Copper-rubber interface delamination in stretchable electronics

Copper-rubber interface delamination in stretchable electronics

J.P.M. Hoefnagels[1*], E.J.L. van der Zanden[1,2], P.H.M. Timmermans[2], O. van der Sluis[2], M.G.D. Geers[1]

[1] Eindhoven University of Technology, Dept. of Mechanical Engineering, Eindhoven, The Netherlands
[2] Philips Applied Technologies, Product and Process Modeling group, Philips, Eindhoven, The Netherlands
*e-mail: j.p.m.hoefnagels@tue.nl, tel:+31-40-2475894

Next generation microelectronic devices will be flexible, rollable and capable of extreme elongations. The latter aspect enables novel applications such as sensitive skin for robots and prostheses, health monitors to measure all sorts of human body functions, retinal-shaped photosensor arrays, and neural interfaces. Stretchable electronics consist of small rigid microchips on a highly compliant substrate, circuited by metal wires which must be highly stretchable. Stretchability is achieved using mechanistic patterns. Ensuring interface integrity between the metallic lines and the substrate forms a huge engineering challenge, making interface integrity the key limiting factor in stretchable electronics development.

The present work meticulously characterizes interfacial delamination in the copper/rubber model interface system. First, 'small-scale' 90º peel tests were performed *in-situ* in an environmental scanning electron microscopy (ESEM) to enable microscopic visualization of the progressing delamination front (Fig 1). In addition, the copper/rubber system was characterized by 'large-scale' 90º peel tests with real-time high-speed video imaging (Fig. 2(a)) to obtain adhesion energies and rubber delamination geometries. Finally, to quantify the interface properties, numerical simulations of the peel test were performed by developing a finite element model (Fig. 2(b)) that incorporates cohesive zone elements [1] to describe the transient delamination process during the peel test. The model parameters were determined using an extensive model parameter sensitivity study, as detailed in [2].

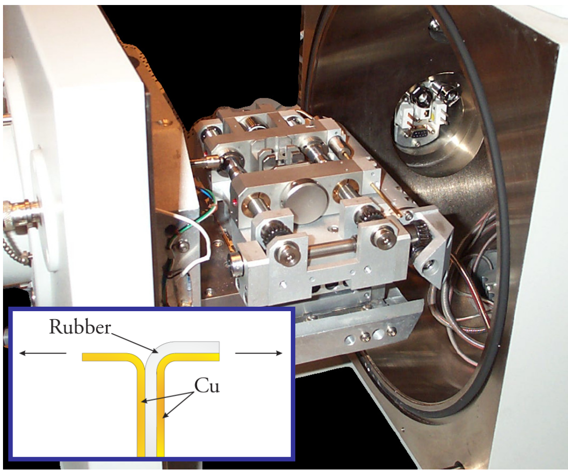

Fig. 1(a). *Schematic of the 'small scale' 90^o peel test. An extra layer of copper is added to the copper/rubber system. The copper ends are loaded under tension in a micro-tensile stage (Kammrath & Weiss). The micro-tensile stage is placed in the ESEM to enable in-situ SEM observation of the delamination.*

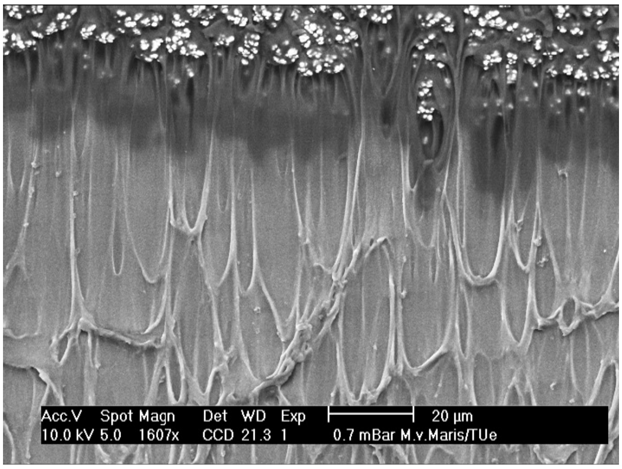

Fig. 1(b). *In-situ ESEM image of a progressing delamination front of the copper rubber (PDMS) interface. The dominant energy dissipation mechanism is the rupture of the rubber fibrils. (Note that for this specimen >80% of delaminated Cu surface is still covered with rubber)*

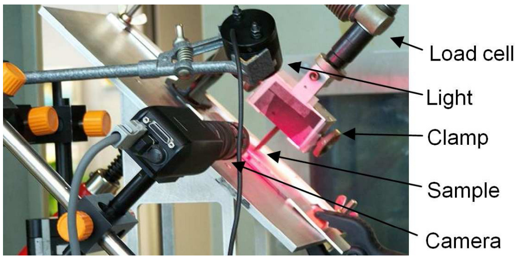

Fig. 2(a). *'Large-scale' 90^o peel-test set-up with camera to study the local delamination front geometry.*

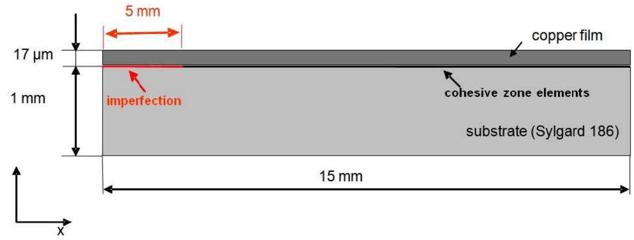

Fig. 2(b). *Schematic illustration of the numerical model to simulate the plane-strain peel-tests (not to scale).*

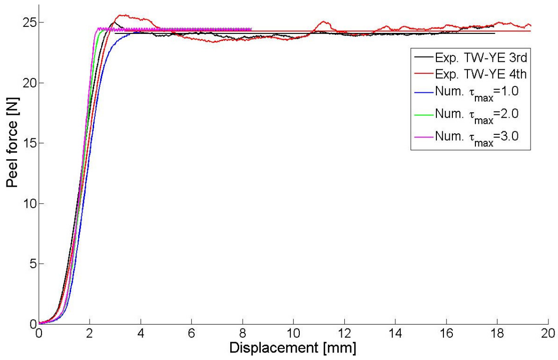

Fig. 3(a). *Model validation: measured and calculated peel-force–displacement curves, for different values of the fibril length τ_{max} used in the simulations.*

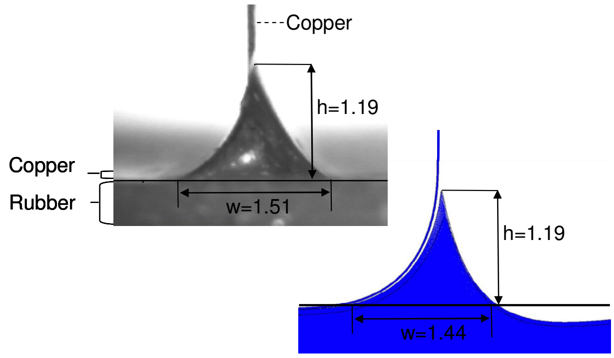

Fig. 3(b). *Model validation: measured and calculated local deformation geometry of the rubber and copper near the delamination front.*

The experimental-numerical study into copper/rubber delamination has yielded the following main conclusions:

- High adhesion energies are achieved for rough copper surfaces with deep 'valleys'. For these interfaces, actual fibrillation of rubber at the peel front is observed at the micron scale (Fig. 1(b)), and the energy dissipation upon delamination is dominated by the formation, stretching, and rupture of ~20µm-long rubber fibrils.
- Energy dissipation in the fibrils is in close competition with delamination of the fibrils from the Cu interface. Fibrillation is enabled by hampering the debonding of rubber (fibrils) from the copper surface through an interplay of local surface area enlargement, mechanical interlocking in the roughness 'valleys', and complex mixed-mode loading of the interface at the micron scale (out-of-plane loading on the tops and 'valleys' of the copper roughness extrusions versus in-plane loading on the walls of the extrusions). Therefore, the degree to which the delaminated Cu surface is still covered with rubber increases with increasing copper roughness.
- Environmental conditions have a large influence on the delamination process. For instance, the rubber becomes significantly more brittle and fractures at a lower strains for the low pressure (0.8 mbar) and low humidity (<1 %RH) as used in the ESEM.
- Interestingly, experimental observations show that the rubber is severely lifted at the delamination front due to its high compliance (Fig. 3(b)). Although the microscopic surface morphology is neglected, the cohesive zone model shows good agreement with the peel force-displacement curves (Fig. 3(a)) and the rubber-lift geometry (Fig. 3(b)). It is thus concluded that the numerical model is able to describe the copper-rubber interface and can be used to simulate the delamination behavior of actual 3D stretchable electronics structures [2].

REFERENCES

[1] Van Hal, B.A.E., Peerlings R.H.J., Geers M.G.D., Van der Sluis, O. Cohesive zone modeling for structural integrity analyses of IC interconnects, Microelectronics Reliability **47**, 1251-1261 (2007).

[2] Van der Sluis, O., Timmermans, P.H.M., Van der Zanden, E.J.L., Hoefnagels, J.P.M., Analysis of the three-dimensional delamination behavior of stretchable electronics applications, proceeding of the 10th EuroSimE conference (2009).