MODELING CONFIGURATION AND ITS TUNABILITY OF NONLINEAR WRINKLING-INDUCED DELAMINATION

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Summary We have proposed a continuum model and simulation to investigate the morphological evolution of nonlinear wrinkling-induced delamination. The effects of pre-strain and interfacial toughness on the formation and configuration of wrinkling-induced delamination are systematically discussed. In particular, our analyses show that by choosing the setting of pre-strain and interfacial toughness the delamination process can be controlled to develop in the pre-ordered wrinkles.

INTRODUCTION

The structure of thin film with internal stress on elastic substrates has been widely used in thin film technology. When the thin film is under compression, it usually leads to buckling instability with formation of patterns of wrinkle or buckle-delamination [1]. Understanding the thin film morphology mediated by the buckling instability is important in various applications, such as flexible microelectronics, surface coating and thin film metrology. Though wrinkling and delamination often happen separately, recent experiments show that wrinkle and buckle-delamination can co-exist and co-evolve [2]. In addition wrinkling can itself cause delamination. It is, however, still unclear how the wrinkling and buckle-delamination interplay and co-develop. Inspired by previous studies, in this paper, beyond the analysis of the buckling instability, we proposed a continuum modeling and simulation to consider the morphological evolution and its tunability of nonlinear wrinkling-induced delamination.

THEORETIC MODELS

We consider an elastic thin film of thickness h bonded on initially flat elastic substrates and the film is under internal compression. We model the film as an isotropic FvK plate, the semi-infinite substrate being isotropic linear elastic, and the bonding interface between them being cohesive, described by a cohesive zone model. Through a series of derivations the total energy of the system U^{tot} can be simplified as a functional of the normal displacement of the film $\zeta(x_1,x_2,t)$ and the normal displacement jump across the cohesive interface $\Delta_n(x_1,x_2,t)$. Here we neglect the shear displacement jump because it is much smaller and has little effect on the buckling process. The equilibrium solutions of ζ and Δ_n can be obtained by alternatively solving the following Ginzburg-Landau kinetic equations:

$$\frac{\partial\zeta}{\partial t}=-\Gamma_\zeta\frac{\delta U^{tot}}{\delta\zeta},\frac{\partial\Delta_n}{\partial t}=-\Gamma_\Delta\frac{\delta U^{tot}}{\delta\Delta_n}$$

where Γ_ζ and Γ_{Δ_n} are kinetic coefficients. Then the nonlinear buckle and/or delaminated states, as well as the elastic fields in the film and underlying substrate could be simultaneously tracked by numerically solving the reduced forms of the above equations scaled with the length in unit ($r'=r/l$, $l=h$), and the time t in unit τ ($t'=t/\tau$, $\tau=h/\Gamma_\zeta\mu_s$) in the periodic computational domain $512l\times512l$.

MAIN RESULTS

Formation of the wrinkling-induced delamination

Figure 1 shows simulated typical snapshots of the normalized deflection and normal displacement jump in a film-substrate system under the uniaxial compression at different time. The left column is for the pure wrinkling state with strong interfacial toughness γ, which demonstrates that the film deflection gradually evolves into a sinusoidally undulated state with no delamination ($\Delta_n\approx0$). The right column is for the wrinkling-induced delamination state with weak interfacial toughness. The result in Figure 1(d) shows that at the initial stage of the wrinkling stability, there is only elastic displacement jump, and no delamination appears. As shown in Figure 1(e) with the increase of deflection, the amplitude of the displacement jump, Δ_n, increases rapidly and delamination could spontaneously occur at the peak of the deflection since the normal traction is above the interfacial strength at these areas. Figure 1(e)-(f) demonstrate that the configuration of the wrinkling-induced delamination undergoes coarsening and finally becomes a single blister in the computational domain. The amplitude and size of the blister are found to increase with the increase of pre-strain and

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decrease with the increase of interfacial toughness. This is clearly indicated in Figure 2, wherein solid lines show the analytic estimation for the case of macroscopic delamination predicted by Vella [3]. The simulated results agree well with the analytic solution.

Morphology of wrinkling-induced delamination

Figure 3 shows the simulated buckling morphologies of the film under different biaxial pre-strains. The red regions represent the delaminated part. Some of the buckling morphologies have been observed by experiments before.

Controllable patterns of wrinkling-induced delamination

We found two ways to control the patterns of wrinkling-induced delamination. One way is that we choose the values of pre-strain and interfacial toughness such that wrinkling-induced delamination could occur. The top row of Figure 4 shows the unordered random delamination blister formed through this way. The other way is that we firstly allow the film to only wrinkle by choosing the proper values of pre-strain and interfacial toughness, after the ordered wrinkling pattern is formed, we can increase the pre-strain or decrease the interfacial toughness to trigger the delamination instability developing in the well-formed wrinkle. The bottom row of Figure 4 clearly indicates the growth of following wrinkling-induced delamination is guided by the wrinkling pattern and an ordered delamination pattern is obtained.

References

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Figures

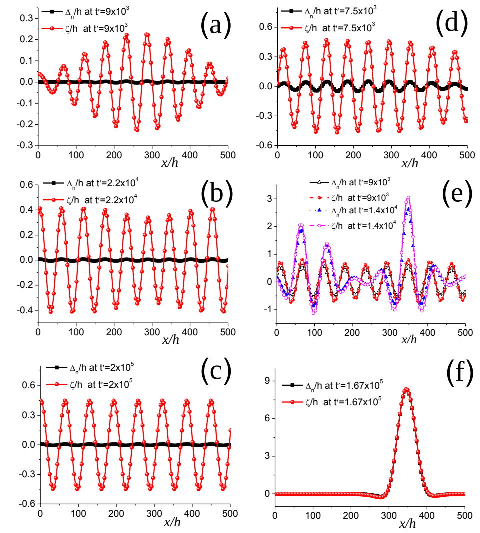

Figure 1

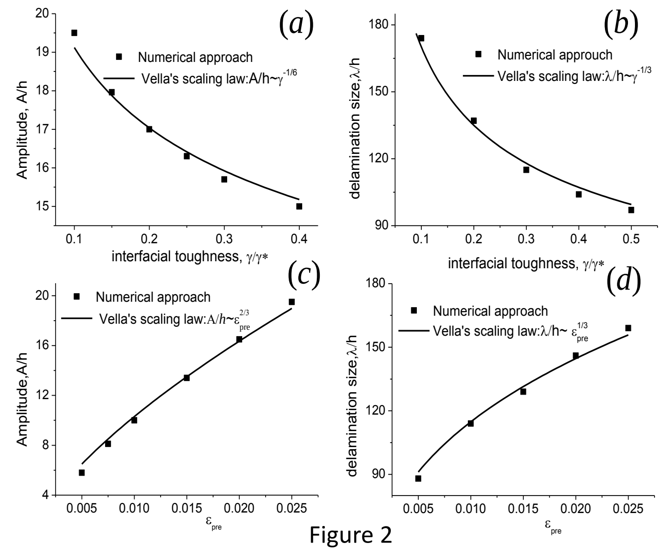

Figure 2

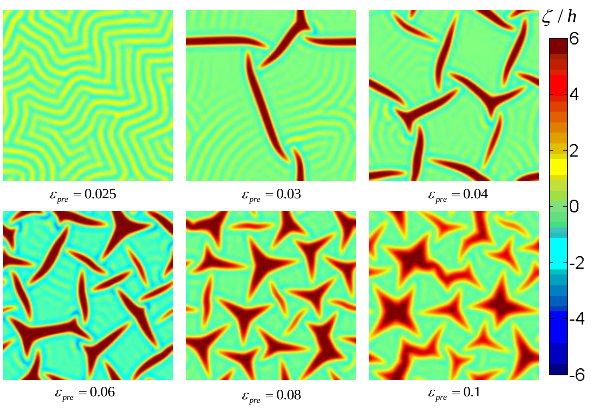

Figure 3

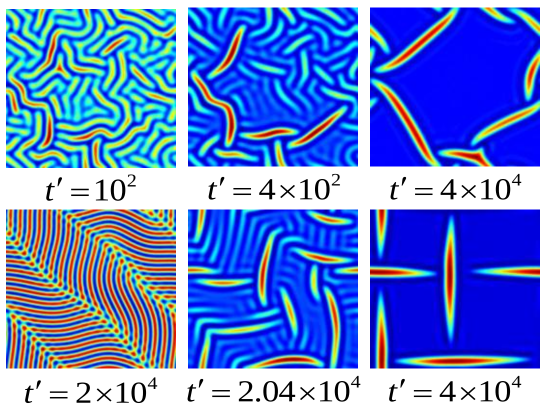

Figure 4