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Accurate measurement of elastic modulus of specimen with initial bending using two-dimensional DIC and dual-reflector imaging technique

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ABSTRACT

Common optical methods are not suitable for accurate measurement of elastic modulus of specimens with initial bending because it is rather difficult to separate the axial strain caused by the axial load from the surface strain which consists of the axial strain and the bending strain caused by additional bending moment. Inspired by the strain-gauge technique, averaging the two strains on the opposite surfaces can eliminate the effect of bending strain of the specimen with initial bending, which is easily implemented by dual-reflector imaging and two-dimensional digital image correlation (2D-DIC). With dual-reflector imaging, the front and rear surfaces of the specimen are recorded by using a single digital camera. Consequently, the strains of two optical extensometers constructed on these two surfaces are obtained with common 2D-DIC, and averaging these strains can eliminate the effect of bending moment and out-of-plane motion of the specimen. Therefore, the elastic modulus can be determined with high measurement accuracy. The effectiveness of the proposed method was first verified using self-manufactured tensile equipment which leads to large out-of-plane motion during the test. Furthermore, uniaxial tensile tests of stainless-steel specimens, including static and continuous tensile tests, were conducted to evaluate the accuracy of the proposed method. The experimental results show good agreement between elastic modulus obtained using the proposed method and a strain gauge and the relative error between them is less than 0.5%, which shows excellent performance of the proposed method on accurate measurement of elastic modulus of specimens with initial bending.

1. Introduction

A tensile test is the most simple and most effective method for determining the mechanical properties of materials. In a tensile test, there are many methods for strain measurement, which could be divided into contact methods and noncontact optical methods. Contact methods mainly include the strain-gauge technique and mechanical extensometers. As a very mature method, the strain-gauge technique can conveniently obtain the linear strain by attaching an electrical-resistance strain gauge to the specimen surface. Although the strain-gauge technique provides a very high strain measurement accuracy, its strain measurement range is generally less than 2%, which is not suitable for measuring the large deformation of a ductile material. When mounted on specimen by two knife edges, a mechanical extensometer measures the average strain in the gauge section of a material test specimen. However, the mechanical extensometer can be easily damaged when the specimen failure occurs. Optical methods such as digital image correlation (DIC) [1–3], electronic speckle-pattern interferometry (ESPI) [4], digital holography [5], and Moiré interferometry [6] can provide noncontact and full-field measurement and thus play an increasingly important role in strain measurement. An optical extensometer, as an optical technique, has a great potential to replace conventional contact methods owing to its noncontact measurement and large strain measurement range.

Similar to a mechanical extensometer, an optical extensometer measures the strain by tracking two feature points that define the gauge length. Early optical extensometers did not fully eliminate the need for contact. For example, Meintjes [7] devised an optical extensometer in which a prism in contact with a sample is used to generate Newton's rings to measure the linear expansion of the sample. A design for a small Fabry–Perot interferometer was described by Dean [8], which serves as an accurate optical extensometer for the measurement of the lateral strain in the sample. With a modulated laser beam, the optical extensometer developed by Blair et al. [9] measures the axial deformation of a borehole by detecting the distance between the reflecting target placed at the desired measurement locations and an optical head. Afterward, a complete contactless optical extensometer was developed. Wu et al. [10] presented a self-designed optical extensometer that

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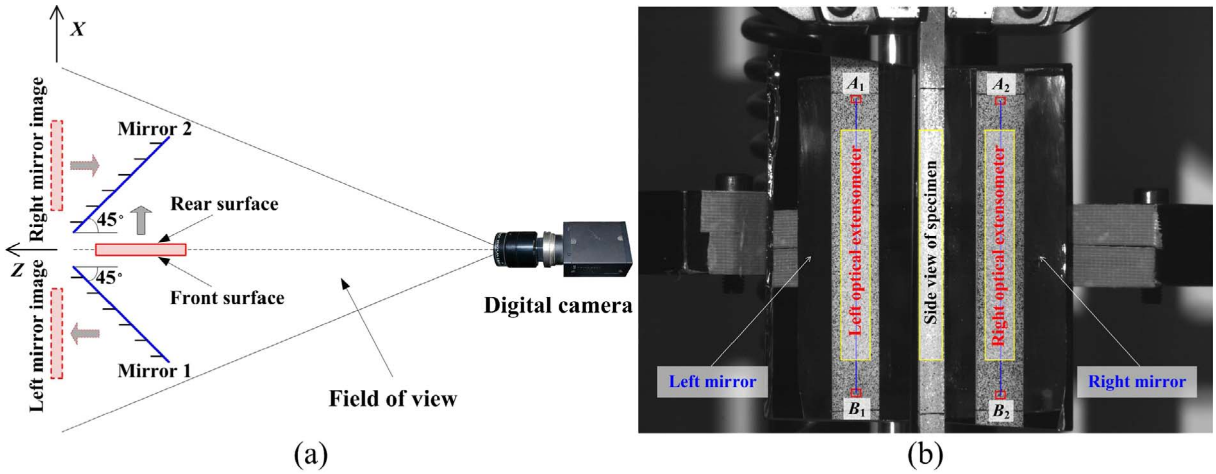

Fig. 1. (a) Schematic of dual reflector imaging and (b) the selection of two gauge points of the optical extensometers on the front and rear surfaces.

mainly consisted of two parallel optical fibers adhered to the specimen and two position sensitive detectors (PSDs). To avoid the inconveniences of laser light [11,12], several methods for processing the specimen surface were employed, such as dot markers by Quatravaux et al. [13] and Ye et al. [14], regular (black and white lines) patterns by Casarotto et al. [15] and Ali et al. [16], and random speckle patterns by Zhang et al. [17] and Bai et al. [18]. Consequently, the relative displacement between the gauge points of an optical extensometer is obtained with many registration algorithms. When a DIC algorithm is applied to a speckle image, a high subpixel accuracy can be achieved; therefore, the DIC technique has attracted an increasing application to optical extensometers [17,19–21].

Although they have a great potential for strain measurement, optical extensometers have two shortcomings. One is the assumption of a nominally planar specimen surface. The other one is that the strain obtained using an optical extensometer is easily affected by the inevitable out-of-plane motion of the specimen during the loading process. Pan et al. [22] found that a bilateral telecentric lens alleviates the effects of out-of-plane motion and lens distortion; thus, the use of a bilateral telecentric lens could improve the strain accuracy of an optical extensometer. Our previous study [18] proposed a high-accuracy optical extensometer that could eliminate the effect of out-of-plane motion after the strain is corrected by means of a rigid correction sheet. To avoid the use of the correction sheet, we recently presented a dual-reflector imaging technique [23], which could record the front and rear surfaces of a specimen using a single digital camera. By averaging the two strain results obtained by the front and rear optical extensometers, the effects of the out-of-plane motion on the strain were effectively removed, which improved the strain measurement accuracy of the optical extensometer.

In engineering tests, thin specimens are prone to bending during manufacturing process. When such specimens are stretched in tensile tests, an additional bending moment will be applied to specimen besides the axial load, which will lead to different strain results on the opposite surfaces perpendicular to the bending plane. In this case, the determination of elastic modulus depends on the measurement of the axial tensile strain caused by the axial force. However, the aforementioned optical extensometer is not suitable for measurement of the axial tensile strain of specimen with initial bending. Although the effect of out-of-plane motion of such specimen can be eliminated with some methods [18,22,24,25], the axial strain caused by the axial load is impossible to be separated from a single surface strain which consists of the axial strain and the bending strain. Correspondingly, the accuracy of elastic modulus is not sufficient enough. Concerning on such situation, resistance strain measurement technique provides a solution that is averaging the two strains on the opposite surfaces to generate the axial strain, which is easily implemented using the bridge circuit of the strain-gauge technique. Inspired by such idea, we utilize the averaging of the two strains on the opposite surfaces obtained with optical extensometers to determine elastic modulus of a specimen with initial bending, which can be easily realized by our already proposed dual-reflector imaging method.

2. Accurate measurement of elastic modulus

2.1. Principles of the high-accuracy optical extensometer

In an optical extensometer, the relative displacement between two gauge points can be detected with feature recognition or the 2D-DIC technique. By dividing the relative displacement by the initial gauge length l_0, the axial strain, which indicates the mean strain within the gauge length of the specimen, will be obtained as follows:

$$\varepsilon = \frac{v^A - v^B}{l_0}, \tag{1}$$

where v^A and v^B denote the v-displacements of the gauge points.

However, out-of-plane motion of the specimen is inevitable during the loading process owing to the existence of Poisson's effect and so on, which will result in an in-plane image displacement. Therefore, the displacement caused by deformation is easily corrupted by the rigid out-of-plane motion of the specimen; thus, the strain accuracy of the optical extensometer is always unsatisfactory. Consequently, dual-reflector imaging, as shown in Fig. 1(a), is adopted here to eliminate the effects of out-of-plane motion and to improve the strain accuracy of the optical extensometer.

In dual-reflector imaging, the side view of specimen in Fig. 1(a) is placed in front of the digital camera, which means that the specimen surface to be detected is parallel to the optical axis of the digital camera. In particular, the specimen is loaded along the Y-axis direction, which is perpendicular to the figure plane. Two symmetrical mirrors are arranged at an angle of 45° with respect to the specimen surface. From the perspective of the digital camera, the front and rear specimen surfaces are imaged at the positions of the red dashed lines and captured with the digital camera. With the proposed optical setup, the front and rear surfaces of specimen are respectively recorded on the left and right parts of a single image. Fig. 1(b) shows an example of a recorded image of a specimen from an experiment. During the loading process, the out-of-plane motion of the specimen will cause the left and right mirror images to move the same distance in opposite directions. For the digital camera, the front and rear surfaces of the specimen have the same object distance owing to the symmetrical arrangement of the two mirrors in Fig. 1(a). Therefore, the image displacements caused by the