Harnessing Wrinkle Delamination Mechanics to Measure and Pattern Polymer Coatings

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INTRODUCTION

Compressive stresses in stiff polymer coatings can give rise to surface instabilities in which the coating adopts a sinusoidally wrinkled morphology with a dominant wavelength, d (Figure 1a). Such instabilities are generally observed for polymer coatings that are well-adhered to compliant substrates. Compressively stressed coatings may also simply delaminate over a localized area—these features, commonly called blisters, are formed in systems where the compliance of the substrate is high and/or coating-substrate adhesion is poor. Between these two extremes of behavior, one can observe "wrinkling delamination", where a coating initially wrinkles but then forms blisters of width L that relax the wrinkling stability within an approximate width R (Figure 1b). While both wrinkling instabilities and buckle delamination have been well-studied in the literature, wrinkling delamination has received very little attention. This talk will lay a theoretical foundation for wrinkling delamination and demonstrate how studying this phenomenon can lead to new approaches for measuring the adhesion strength of polymer coatings and patterning microscale features.
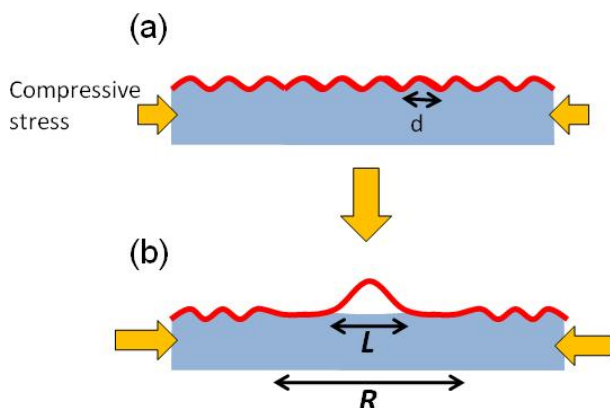

Figure 1. Wrinkle delamination for a coating subjected to compressive stresses on a compliant substrate.

EXPERIMENTAL[†]

Our results were obtained by incrementally compressing spin-cast polystyrene (PS) films that had been transferred from Si substrates to polydimethylsiloxane (PDMS) substrates. The strain was increased in increments of ≈ 0.5 % and d, R, and L were measured using optical microscopy. Tapered delamination blisters were produced by flow-coating PS with an increasing speed to produce a thickness gradient.[1]

RESULTS AND DISCUSSION

A number of key features distinguish wrinkle delamination from buckle delamination. In forming a delamination within a wrinkled coating, the system chooses a delamination length, L, which balances the relaxation of bending and deformational energy in the coating and substrate with the energy required to debond the coating. As a result, L scales with the coating thickness, h, as $L \sim h^{4/3}$. This behavior is intermediate to the cases of buckle delamination from rigid substrates[2] ($L \sim h^{3/2}$) and large buckle delamination (without wrinkling) from compliant substrates[3] ($L \sim h^{6/5}$).

Another unique feature of wrinkling delamination is that L is essentially strain independent for small deformations because this delamination event is a consequence of release of excess strain energy. This result has important practical consequences for using wrinkling delamination as a characterization technique, as strain is often the most difficult parameter to accurately measure when studying instability patterns in thin coatings. Because $L \sim W^{1/3}$, where W is the work of adhesion of the polymer coating, straightforward strain-independent measurements of the delamination width can be used to estimate the bonding energy of the coating in wrinkled systems. Using this technique, we measured an average value of W = 53 mN/m ± 24 mN/m for the PS-PDMS system, which is in excellent agreement with previous estimates.[4]

Another practical application of this work is the ability to tune L by introducing gradients in a relevant governing parameter. For example, since $L \sim h^{4/3}$, introducing a gradient in h leads to a tapered buckle delamination blister, as shown in Figure 2. The ability to easily produce such features in coatings may lead to new fabrication techniques in application areas such as microfluidics.
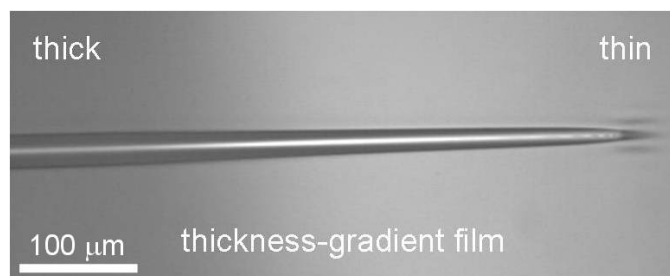

Figure 2. A gradient-thickness PS coating displaying a tapered buckle delamination. The coating decreases in thickness from left to right.

CONCLUSIONS

The mechanics of wrinkle delamination differs in a number of important ways from traditional buckle delamination mechanics that assumes a rigid substrate. By accommodating strain via local wrinkle relaxation, the coating adopts a delamination width L that is essentially strain-independent, making measurements of W extremely straightforward for such systems. In addition, we expect the ease with which L can be tuned by modulating factors such as h and W to lead to new approaches for patterning microscale features such as microfluidic channels.

REFERENCES
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[†] Equipment and instruments or materials are identified in this work in order to adequately specify the experimental details. Such identification does not imply recommendation by the National Institute of Standards and Technology (NIST), nor does it imply that the materials are necessarily the best available for the purpose.