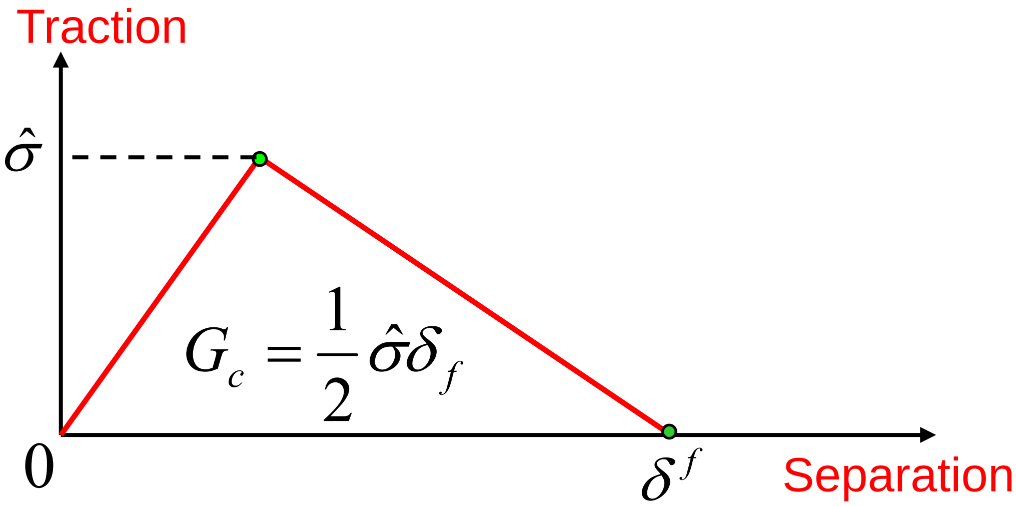
III: Stable delamination

A for barrierless delamination, and **B** with an initiation barrier

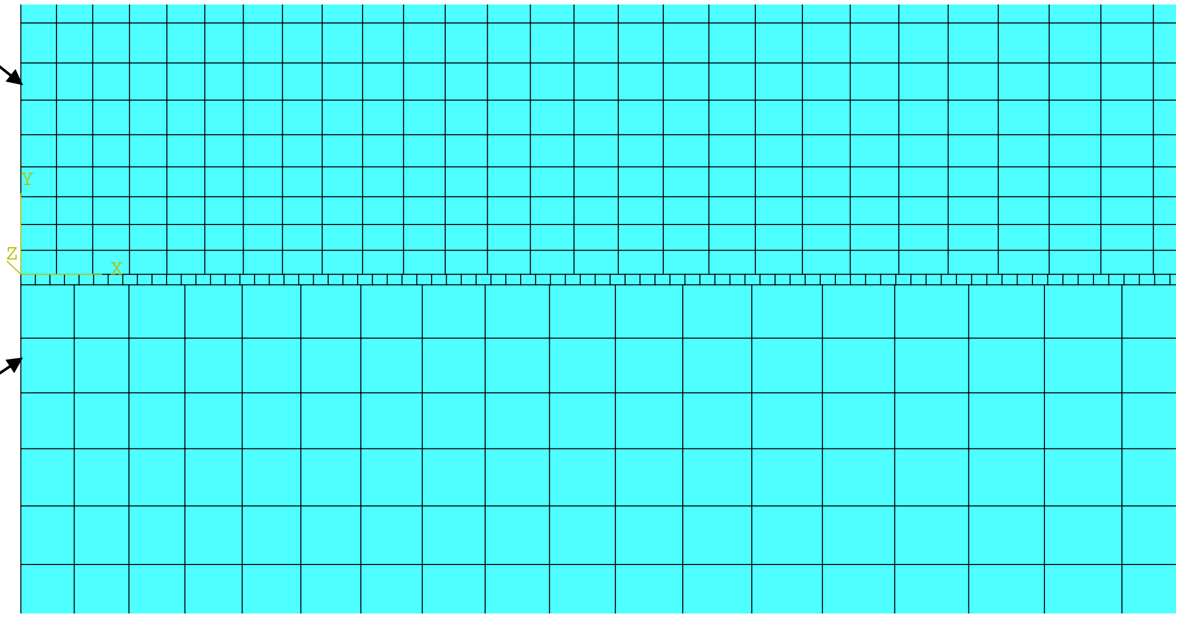
Mei, Pang, and Huang, Int. J. Fracture 148, 331 (2007).

Initiation of delamination by cohesive zone modeling (CZM)





$$G_c = \frac{1}{2}\hat{\sigma}\delta_f$$



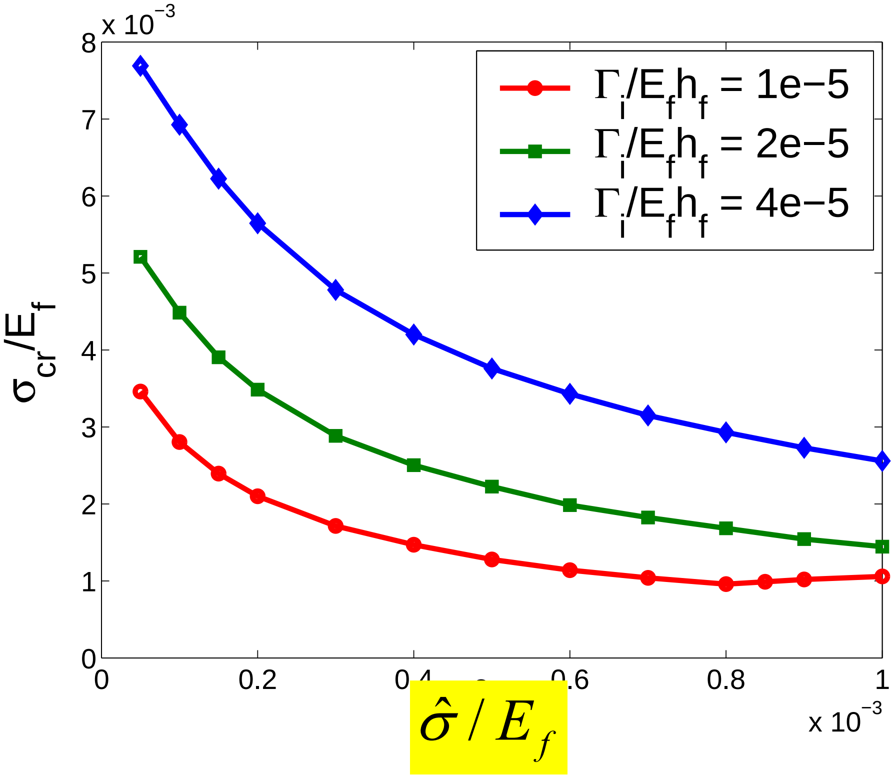
Channel crack face

Cohesive interface elements

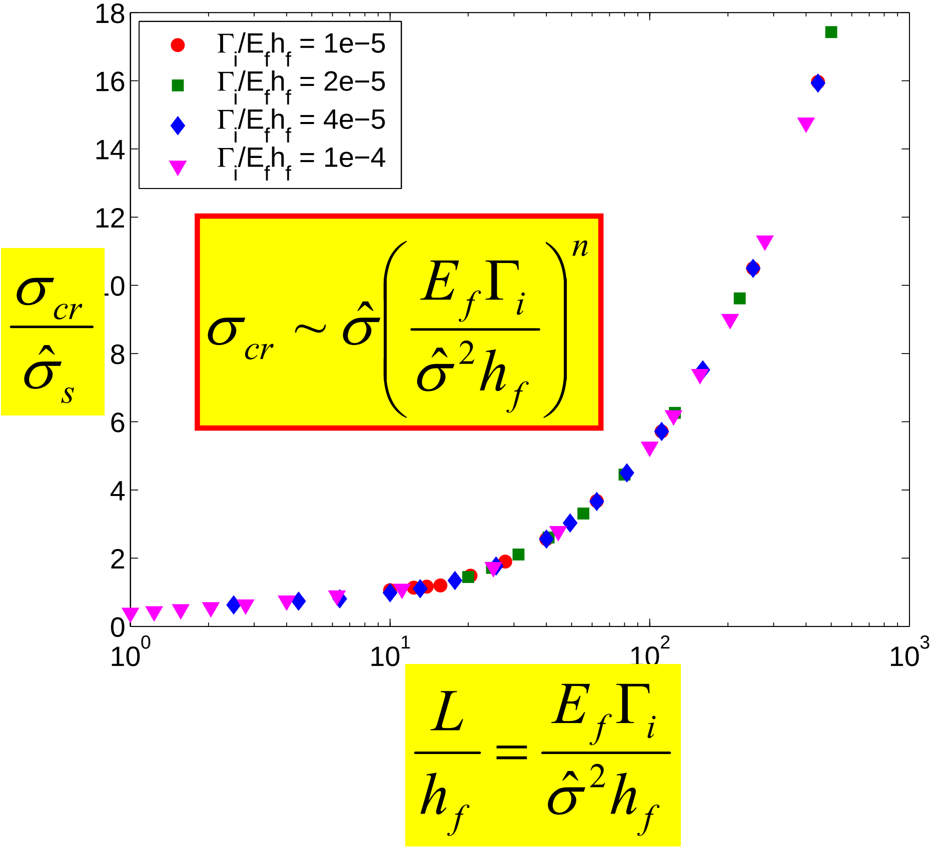
Symmetry boundary

Critical stress for interfacial delamination

<u>SiN film on Kapton substrate:</u> $\alpha = 0.9672, \beta = 0.2552$



$$\hat{\sigma} / E_f$$



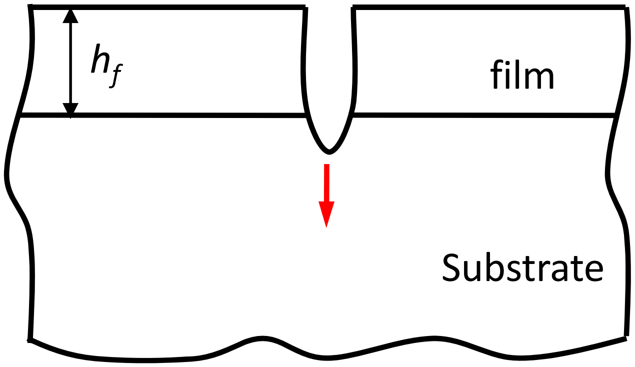
$$\frac{\sigma_{cr}}{\hat{\sigma}_s}$$

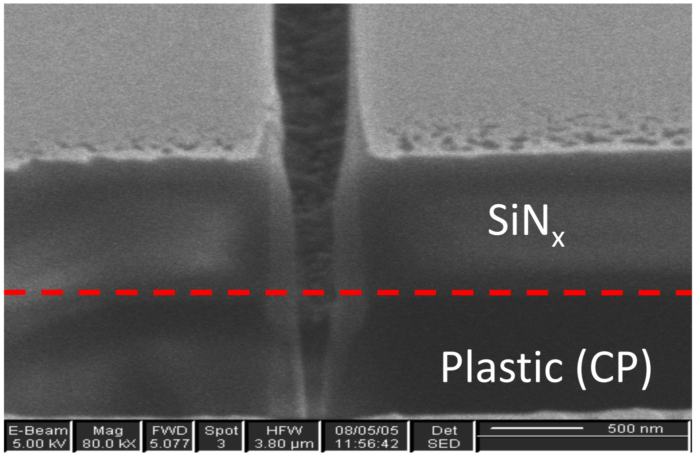
$$\sigma_{cr} \sim \hat{\sigma}\left(\frac{E_f \Gamma_i}{\hat{\sigma}^2 h_f}\right)^n$$

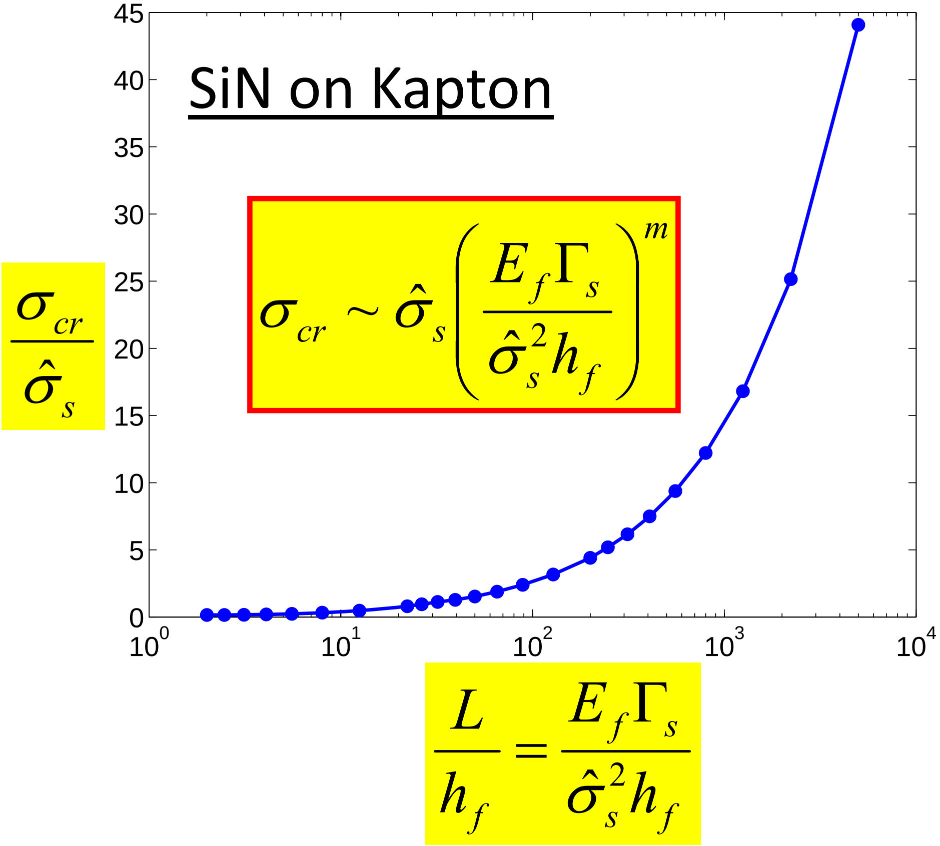
$$\frac{L}{h_f} = \frac{E_f \Gamma_i}{\hat{\sigma}^2 h_f}$$

- **Small-scale bridging (SSB):** $L/h_f << 1$, $\sigma_{cr} \to 0$ (LEFM);
- **Large-scale bridging (LSB):** a cohesive zone develops before crack initiation

Critical stress for substrate cracking







$$\frac{\sigma_{cr}}{\hat{\sigma}_s}$$

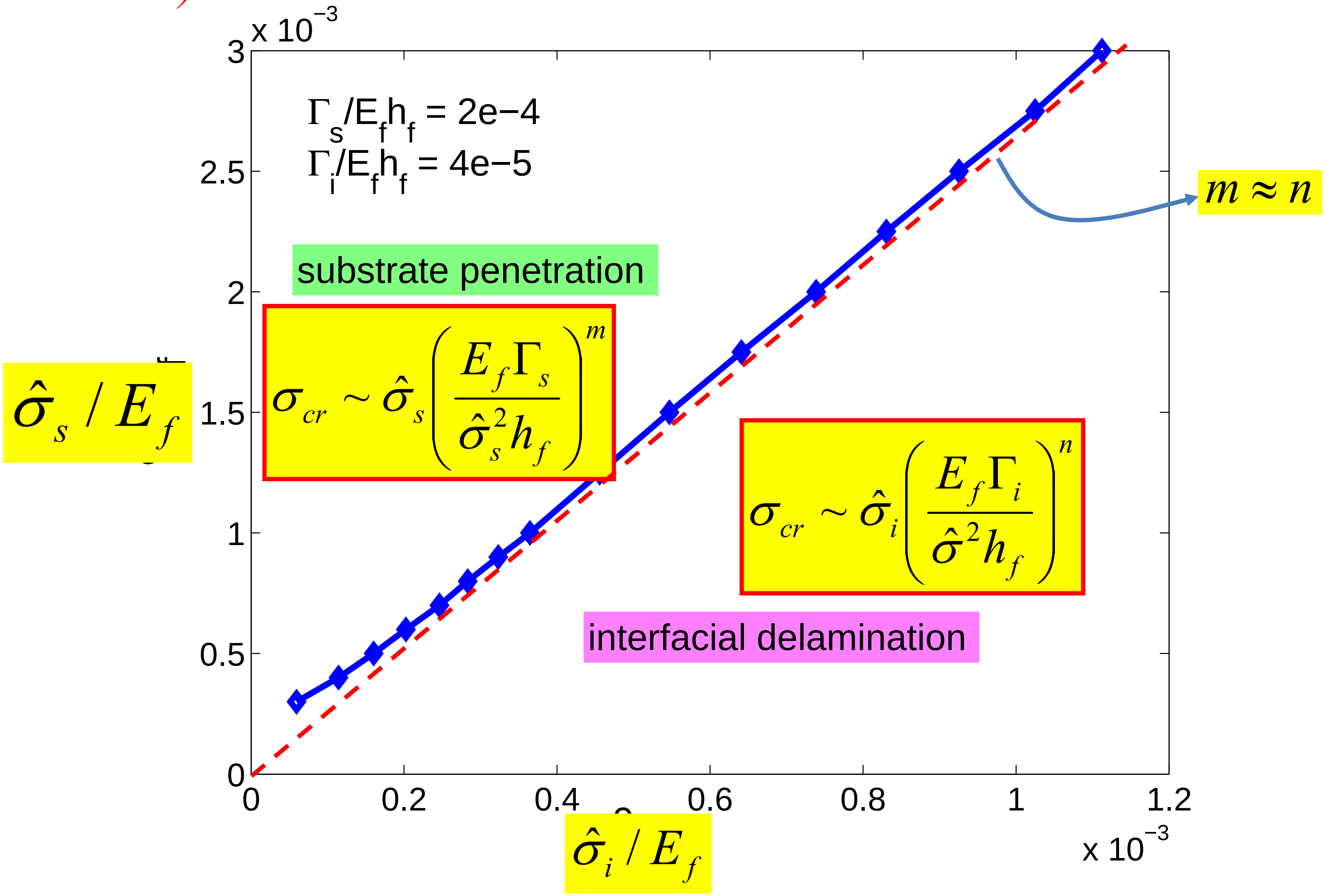
$$\sigma_{cr} \sim \hat{\sigma}_s \left(\frac{E_f \Gamma_s}{\hat{\sigma}_s^2 h_f} \right)^m$$

$$\frac{L}{h_f} = \frac{E_f \Gamma_s}{\hat{\sigma}_s^2 h_f}$$

- **Small-scale bridging (SSB):** $L/h_f << 1$, $\sigma_{cr} \to 0$ (LEFM);
- **Large-scale bridging (LSB):** a cohesive zone develops before crack initiation

Delamination or Penetration?

- *LEFM: energy based criterion (He and Hutchinson, 1992).*
- *CZM: combined strength and toughness criterion (Parmigiani and Thouless, 2006).*

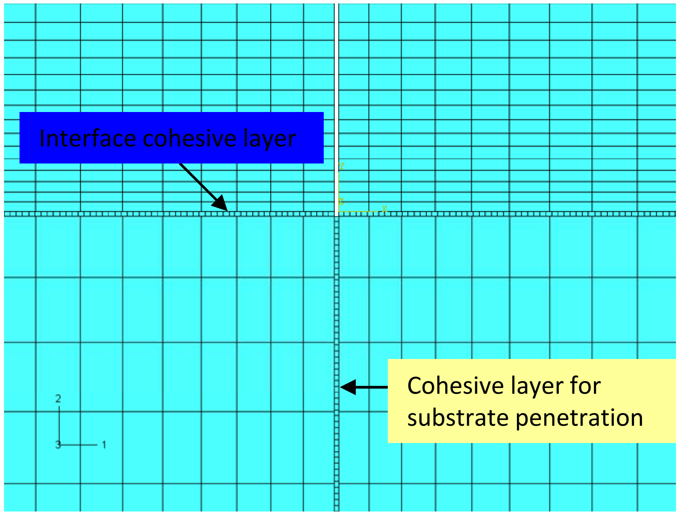


$$\sigma_{cr} \sim \hat{\sigma}_s \left(\frac{E_f \Gamma_s}{\hat{\sigma}_s^2 h_f} \right)^m$$

$$\sigma_{cr} \sim \hat{\sigma}_i \left(\frac{E_f \Gamma_i}{\hat{\sigma}^2 h_f} \right)^n$$

$m \approx n$

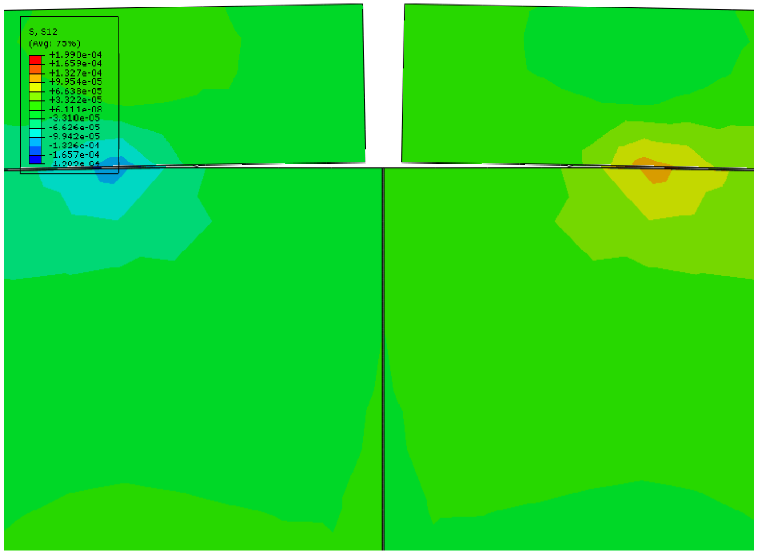
CZM simulations with competing crack paths

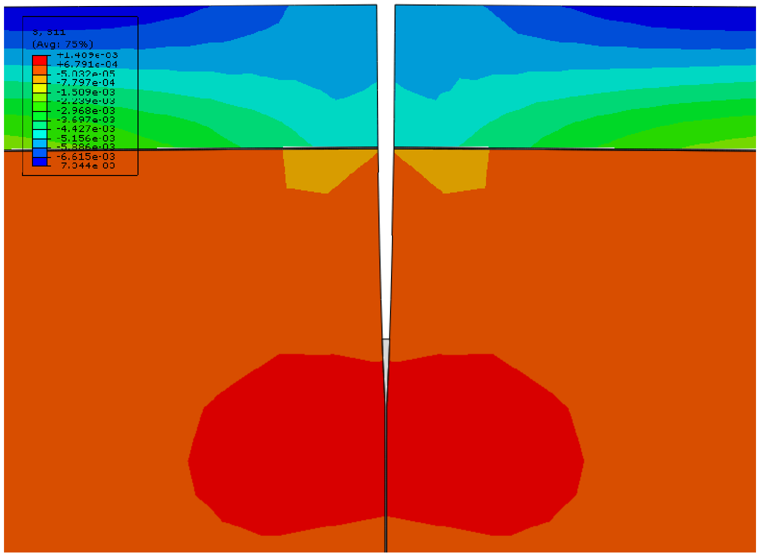


Interface cohesive layer

Cohesive layer for substrate penetration

Two layers of cohesive elements are assigned along the competing crack paths.





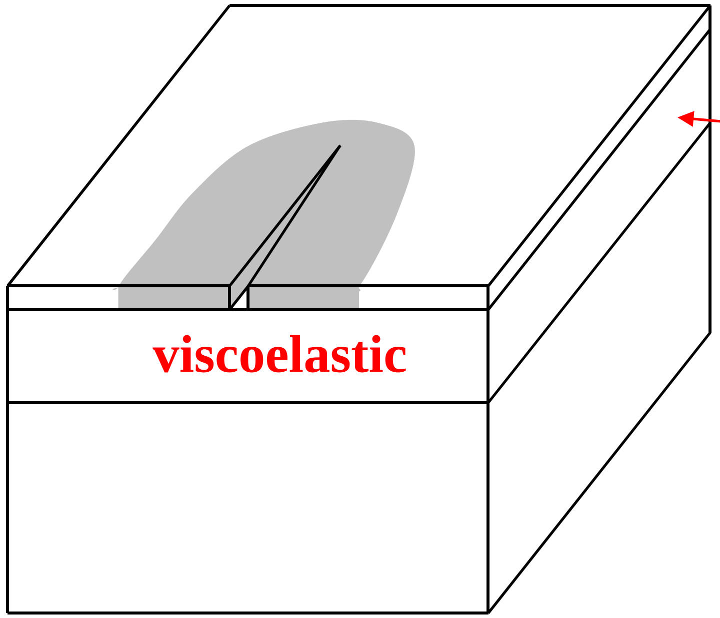
Effect of substrate constraint on film cracking

- On *elastic* substrates:
  - Weak constraint by a compliant substrate
  - Loss of constraint by interfacial delamination or substrate cracking

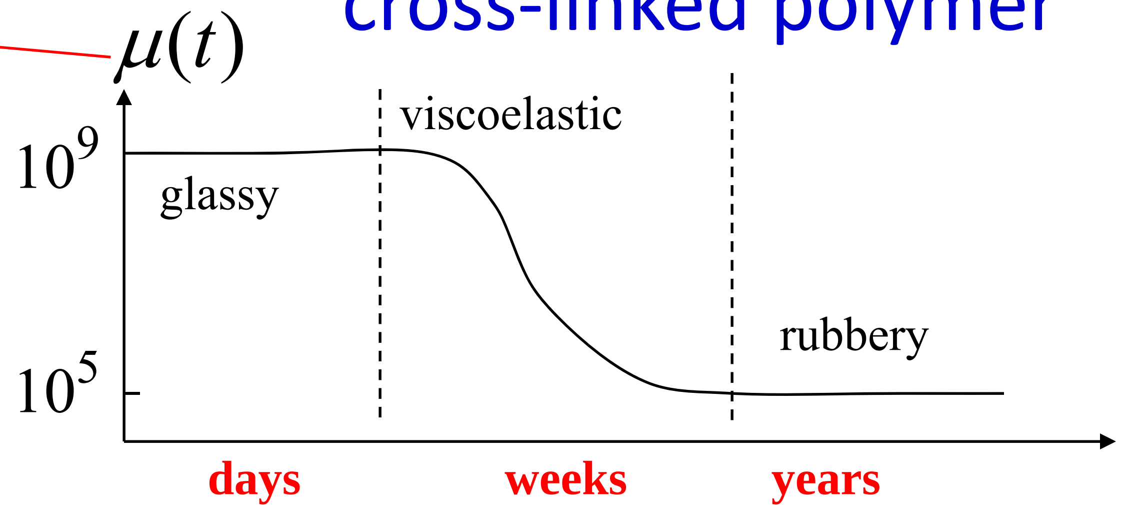
- On *viscoelastic* substrates:
  - Substrate creep

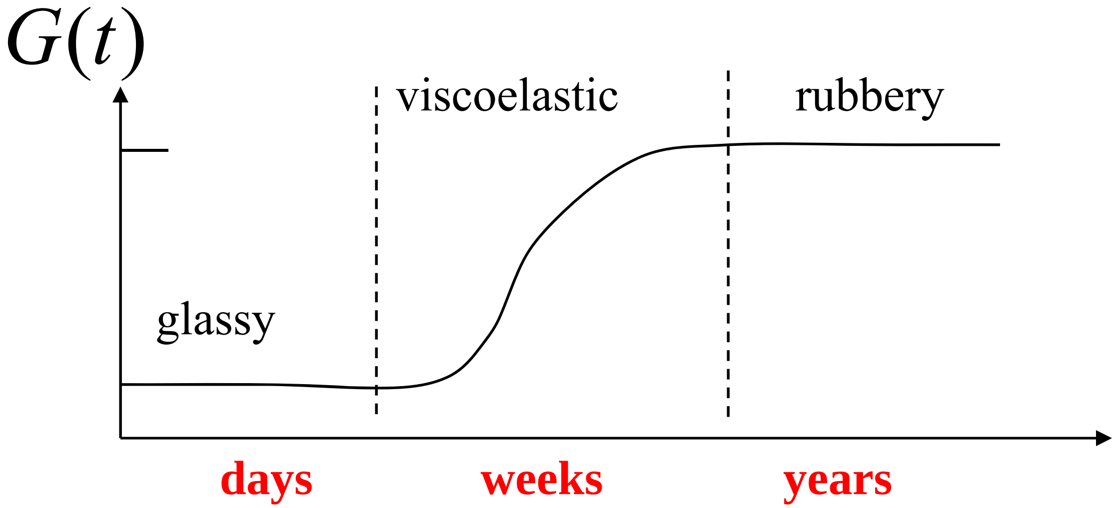
- On *elastoplastic* substrates:
  - Substrate plasticity
  - Substrate ratcheting under cyclic temperatures

On a viscoelastic layer



cross-linked polymer

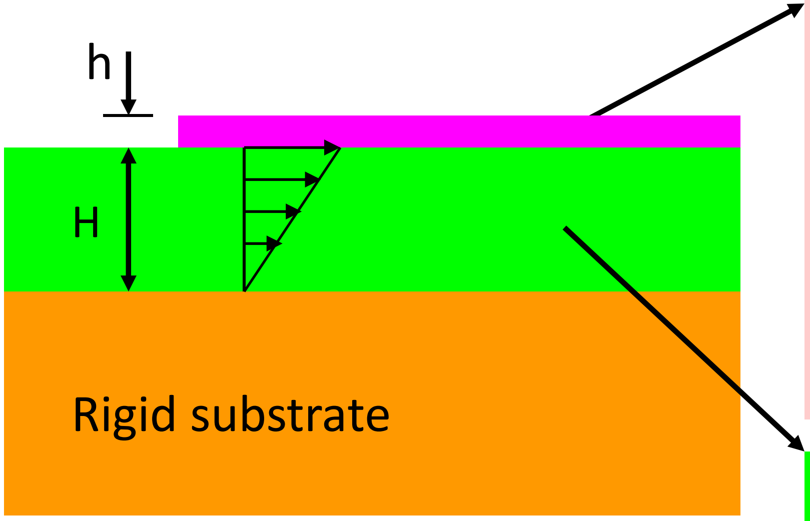




- Two elastic limits: glassy and rubbery, with different constraint.
- In between: viscoelastic deformation leads to gradual loss of constraint over time; stress relaxes in the wake of the channel crack, but intensifies at the crack front.

Suo et al., *J. Mech. Phys. Solids* 51, 2169 (2003).

A Shear Lag Model



Elastic film:

$$\sigma_{\alpha\beta,\beta} = \tau_\alpha / h$$

$$\sigma_{\alpha\beta} = \sigma\delta_{\alpha\beta} + \bar{E}\left[(1-\nu)\varepsilon_{\alpha\beta} + \nu\varepsilon_{\gamma\gamma}\delta_{\alpha\beta}\right]$$

$$\varepsilon_{\alpha\beta} = \frac{1}{2}\left(u_{\alpha,\beta} + u_{\beta,\alpha}\right)$$

Viscous underlayer: $\tau_\alpha = \frac{\eta}{H}\frac{\partial u_\alpha}{\partial t}$

$$\rightarrow \boxed{\frac{\partial u_\alpha}{\partial t} = D\left(\frac{1-\nu}{2}u_{\alpha,\beta\beta} + \frac{1+\nu}{2}u_{\beta,\beta\alpha}\right)}$$

Effective diffusivity: $D = \bar{E}Hh/\eta$

Elsasser, 1969.
Rice, 1980.
Huang et al., 2001.

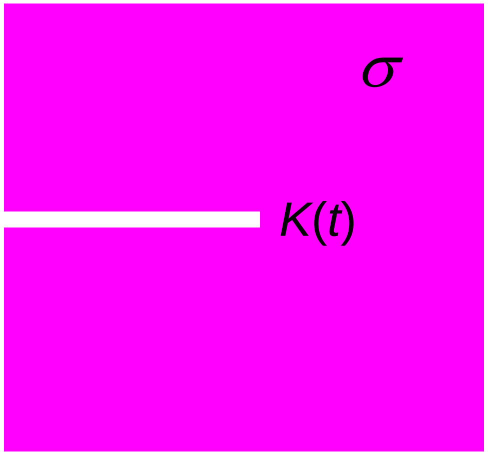
Stationary long crack in a blanket film

Length scale = $(Dt)^{1/2}$

Dimensional consideration: $K \propto \sigma (Dt)^{1/4}$

Analytical solution:
(Laplace transform)

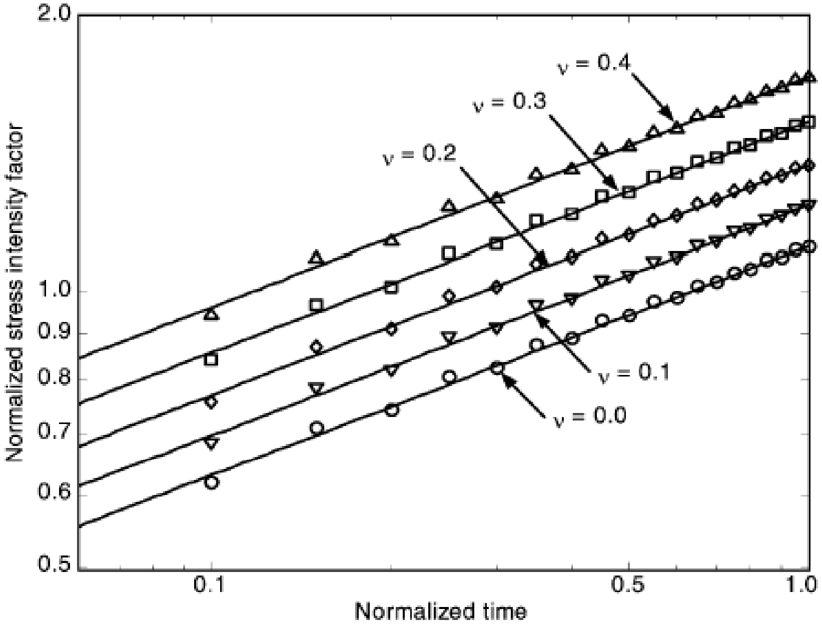
$$K(t) = 1.103\sqrt{1-\nu^2}\,\sigma\left(Dt\right)^{1/4}$$



Gradual loss of constraint:

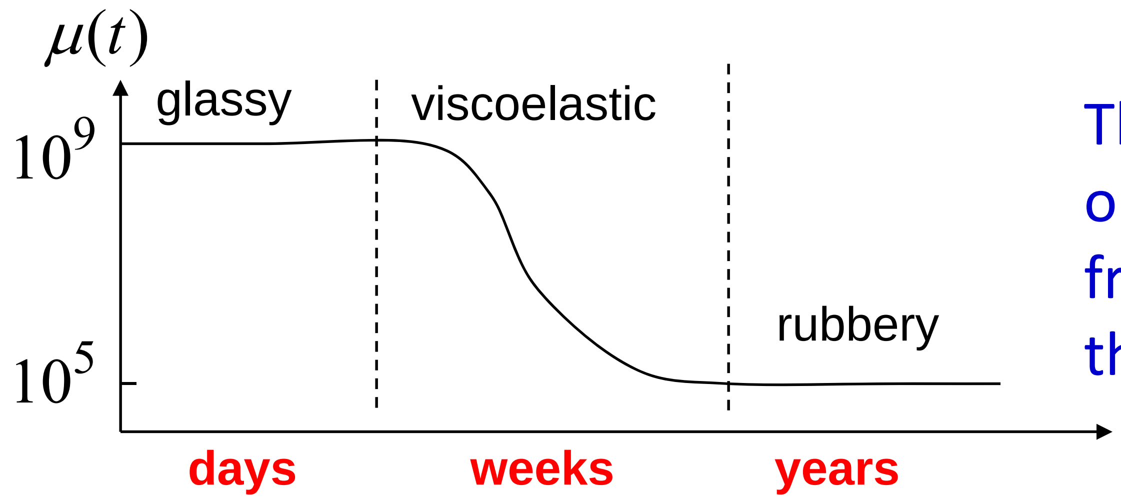
- When $t = 0$, $K = 0$
- When $t \to \infty$, $K \to \infty$

- Delayed growth when $K(t) = K_c$

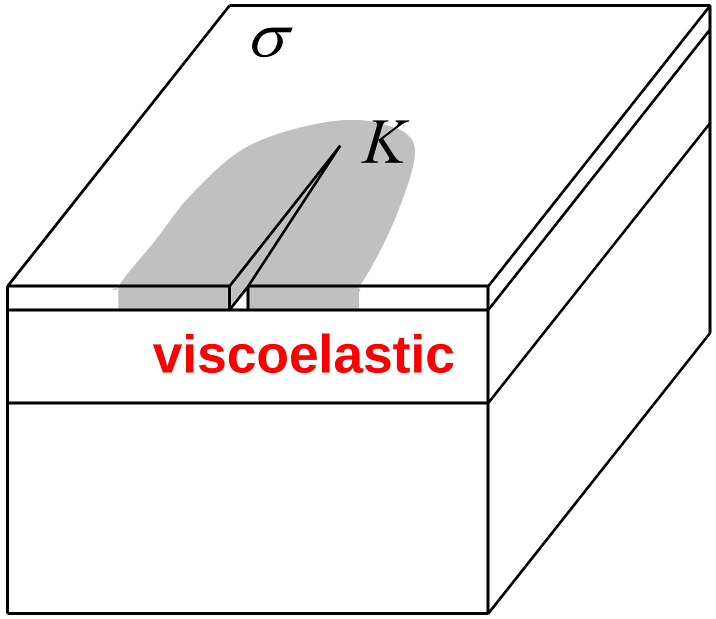


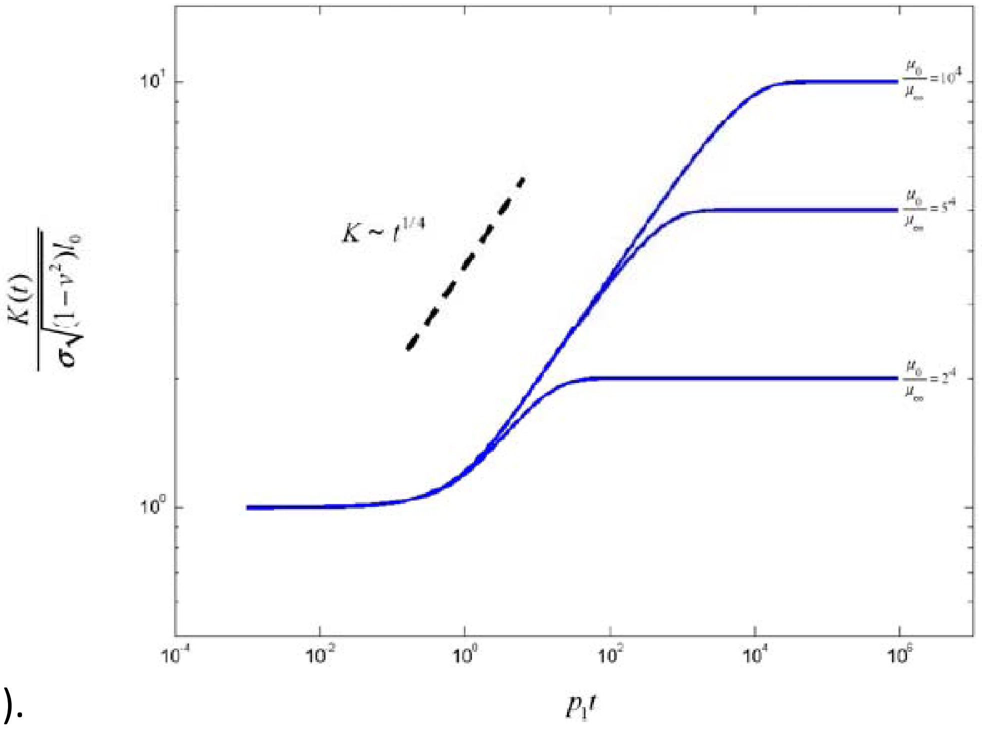
Huang et al., *Acta Mater* 50, 4137 (2002).

Viscoelastic underlayer with elastic limits



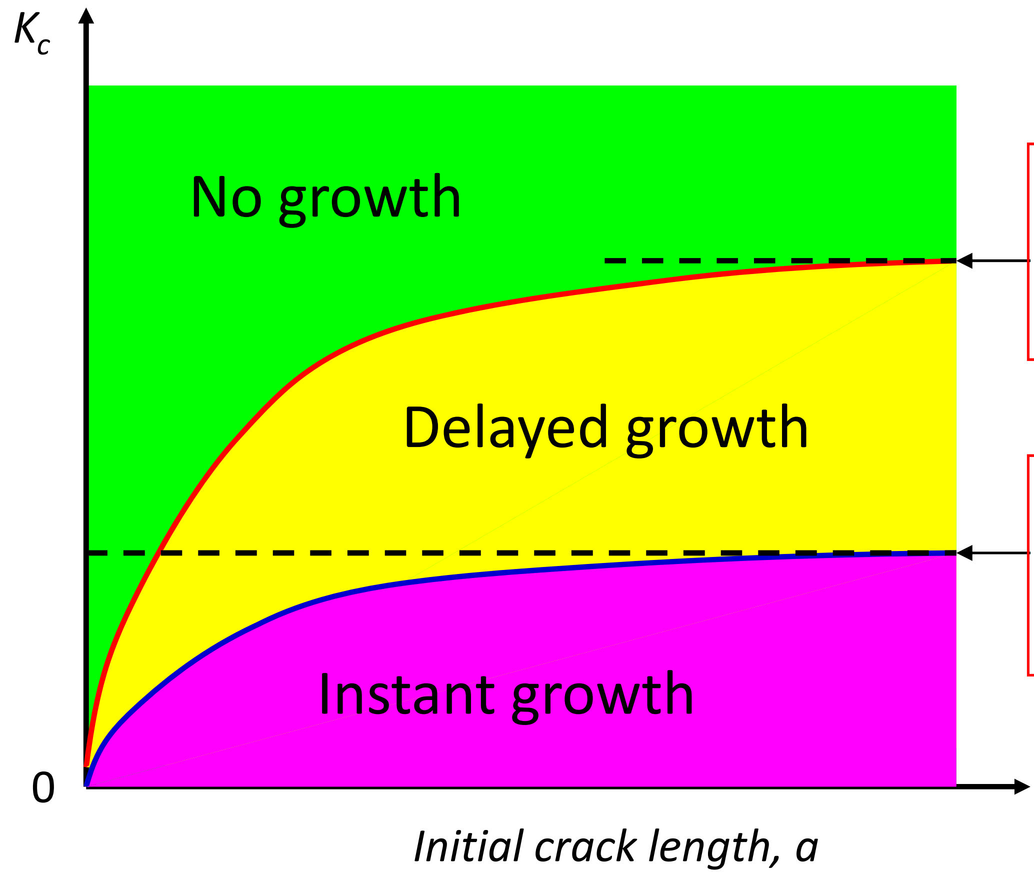
The effect of constraint on film cracking reduces from the glassy state to the rubbery state.





Suo et al., *J. Mech. Phys. Solids* 51, 2169 (2003).

Viscoelastic underlayer, finite crack length



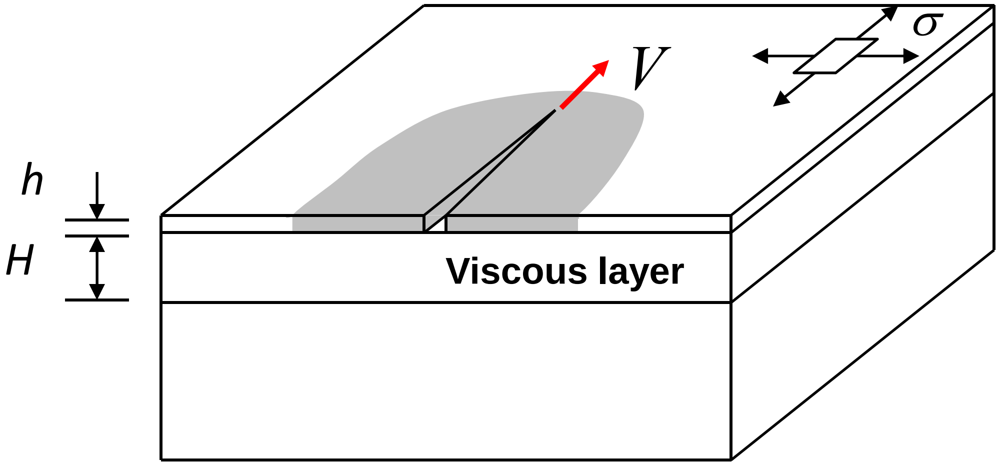
$$K_r = \sigma\sqrt{1-\nu_r^2}\left(\frac{\bar{E}_f hH}{\mu_r}\right)^{1/4}$$

$$K_g = \sigma\sqrt{1-\nu_g^2}\left(\frac{\bar{E}_f hH}{\mu_g}\right)^{1/4}$$

A finite crack in the film may grow after a delay time, due to loss of constraint by viscoelastic deformation of the underlayer.

Suo et al., *J. Mech. Phys. Solids* 51, 2169 (2003).

Creep-modulated crack growth



Crack growth criterion: $K = K_c$

Length scale: $\Lambda = \left(\frac{K_c}{\sigma}\right)^2$

Time scale: $t_0 = \frac{\Lambda^2}{D} = \left(\frac{K_c}{\sigma}\right)^4 \frac{\eta}{Hh\overline{E}}$

Representative values

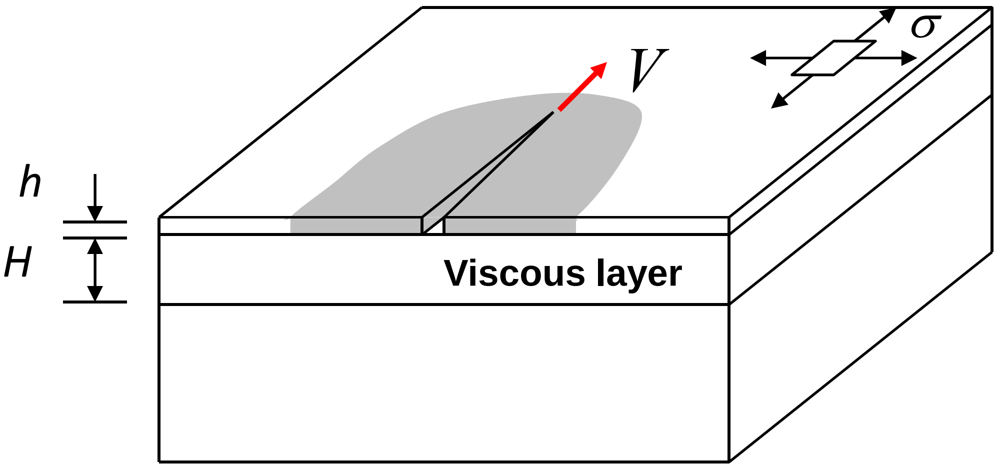
$K_c = 1\mathrm{MPa}\sqrt{\mathrm{m}}$ σ = 500 MPa

E = 10^{11}N/m^2, η = 10^{10} sN/m^2, h = 0.1 μm, and H = 1 μm

Λ = 4μm, t_0 = 16s

Liang *et al.*, *Experimental Mechanics* **43**, 269-279 (2003).

Steady-State Crack Velocity



Slow growth: *K* increases, as the underlayer creeps

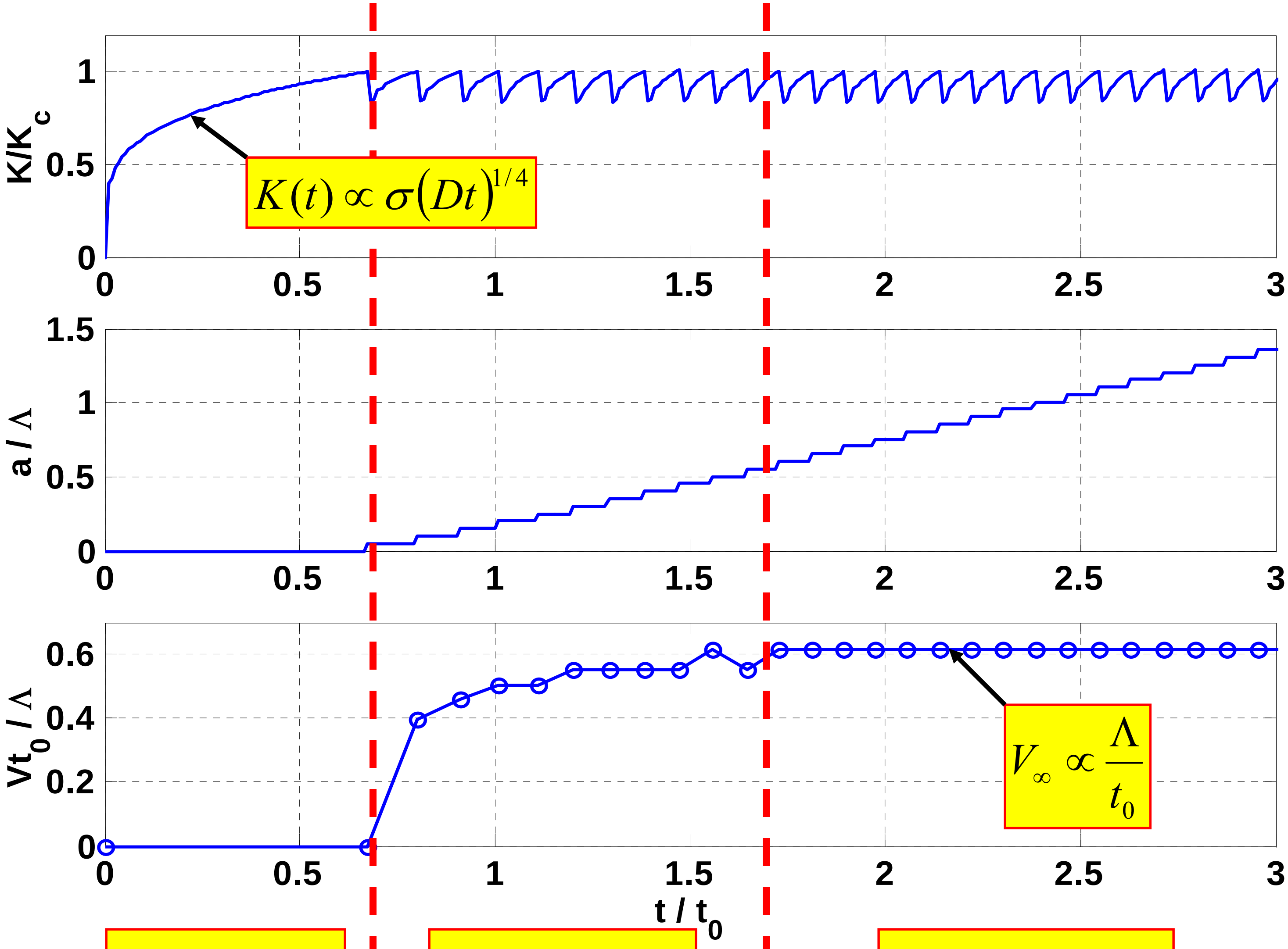
Fast growth: *K* decreases, as the fresh crack opening is constrained

Steady-state velocity:

$$V_{ss} = \chi(\nu)\frac{\Lambda}{t_0} = 0.5\frac{\bar{E}Hh\sigma^2}{\eta K_c^2}$$

Liang *et al.*, *Experimental Mechanics* **43**, 269-279 (2003).

Numerical simulation of crack growth



$K(t) \propto \sigma (Dt)^{1/4}$

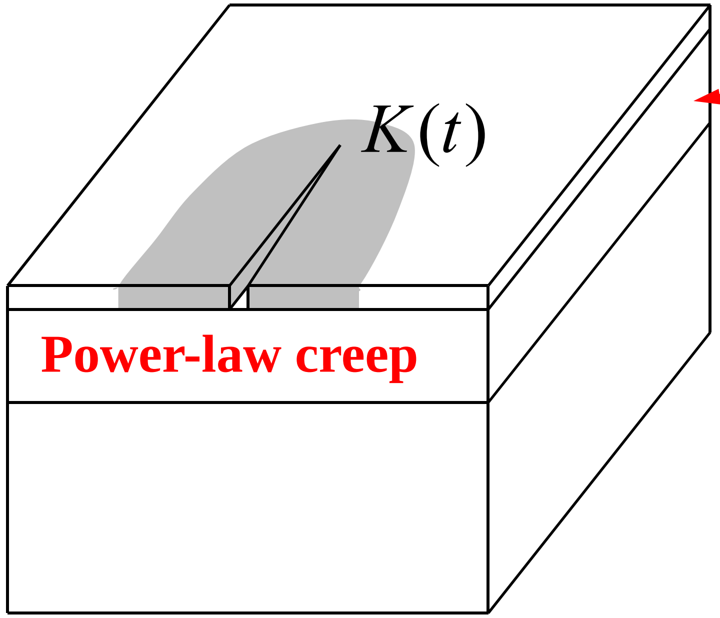
$V_{\infty} \propto \frac{\Lambda}{t_0}$

Stationary crack

Transient state

Steady state growth

Scaling for power-law creep



$$\frac{d\gamma}{dt} = B\tau^{n}$$

For a stationary long crack:

$$K(t) \sim \sigma^{\frac{3n+1}{2(n+1)}} t^{\frac{1}{2(n+1)}}$$

For steady-state crack growth:

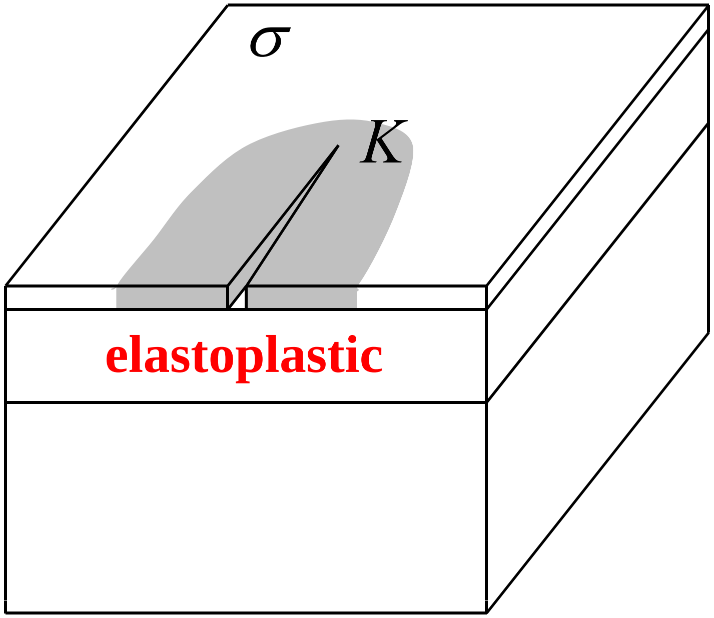
$$V_{SS} \sim \frac{\sigma^{3n-1}}{B^{n} K_{c}^{2n}}$$

Liang *et al.*, *Int. J. Fracture* **125**, 335 (2004).

Effect of substrate constraint on film cracking

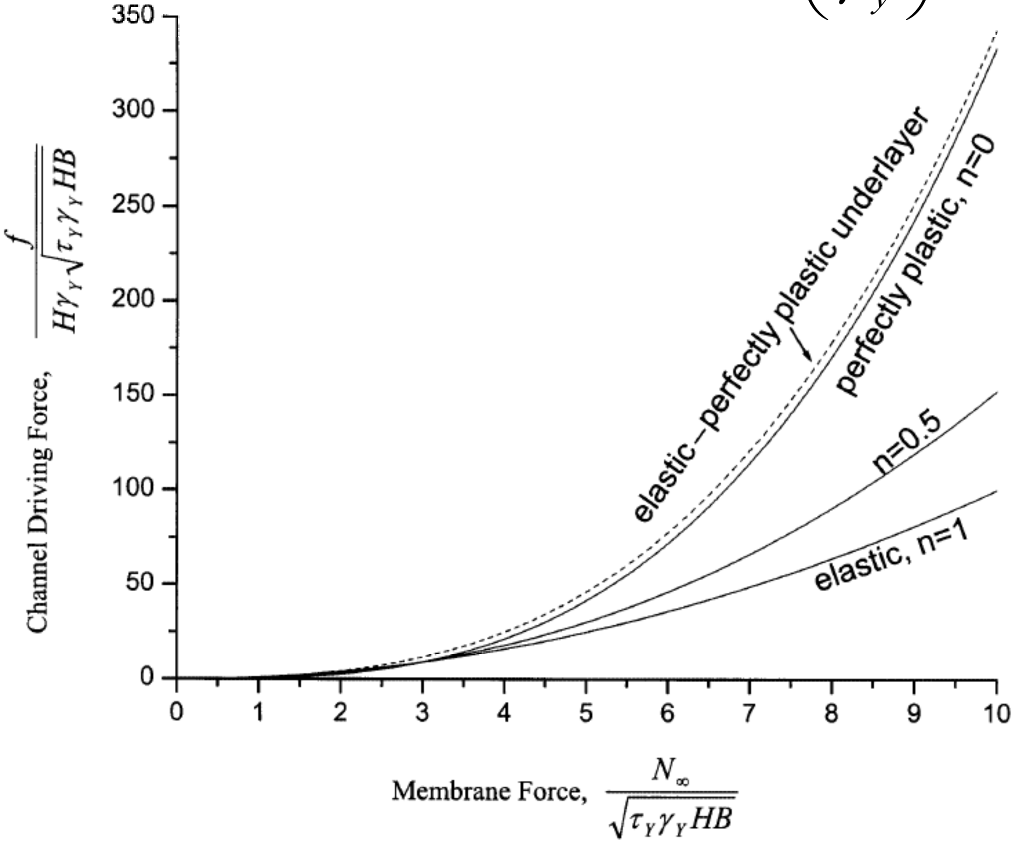
- On *elastic* substrates:
  - Weak constraint by a compliant substrate
  - Loss of constraint by interfacial delamination or substrate cracking
- On *viscoelastic* substrates:
  - Loss of constraint over time by substrate creep
  - delayed fracture
  - steady-state creep-modulated crack growth
- On *elastoplastic* substrates:
  - Substrate plasticity
  - Substrate ratcheting under cyclic temperatures

On plastically deformable substrates



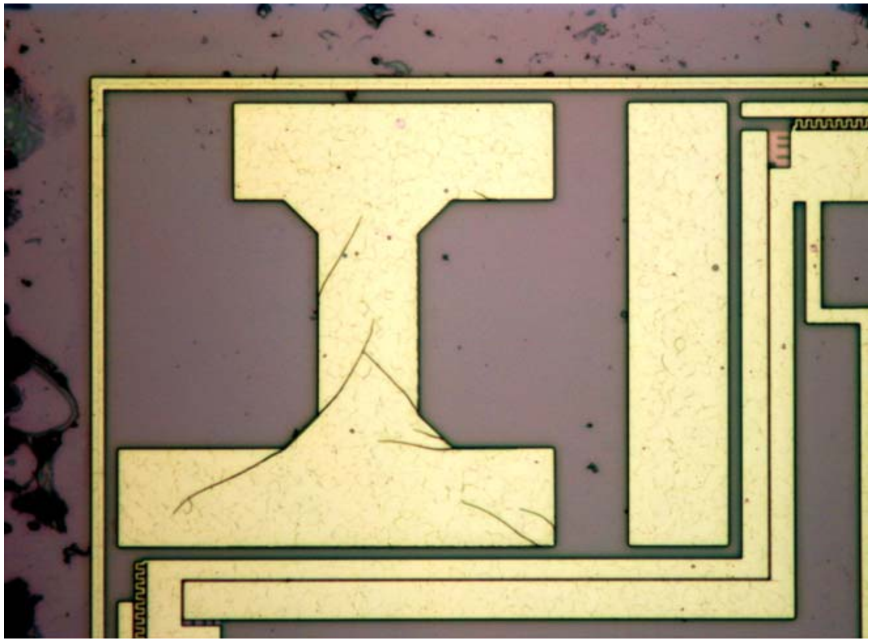
Hu and Evans, 1989.
Beuth and Klingbeil, 1996.
Ambrico and Begley, 2002.
Suo, 2003.

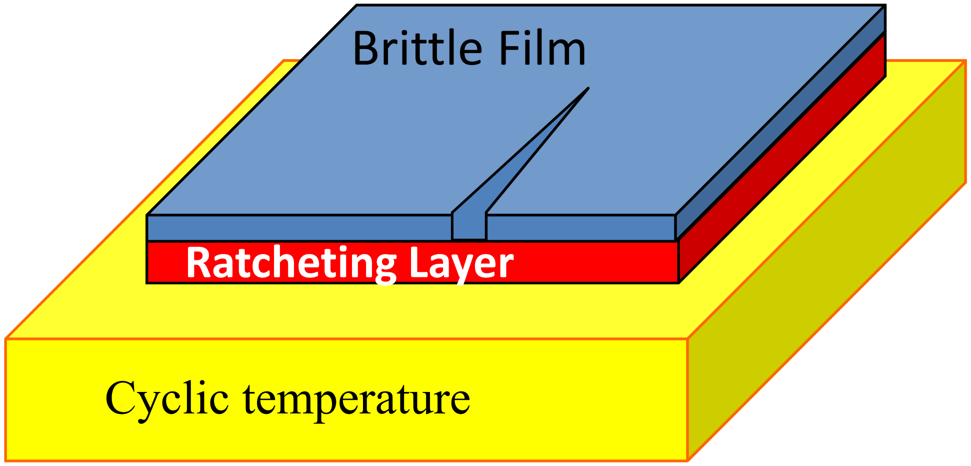
Power-law plasticity: $\tau = \tau_y \left(\frac{\gamma}{\gamma_y} \right)^n$



As the substrate deforms plastically, the elastic constraint on film cracking is partially lost and the crack driving force increases.

Ratcheting-Induced Cracking under cyclic temperatures

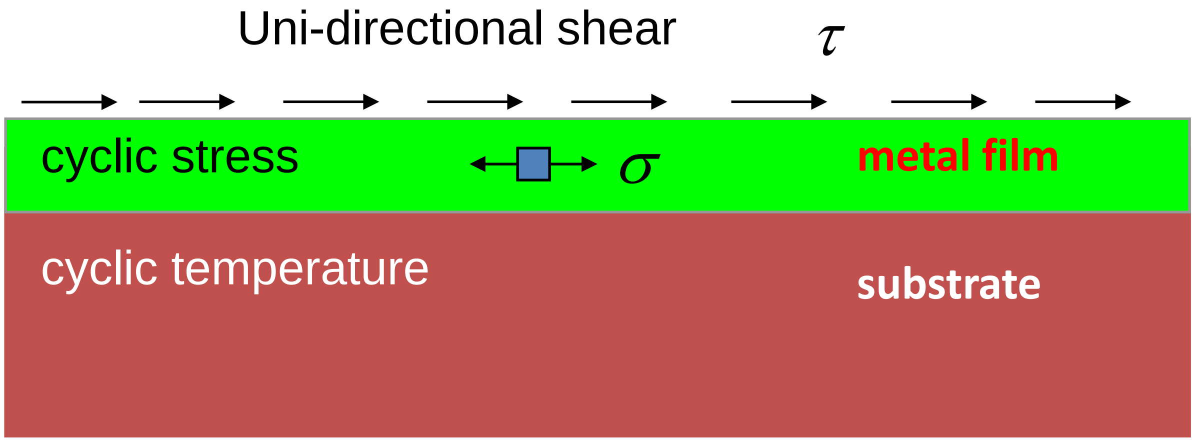




SiN film on Al

Huang, Suo, Ma, *J. Mech. Phys. Solids* **50,** 1079 (2002)

Metal Film Crawling by Ratcheting

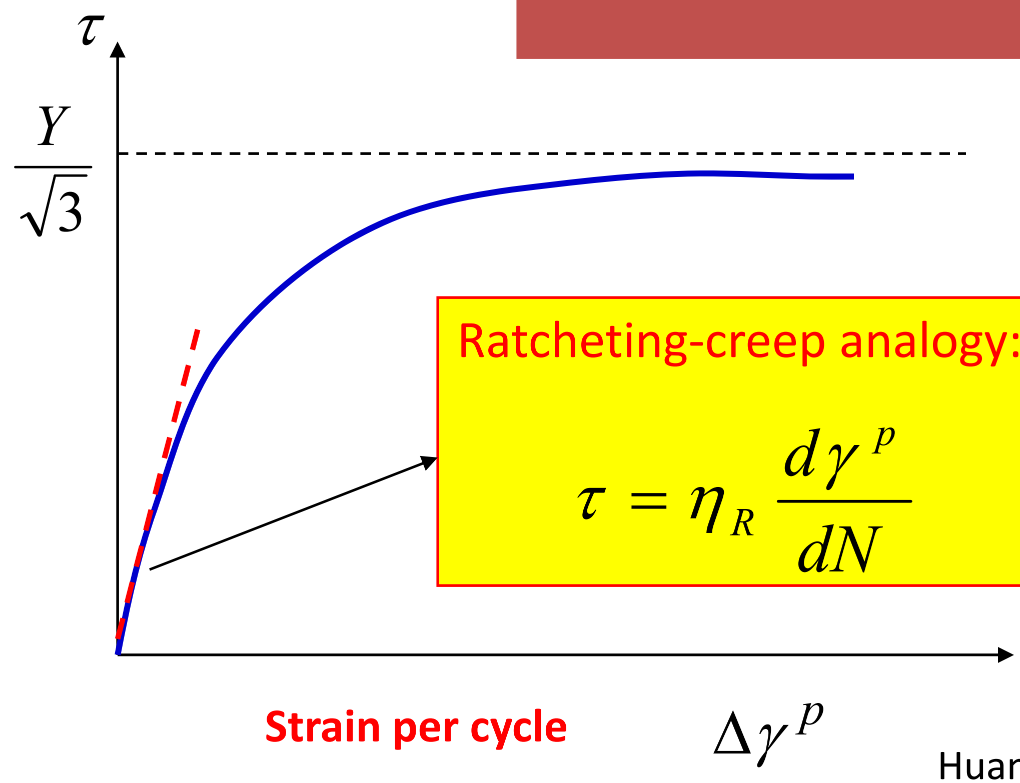

Uni-directional shear τ

cyclic stress σ

metal film

cyclic temperature

substrate

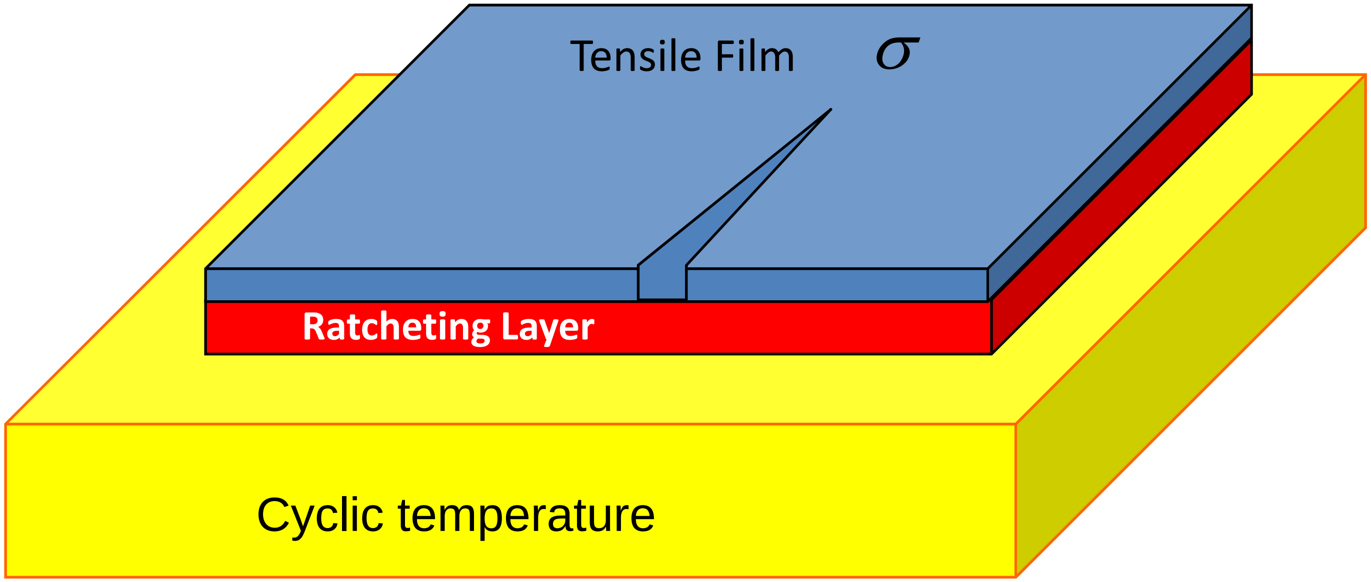


Ratcheting-creep analogy:

$$\tau = \eta_R \frac{d\gamma^p}{dN} \qquad \eta_R = \frac{E_m}{12(1-v_m)}\left[\frac{E_m\Delta\alpha\Delta T}{(1-v_m)Y} - 2\right]^{-1}$$

Huang, Suo, Ma, *Acta Materialia* **49**, 3039-3049 (2001).

Ratcheting-induced crack growth



Stress intensity factor of a stationary long crack:

$$K(N) = 1.103\sqrt{1-\nu^2}\,\sigma\left(\frac{\bar{E}hH}{\eta_R}N\right)^{1/4}$$

Steady state growth rate:

$$\frac{da}{dN} = 0.5\frac{\bar{E}Hh\sigma^2}{\eta_R K_c^2}$$

Liang *et al.*, *Experimental Mechanics* **43**, 269-279 (2003).

Summary : Effects of substrate constraint on fracture of elastic films

- On *elastic* substrates:
  - Weak constraint by a compliant substrate
  - Loss of constraint by interfacial delamination or substrate cracking

- On *viscoelastic* substrates:
  - Loss of constraint over time by substrate creep
  - delayed fracture
  - steady-state creep-modulated crack growth

- On *elastoplastic* substrates:
  - Loss of constraint due to plastic deformation of substrate
  - Plastic ratcheting induced crack growth under cyclic temperatures