STRESS ANALYSIS FOR COMBINATORIAL BUCKLING-BASED METROLOGY OF THIN FILM MODULUS*

Shu Guo, Christopher M. Stafford and Martin Y.M. Chiang
National Institute of Standards and Technology, Gaithersburg, MD, USA
chris.stafford@nist.gov

Introduction

We recently reported on a new buckling-based metrology for probing the elastic modulus of thin polymer films [1]. In this experimental geometry, a thin film of interest is transferred to a relatively thick elastic substrate, and buckling is induced by compression of the laminate. This buckling instability is highly periodic with a wavelength that is dependent on the mechanical properties of both the upper film and substrate as well as the thickness of the upper film, as shown in Equation 1. [2, 3]

$$d = 2\pi h \sqrt[3]{\frac{(1-\nu_s^2)E_f}{3(1-\nu_f^2)E_s}} \qquad (1)$$

Notation: E is the elastic or Young's modulus, ν is Poisson's ratio, h is the thickness of the upper film, and d is the wavelength of the buckling instability. Subscripts f and s denote the film and substrate, respectively. Eq. 1 can be rearranged to solve for the modulus of the upper film:

$$\frac{E_f}{(1-\nu_f^2)} = \frac{3E_s}{(1-\nu_s^2)}\left(\frac{d}{2\pi h}\right)^3 \qquad (2)$$

We argue that this new metrology is ideally positioned as a unique combinatorial and/or high-throughput measurement platform since gradient films can be easily integrated into the experimental design and the measurement time is a matter of seconds per data point. Gradient films could be continuous (constant change in parameter *A*) or discrete (step-wise change in parameter *A*) as a function of spatial position in the film, as shown in Figure 1.

A crucial concern in this new metrology is the potential for interactions between neighboring sections along the gradient. The primary example of this would be a sample with discrete changes in modulus of the material being studied. The stresses acting on the adjacent specimens may interact with each other if they are too close, thus the wavelength on the buckled the specimen would deviate from a single specimen with same geometric and material properties. In this presentation, a numerical analysis with FEA is conducted to investigate such interactions.

FEA analysis and discussion

Finite element analysis (FEA) was employed to conduct interaction analysis on the buckling of a film supported by an elastic media. A one-dimensional gradient was applied on either thickness or Young's modulus of the film. Both continuous and discrete gradients in the thickness and modulus of the film were analyzed.

For the case of continuous gradient, both the deflection magnitude and wavelength of the buckled film are dependent on the spatial position along the gradient. Figure 2 shows the schematic of the FEA model with thickness gradient in the film. Figure 3 illustrates the deformed shape of such a specimen. The FEA simulation suggests that the wavelength interaction of a film with a typical thickness gradient in our experiments can be ignored because the gradient is too small (~10^2 nm/40 mm). At each position, the film can be considered as uniform in thickness since the measurement area is small compared to the slope of the gradient (laser spot for light scattering method: < 1 mm^2). Although stronger interaction was observed in the FEA models having higher thickness gradient as shown in the FEA analysis, such steep gradients are rarely feasible experimentally. Figure 4 shows the deformed shape of a specimen with modulus gradient in the film. As shown in Eq. 1, since the wavelength, *d*, is proportional to the cubic root of the modulus ratio between the film and substrate, thus the measurement is less sensitive to the ratio as compared to the thickness of the film. Furthermore, since the critical strain for buckling is the function of modulus ratio[4], but independent of film thickness, the film starts to buckle at the end where critical stress is reached. Our FEA results show that global buckling happens only when the modulus gradient is shallow. Wavelength interaction needs to be taken into account only if the gradient is steep.

For discrete gradient situation, the stress distribution around the corners of the cutting edge was analyzed and a guide was proposed for fabricating discrete libraries of a combinatorial or high throughput specimen. Furthermore, the interaction of the wavelength between adjacent films was also investigated. Similar as in the observation of the combinatorial edge delamination method [4], the cutting depth is a critical parameter affecting the stress distribution and should be larger than a threshold value.

Conclusions

In this presentation, we introduced a numerical analysis (FEA) on the interaction between adjacent regions in a thin film having a gradient on either thickness or modulus. The FEA results suggested that for actual experimental specimens, the interaction could be ignored due to very small gradient. For the discrete gradient specimens, the gap between each region, the depth of the slots separating neighboring regions and film thickness should satisfy an equation so that the stress interaction is small enough that each region can be treated as a single specimen.

* Contribution of the National Institute of Standards and Technology, not subject to copyright in the United States.

References

1. C.M. Stafford, C. Harrison, K. L. Beers, A. Karim, E. Amis, M. R. Vanlandingham, H.-C. Kim, W. Volksen, R. D. Miller, and E. Simonyi, *Nature Materials*, 2004, 3, pp545-550.
2. M. A. Biot, *J. Appl. Mech.*, 1937, A4, ppA1-A7.
3. A. L. Volynskii, S. Bazhenov, O. V. Lebedeva and N. F. Bakeev, *J. Mater. Sci.*, 2000, 35, pp547–554.
4 M. Y.M. Chiang, W.-l. Wu, J. He and E. Amis, *Thin Solid Films*, 2003, 437, pp197-203.

Figures

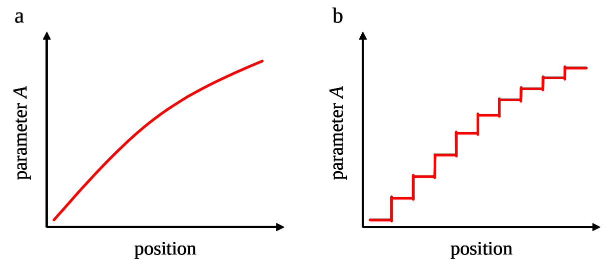

Figure 1. Examples of (a) continuous and (b) discrete gradients in parameter *A* as a function of spatial position along one axis of the film.

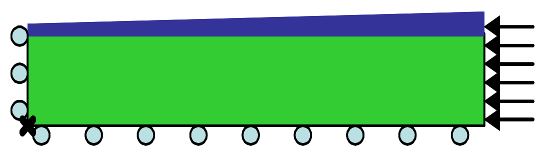

Figure 2. Schematic of FEA model of a film possessing a gradient in thickness.

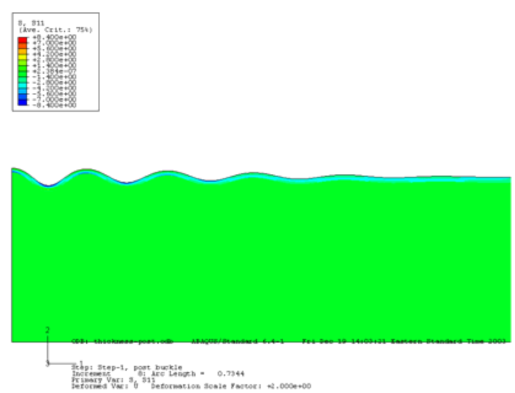

Figure 3. Deformed shape of a film possessing a gradient in thickness.

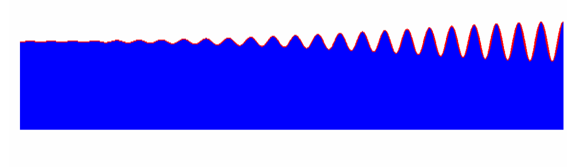

Figure 4. Deformed shape of a specimen with film possessing a gradient in modulus. The modulus at left end is larger than at the right end.