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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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<span id="page-1-0"></span>**KORK ERKER ADE YOUR** 

#### Layers and laminate properties

Metal foil (fully annealed AA1200 aluminium) Stiff and Brittle

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

Polymer (PolyEthene LDPE, LD270) Weak and Soft

 $t_l = 27 \mu m$ ,  $E_l = 126 MPa$ ,  $\sigma_{bl} = 8MPa$ ,  $\nu_l = 0.45$ ,  $F_l = 2N$ 

The laminate (homogenized, plane stress) Stiff and Ductile

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

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## Necking vs fracture

Fracture toughness of aluminium is  $\approx 24 \text{ MPa m}^{1/2}$ . Measured toughness of an  $9\mu$ m aluminium foil is 3.5 MPa m<sup>1/2</sup> due to necking.

The stress intensity factor is

 $K \sim$  sheet thickness<sup>1/2</sup>

A sheet thickness  $> 400 \mu m$  is needed to restore  $K_{1c}$  fracture control.

The largest load per unit of length

 $P \sim$  sheet thickness<sup>3/2</sup>

4 D > 4 P + 4 B + 4 B + B + 9 Q O

A sheet thickness  $> 32 \mu m$  is needed to provide the strength of a non necking 9*µ*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*µ*m slices using a Leica mikrotome

Coated in a Cressington 108 auto sputter.



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#### 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)

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## Cross sections of the homogeneous materials

Without crack the polymer thickness decrease from 27*µ*m to 10*µ*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.**K ロ ▶ K @ ▶ K 할 X X 할 X 및 할 X X Q Q O** 

#### 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)

4 D > 4 P + 4 B + 4 B + B + 9 Q O

(Hutchinson, 2013)  $\sigma_B/\sigma_A = 0.002$  or  $\sigma_A/\sigma_B = 0.002$  $N_A = N_B = 0.1$  and  $h_A/h_B = 2$ 



 $L/H = 10$ , 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  $x =$  const.

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#### Localised plastic deformation



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#### Mechanics of the neck

*F*, per unit of length

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

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

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

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

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

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

#### Mechanics of the neck

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

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

*F*, per unit of length

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

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

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

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

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

## Strength of the necking region

$$
t_A(\delta) = h_A - \delta \quad \text{and} \quad t_L(\delta) = h_L - \delta \quad \text{for} \quad \delta < h_A, \tag{8}
$$
\n
$$
t_A(\delta) = 0 \quad \text{and} \quad t_L(\delta) = h_L - \delta \quad \text{for} \quad h_A \le \delta < h_L, \tag{9}
$$
\n
$$
\text{and}
$$

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

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Force per unit of length:

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

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

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

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

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

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

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#### Critical stress



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

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# (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.

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