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ORIGINAL RESEARCH

Measurement of the mechanical properties of nickel film based on the full-field deformation: An improved blister method

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Abstract To characterize the mechanical properties of thin films, an improved blister method is proposed, which combines a digital speckle correlation method with the blister test. Based on this method, an experimental setup is developed to measure Young's modulus, residual stress, and interfacial adhesion energy of an electroplated nickel film. The results show that the improved blister method has the advantage of a high accuracy full-field measurement with the simple operation and low requirement on environments, which can be used to characterize the mechanical properties of films with various scales from laboratorial to industrial applications.

1. Introduction

Thin films have been widely used in wear-resistant coating on cutting tools [1], anticorrosion coating of plates [2] and thermal barrier coatings on turbine blades [3]. Unfortunately, the premature fracture usually occurs in films or coatings when they are in service. The mechanical properties of thin films play an important role in their design and applications. Many techniques have been used to characterize the mechanical properties of bulk materials, but they cannot be directly applied to thin films [4,5]. Over the last decades, some new methods have been developed to measure the mechanical properties of thin films such as uniaxial tension [6], indentation [7],

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scratching [8], etc. Among these methods, samples are easily prepared in indentation and scratching tests, however, the measurement results are often affected by substrate [9] and the thickness of a thin film [10]. In contrast, it is difficult to fabricate and handle the samples in uniaxial tensile tests in a micron or submicron scale.

Similar to indentation and scratching tests, the advantage of a blister method is the minimal sample preparation and handling. Furthermore, the blister test can be used to estimate the adhesion energy of film/substrate because the dissipated energy in the test contributes to interfacial debonding. Hence, the blister test has been widely applied to characterize the mechanical properties of silicon nitride [11–17], polymer [18,19], metal [20–24], and diamond films [1]. It is worth noting however, that the accuracy and reliability of the blister test is mainly affected by the assumed load-deflection equation, samples and data measurements [25]. Small and Nix analyzed the influence of initial conditions, such as residual stress and thickness of films, by finite element simulation [26]. Maier-Schneider et al. [27] compared the square film models proposed by Tabata et al. [16] and Vlassak and Nix [11], and showed that the latter is more precise. Jiang et al. [28,29] investigated the influence of plastic deformation on the adhesion energy and found that the plastic work in substrate contributes significantly to the critical pressure. With the rapid development of a silicon micromachining technology, it has been possible to manufacture samples with precisely controlled dimensions [11,12].

Generally, the deformation measurement is essential for the determination of physical and mechanical properties in the blister test. The methods used to conduct the deformation measurement include using a cathetometer [30] and displacement sensor [3]. However, these traditional technologies are only suitable for point measurements, and it is difficult to extract the meso/micro-deformation information such as interface debonding. Hence, it is necessary to measure the three-dimensional deformation morphology of displacements or strains. The whole field measurement techniques include the fringe projection [31], speckle interference [20], and surface profiler [23]. These methods can be used to determine the deformation of a film at different points, but their experimental operation is complex and due to external vibration, the interferometric beam may easily deviate from the original optical path.

The digital speckle correlation method (DSCM) is applied for deformation measurements with the advantage of simple optical path, high accuracy and no requirement of vibration isolation [32,33]. According to the investigation by Zhu et al. [32], an accurate three-dimensional measurement deformation system calibrated with telemetric lens was developed. The measurements on deformation by DSCM are in agreement with those obtained by electronic speckle pattern interferometry (ESPI). Yan et al. realized the orientation function of an optical mouse based on DSCM [33]. The experiments showed that such an orientation function is consistent with simulation results. To the best of our knowledge, there are few studies on the deformation measurement by using DSCM in the blister test. In this paper, DSCM is used to study the deformation characterization of nickel films. Typical mechanical properties are analyzed based on the evolution of the displacement field during the blister test.

2. The principle of DSCM

In the application of DSCM, speckle patterns on a specimen surface before and after deformation are digitized into source and target images. As illustrated in Fig. 1(a), points $P(x_P, y_P)$ and $Q(x_Q, y_Q)$ in the source image move to P^* and Q^* in the target image. The relationship of these two points can be written as

$$\begin{aligned} x_Q &= x_P + \Delta x \\ y_Q &= y_P + \Delta y \end{aligned} \tag{1}$$

where Δx and Δy are the distances between points P and Q along x and y directions, respectively. After deformation, displacements of point P are u_P and v_P in the x and y directions, respectively. Then

$$\begin{aligned} x_P^* &= x_P + u_P \\ y_P^* &= y_P + v_P \end{aligned} \tag{2}$$

Similarly, displacements of point Q are

$$\begin{aligned} x_Q^* &= x_Q + u_Q \\ y_Q^* &= y_Q + v_Q \end{aligned} \tag{3}$$

In consideration of tensile and shear effects with very small Δx and Δy, u_Q and v_Q can be represented as [34]

$$\begin{aligned} u_Q &= u_P + \frac{\partial u_P}{\partial x}\Delta x + \frac{\partial u_P}{\partial y}\Delta y \\ v_Q &= v_P + \frac{\partial v_P}{\partial x}\Delta x + \frac{\partial v_P}{\partial y}\Delta y \end{aligned} \tag{4}$$

Substituting Eqs. (1) and (4) into (3), we have

$$\begin{aligned} x_Q^* &= x_P + u_P + \frac{\partial u_P}{\partial x}\Delta x + \frac{\partial u_P}{\partial y}\Delta y \\ y_Q^* &= y_P + v_P + \frac{\partial v_P}{\partial x}\Delta x + \frac{\partial v_P}{\partial y}\Delta y \end{aligned} \tag{5}$$

That is, for an arbitrary point Q, we have

$$\begin{aligned} x^* &= x + u + \frac{\partial u}{\partial x}\Delta x + \frac{\partial u}{\partial y}\Delta y \\ y^* &= y + v + \frac{\partial v}{\partial x}\Delta x + \frac{\partial v}{\partial y}\Delta y \end{aligned} \tag{6}$$

In the case of a very small PQ, the following relationships can be obtained:

$$\begin{aligned} dx &= x_Q - x_P, \quad dy = y_Q - y_P \\ dx^* &= x_Q^* - x_P^*, \quad dy^* = y_Q^* - y_P^* \end{aligned} \tag{7}$$

It is obvious that the distances of PQ before and after deformation are

$$\begin{aligned} |PQ|^2 &= (dx)^2 + (dy)^2 \\ |P^*Q^*|^2 &= (dx^*)^2 + (dy^*)^2 \end{aligned} \tag{8}$$

Thus, the strain in the x direction can be defined as

$$\varepsilon_{xx} = \frac{|P^*Q^*| - |PQ|}{|PQ|} \cong \frac{\partial u}{\partial x} + \frac{1}{2}\left[\left(\frac{\partial u}{\partial x}\right)^2 + \left(\frac{\partial v}{\partial x}\right)^2\right] \tag{9}$$

Following the same procedure, the strain components in other directions can be written as

$$\varepsilon_{xx} = \frac{\partial u}{\partial x} + \frac{1}{2}\left[\left(\frac{\partial u}{\partial x}\right)^2 + \left(\frac{\partial v}{\partial x}\right)^2\right]$$