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

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

Necking vs fracture

Fracture toughness of aluminium is ≈ 24 MPa m$^{1/2}$.
Measured toughness of an 9μm aluminium foil is 3.5 MPa m$^{1/2}$ due to necking.

The stress intensity factor is

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

A sheet thickness $> 400\mu$m is needed to restore $K_{\mathrm{I}c}$ fracture control.

The largest load per unit of length

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

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

The fracture mechanical test

Test specimen geometry:

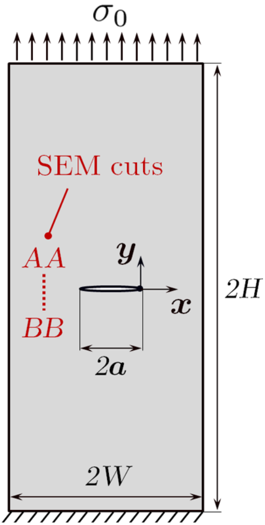
Crack lengths 2mm to 45mm,
width 95mm and height 230mm

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

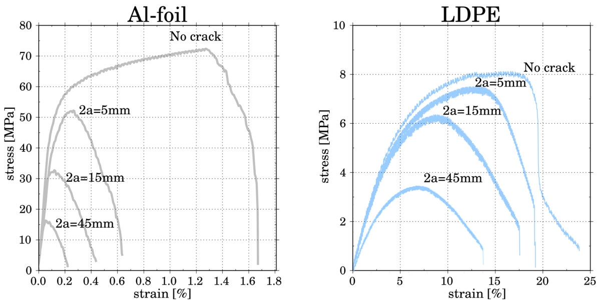
15keV Hitachi TM-1000-Tabletop SEM

50μm slices using a Leica mikrotome

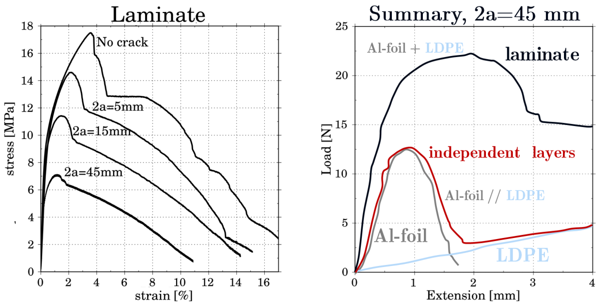
Coated in a Cressington 108 auto sputter.



Test results



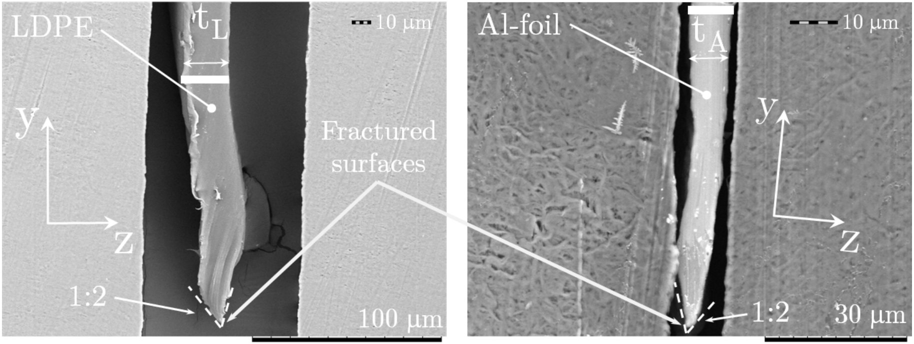
Stress vs. strain for tensile tests a) Al-foil (Majeed &Sharif, 2012), b) Polymer (Jemal &Katangoori, 2011)



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)

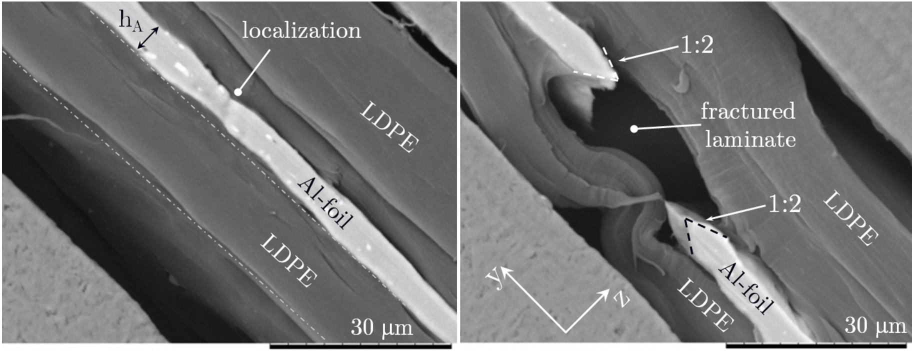
Cross sections of the homogeneous materials

Without crack the polymer thickness decrease from 27μm to 10μm. (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.

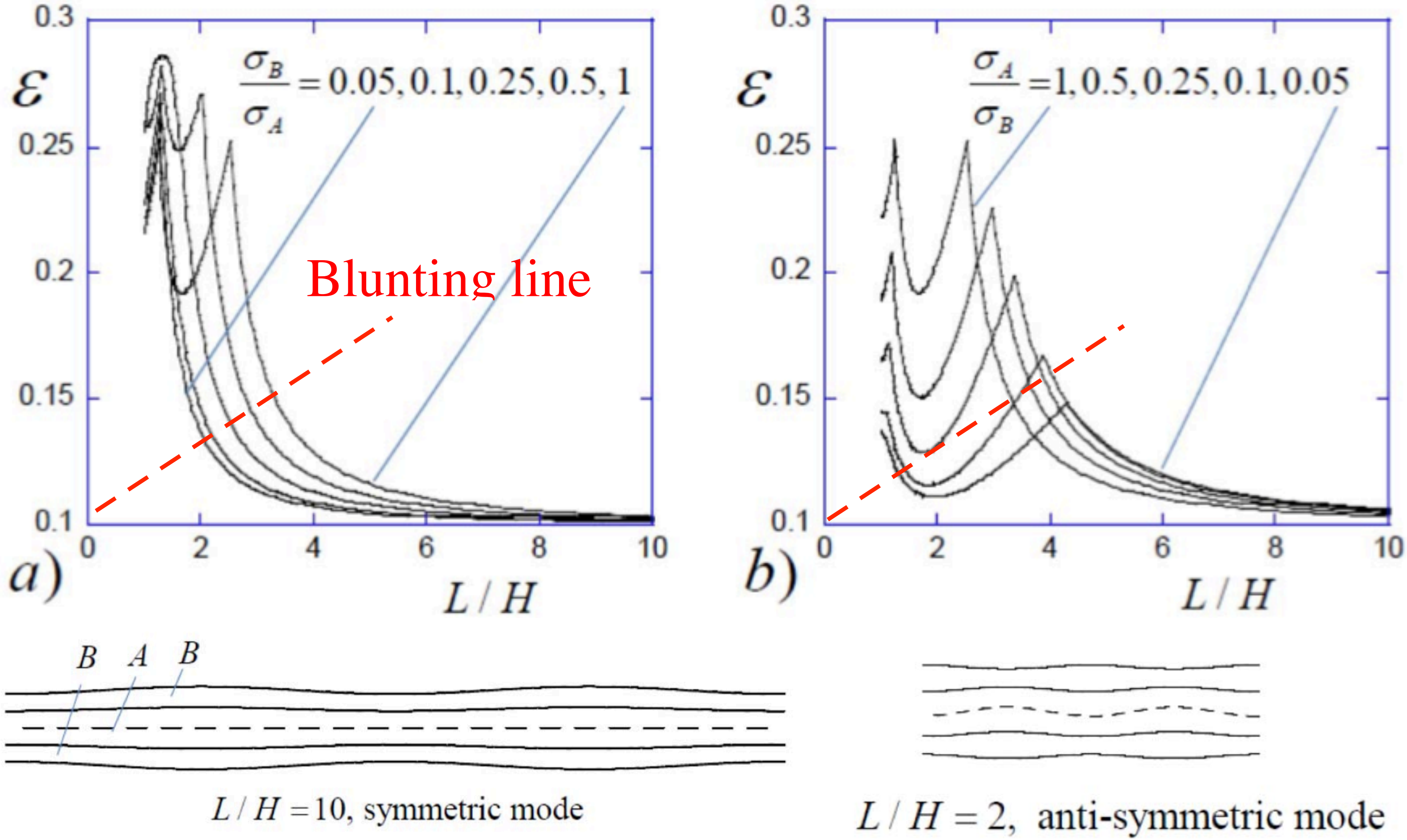
4. The polymer delays the necking of the aluminium foil

(Kao-Walter, 2002), (Xue&Hutchinson, 2007), (Li&Suo, 2007), (Jia&Li, 2013)

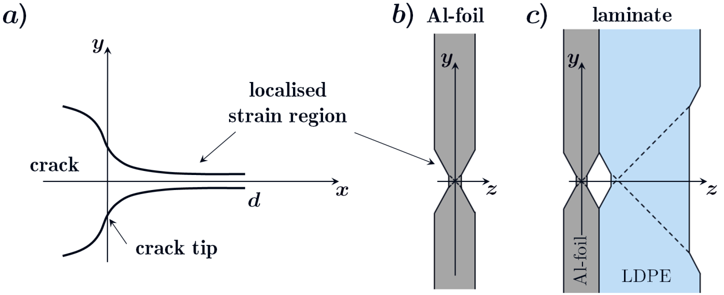
5. The neck in the aluminium gives local straining in the polymer
6. The polymer does what it can to resist large straining
7. The polymer fails through necking (at a very small average strain)

$N_A = N_B = 0.1$ and $h_A/h_B = 2$ (Hutchinson, 2013)

$\sigma_B/\sigma_A = 0.002$ or $\sigma_A/\sigma_B = 0.002$

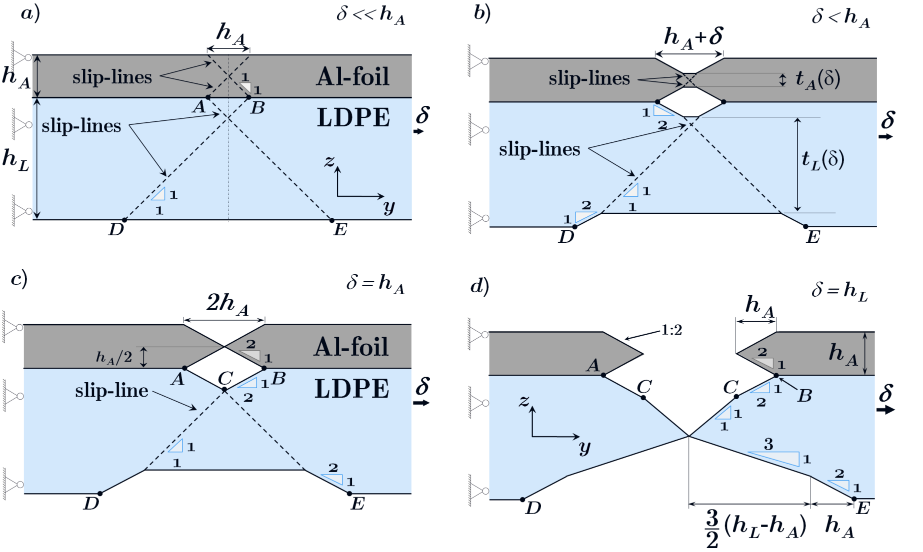


Work of failure



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

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

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

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

$$t_A(\delta) = h_A - \delta \,. \tag{4}$$

$$\frac{\mathrm{d}z}{\mathrm{d}y} = \pm \frac{h_A - t_A}{h_A + \delta - t_A} = \pm \frac{1}{2} \,. \tag{5}$$

$$\mathrm{d}z/\mathrm{d}y = \pm 1. \;\; \mathrm{d}z/\mathrm{d}y = \pm 1/3,$$

Mechanics of the neck

von Mises effective stress, σ_e, and the stress at break, σ_b, becomes

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

F, per unit of length

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

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

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

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

$$t_A(\delta) = h_A - \delta \,. \tag{6}$$

Strength of the necking region

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

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

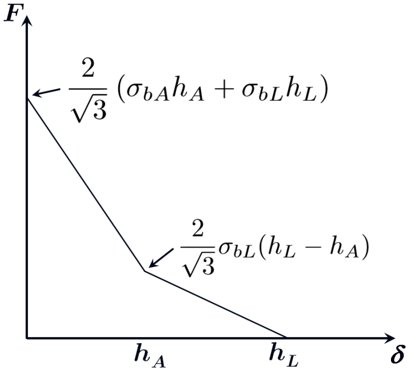
and

$$t_A(\delta) = t_L(\delta) = 0 \qquad \text{for} \quad h_L \le \delta\,. \tag{10}$$

Force per unit of length:

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

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:

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

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

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

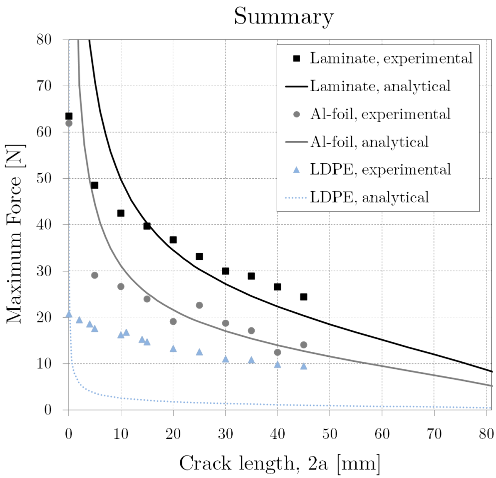
$$\sigma_c = \sqrt{J_c \frac{E}{\pi a}} \frac{1}{\phi\left(\frac{a}{W}\right)} = \sqrt{\frac{1}{\sqrt{3}} \left(\frac{\sigma_{bA} h_A^2 + \sigma_{bL} h_L^2}{h_A + h_L} \right) \frac{E}{\pi a}} \frac{1}{\phi\left(\frac{a}{W}\right)} \,. \tag{13}$$

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
$\upsilon[-]$	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

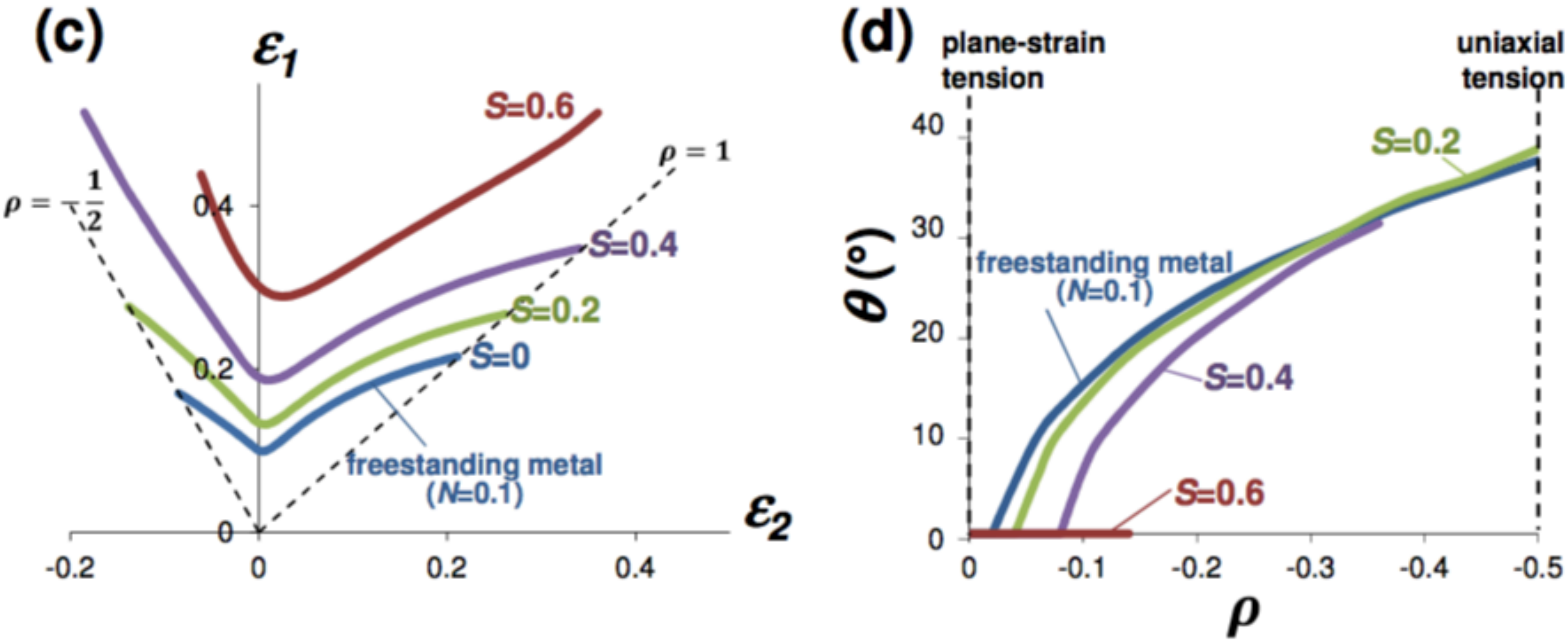


Force vs. crack length of LDPE, Al-foil and Laminate.

(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.