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## Fracture of a Thin Laminated Foil: Lecture at ECF20 Trondheim, Noway. Orationem Meam.

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# Fracture of a Thin Laminated Foil

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## Layers and laminate properties

Metal foil (fully annealed AA1200 aluminium)      **Stiff and Brittle**

$$t_A = 9\mu\text{m}, E_A = 71\text{GPa}, \sigma_{bA} = 73\text{MPa}, \nu_L = 0.33, F_A = 12.5\text{N}$$

Polymer (PolyEthene LDPE, LD270)      **Weak and Soft**

$$t_L = 27\mu\text{m}, E_L = 126\text{MPa}, \sigma_{bL} = 8\text{MPa}, \nu_L = 0.45, F_L = 2\text{N}$$

The laminate (homogenized, plane stress)      **Stiff and Ductile**

$$t_{lam} = 36\mu\text{m}, E_{lam} = 18\text{GPa}, \sigma_{blam} = 27\text{MPa}, \nu_{lam} = 0.3, F_{lam} = 22.5\text{N}$$

## Necking vs fracture

Fracture toughness of aluminium is  $\approx 24 \text{ MPa m}^{1/2}$ .

Measured toughness of an  $9\mu\text{m}$  aluminium foil is  $3.5 \text{ MPa m}^{1/2}$  due to necking.

The stress intensity factor is

$$K \sim \text{sheet thickness}^{1/2}$$

A sheet thickness  $> 400\mu\text{m}$  is needed to restore  $K_{Ic}$  fracture control.

The largest load per unit of length

$$P \sim \text{sheet thickness}^{3/2}$$

A sheet thickness  $> 32\mu\text{m}$  is needed to provide the strength of a non necking  $9\mu\text{m}$  aluminium foil.

# The fracture mechanical test

Test specimen geometry:

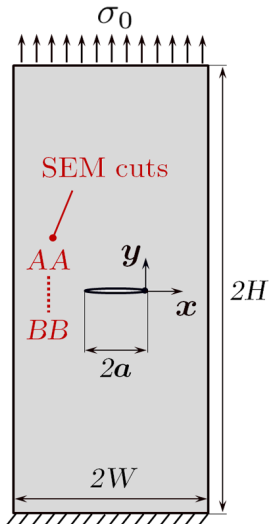
Crack lengths 2mm to 45mm,  
width 95mm and height 230mm

ASTM (D882-91): 2.5kN load cell,  
load speed 7 mm/min

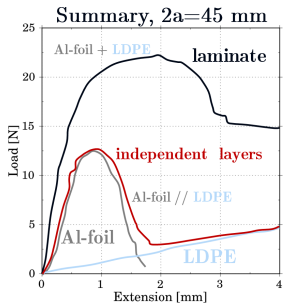
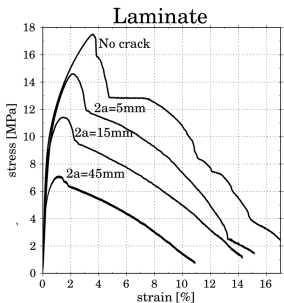
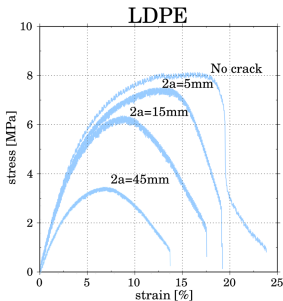
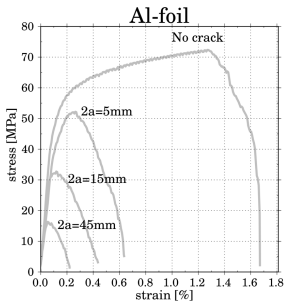
15keV Hitachi TM-1000-Tabletop SEM

50 $\mu$ m slices using a Leica mikrotome

Coated in a Cressington 108 auto sputter.



# Test results

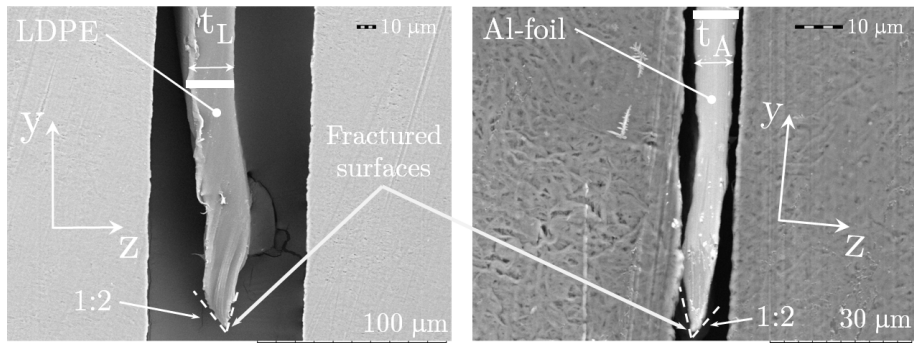


Stress vs. strain for tensile tests a) Al-foil (Majeed & Sharif, 2012), b) Polymer (Jemal & Katangoori, 2011)

a) Stress vs. strain for the laminate. b) Load vs. extension. Summary of the aluminium, polymer and laminate results. Crack length 45 mm. (Kao-Walter et al., 2002)

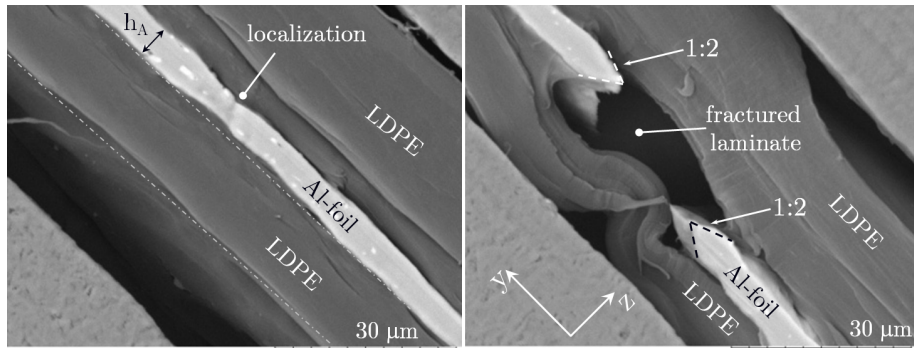
## Cross sections of the homogeneous materials

Without crack the polymer thickness decrease from  $27\mu\text{m}$  to  $10\mu\text{m}$ . (Jin&Wang, 2009). Here with a 45mm central crack.



Micrographs of the fractured cross-sections of freestanding polymer (left) and freestanding aluminium (right) layers stretched to fracture. Holders are seen on the sides of the specimen.

## Profiles laminates



Micrographs of localised plastic deformation in a double-sided coated aluminium. (left) Initiation of necking and (right) complete fracture of the aluminium layer.



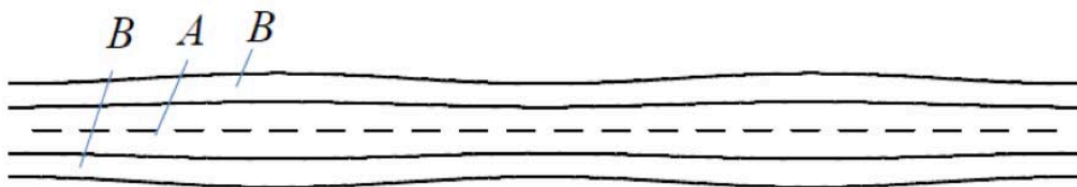
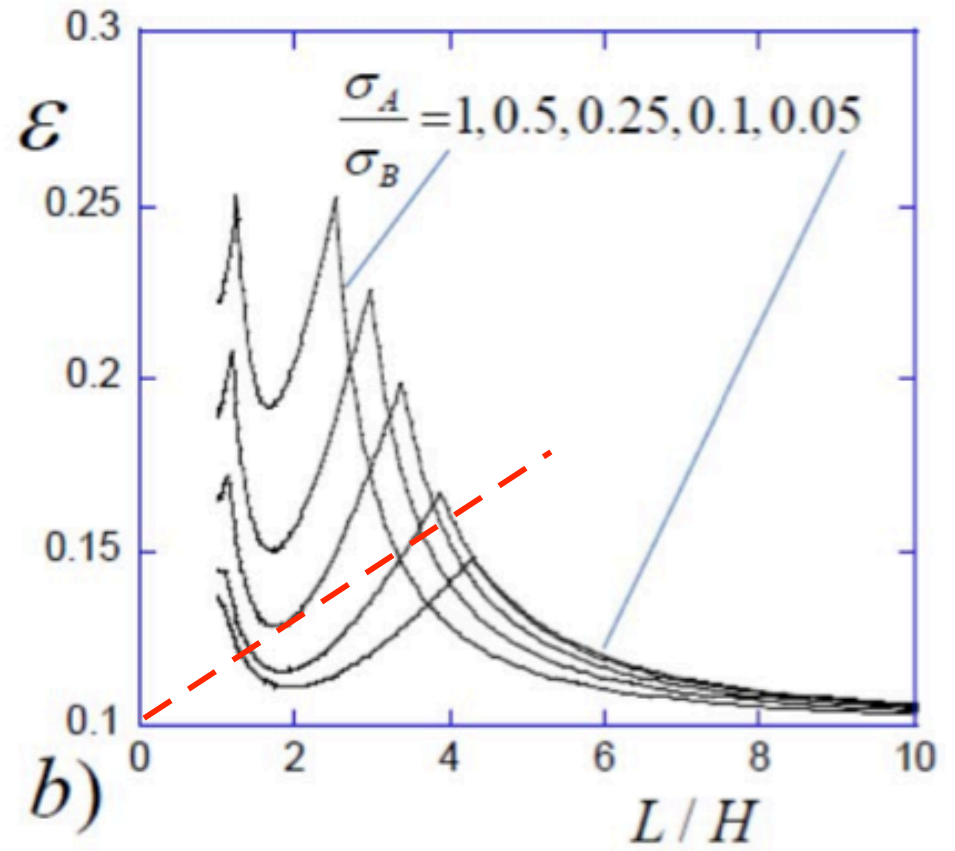
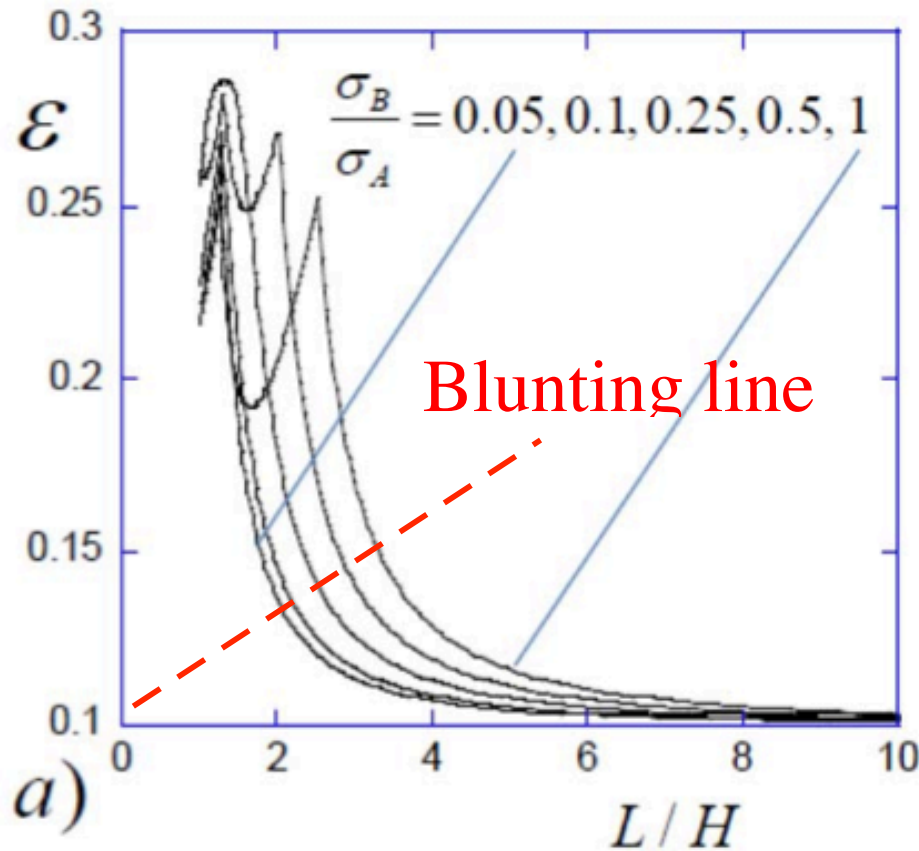
# The fracture process

1. Blunting of the crack tip to a sufficient width
2. A band of localised straining develops
3. Load carried decreases with decreasing neck cross-section  
(Barenblatt, 1959), (Dugdale, 1960), etc.
4. The polymer delays the necking of the aluminium foil  
(Kao-Walter, 2002), (Xue&Hutchinson, 2007), (Li&Suo, 2007), (Jia&Li, 2013)
5. The neck in the aluminium gives local straining in the polymer
6. The polymer does what it can to resist large straining
7. The polymer fails through necking (at a very small average strain)

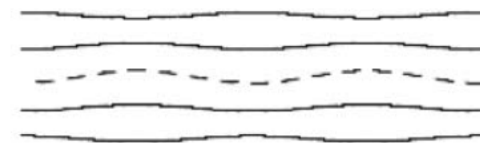
$$N_A = N_B = 0.1 \text{ and } h_A/h_B = 2$$

(Hutchinson, 2013)

$$\sigma_B/\sigma_A = 0.002 \text{ or } \sigma_A/\sigma_B = 0.002$$

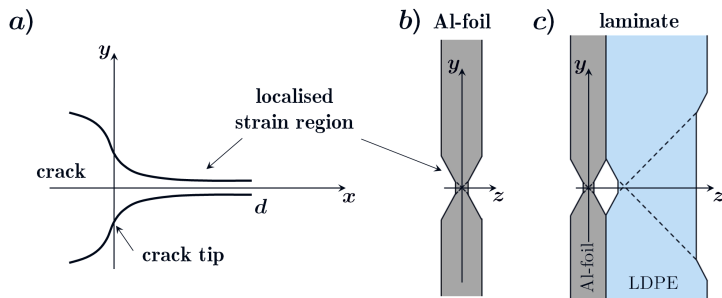


$L/H = 10$ , symmetric mode



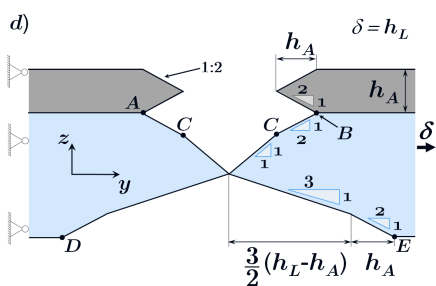
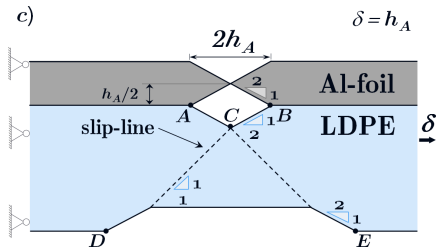
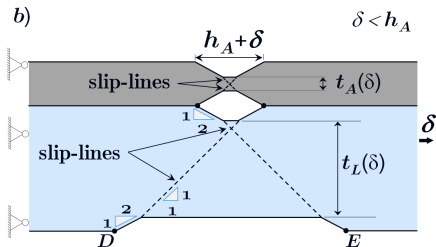
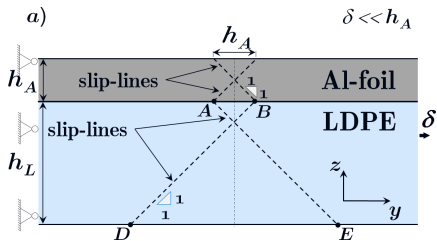
$L/H = 2$ , anti-symmetric mode

# Work of failure



Strip yield zone ahead a crack tip. a) the crack geometry in the plane  $z = 0$ . b and c) the slip region as seen in a plane  $x = \text{const}$ .

# Localised plastic deformation



## Mechanics of the neck

$F$ , per unit of length

$$F = \sigma_y t = \frac{2}{\sqrt{3}} \sigma_b t \approx 1.15 \sigma_b t, \quad (1)$$

$$F = \frac{2}{\sqrt{3}} (\sigma_{bA} t_A + \sigma_{bL} t_L), \quad (2)$$

$$V - V_o = (h_A + \delta - t_A)(h_A + t_a)/2 + t_A^2 - h_A^2 = \frac{1}{2}(\delta + t_A - h_A)(t_A + h_A). \quad (3)$$

$$t_A(\delta) = h_A - \delta. \quad (4)$$

$$\frac{dz}{dy} = \pm \frac{h_A - t_A}{h_A + \delta - t_A} = \pm \frac{1}{2}. \quad (5)$$

$$dz/dy = \pm 1. \quad dz/dy = \pm 1/3,$$

## Mechanics of the neck

von Mises effective stress,  $\sigma_e$ , and the stress at break,  $\sigma_b$ , becomes

$$\sigma_e = \sqrt{\frac{(\sigma_x - \sigma_y)^2}{2}} = \frac{\sqrt{3}}{2}\sigma_y \approx 0.866\sigma_y = \sigma_b, \quad (2)$$

$F$ , per unit of length

$$F = \sigma_y t = \frac{2}{\sqrt{3}}\sigma_b t \approx 1.15\sigma_b t, \quad (3)$$

$$F = \frac{2}{\sqrt{3}}(\sigma_{bA}t_A + \sigma_{bL}t_L), \quad (4)$$

$$V = (h_A + \delta - t_A)(h_A + t_A)/2 + t_A^2.$$

$$V - V_o = (h_A + \delta - t_A)(h_A + t_A)/2 + t_A^2 - h_A^2 = \frac{1}{2}(\delta + t_A - h_A)(t_A + h_A). \quad (5)$$

$$t_A(\delta) = h_A - \delta. \quad (6)$$

## Strength of the necking region

$$t_A(\delta) = h_A - \delta \quad \text{and} \quad t_L(\delta) = h_L - \delta \quad \text{for} \quad \delta < h_A, \quad (8)$$

$$t_A(\delta) = 0 \quad \text{and} \quad t_L(\delta) = h_L - \delta \quad \text{for} \quad h_A \leq \delta < h_L, \quad (9)$$

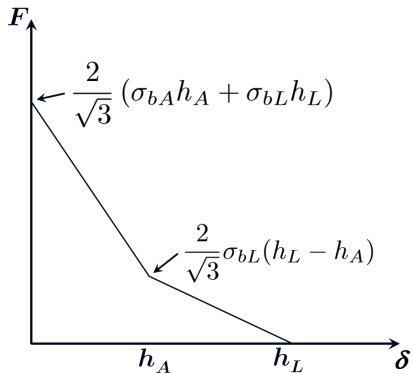
and

$$t_A(\delta) = t_L(\delta) = 0 \quad \text{for} \quad h_L \leq \delta. \quad (10)$$

Force per unit of length:

$$\begin{cases} F = \frac{2}{\sqrt{3}}[\sigma_{bA}h_A + \sigma_{bL}h_L - (\sigma_{bA} + \sigma_{bL})\delta] & \text{for } \delta < h_A, \\ F = \frac{2}{\sqrt{3}}\sigma_{bL}(h_L - \delta) & \text{for } h_A \leq \delta < h_L, \\ F = 0 & \text{for } h_L \leq \delta. \end{cases} \quad (11)$$

## Cohesive properties



Force in the  $y$ -direction per unit of length in the  $x$ -direction versus displacement across the band of localised strain. The force represents the load carrying capacity of the band of localised strain.



## Work of failure, critical stress

Work of failure - J-integral for a path surrounding the cohesive zone:

$$J_c = \frac{1}{h_A + h_L} \int_0^d F(\delta) \frac{\partial \delta}{\partial v} dv = \frac{1}{h_A + h_L} \int_0^{h_A + h_L} F(\delta) d\delta. \quad (11)$$

$$J_c = \frac{1}{\sqrt{3}} \left( \frac{\sigma_{bA} h_A^2 + \sigma_{bL} h_L^2}{h_A + h_L} \right). \quad (12)$$

Critical stress based on cohesive zone law and an assumed small scale yielding.

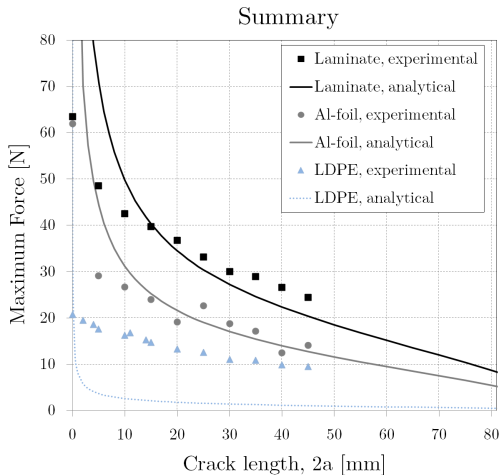
$$\sigma_c = \sqrt{J_c \frac{E}{\pi a \phi \left( \frac{a}{W} \right)}} = \sqrt{\frac{1}{\sqrt{3}} \left( \frac{\sigma_{bA} h_A^2 + \sigma_{bL} h_L^2}{h_A + h_L} \right) \frac{E}{\pi a \phi \left( \frac{a}{W} \right)}}. \quad (13)$$

# Material parameters

Comparison of structural and material parameters for the different test specimens.

	Al-foil	LDPE	laminate
$h[\mu m]$	9,0	27	36
$E [GPa]$	71,0	0.126	17.9
$\nu[-]$	0.3	0.45	0.3
$\sigma_b [MPa]$	73.0	8.0	26.6
$J_c [N/m]$	188	82.6	109

# Critical stress

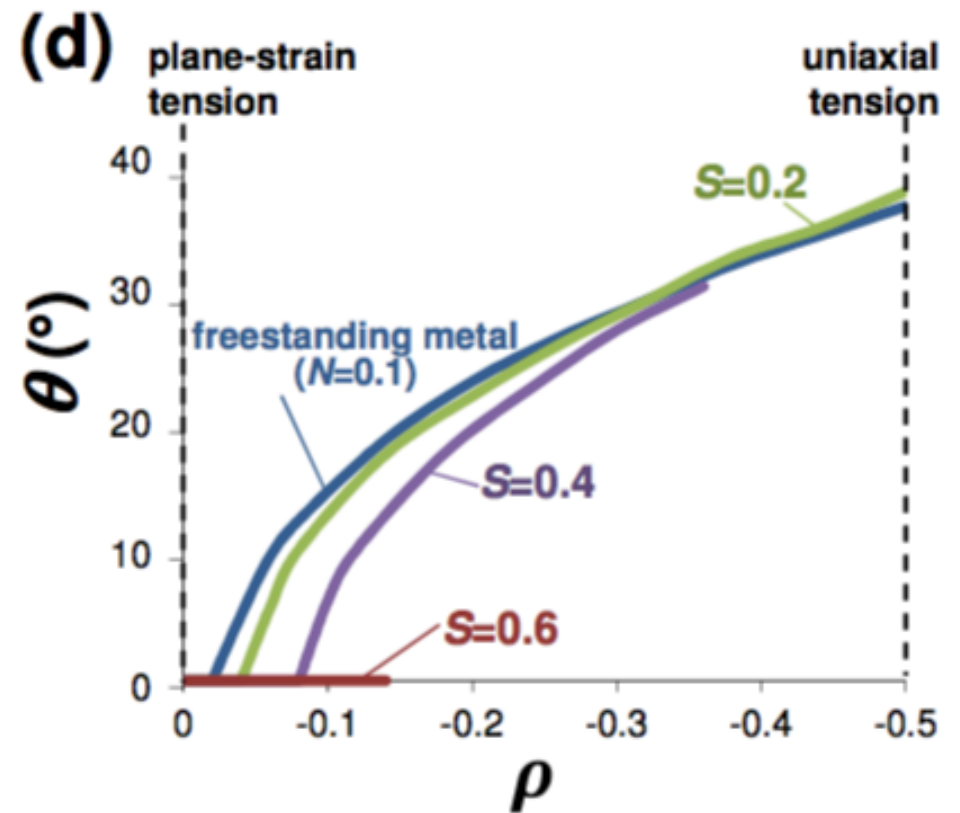
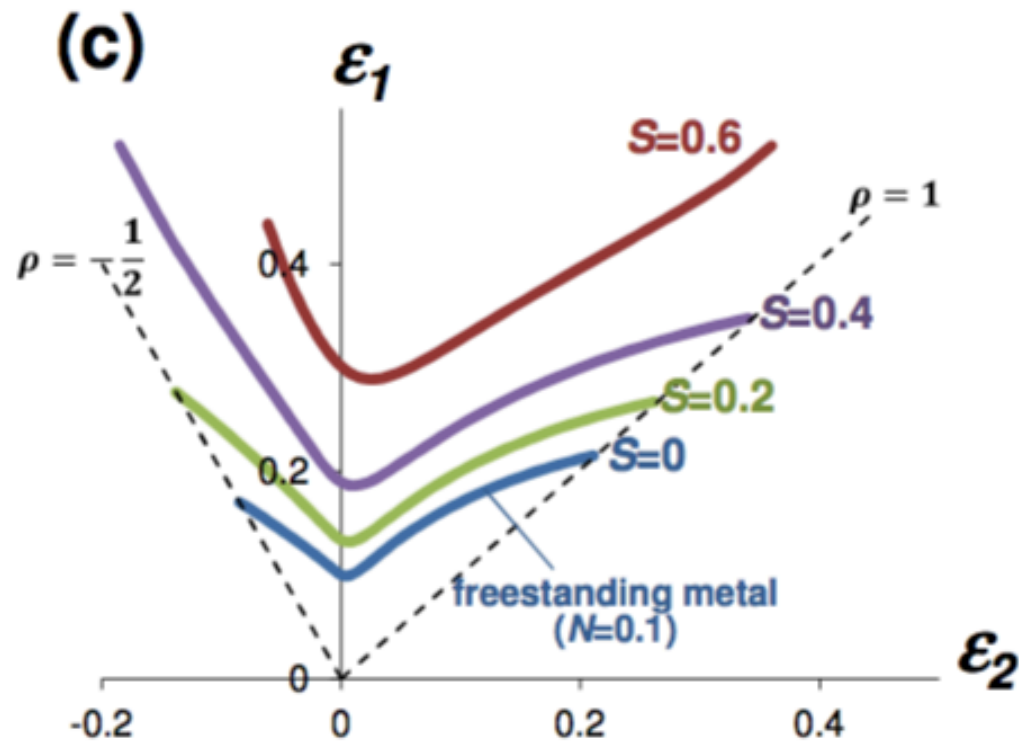


Force vs. crack length of LDPE, Al-foil and Laminate.

(Jia&Li, 2013)

Neo-Hookean polymer and power-law metal ( $N=0.1$ )

$$S = EH/Kh = 0.005$$



# Conclusions

- The initiation of necking in an aluminium foil is delayed by a weak polymer layer.
- The polymer is preliminary expected to increase the toughness of the aluminium by 10% but is found add near a 100%.
- A necking model predicts the toughness of the single aluminium foil and the aluminium-polymer laminate but fails to describe the single polymer film.
- A mechanism for a propagating necking might be arranged with proper materials selection.