Some Observation Regarding Soft-Hard Laminates

Invited Talk, MFAPI conference at Shanghai University, Orationem Meam

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Tough Elastic Plastic Laminates through Instigated Strain Localisation

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Some Observations Regarding Soft-Hard Laminates

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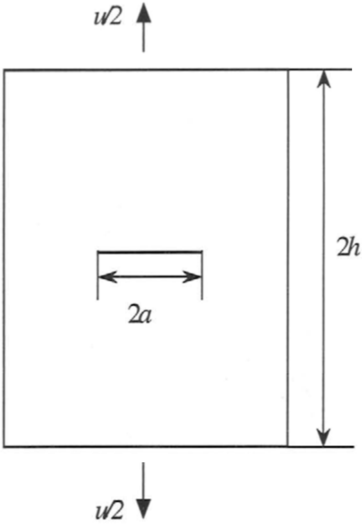
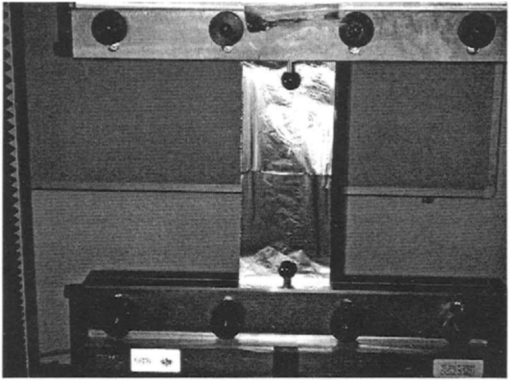
specimen and experimental setup



(a). *Centre cracked panel.*



(b). *Set-up for fracture mechanical testing of laminated composites. The specimen shown here is case 4.*

Fracture mechanical test

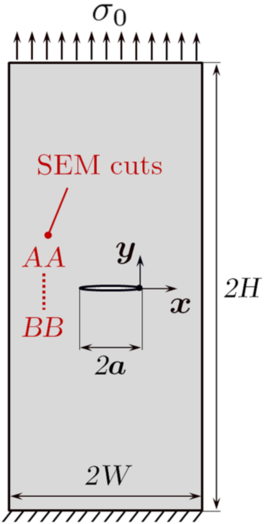
Crack lengths 2 to 45mm
Sheet width 95mm height 230mm

Load cell 2.5kN, speed 7mm/min

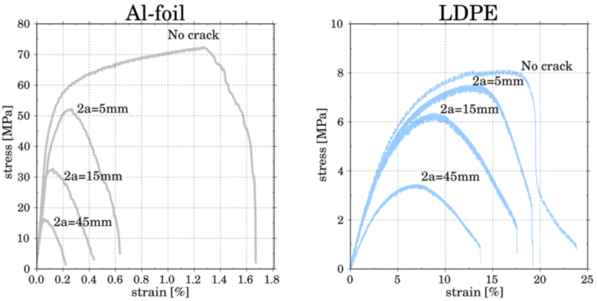
15keV Hitachi TM-1000-Tabletop SEM

50μm slices using a Leica mikrotome

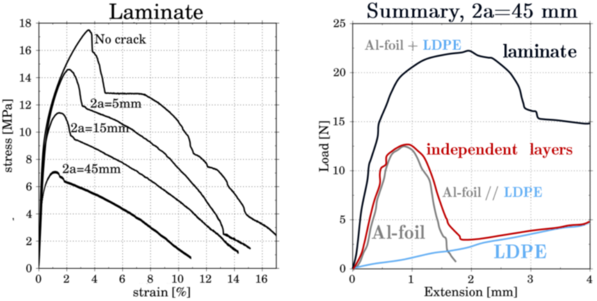
Coated in a Cressington 108 auto sputter



Tensile tests



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)

Layers and laminate properties

Metal foil (fully annealed AA1200 aluminium) Stiff and Brittle

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

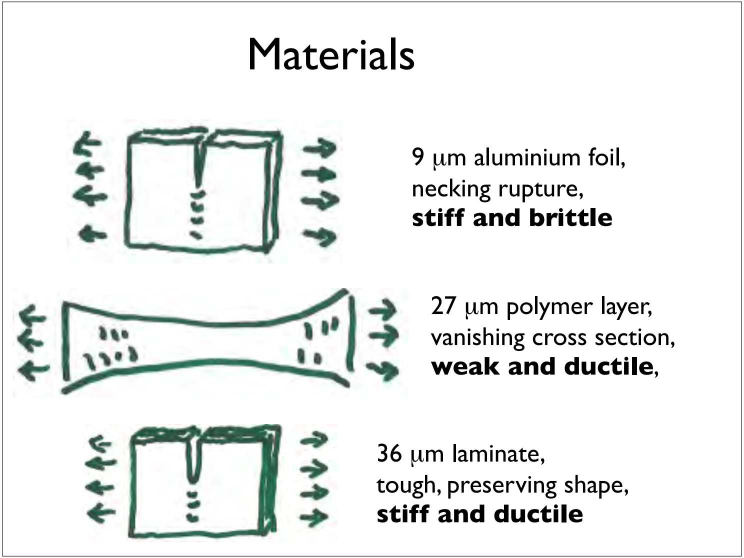
Polymer (PolyEthene LDPE, LD270) Weak and Soft

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

The laminate (homogenized, plane stress) Stiff and Ductile

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

Materials involved



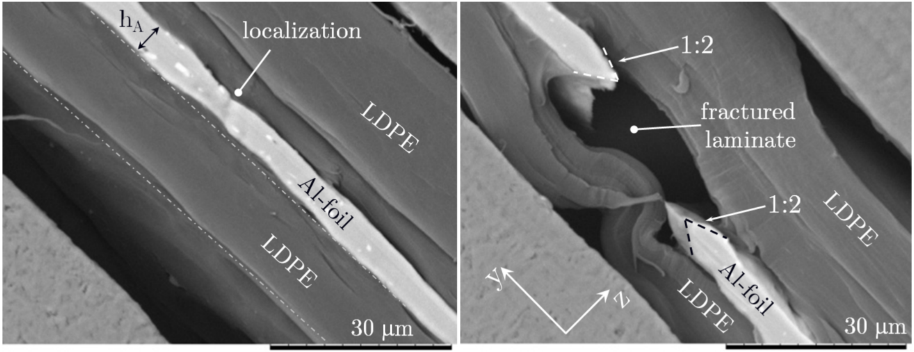
Materials

9 µm aluminium foil,
necking rupture,
stiff and brittle

27 µm polymer layer,
vanishing cross section,
weak and ductile,

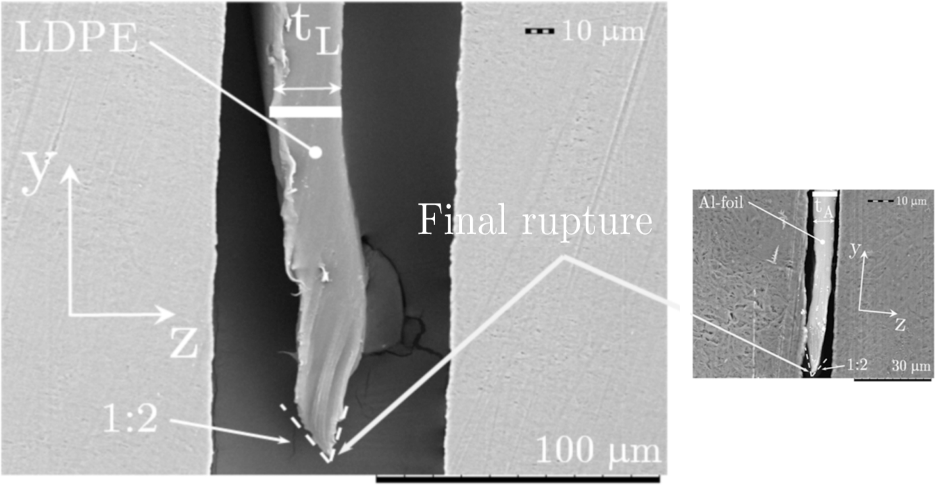
36 µm laminate,
tough, preserving shape,
stiff and ductile

Post test SEM images



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

SEM micrographs



Micrographs of cross-sections of freestanding polymer and freestanding aluminium foils stretched to failure. Initial crack length 45mm

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

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

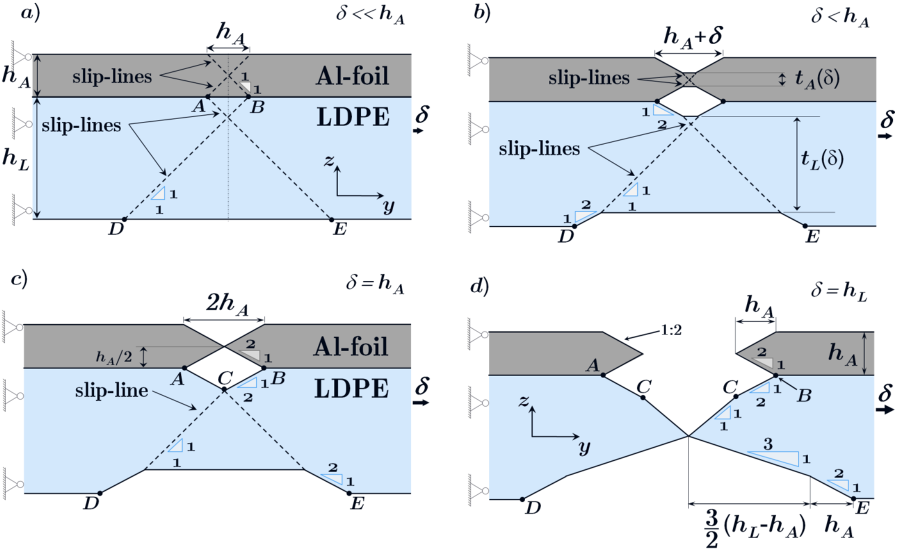
A sheet thickness $> 400\mu$m is needed to restore $K_{\mathrm{I}c}$ fracture control.

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.

Necking - Localised plastic deformation



Slip-line solutions composed of constant stress fields

Limit load leading to total delamination

Released energy from the detached layer

$$G = \frac{\epsilon^2 E h}{2}$$

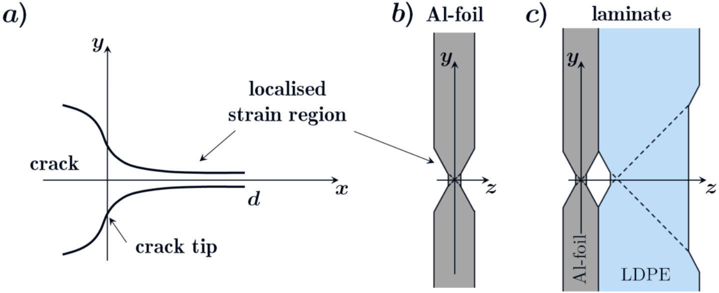
A delamination test determines the required

$$G_i = G$$

Fracture mechanical properties gives the required energy if the crack chooses to grow in the substrate

$$G_{sub} = G = \frac{K^2_{\mathrm{I}c,\mathrm{sub}}}{E_{\mathrm{sub}}}$$

Work of failure



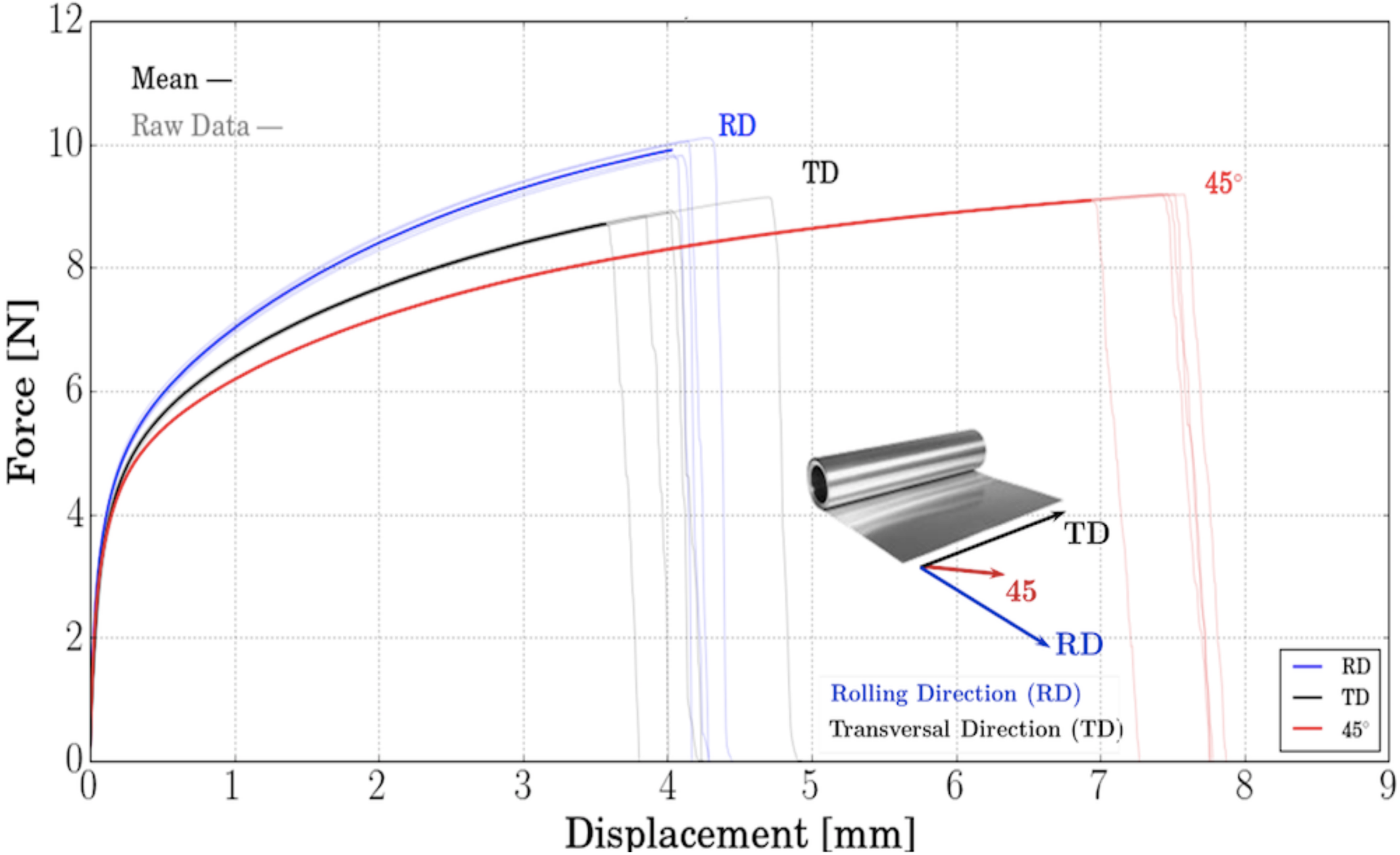
Strip yield zone ahead a crack tip. a) the crack geometry in the plane $z = 0$. b) the slip region as seen in a plane $x =$ const. in the region $0 \leq x \leq d$ for the Al-foil and c) in the laminate.

$$J_c = \frac{1}{h_A + h_L} \int_0^{h_A+h_L} F(\delta)\mathrm{d}\delta = \frac{1}{\sqrt{3}} \left(\frac{\sigma_{bA} h_A^2 + \sigma_{bL} h_L^2}{h_A + h_L} \right) .$$

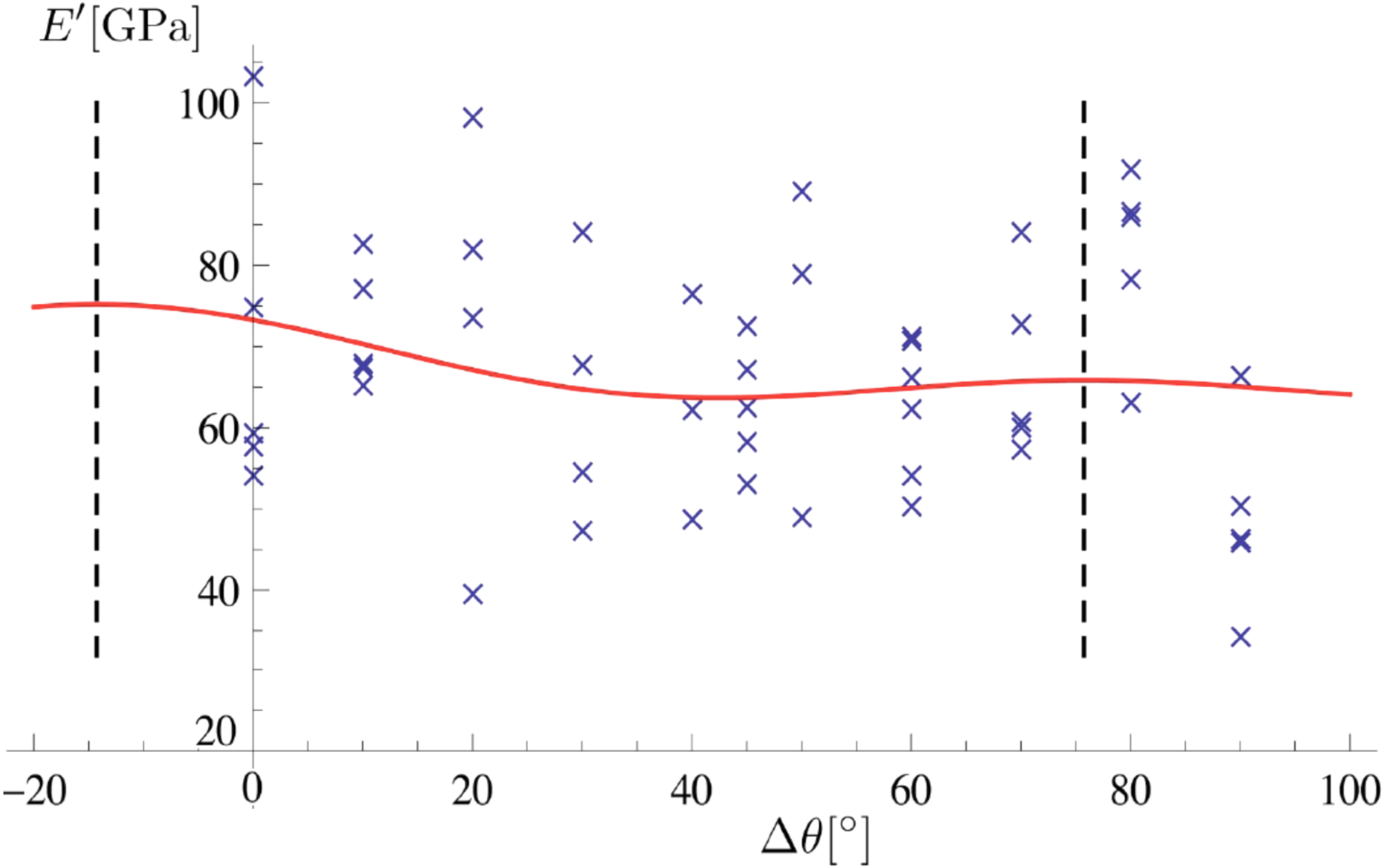
The fracture process

1. Increasing load blunts the crack tip
(Levy et al., 1971), (McMeeking, 1977).
2. A band of localised straining
(Dugdale, 1960), (Suo et al., 2010), (Kroon&Elmukashfi, 2013).
3. The load carrying capacity decreases at increasing straining
(Barenblatt, 1959), (Needleman et al., 2013), (Tvergaard&Hutchinson, 2012).
4. The polymer interferes with the necking process
(vanderGiessen&Needleman, 2002), (Sedighiamiri et al., 2011), (Kao-Walter, 2002).
5. The polymer gives its utmost to prevent necking of the aluminium
(Hutchinson, 2013)
6. The aluminium fails, the polymer fails through necking

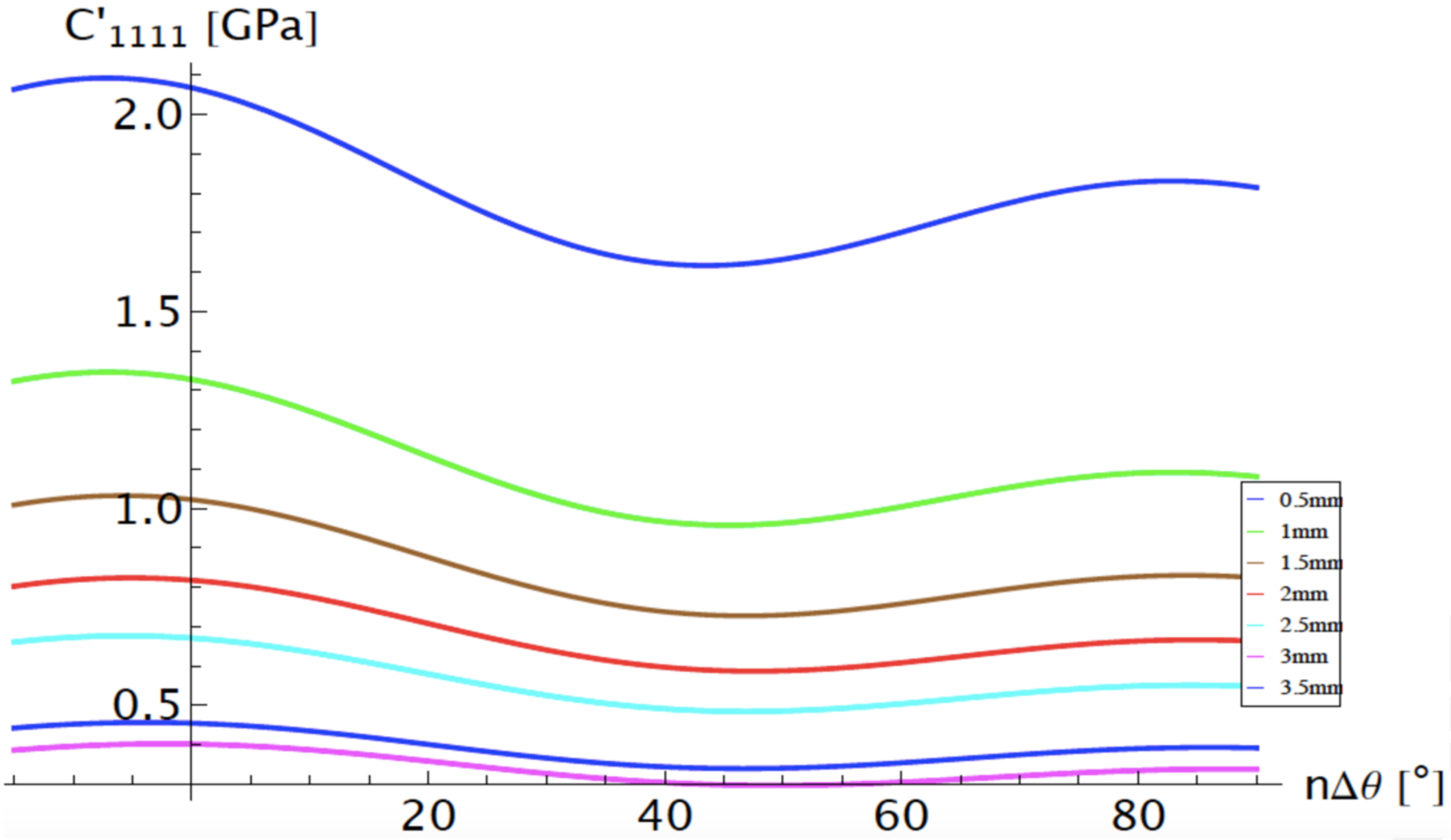
Tensile test results



Elastic modulus of 0° rolled aluminium



Decresing anisotropy with increasing stretching



Mechanics of the neck

F, per unit of length

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

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

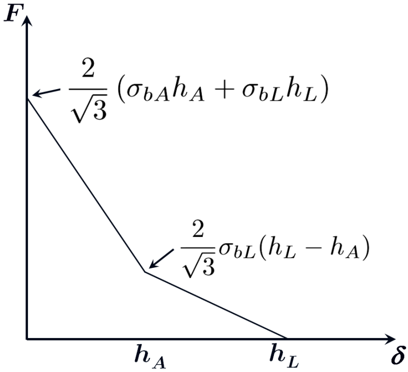
$$V - V_o = (h_A + \delta - t_A)(h_A + t_a)/2 + t_A^2 - h_A^2 = \frac{1}{2}(\delta + t_A - h_A)(t_A + h_A) \,. \tag{3}$$

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

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

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

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:

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

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

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

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

Strength of the necking region

(Dugdale, 1960), (Merchant et al., 1999), (Kao-Walter et al., 2002).

$$t_A(\delta) = h_A - \delta \quad \text{and} \quad t_L(\delta) = h_L - \delta \qquad \text{for} \quad \delta < h_A\,, \tag{6}$$

$$t_A(\delta) = 0 \quad \text{and} \quad t_L(\delta) = h_L - \delta \qquad \text{for} \quad h_A \leq \delta < h_L\,, \tag{7}$$

and

$$t_A(\delta) = t_L(\delta) = 0 \qquad \text{for} \quad h_L \leq \delta\,. \tag{8}$$

Force per unit of length

$$\begin{cases} F = \frac{2}{\sqrt{3}}[\sigma_{bA} h_A + \sigma_{bL} h_L - (\sigma_{bA} + \sigma_{bL})\delta] & \text{for} \;\; \delta < h_A\,, \\ F = \frac{2}{\sqrt{3}}\sigma_{bL}(h_L - \delta) & \text{for} \;\; h_A \leq \delta < h_L\,, \\ F = 0 & \text{for} \;\; h_L \leq \delta\,. \end{cases} \tag{9}$$

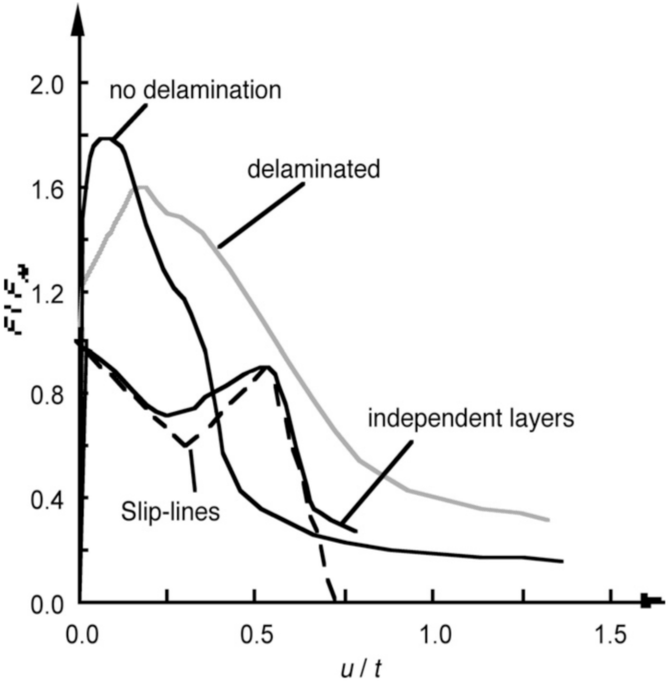
Material parameters

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

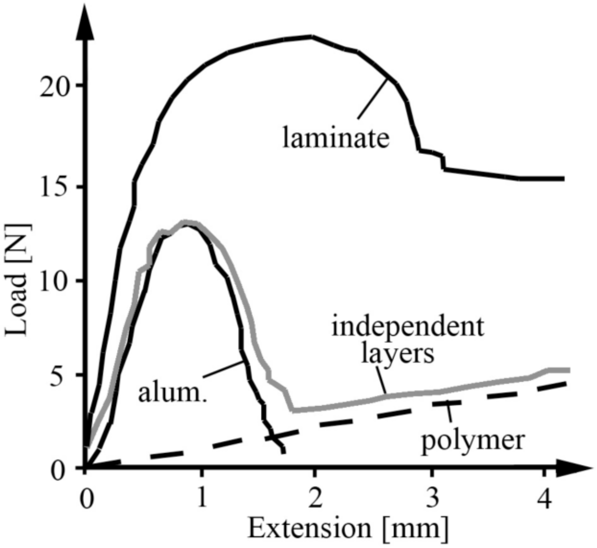
	Al-foil	LDPE	laminate
$h[\mu m]$	9,0	27	36
E $[GPa]$	71,0	0.126	17.9
$\upsilon[-]$	0.33	0.45	0.30
σ_b $[MPa]$	73.0	8.0	26.6
J_c $[N/m]$	188	82.6	109
F_{max} $[N]$ $\{2a{=}45mm\}$	14,0	9,4	24,4

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

Simulated and observed results

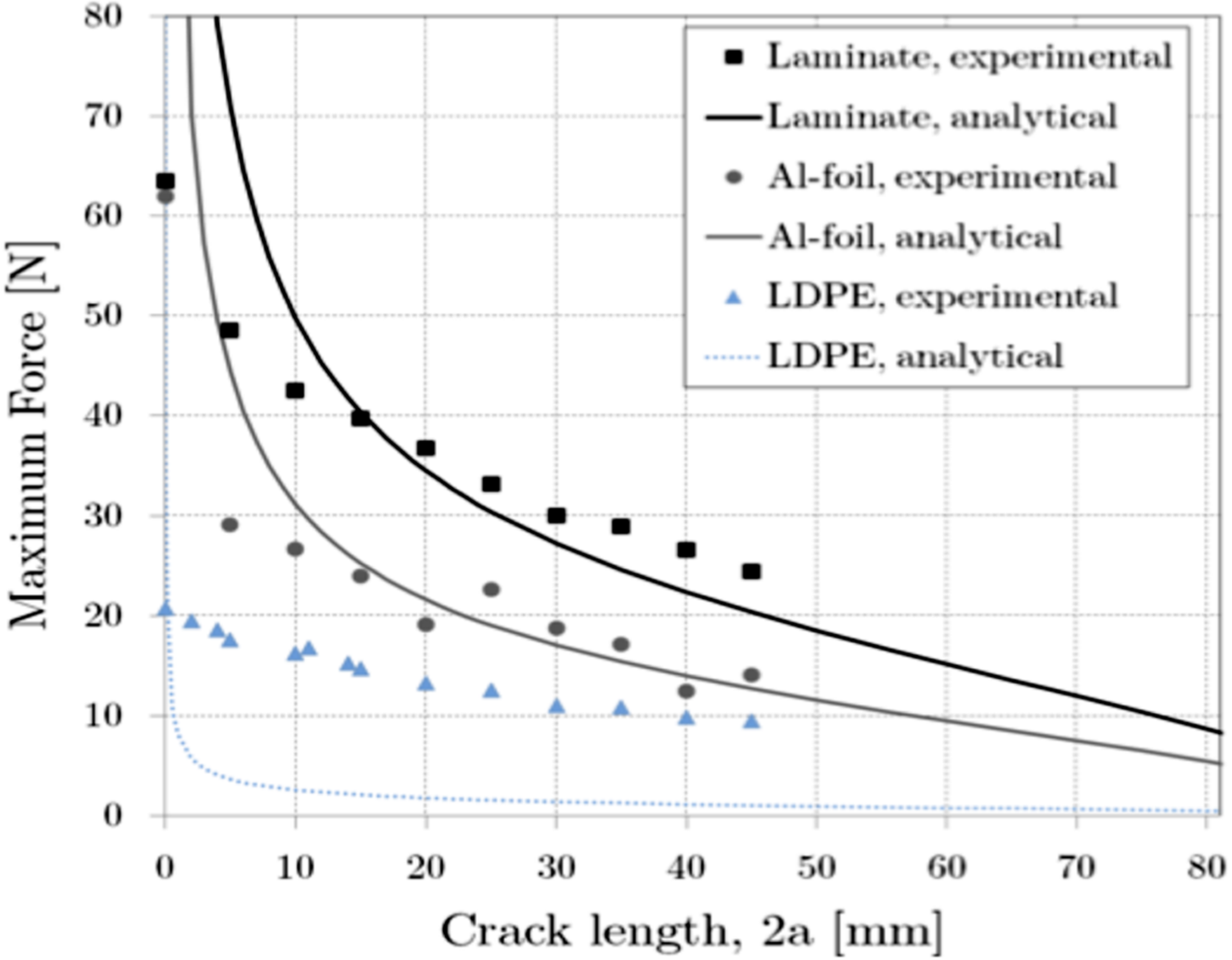


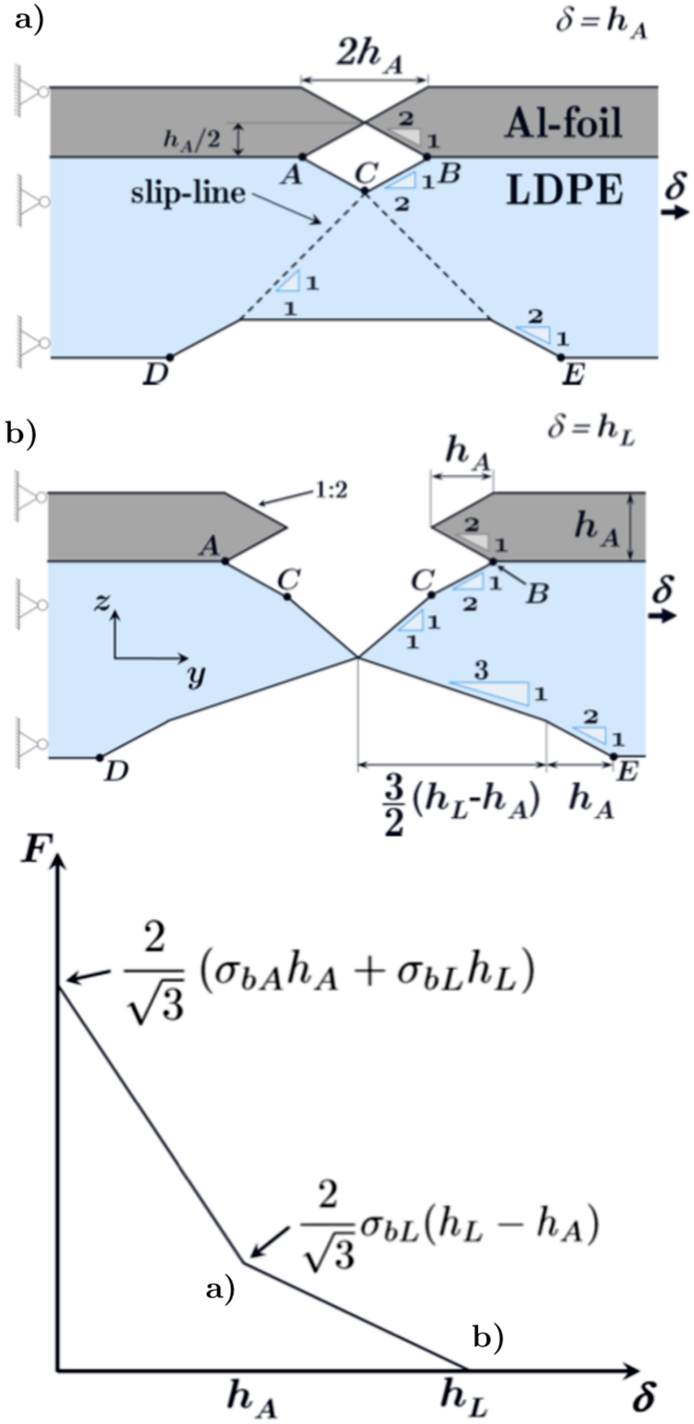
Simulated
short specimens



Long specimens,
observations
(fracture)

Cohesive zone results

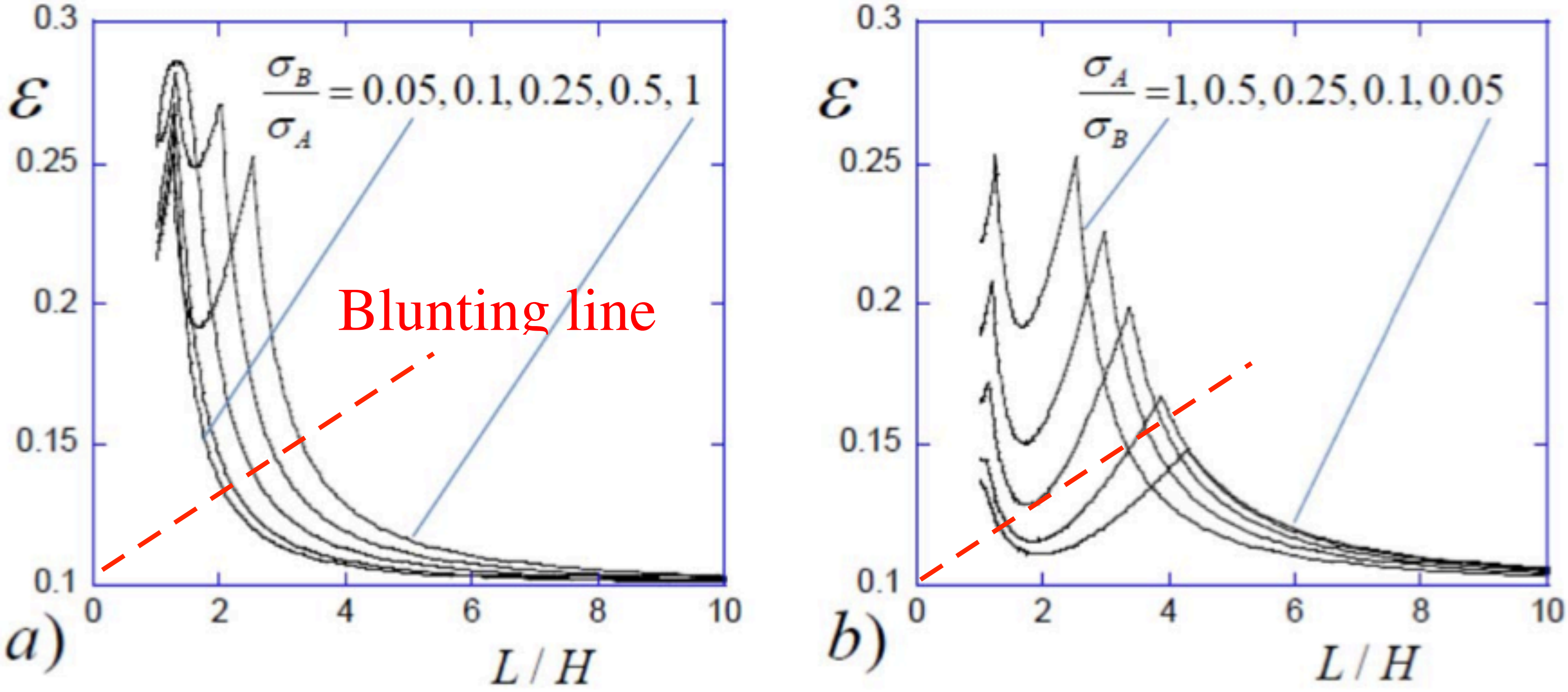


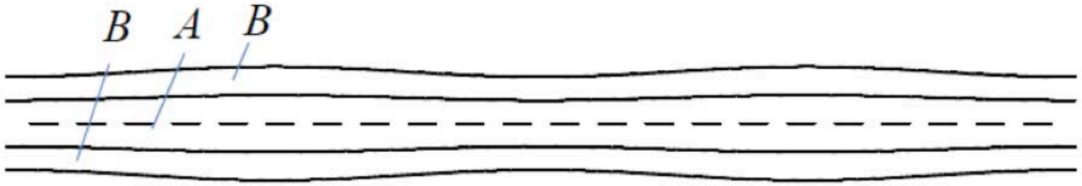


$N_A = N_B = 0.1$ and $h_A/h_B = 2$

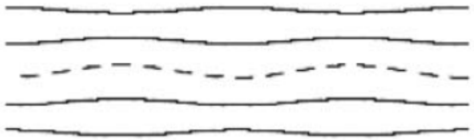
(Hutchinson, 2013)

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





$L/H = 10$, symmetric mode



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

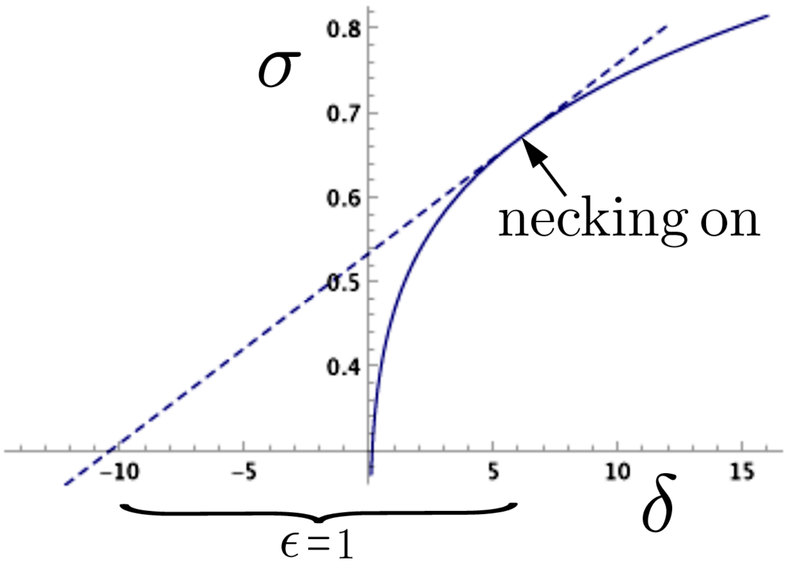
Multiple Necking

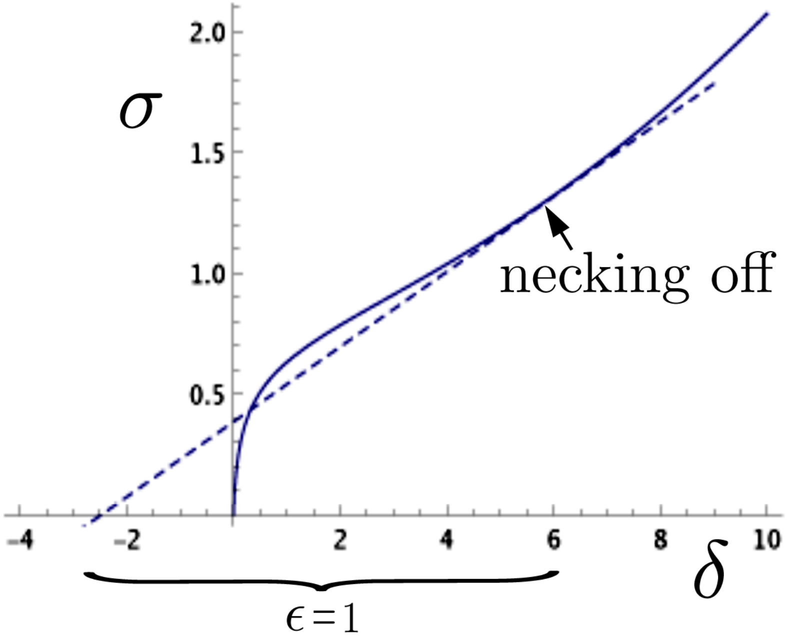
The force increase rate

$$\frac{\mathrm{d}F}{\mathrm{d}\delta} = \frac{A}{\ell}\left(\frac{\mathrm{d}\sigma}{\mathrm{d}\epsilon} - \sigma\right)$$

which gives

$$\frac{\mathrm{d}F}{\mathrm{d}\delta} = 0 \;\Rightarrow\; \frac{\mathrm{d}\sigma}{\mathrm{d}\epsilon} = \sigma$$

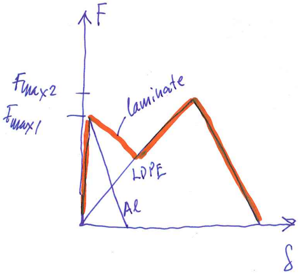




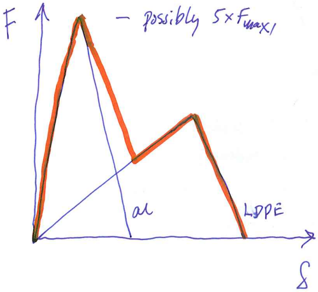
Other possible scenarios

Different adhesives and different materials

strong polym.



high adhesion



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.

Conclusions

- Fracture toughness computed from micro-mechanical processes.
- A slip-line theory verifies the toughness of the freestanding aluminium foil and the aluminium-polymer laminate.
- The slip-line theory fails to predict the freestanding polymer film.
- The necking of the aluminium is postponed to larger straining. Possibly the neckning of the polymer is advanced. Both give higher load resistance than expected.
- A mechanism for multiple necking is foreseen. n-multiple neckning gives a $\sqrt{n}$-folded increase of the fracture tougness.
- A mechanism for prevention of necking in the aluminium is foreseen. This may give a five-folded increase of the fracture toughness.

Conclusions

- A micro-mechanical approach utilizing SEM-micrographs, micro-mechanisms, and analytical expressions motivated the derivation of an analytical expression suitable to calculate the fracture toughness of freestanding and laminated thin Al-foil.
- A slip-line theory was adopted with a final inclination (1:2) of the fractured cross-sections. The slip-line model is verified for freestanding Al-foil by inspection of SEM micrographs. This theory is not sufficient to explain the governing phenomena and deformation mechanisms of the single LDPE-film since it is deformed significantly more than the Al-foil. LDPE untangle, re-orient and strain-harden during the deformation process.
- The slip-line theory is also applicable on the cross sections in the Al-foil created by the Al-foil laminated with a LDPE layer.
- LEFM (valid approximately when 2a¿15 mm) was used to derive an analytical expression for prediction of the critical load for centre cracked specimens. This equation is accurate both for freestanding Al-foil and a packaging laminate consisting of one-side laminated Al-foil with LDPE. This expression can be used when the plastic