Copper-rubber interface delamination in stretchable electronics

Johan Hoefnagels
Jan Neggers
Peter Timmermans
Olaf van der Sluis
Marc Geers
Stretchable electronics

Sensitive skin for robots and prostheses

Health monitor, measuring all sorts of human body functions

Retinal-shaped photosensor arrays

Neural interfaces

T. Someya, Nature, 2004

www.flatrock.org.nz/topics/info_and_tech/this_is_unreal.htm

doheny.org

11th Stress Workshop, Bad Schandau, April 12-14 2010
Stretchable electronics

Stretchability conflict:

Overall stretchability

> 10%

Metal stretchability

< 1%
Suggested solution for stretchable wires:

- Si nanoribbons on elastomeric substrate
- Y-crack in ultra thin films on stretchable substrate
- Mechanistic patterns in metal lines
2D Mechanistic patterns:

Known failure cases:
• max. stretchability
• complex loading
• cyclic loading
• creep
• temperature/humidity
• miniaturization

Interface delamination

Aim:
• Characterize interface delamination
• Application in numerical model to simulate interface delamination
Overview

- Copper-rubber Bi-layer samples
- 90° peel-off tests
- Cohesive zone model
Copper-rubber Bi-layer samples

- Two types of Copper
  - printed circuit board grade Cu foil
  - thickness 35 µm
  - Roughness:

- Three types of rubber
  1. 3–5 µm deep fractal surface
  2. PDMS (Sylgard 186; Dow Corning)
     - "rough" copper
       - molded @ T_{room}
       - thickness = 1 mm
  3. TPU (Walupur; Epurex)
     - extra electropolishing step
     - 5–10 µm sized protrusions
     - "extra rough" copper
       - laminated @ 180 °C → “TPU 180”
       - laminated @ 200 °C → “TPU 200”
Samples

Cu on rubber

![Graph showing stress-strain curves for different materials: Copper, Walopur (TPU), Sylgard 186 (PDMS).]
“Large scale” 90° peel test

- (Large) tensile stage (Zwick 1474)
- Sample size: 18 x 84 mm
- Samples under 45° → force constant @ 90°
“Large scale” 90° peel test

Work Of Separation (WOS) calculated from steady state peel force:

\[ G_c = \frac{F}{W} \]
“Large scale” 90° peel test

Lifted rubber seen at peel front

- Camera system on peel test setup
“Small scale” 90° peel test

Sample size: 20 x 10 mm

Micro-tensile stage (Kammrath & Weiss)

Climate box

ESEM
Influence of Copper roughness

“Rough” Cu

Uncovered surface

Surface after peeling

“Extra rough” Cu

EDX-Analysis:

PDMS

$(C_2H_6OSi)_n$
Influence of Copper roughness

"Rough" Cu

Uncovered surface

Surface after peeling

"Extra rough" Cu

40% increase in WOS
Influence of Copper roughness

“Rough” Cu

“Extra rough” Cu

- Larger interfacial area
- Mixed-mode loading
- Mechanical interlocking

40% increase in WOS
• Higher WOS \(\Rightarrow\) *suggests* larger Int. Adhesion \(\Rightarrow\) higher \(A_{\text{rubber}}\)

• Stronger rubber \(\Rightarrow\) fractures less easily \(\Rightarrow\) lower \(A_{\text{rubber}}\)

\(\Rightarrow\) Rubber Strength in competition with Interface Adhesion

\begin{align*}
\text{TPU200} & & A_{\text{rubber}} &= (6 \pm 2)\% \quad G_c &= (3.7 \pm 0.1) \text{ kJ/m}^2 \\
\text{TPU180} & & A_{\text{rubber}} &= (12 \pm 1)\% \quad G_c &= (2.9 \pm 0.1) \text{ kJ/m}^2 \\
\text{PDMS} & & A_{\text{rubber}} &= (87 \pm 3)\% \quad G_c &= (1.3 \pm 0.1) \text{ kJ/m}^2
\end{align*}
Influence of rubber material

SEM analysis of peeled surface:

TPU200

- $G_c = (3.7 \pm 0.1) \text{ kJ/m}^2$
- $A_{rubber} = (6 \pm 2)\%$

PDMS

- $G_c = (1.3 \pm 0.1) \text{ kJ/m}^2$
- $A_{rubber} = (87 \pm 3)\%$

Hypothetically:

- Int. Adhesion increased such that $A_r = 87\% \rightarrow G_c (> ) > 3.7 \text{ kJ/m}^2$

$\rightarrow$ En. Dissipation fracture process TPU $> 3 \times$ fracture process PDMS
In-situ real-time delamination analysis

- Optical microscopy
- Environmental SEM

Rubber

Copper

0.05 mm

50 μm
In-situ real-time delamination analysis

For all 3 rubbers:

- Formation, stretching and rupture of fibrils $\Rightarrow$ high energy dissipation
- Fibrils 20 to 60 $\mu$m long; Averaged fibril length $\sim$50 $\mu$m
- Delaminated Cu surface never 100% clean and never 100% covered with rubber

Delicate Balance:
Formation, stretching and rupture of fibrils $\iff$ Debonding of Cu-rubber interface
In-situ real-time delamination analysis

Intensionally too high e-beam current and acceleration voltage

Delicate Balance:
Formation, stretching and rupture of fibrils ↔ Deboning of Cu-rubber interface
Fibril interface model

- 2D plane-strain FEM model
- Sample dimensions from exp.
- Cohesive zone elements at interface
- Cohesive zone model for fibrillation ($A_r = 100\%$):
  - Smith-Ferrante TSL
  - $\beta = 1$

- Fit parameters: $G_c$ & $\tau_{\text{max}}$

v.d.Bosch et al. (2007); van Hal et al. (2008)
Fibril interface model: material characterization

- 35 µm thick electrodeposited copper film → tensile test → elasto-plastic behavior directly implemented in FEM model

- PDMS Sylgard 186 rubber → tensile and planar extension tests → hyper-elastic material model

- Fracture toughness of rubber: $J_c = (16 \pm 2) \text{ kJ/m}^2$

- Mesh refinement okay
Fibril interface model: $G_c$

Influence cohesive zone parameter $G_c$: Work of Separation
Fibril interface model: $\tau_{\text{max}}$

Influence cohesive zone parameter $\tau_{\text{max}}$: fibril length

![Graph showing peel force vs. displacement with different values of $\tau_{\text{max}}$.]
Fibril interface model: fit on exp.

Best fit for:
- $\tau_{\text{max}} = 1.5$ MPa
- $G_c = 1.3$ kJ/m$^2$
Fibril interface model: validation

Influence $\tau_{\text{max}}$ on lift-off geometry:

$\tau_{\text{max}} = 2.5$ MPa
$\tau_{\text{max}} = 1.5$ MPa
$\tau_{\text{max}} = 0.9$ MPa
Fibril interface model: validation

For optimized parameters: \( (\tau_{\text{max}} = 1.5 \text{ MPa} \ & \ G_{c} = 1.3 \text{ kJ/m}^2) \)

<table>
<thead>
<tr>
<th></th>
<th>Height [mm]</th>
<th>Width [mm]</th>
<th>Radius [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experiment</td>
<td>~1.2</td>
<td>~1.5</td>
<td>~1.4</td>
</tr>
<tr>
<td>Simulation</td>
<td>~1.0</td>
<td>~1.4</td>
<td>~1.5</td>
</tr>
</tbody>
</table>
Fibril interface model: validation
Fibril interface model: considerations

• Fibril length:
  • Experiment:
    → fibril length ~50 μm
  • Simulations (with $\tau_{\text{max}} = 1.5 \text{ Mpa}$ & $G_c = 1.3 \text{ kJ/m}^2$):
    → $\delta_c \approx 330 \mu m$ → maximum fibril length > 1mm

• Explainations:
  • cohesize zone (CZ) spatially homogenizes all tractions
    → load carrying area of CZ factor 10 – 100 larger
    → overestimation fibril length of factor 10 – 100
  • Assumption of hyper-elastic material model for rubber layer
    → all plasticity near interface lumbed into CZ

• Notes of caution:
  − How realistic for shear loading in stretchable electronics?
  − Still fibrillation for interconnect dimension(s) < 50μm?
Conclusions

Delicate balance between Fibrillation ↔ Cu-rubber interface debonding

- Interfacial debonding
- Larger interfacial area
- Mixed-mode loading
- Mechanical interlocking
- Formation, stretching & rupture of fibrils

• Cohesive zone model:
  • able to accurately describe peel force-displacement curve & rubber-lift geometry
  • caution when applying to other loading conditions / sample geometries