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Extended abstract

Ductility of a Thin Metal Film on a Polymer Substrate

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Work with
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Deformable electronics have diverse applications, such as curved imaging surfaces, sensor skins, and electronic textiles. One way to make a deformable device is to start with a polymer substrate, fabricate on the substrate small islands with a stiff material (e.g., silicon nitride), and place on the islands all brittle components (e.g., silicon and silicon dioxide). When the structure is stretched, strains are small in the islands and in the brittle components, but large in parts of the polymer substrate left uncovered by the islands. Metal films, deposited on the polymer substrate to connect the islands, must deform with the substrate. A key question is whether the metal films can survive large strains without rupture.

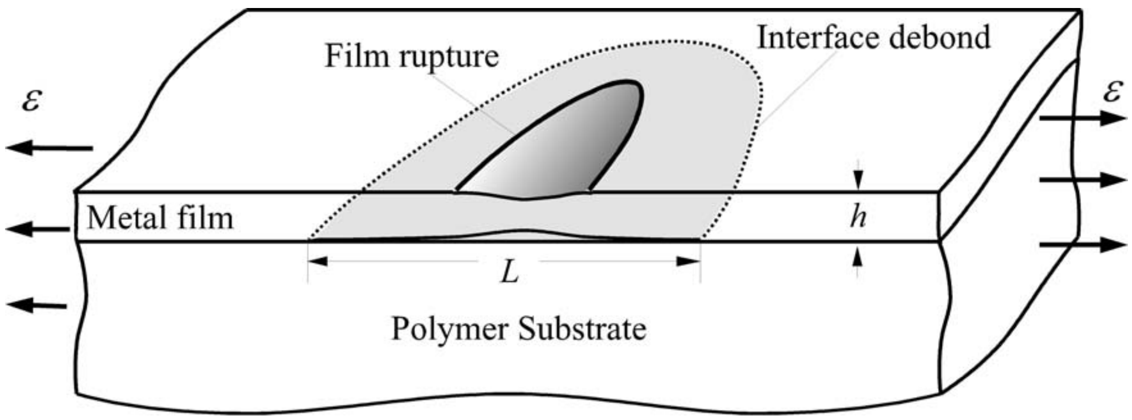


Fig. 1 A metal film is initially bonded to a thick polymer substrate. Subject to a tensile strain in the plane of the film, the film rupture and the interface debond co-evolve. The rupture occurs by localized strain in a segment of the film, of length comparable to the film thickness, but debond spreads over a segment of the interface many times the film thickness.

The present paper considers this question for an idealized structure: a blanket metal film bonded to a polymer substrate, subject to a tensile strain in the plane of the film (Fig. 1). Attention is restricted to metal films that rupture by strain localization (e.g., necking or forming a shear band). Strain localization causes a large local elongation in the metal film, which cannot be accommodated by the polymer substrate subject to a modest strain. One therefore expects that, substrate-bonded and strain delocalized, the metal film may deform uniformly far beyond when strain localization would occur if the film were freestanding. Of course, substrate constraint disappears if the metal film debonds from the polymer substrate. When the laminate is subject to a modest tensile strain, we expect strain localization and debond to co-evolve. Without debonding, the polymer substrate suppresses strain localization in the metal. Without localization, no traction exists on the interface to drive debonding. The conundrum parallels that of buckle-debond co-evolution of a compressive film on a substrate.

A freestanding polycrystalline thin metal film may strain somewhat beyond the elastic limit. Dislocations pile up at grain boundaries, and harden the film. Strain localization has also been observed in polycrystalline copper and aluminum films. The analysis in the subsequent sections will assume that the metal film hardens weakly, such that the necking strain for the freestanding film, ε_N, is only slightly larger than the elastic limit strain.

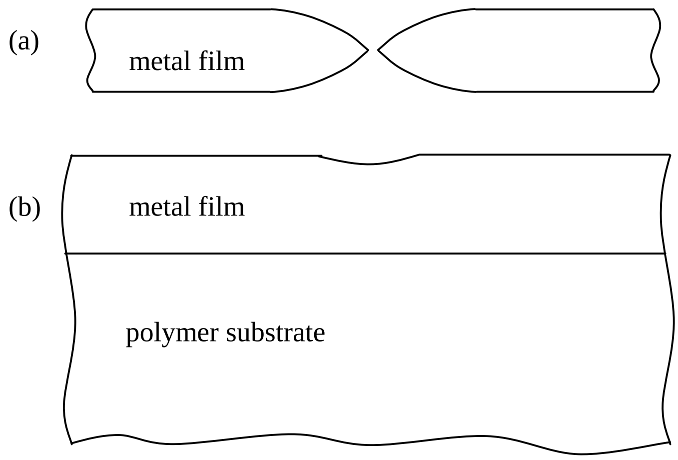


Fig.2 When rupture is caused by strain localization, local thinning leads to local elongation. (a) For a freestanding metal film, the local elongation is accommodated by rigid body motion of the ruptured halves. (b) For a substrate-bonded film, the local elongation may be suppressed by the substrate.

The invisible ductility can be made visible. Figure 2 compares the freestanding and the substrate-bonded films. At the site of rupture, strain localization causes a large local elongation on the order of the film thickness. The local elongation requires space to accommodate. This space is available to the freestanding film, but unavailable to the substrate-bonded film subject to a modest tensile strain. Consequently, the polymer substrate may delocalize deformation in the metal film, carrying the metal film to strains far beyond its necking limit without rupture. Figure 2 illustrates strain localization by necking, but similar arguments apply to localization by forming a shear band.

When the applied strain is small, the laminate deforms uniformly. When the applied strain is large, nonuniform deformation develops. We perform a bifurcation analysis. Figure 3 plots the bifurcation strain as a function of the wave number. The main features are readily understood. When the wavelength is large compared to the film thickness ($kh \to 0$), the metal film is negligible, and the critical strain corresponds to that of the surface mode for the freestanding polymer. When the wavelength is small compared to the film thickness ($kh \to \infty$), the polymer substrate is unimportant, and the critical strain corresponds to that of the surface mode for the freestanding metal. Even when the strain exceeds the ellipticity limit of the film, displacement continuity at the interface suppresses the localized shear band, and the perturbation is still sinusoidal.

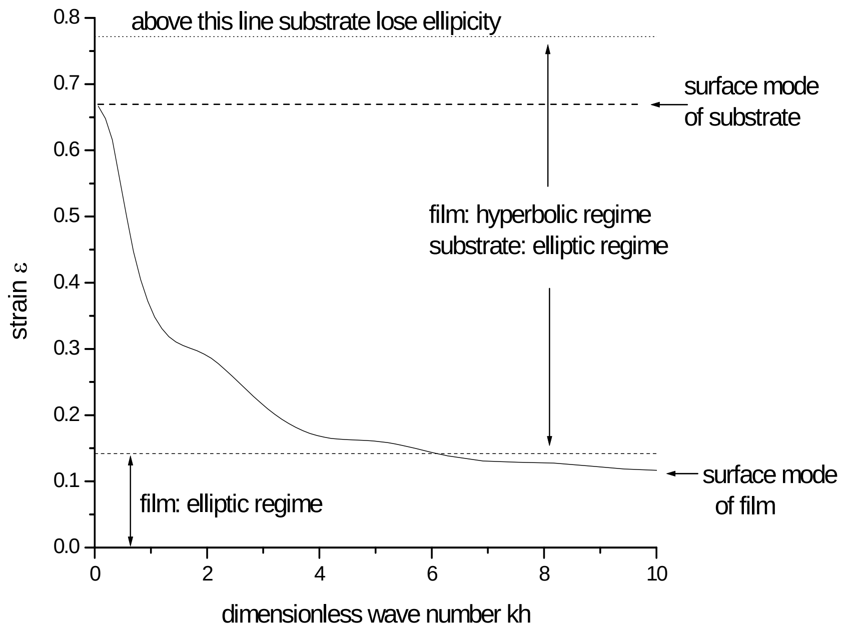


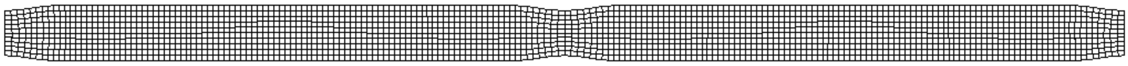
Fig. 3 The critical strain as a function of the wave number for the metal-on-polymer. h is the thickness of the metal film, and k is the wavenumber of the perturbation.

Upon debonding from the substrate, the film becomes freestanding. As pointed out before, debonding and strain localization will progress simultaneously. The debond length will depend on the adhesion between the metal and the polymer, as well as the stress-strain relations of the two materials. Figure 4 shows several results of finite element simulation.

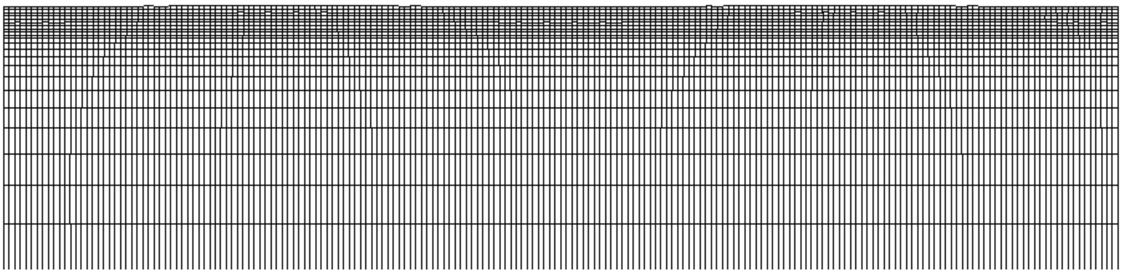
References:

1. T. Li, Z.Y. Huang, Z.C. Xi, S.P. Lacour, S. Wagner, Z. Suo. Delocalizing strain in a thin metal film on a polymer substrate. Mechanics of Materials. In press.

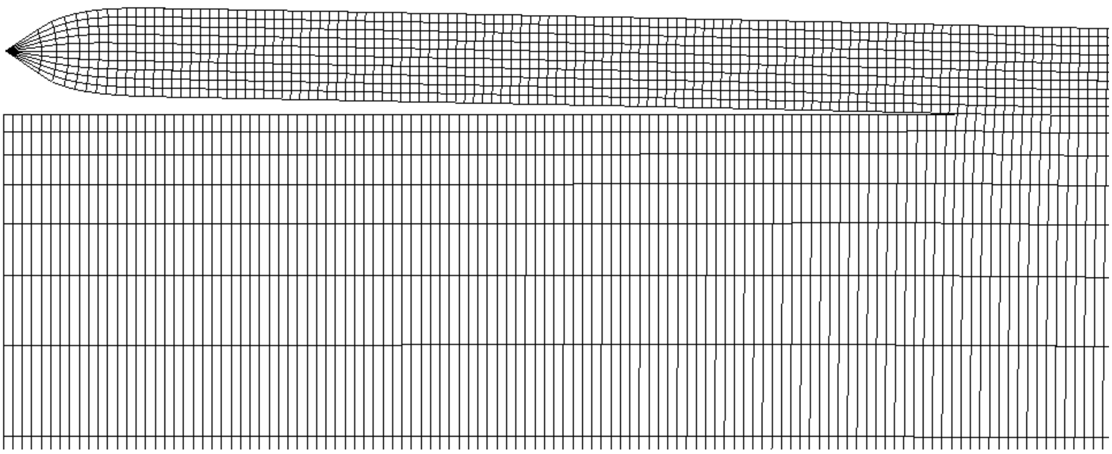
2. T. Li, Z.Y. Huang, Z. Suo, S.P. Lacour, S. Wagner. Stretchability of thin metal films on elastomer substrates. Appl. Phys. Lett. In press.



(a) Free-standing film. $\varepsilon = 0.023$



(b) Substrate-supported film. $\varepsilon = 0.79$



(c) Partially debonded film. $\varepsilon = 0.05$

Fig.4 (a) A free-standing film ruptures at a small strain. (b) A substrate-supported film sustains a large strain. (c) When the film is debonded from the substrate, the film ruptures at a small strain.