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Phase-shifted reflective coherent gradient sensor for measuring Young's modulus and Poisson's ratio of polished alloys

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ABSTRACT

In this study, the Young's modulus and Poisson's ratio of Ni-Cr Alloy are measured using phase-shifted reflective coherent gradient sensing (CGS) method. Three-point bending experiment is applied to obtain the Young's modulus by measuring the specimen out-of-plane displacement slopes. Bending experiment of a circular plate with fixed edges loaded by a centric concentrated force is applied to obtain the specimen bending stiffness. The Poisson's ratio is then solved by substituting the bending stiffness into Young's modulus. The results show that the phase-shifted reflective CGS method is valid for measuring Young's modulus and Poisson's ratio of metals and alloys. In addition, the reflective specimen surfaces are obtained with precision finishing operations and the polishing parameters are optimized for CGS measurement. This method is more effective than the reflecting film transfer method, which is widely used in previous studies.

1. Introduction

Young's modulus and Poisson's ratio are the most important elastic parameters in mechanical analysis [1,2]. There are a large number of literatures focusing on the measurement of these two parameters [3–5]. The most popular method is measuring with strain gauge or strain gauge rosette, which can be used to obtain the surface strain in different directions [6,7]. However, strain gauges can only provide the average strain value in a local area. The method fails when the deformation is inhomogeneous, such as in the measurement of inhomogeneous residual stresses or stress concentration factors [8–12]. Another popular method is measuring with extensometer [13,14]. This method has high precision and is easy to operate. However, the extensometer must be connected with the specimen, which is the vital limitation of extensometer.

The most popular full-field and non-contact method to measure Young's modulus and Poisson's ratio is digital image correlation (DIC), which is widely used in many fields [15,16]. However, DIC method fails in measuring small deformations because the accuracy of DIC method is much lower than the accuracy of strain gauge or extensometer. The high-accuracy two dimensional DIC measurement can reach a strain accuracy of 75με, according to the latest literature [17]. However, there are many interference methods to measure full-field deformations with high accuracies, such as holographic interference [18], laser speckles [19], electronic speckle pattern interferometry (ESPI) [20] and Moire interferometry [21]. The displacement measurement accuracy of these methods are submicron scale, which are equivalent to the laser wavelength. However, all of these methods are sensitive to rigid displacements. Therefore, non-vibrating environment is strongly required and the rigid displacement eliminating process is always necessary for correct results. Moreover, by all of these methods above, the specimen displacements are obtained directly with experiment noises. The strain values are then obtained by numerical difference method, which enlarges the experiment noises in measuring displacement. Therefore, the specimen displacement field is better to be obtained by a high accuracy, full-field and non-contact method which is also insensitive to vibrations and can reduce the experiment noises.

CGS method is a full-field, real-time and non-contact interference method [22], which is insensitive to vibration and able to provide the full-field slopes of reflective surfaces [23–27]. There is no need to eliminate rigid displacement for CGS method. In addition, the out-of-plane displacements of reflective surfaces can be obtained by numerical integration method, which can reduce the experiment noises in measuring slopes. In previous studies, the reflective CGS method was used to measure the slopes of thin films [28,29] and the crack tip *K*-dominance of metals [30,31]. However except for these applications, there are few applications of reflective CGS method because it is hard to obtain optical flat reflective surfaces.

In this work, the Young's modulus and Poisson's ratio of Ni-Cr Alloy are measured using reflective CGS method. The measurement accuracy is improved significantly by using the phase shifting technology in CGS method, which is proposed by the authors in previous study [32].

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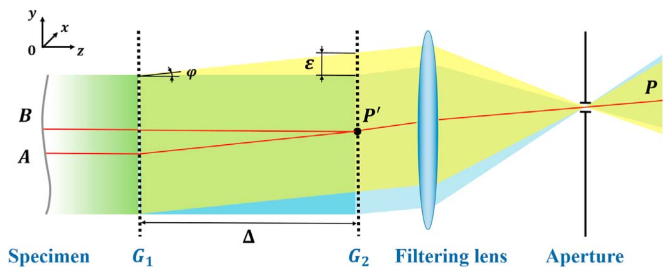

Fig. 1. The principle of CGS method (G_1 and G_2 are two Ronchi gratings).

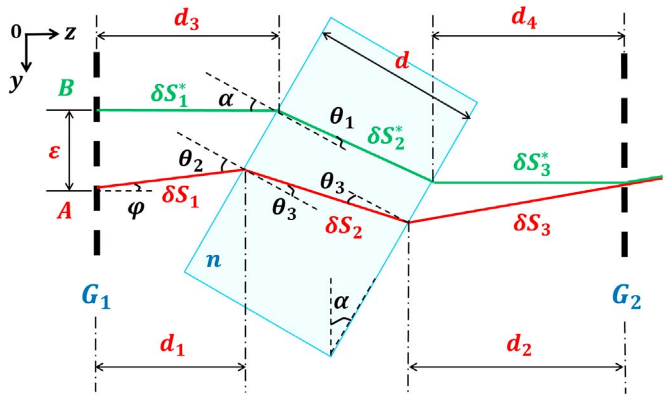

Fig. 2. The principle of plane-parallel plate rotating method.

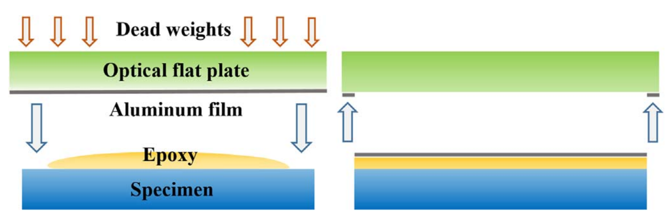

Fig. 3. The principle of reflective film transferring method: the film transfer and remove process.

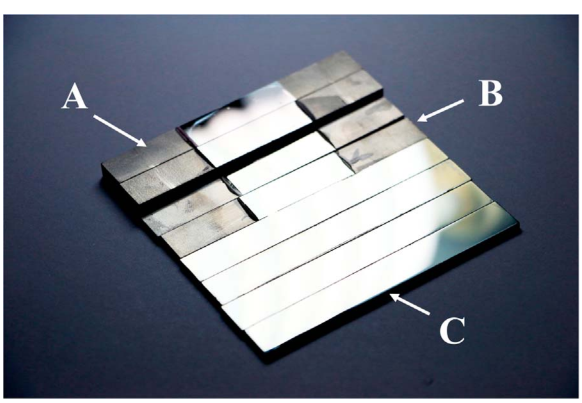

Fig. 4. Three specimen groups obtained by different methods.

There-point bending experiment is applied to obtain the Young's modulus by measuring the specimen out-of-plane displacement slopes. Bending experiment of a circular plate with fixed edges loaded by a centric concentrated force is applied to obtain the specimen bending stiffness. The Poisson's ratio is then solved by substituting the bending stiffness into Young's modulus. The results show that the phase-shifted reflective CGS method is valid for measuring Young's modulus and Poisson's ratio of metals and alloys.

2. Theory and Methodology

Fig. 1 shows the principle of reflective CGS method. A collimated parallel beam is reflected from the specimen, carrying the out-of-plane deformation information of specimen. Then the reflected beam pass through the first Ronchi grating (G_1). The yellow beam represents the diffracted beam with +1 order, while the blue beam represents the diffracted beam with 0 order. Both diffracted beams hit the second grating G_2, which is identical with G_1. The distance between two gratings is Δ, the first order diffraction angle of the grating is φ. Therefore, the shearing displacement of the two beams on G_2 is ε, which is determined by Eq. (1).

$$\varepsilon = \Delta\bullet\tan\varphi \approx \Delta\bullet\varphi \tag{1}$$

In this study, the grating frequency is $f = 40$ lines/mm, the laser wavelength is λ=532 nm, so the first order diffraction angle of the grating is 1.22°, which can be calculated via Eq. (2).

$$\varphi=\sin^{-1}\lambda/p\approx\lambda\bullet f \tag{2}$$

where p is the grating pitch. The diffracted beams on the right side of G_2 are named with $E^b_{0,1}$, $E^y_{1,0}$. The superscript 'b' represents the blue beam, while 'y' represents the yellow beam. The subscripts represent the beam orders diffracted by two gratings. The direction and intensity of $E^b_{0,1}$ and $E^y_{1,0}$ are the same, while the light paths of the two beams are different. Therefore, there are interference fringes on the right side of G_2, which are schematically shown as the green area in Fig. 1. The intensity of point P on the screen depends on the light path difference between the two beams reflected from point $A(x, y)$ and $B(x, y + \varepsilon)$. In the reflection mode, the light path difference between the two beams is determined by the specimen surface.

$$\delta S(x, y+\varepsilon)-\delta S(x, y) = 2\delta w \tag{3}$$

where $\delta S(x, y + \varepsilon)$ and $\delta S(x, y)$ are the light paths of the two reflected beams, δw is the out-of-plane deformation difference between point A and B. In addition, the fringe order N is determined by the following interference equation:

$$\delta S(x, y + \varepsilon)-\delta S(x, y)=N\lambda \tag{4}$$

Divide both sides of Eqs. (3) and (4) with ε and combine with Eqs. (1) and (2):

$$\frac{\delta w}{\varepsilon}=\frac{Np}{2\Delta} \tag{5}$$

Eq. (5) becomes into a differential equation when the two beam shearing displacement is close to zero:

$$\lim_{\varepsilon\to 0}\frac{\delta w}{\varepsilon}=\frac{\partial w}{\partial y}=\frac{Np}{2\Delta} \tag{6}$$

As can be seen from Eq. (6), the interference fringes of reflective CGS method represent the out-of-plane displacement gradient (slope) contours.

Kramer et. al. developed a temporal phase shifting method in CGS using lateral translation of the second grating for static measurements [34,35]. In previous work [32], phase shifting can be introduced by simply rotating a plane-parallel plate between the two gratings, which has been applied to the spatially-phase-shifted method for dynamic measurement [36]. As shown in Fig. 2, there is a plane-parallel plate between two gratings, which is the phase shifter in this work.

The red and green beams represent two reflection beams from the specimen surface (point A and B). The light path of the two beams can be determined by Eq. (7):

$$\begin{cases}\delta S_A=\delta S_1^*+\delta S_2^*+\delta S_3^*=d_3+d_4+\frac{nd}{\cos\theta_1}\\ \delta S_B=\delta S_1+\delta S_2+\delta S_3=\frac{d_1+d_2}{\cos\varphi}+\frac{nd}{\cos\theta_3}\end{cases} \tag{7}$$

In addition, we have,