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A new application of digital image processing to investigate thin compressed films: The measurement of buckling propagation

S.B. Wang, Y.Z. Fang, H.K. Jia *, L.A. Li, Z.Y. Wang, S.J. Zhang

Mechanics Department, Tianjin University, Tianjin 300072, PR China

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ABSTRACT

Thin films are used increasingly in technological applications involving microelectromechanical systems, optical reflectors, filters, dielectric stacks, and lithographic resists. However, although the mechanical properties of these submicrometer-thick films are paramount for their effective utilization, many issues remain unresolved to date on the measurement of such properties in thin-film systems. In this paper, an electromechanical device is designed to study the mechanical properties and stability of thin films using two piezoelectric translators. The buckling propagation of thin compressed titanium films deposited on organic glass substrates is investigated utilizing an optical microscope. The rigid-body displacement of the observation field, which is caused by external uniaxial compressive loading, is calculated by the digital image correlation method. Edge detection and filter are carried out to obtain binary images in which the edges of the buckle are obvious, and false noise is eliminated. Therefore, a series of binary images obtained under different loads contains the information on buckling propagation. Further, rigid-body displacement could be compensated for digitally, and the propagation of buckles could be singled out. The experimental results confirm the theoretical proposition that "subcritical" defects can be used to indicate the rigid-body displacement of a substrate. The same method can be used to investigate other problems associated with film buckling.

1. Introduction

As technology continues to trend towards smaller, thinner, and lighter devices, more stringent demands are placed on thin films such as microelectromechanical systems (MEMSs), dielectric coatings, and electronic packaging. Therefore, the requirement for testing platforms to determine rapidly the mechanical properties of thin films is increasing imminently. Buckling of a film/substrate system represents a variety of applications, ranging from stretchable electronics to micronanometrology. In engineering, buckling is a structural failure mode to react to the bending moment generated by compressive load or other situations. Comprehension of thin-film buckling is important in many emerging applications where buckling control is needed, such as stretchable electronics, MEMSs, thin-film metrology, and optical devices. Over the past several decades, with much theoretical and experimental progress, various mechanisms for buckling investigation have been proposed and extensively documented in the literature [1–4]. In conclusion, buckles will propagate in thin films if the induced energy release rate exceeds the interface fracture toughness.

Thin films deposited on substrates are generally subject to residual stress due to thermal expansion misfit [2], which may lead to system breakdown. Under equibiaxial residual compression, the film commonly either fully adheres or fully delaminates. Therefore, application of external uniaxial loading control to produce local buckle and propagation is common [5,6]. Quantitative comprehension of local buckles is helpful in determining the local adhesion of interfaces [7].

For buckling of a film/substrate system, Moon and Chung point out [8], small "subcritical" interface defects remain attached to the substrate, whose statistical upper limit of diameter is 20 times the thickness of the film, while larger "supercritical" defects induced by interface separation may lead to buckles. This standpoint was confirmed with focused ion beam images. Fig. 1 illustrates the cross-sections of a specimen with interface defects. Jiang et al. [9] present experimental and theoretical studies on the mechanics of thin-film buckling on compliant substrates. In particular, accurate measurements of the structural wavelengths and amplitudes of thin, single-crystal ribbons of silicon covalently bonded to elastomeric substrates of poly(dimethylsiloxane) reveal responses that wavelengths change in an approximately linear fashion with the strain in the substrate for all strain values above the critical strain for buckling. A finite-deformation theory [10] was applied to examine the mechanics of thin-film buckling

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* Corresponding author. Tel.: +86 22 27406912; fax: +86 22 27406388.
E-mail address: jiahaikun1984@163.com (H.K. Jia).

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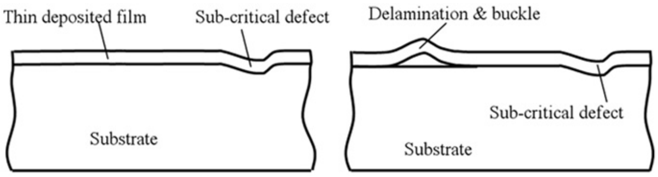

Fig. 1. Cross-section illustrations of the specimen with interface defects.

on compliant substrates. Perturbation analysis was performed for this highly nonlinear system to obtain an analytical solution. The results accord well with experiments and finite element analysis in wavelength and amplitude. Fei et al. [11] present a nonsinusoidal surface profile of thin Au film buckling deposited on compliant substrates, specifically a secondary dip on top of a buckling wave. An efficient measurement method [12] was introduced to measure the elastic moduli of nanoscale polymer films in a rapid and quantitative manner with neither expensive equipment nor material-specific modeling.

Experimental studies show that deformation fields are often used to analyze the buckling of thin films. However, axial displacements of the observation field occur in the process of loading, especially when clamps are fixed. Such inevitable displacements pose an obstacle in tracking one specified region where buckling occurs. Now that any observed movement of a specimen can be interpreted as the superposition of deformation onto displacement, this work mainly aims to overcome the problem of extracting the deformation of buckle edges from the observation image by eliminating undesirable displacement with emphasis on subcritical defects. Such defect is shown to be a good indicator of the rigid-body displacement of the substrate.

2. Experimental setup and methodology

2.1. Compensation for rigid-body displacement

The subcritical defects were emphasized to exhibit the character of the substrate in film surface topologies because the thickness of the deposited film was uniform. As a result, the subcritical defects can be used to indicate the displacement of the substrate.

The digital image correlation method (DICM), which was originally introduced by Peters and Ranson [13] was applied to compensate for the rigid-body motion of a specified region with subcritical defects in the film surface. The principle of DICM is illustrated in Fig. 2. The laser speckle pattern, natural texture, or artificial speckle sprayed on the surface of the specimen provided information to calculate the displacement and strain. Over the past two decades, DICM has been widely used in experimental mechanics [14–16]. We believe that subcritical defects can also be used in DICM as a kind of speckle in a broader sense.

The cross-correlation coefficient is defined by

$$C(u,v)=\frac{\sum_{i=1}^{m}\sum_{j=1}^{n}f_{i,j}\,g_{i+u,j+v}}{\sqrt{\sum_{i=1}^{m}\sum_{j=1}^{n}f_{i,j}^{2}}\sqrt{\sum_{i=1}^{m}\sum_{j=1}^{n}g_{i+u,j+v}^{2}}}, \qquad (1)$$

where f is the gray level of the selected region in the original image, and g is the gray level of the corresponding region in the deformed image; u and v are the displacement components of the reference point in the two axial directions; m and n are the height and width of the subregion, respectively.

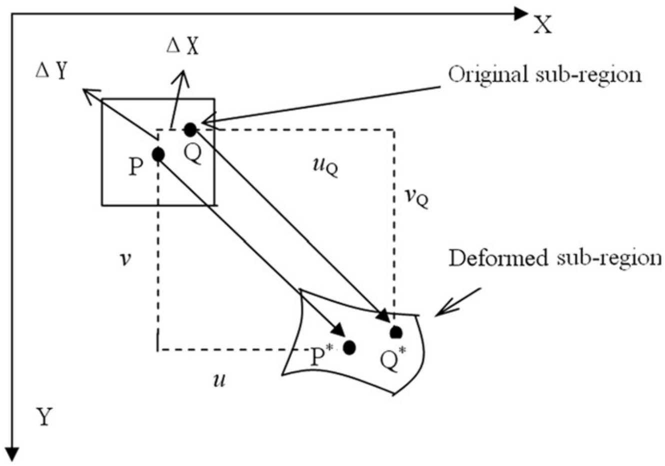

Fig. 2. Illustration of the principle of DICM.

2.2. Edge detection and filter of the image

For some buckles, deformation is so subtle that a simple filter will cause fatal damage to the details. However, without filtering, a lot of noise will appear in the image. In common threshold processing, the threshold is set dependently on the actual noise, particularly the clarity of the object edges. After edge detection, object edges with a high gray gradient become continuous, indicating that a high threshold has no negative impact. However, a series of discrete points will be produced by edge detection on the edges of objects with a low gray gradient. The lower threshold for edge detection is conducive to the continuity of object edges, but this will result in additional false noise. Therefore, after edge detection, a filter is used to eliminate the additional false noise.

Roberts, a 2×2 template [17], which operates with the difference between two adjacent pixels in the diagonal direction, is defined by

$$g(x,y)=\{[\sqrt{f(x,y)}-\sqrt{f(x+1,y+1)}]^{2}+[\sqrt{f(x+1,y)}-\sqrt{f(x,y+1)}]^{2}\}^{1/2}. \qquad (2)$$

Improved image edge detection can be conducted by the following steps:

Step 1: To the original image, application of image edge detection is carried out by the Roberts operator.

Step 2: The first threshold is determined for the gray level of each pixel to obtain a binary image, in which the false edges have been eliminated.

Step 3: Gaussian filter operation is applied to each pixel and its adjacent subdomains in the obtained binary image, and the second threshold for convolution is determined to obtain another binary image. The pixels whose convolution values are greater than those in the second threshold are set to bright, while the pixels whose convolution are less are set to dark.

The first threshold for the gray level was relatively small to avoid loss of potential true edges. The second threshold for convolution is to eliminate isolated bright spots in filter operation subdomains.

2.3. Digital image processing

The experimental equipment is shown in Fig. 3. The specimen was deformed by two piezoelectric translators (PZTs). During the compression, the displacements of the two sides of the specimen