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Measuring thickness change of transparent plate by electronic speckle pattern interferometry and digital image correlation

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ABSTRACT

The thickness change of transparent plates was measured by electronic speckle pattern interferometry (ESPI) method and digital image correlation (DIC) method. An out-of-plane ESPI system was developed based on the Michelson interferometer, and a new thickness measurement method was designed, which is on the basis of Snell's law of refraction and DIC. The main principles and experimental procedures of these two methods were presented. The thickness change of polymethyl specimens under uniaxial tensile loading were measured by the optical techniques and compared with each other. The results reveal that the data obtained with DIC method achieve better linearity than ESPI.

1. Introduction

Thickness is an important parameter of a transparent plate. It is necessary to measure the variation of the thickness before and after deformation under loading. There are many optical methods which have been developed for the measuring thickness nondestructively. Spectroscopic ellipsometry technique involving the setting up of a suitable model, such as the incoherent reflection model [1], is often used. Wavelength scanning method is well known. This method is sometimes applied in combination with other techniques, such as with the wavelet transform technique [2], confocal microscopy [3], or phase-shifting method [4]. Interferometers are frequently used [5–10]. The principle of these methods is based on the measurement of fringes or laser speckles which carry information about the thickness. Among all optical interferometric techniques, electronic speckle pattern interferometry (ESPI) is widely used for deformation studies, and it is the most practical and powerful one [11].

Digital image correlation (DIC) is a computer vision technique which is used to measure the surface displacements of deforming materials. Compared with other optical techniques, DIC shows special advantages, such as simple optical setup and specimen preparation, no special requirement for environment. Furthermore, DIC measurements can be performed by non coherent illumination using the specimen's surface texture or pattern projection for image correlation. It has been widely applied in displacement measurement. To obtain out-of-plane displacement, two cameras are required to observe the object from two different directions [12–14]. Tay et al. [15] had proposed a method which combined DIC with pin-hole camera imaging model, and thus it is able to determine out-of-plane displacement using a single camera. Furthermore, in Ref. [9] 3D displacement data is obtained with a single image recording device by numerical evaluation of speckle patterns that are generated by illumination the object with coherent laser light.

In this paper, an out-of-plane ESPI system was developed based on the Michelson interferometer and a new thickness measurement method was designed, which is on the basis of Snell's law of refraction and DIC. Previously, the relationship between the optical path difference in the system and the thickness change was given. The procedure of calculating the thickness changes from the in-plane displacements obtained by DIC was also presented. In order to verify the feasibility and effectiveness of the proposed techniques, the thickness changes of transparent polymethyl specimens under uniaxial tensile loading were measured by the two methods and compared with each other, finding good agreement between them. The results also reveal that the data obtained by DIC method achieve better linearity.

2. Techniques of measurement

2.1. ESPI

For deformation measuring, an initial (reference) speckle pattern image from the surface target is taken. This reference image is automatically subtracted from the incoming data when the object

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under study is deformed. Then, using four steps phase-shifting technique, the phase distribution can be calculated.

The measured intensity of a CCD detector may be written as

$$I(x,y,n\alpha) = a(x,y) + b(x,y)\cos[\phi(x,y) + n\alpha], \quad n = -N,\ldots,0,\ldots,N, \tag{1}$$

where $\phi(x, y)$ is the phase to be determined, $a(x, y)$ is the slowly varying background illumination, and $b(x, y)$ is the contrast of the interference fringes. The parameter α is the phase step between the interferograms obtained by linearly varying the path difference between the test and reference beams [16].

The searched phase can be solved by

$$\phi = \arctan\left(\frac{I(3\alpha)-I(\alpha)}{I(0)-I(2\alpha)}\right). \tag{2}$$

In the case of an out-of-plane interferometer with illumination perpendicular to the object surface, the relationship between phase difference and the optical path difference is given by [17]

$$\phi = \frac{4\pi}{\lambda}w \tag{3}$$

where λ is the illuminating source wavelength and w is the out-of plane displacement measured by the optical arrangement shown in Fig. 1.

As shown in Fig. 2, the optical path difference (OPD) in this system, when testing a single plane parallel plate, is given by

$$OPD = 2^*(OA-OB) = 2\Delta d = 2w \tag{4}$$

where Δd is the change in the thickness.

According to Eqs. (2)–(4), the changes in the thickness can be calculated as

$$\Delta d = \frac{\lambda}{4\pi}\arctan\left(\frac{I(3\alpha)-I(\alpha)}{I(0)-I(2\alpha)}\right). \tag{5}$$

2.2. DIC method

2.2.1. DIC theory

DIC method is performed between two images of the object surface taken before and after deformation, which are referred to as the reference image and the target image, respectively. The basic principle of DIC is schematically illustrated in Fig. 3. A square

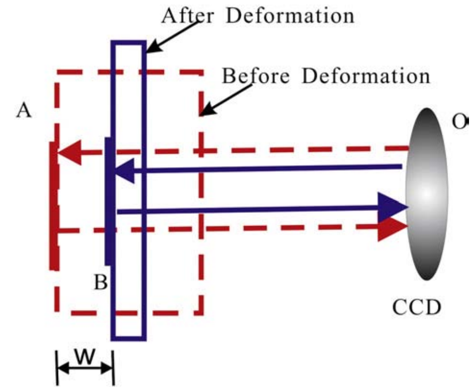

Fig. 2. Relation between OPD and thickness change.

reference subset of $(2M+1)\times(2M+1)$ (where M is a positive integer) pixels centered at the current point $A(x,y)$ from the reference image is chosen and used to find the corresponding location with the same size centered at the point $B(x', y')$ in the target image. Once the location is found, the displacement components of the reference and target subset centers can be determined by using a correlation function. In this paper, the following correlation function was used [18],

$$C = \frac{\sum_{x=-N}^{N}\sum_{y=-N}^{N}\left[f(x,y)-\bar{f}(x,y)\right]\left[g(x',y')-\bar{g}(x',y')\right]}{\sqrt{\sum_{x=-N}^{N}\sum_{y=-N}^{N}\left[f(x,y)-\bar{f}(x,y)\right]^2}\sqrt{\sum_{x=-N}^{N}\sum_{y=-N}^{N}\left[g(x',y')-\bar{g}(x',y')\right]^2}} \tag{6}$$

where $f(x, y)$ and $g(x', y')$ are the gray-level intensity of the reference image and the target image, respectively, $\bar{f}(x,y) = \left(1/(2N+1)^2\right)\sum_{x=-N}^{N}\sum_{y=-N}^{N}[f(x,y)]$ and $\bar{g}(x',y') = \left(1/(2N+1)^2\right)\sum_{x=-N}^{N}\sum_{y=-N}^{N}[g(x',y')]$ are the mean intensity values of reference and target subsets, respectively.

2.2.2. Retrieval of the thickness

The arrangement is shown in Fig. 4. The light beam from the laser falls on the transparent specimen, a part of the beam is reflected back, the remaining portion is transmitted through the specimen and refracted. Then, a laser spot is generated on the plane by the refracted ray. The changes in the thickness can be obtained by determining the

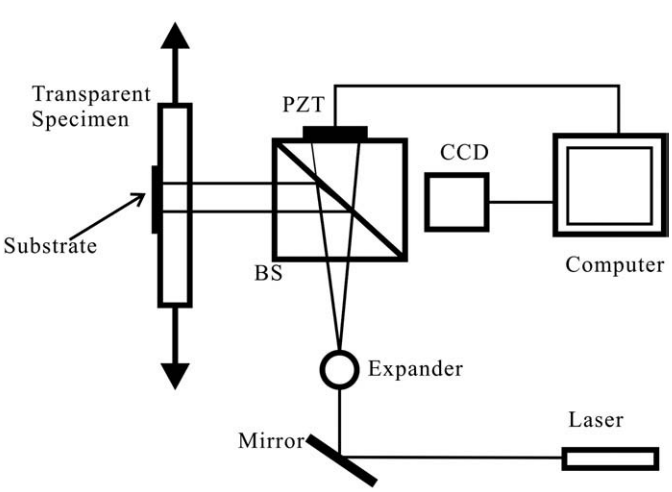

Fig. 1. Schematic of ESPI system.

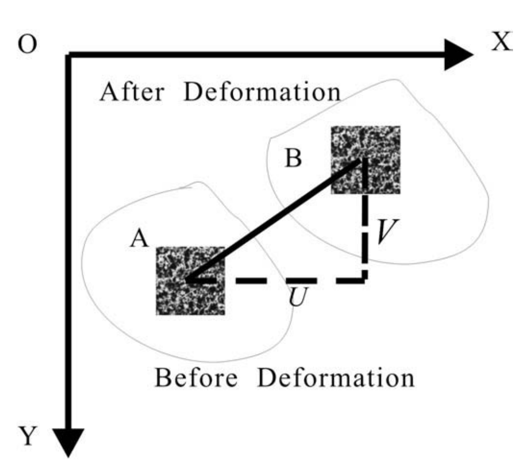

Fig. 3. Subsets before and after deformation.