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Influence of substrate mechanical behaviour on crack patterns in thin films under uniaxial loading

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Extended Abstract

Abstract

Thin coatings deposited on compliant substrates are widely used to tailor surface characteristics such as refractive index, electrical conductivity, chemical protection, or resistance to wear. A major challenge in these systems is fracture propagation, particularly for devices subjected to large deformations, such as stretchable electronic systems whose performance strongly depends on the mechanical robustness of conductive layers embedded within soft materials. When the substrate is deformed, the thin film is subjected to compressive or tensile loading. Under compression, surface instabilities such as wrinkling may develop and evolve into delamination blisters, whereas tensile loading typically results in through-thickness cracking and fragmentation of the film. Channel crack propagation has been extensively investigated for brittle and ductile coatings. For films supported by elastomeric substrates, cracks may propagate deeply into both the coating and the substrate. However, for coatings deposited on polymer substrates exhibiting elastic-plastic behaviour, the fragmentation mechanisms at large strains remain insufficiently understood. In particular, a saturation of crack density at high strain levels and a distribution of crack openings cannot be explained by purely elastic approaches or classical shear-lag models. In this work, we investigate the fragmentation of brittle thin films on polymeric substrates using finite element simulations incorporating a mixed-mode cohesive zone framework of the interface and an elastic-plastic behaviour for the substrate, which enables characterization of plastic strain localization and the spatial extent of plastic deformation. An elastic brittle ZnO film is considered with two elastic-plastic substrates, ETFE (ethylene tetrafluoroethylene) and Kapton (polyimide), which exhibit different hardening behaviours and lead to distinct saturation patterns. The evolution of the maximum tensile stress σ_{max} at the middle point between two neighbouring cracks is analysed as a function of the applied strain $\bar{\varepsilon}$ and the crack spacing L. In both cases, a stress saturation is observed, as σ_{max} reaches a maximum despite increasing $\bar{\varepsilon}$. The maximum stress level depends on both L and the substrate nature, with higher saturation stress obtained for Kapton at similar crack spacing. By extensively studying the relationships between σ_{max}, L and $\bar{\varepsilon}$, a quantitative relationship between the fracture tensile stress T_{max} and a saturated crack spacing L_{sat} is established. This framework makes it possible to predict the range of fragment lengths if T_{max} is known, and conversely to infer an approximate value of T_{max} from experimental measurements of saturation crack spacing. This work highlights the crucial influence of the substrate on crack pattern formation in thin-film systems and provides a robust tool for interpreting crack patterns in flexible and stretchable electronic devices, allowing for the determination of coating strength.

Keywords:

Thin flim fragmentation elastic-plastic polymer substrates crack saturation finite element simulations