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A novel 3D deformation measurement method under optical microscope for micro-scale bulge-test

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ABSTRACT

A micro-scale 3D deformation measurement method combined with optical microscope is proposed in this paper. The method is based on gratings and phase shifting algorithm. By recording the grating images before and after deformation from two symmetrical angles and calculating the phases of the grating patterns, the 3D deformation field of the specimen can be extracted from the phases of the grating patterns. The proposed method was applied to the micro-scale bulge test. A micro-scale thermal/mechanical coupling bulge-test apparatus matched with the super-depth microscope was exploited. With the gratings fabricated onto the film, the deformed morphology of the bulged film was measured reliably. The experimental results show that the proposed method and the exploited bulge-test apparatus can be used to characterize the thermal/mechanical properties of the films at micro-scale successfully.

1. Introduction

With increasing applications of thin films in many areas [1–4], the mechanical property characterization of thin films is crucial. Conventional applied methods, such as the wafer curvature method based on the Stoney's formula and the nano-indentation method [5,6], have been applied to characterize the mechanical properties of the thin films. Although the wafer curvature method is easy to implement and applied to measure the residual stress of the films, it's hard to extract other properties of the films. The nano-indentation test can be used to characterize the elastic-plastic properties of the film, but influences of substrates can't be eliminated. So the above mentioned methods have limitations for the mechanical properties characterization of thin films.

To characterize the mechanical properties of free-standing films, micro-tensile test and bulge-test were developed. The micro-tensile test can measure the intrinsic properties of the films directly and constitutive behaviors with the increasing load applied [7]. Sharpe et al. proposed a micro-tensile test technique, which can measure the strain of free-standing films in micro-region based on the optical interferometric strain gauge method [8]. The strain can be exactly obtained with the interferometric method. Li et al. proposed a compact in situ micro tensile apparatus together with the scanning electron microscope (SEM) to characterize the mechanical properties of the free-standing films [9]. In this method gratings were fabricated on the films by focused ion beam milling, and the strain field can be extracted by the fabricated gratings. The advantage of the SEM scanning moiré method is full field deformation measurement compared with optical interferometric strain gauge method.

Even though the micro-tensile test methods can satisfy the demand for the mechanical characterization of the free-standing films, some special requirements cannot be perfectly fulfilled, such as the measurement of polymer films. When buckling is more likely to occur [10], the out-of-plane displacement will bring difficulty to the measurement. Comparatively, bulge-test methods are more competent [11–13]. The mechanical properties of the film are determined from the related pressure-deflection theory [14–16].

The critical technique of the bulge-test method is the characterization of the out-of-plane deflection of the films [17]. Especially, for micro-scale bulge-test, the 3D deformation characterization is challenging [18,19]. Many research works have been carried out to provide techniques to characterize the 3D deformation in micro/nano scale [20]. The microscopic 3-D displacement field measurement by digital image correlation method has been proposed and the speckle patterns were obtained by two CCD cameras of the stereomicroscope [21]. Shi et al. [22] have proposed the fringe projection combined with the digital image correlation method to characterize the out-of-plane deformation of small objects. Wu et al. [23] characterized the 3D deformation of thin films in SEM by grating based method.

Even though the digital image correlation method is widely used in the measurement field, the image distortion induced from the mi-

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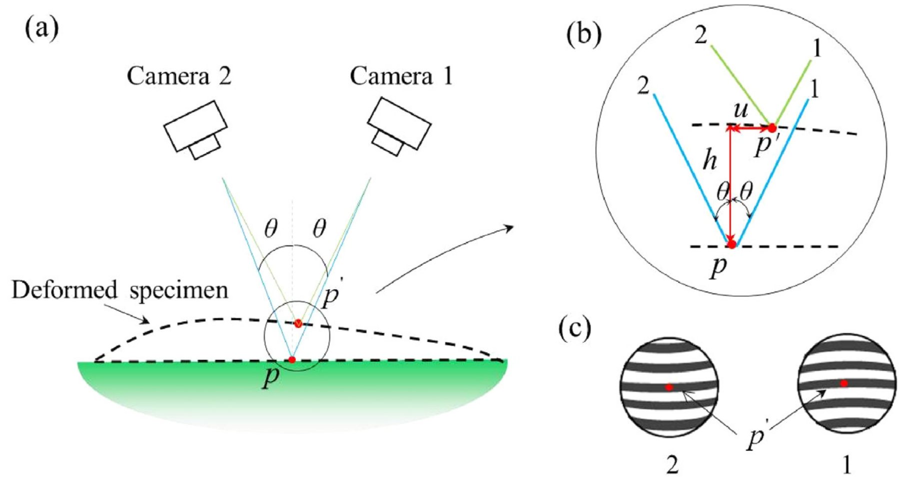

Fig. 1. A schematic of the basic principle of the proposed 3D deformation measurement method: (a) two symmetric CCDs are used to capture the grating images before and after deformation; (b) the point p moves to p' and the number 1 and 2 corresponds to the light path of camera 1 and 2; (c) the deformed grating images obtained by two CCDs.

croscopy imaging system will bring significant error to this method. This error is especially prominent for optical microscope due to small depth of field. So evaluation and elimination of errors are required, which is relatively complicated.

In this paper, we demonstrate a 3D deformation measurement method to characterize the deflection of the micro-scale bulge-test. which is integrated with the super-depth microscope. The 3D displacement fields of the deflected film were obtained, more than the morphology obtained by the white light interferometer [13]. This method is based on the grating based measurement method and the digital phase shifting technique. Compared with the SEM digital image correlation method [18], the grating based measurement method [24,25] is less affected by image distortion and drifting. With the proposed method, thermal/mechanical coupling bulge-test to the polyimide films was performed. The results indicate the feasibility of this method.

2. Theoretical background

2.1. Basic principles

The proposed method is based on gratings, so micro/nano-gratings need to be fabricated on the specimen before deformation. It is assumed that the specimen grating is uniform and the pitch is d, and the fringe is parallel to the y axis. The gratings along the x axis can be expressed by Fourier series as [26]:

$$I = A_0 + \sum_{n=1}^{\infty} B_n \cos\frac{2\pi n}{d}x + \sum_{n=1}^{\infty} C_n \sin\frac{2\pi n}{d}x \tag{1}$$

where I is the intensity of the specimen gratings, A_0, B_n, C_n are constants, which can be determined from the fringe profile of the gratings. It is assumed that the specimen surface is flat before deformation. In our testing system, there are two digital cameras symmetric about the normal direction of the specimen surface (Fig. 1(a)). It should be noted that in this method the specimen is in micro-scale and far less than the distance from the CCD to the specimen surface. So it is approximately regarded that the two CCDs are symmetric about the normal of every point on the specimen surface. The approximation will bring slight deviation to the measurement, which will be discussed later in the text.

Due to the CCD is oblique to the specimen grating, the pitch of the grating image obtained by the two CCDs is $d'=d\cos\theta$. When the specimen deformed and the point p moves to p' (Fig. 1(b)), the displacement of the corresponding point p' in the grating image (Fig. 1(c)) obtained by camera 1 is $u-h\tan\theta$ (Fig. 1(b)). So the coordinate of p' $x_1=x-h\tan\theta+u$. The displacement by camera 2 is $h\tan\theta+u$. The corresponding coordinate of p' is $x_2=x+h\tan\theta+u$. So the grating intensity obtained by the two cameras is expressed as:

$$\begin{cases} I_1 = A_0 + \sum\limits_{n=1}^{\infty} B_n \cos\dfrac{2\pi n}{d'}x_1 + \sum\limits_{n=1}^{\infty} C_n \sin\dfrac{2\pi n}{d'}x_1 \\ I_2 = A_0 + \sum\limits_{n=1}^{\infty} B_n \cos\dfrac{2\pi n}{d'}x_2 + \sum\limits_{n=1}^{\infty} C_n \sin\dfrac{2\pi n}{d'}x_2 \end{cases} \tag{2}$$

Here the two cameras are regarded as exactly the same, so the coefficients of the two formulas in Eq. (2) are the same. From Eq. (2), the in-plane displacement in x direction and out-of-plane displacement are included in the deformed grating images. u and h are related with the phases of the gratings. To extract the two components, the phases of the gratings are to be calculated. Digital moiré method was applied in the process to extract the phase information. Firstly, digital reference grating was generated by the computer program. The generated grating fringes are parallel to the y axis and the intensity of the sinusoidal grating can be expressed as:

$$I_0 = a_0 + b_0 \cos\frac{2\pi}{d_0}x + c_0 \sin\frac{2\pi}{d_0}x \tag{3}$$

where a_0, b_0, c_0 are constants, and d_0 is the pitch of the reference gratings. After superimposing the reference gratings with the specimen grating image obtained by camera 1, the results I' is obtained:

$$\begin{aligned} I' = I_0 I_1 = {} & a_0A_0 + b_0A_0\cos\frac{2\pi}{d_0}x + c_0A_0\sin\frac{2\pi}{d_0}x + a_0\sum_{n=1}^{\infty} B_n\cos\frac{2\pi n}{d'}x_1 \\ & + a_0\sum_{n=1}^{\infty} C_n\sin\frac{2\pi n}{d'}x_1 + \frac{1}{2}(b_0C_1 - c_0B_1)\sin\left[\frac{2\pi}{d'}x_1 - \frac{2\pi}{d_0}x\right] \\ & + \frac{1}{2}(b_0B_1 + c_0C_1)\cos\left[\frac{2\pi}{d'}x_1 - \frac{2\pi}{d_0}x\right] \\ & + \frac{1}{2}\sum_{n=2}^{\infty}(b_0C_n - c_0B_n)\sin\left[\frac{2\pi n}{d'}x_1 - \frac{2\pi}{d_0}x\right] \\ & + \frac{1}{2}\sum_{n=2}^{\infty}(b_0B_n + c_0C_n)\cos\left[\frac{2\pi n}{d'}x_1 - \frac{2\pi}{d_0}x\right] \\ & + \frac{1}{2}\sum_{n=1}^{\infty}(b_0C_n - c_0B_n)\sin\left[\frac{2\pi n}{d'}x_1 + \frac{2\pi}{d_0}x\right] \\ & + \frac{1}{2}\sum_{n=1}^{\infty}(b_0B_n + c_0C_n)\cos\left[\frac{2\pi n}{d'}x_1 + \frac{2\pi}{d_0}x\right] \end{aligned} \tag{4}$$

It can be seen that the second line of Eq. (4) is the original reference and specimen grating structures. If d_0 approximately equals to d',