Interaction between cracking and delamination in the failure of thin films

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Introduction

Hard, brittle coatings may exhibit three deformation mechanisms, cracking, delamination and buckling, in response to residual or applied stresses. The interaction between these mechanisms and the inherent statistical nature of the coating strength leads to interesting scaling behaviour as well as interesting pattern formation, such as spiral cracks and telephone chord buckles. In order to advance our understanding of this pathological behaviour that we have encountered in practice we have engaged in a numerical study.

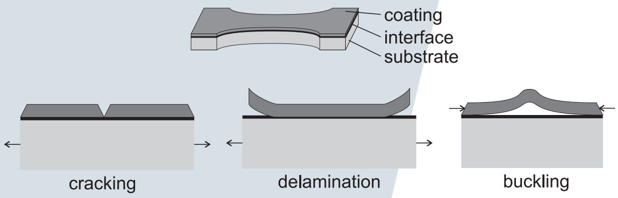

Figure 1 *The three deformation mechanisms.*

Method

The FEM model consists of a substrate, interface and coating (figure 1). All layers are built with linear elastic spring elements. Cracking and delamination are modelled by removing elements whenever an element's elongation reaches a critical value $\varepsilon_i = \varepsilon_0 \pm \Delta\varepsilon_i$. Where $\Delta\varepsilon_i$ is chosen from an uniform distribution, representing statistical disorder. Below we present some typical results.

Cracking and delamination

A *correlation length* $\xi = \left(\frac{G_i}{h_i}\left(\frac{1}{h_c E_c} + \frac{1}{h_s E_s}\right)\right)^{-\frac{1}{2}}$ can be defined, here E is the stiffness and h the height of the substrate (s), interface (i) and coating (c). The mean segment length, during cracking, is normalized by ξ and plotted against the normalized strain ($\varepsilon^n = \frac{\varepsilon}{\varepsilon_0}$), see figure 2.

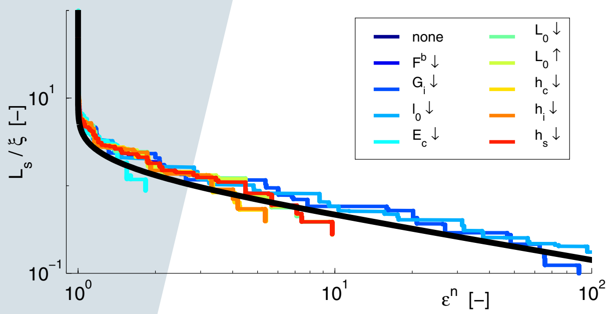

Figure 2 *The normalized segment length against normalized strain during a tensile test of a long thin strip. This curve is material and geometry independent and* $\Delta\varepsilon = 0$*.*

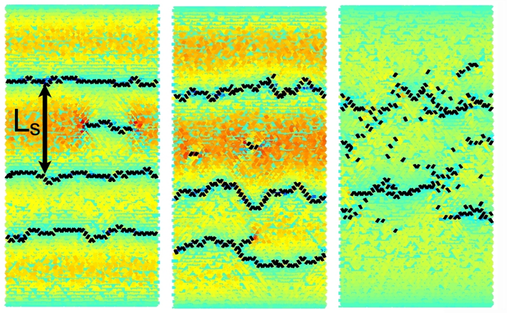

Figure 3 *Influence of disorder in a uniaxially loaded model. For* $\Delta\varepsilon = 0$ *(left),* $\Delta\varepsilon = 0.4\varepsilon_0$ *(middle) and* $\Delta\varepsilon = 0.8\varepsilon_0$ *(right). All at the same amount of broken elements.*

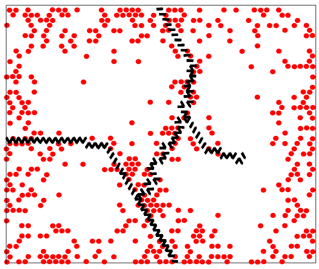

Figure 4 *Cracking (black) and delamination (red) in a bi-axially stressed sample.*

Delamination and buckling

In experiments cracks initiate prior to buckling. Between those cracks delaminated parts will buckle and grow as triangles until they reach another triangles or cracks (figure 5).

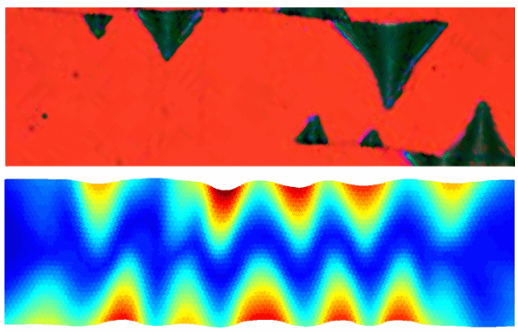

Figure 5 *Triangular buckles between cracks in uniaxial loading, in experiment (upper) and simulation (lower).*

Conclusion

We have developed a simple model that allows us to study the interplay of residual stress, simple external loading, elastic material properties, disorder and geometry on interacting failure modes of a substrate-interface-coating assembly.

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