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Special considerations in reflective coherent gradient sensing method for measuring large deformations

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ABSTRACT

In this study, reflective coherent gradient sensing (CGS) method is introduced to measure large deformations of Ni–Cr alloy in instrumented indentation. The effects of grating distance, collimation property of incident beam, camera lens focal length, screen and specimen location are analyzed. The presence or absence of screen and the camera lens focal length are found out to be the most important factors when measuring large deformations with CGS method. Moreover, we develop a method to obtain the 'true' interferograms by Fourier and inverse Fourier transformation algorithms. The measuring scale of reflective CGS method for large deformation is obtained. A criterion is developed to distinguish the boundaries between small and large deformations in measuring inhomogeneous deformations with reflective CGS method.

1. Introduction

Reflective coherent gradient sensing (CGS) is a full-field, real-time, non-contact and vibration-insensitive optical method [1–3]. It was developed by H. V. Tippur, et al. for measuring the slopes of reflective surfaces [4,5]. In recent years, the method was used for measuring crack tip K dominance in static or dynamic fracture tests [6–8], slopes, shapes and curvatures of reflective surfaces [4,5,9], residual stresses in thin films [10,11], small deformations [12] and so on.

CGS method is valid for measuring small deformations both in transmission and reflection mode, on the assumption of that the incident beam is a collimated beam [5]. However, the interference fringes can also be observed in the large deformation zone, such as in the three-dimensional zone around the crack tip. In previous studies, for geometries where the region outside the three-dimensional zone is K-dominant, the fringes provide an accurate value of two-dimensional stress intensity factor. For geometries where the region inside the three-dimensional zone is not K-dominant, William's expansion is used to obtain the stress intensity factor. The disagreement in the region of $0 \leq r/h \leq 0.5$ ahead of the crack tip is found out to be caused by the breakdown of the two-dimensional assumptions close to the crack tip where three-dimensional deformations are dominant, where h is the specimen thickness [3,6]. The data outside of the near-tip three-dimensional region must be appropriately interpreted taking into account the contribution of higher-order terms to the total stress and deformation fields around the crack tip [7]. However, even the higher-order expansion is not perfectly accurate around the crack tip since it is from a two-dimensional analysis [6–8]. In addition, because of nonuniform surface out-of-plane displacement changes, the incident wave front becomes nonplanar [2].

Therefore, it should be very careful to analyze the near-tip fringes which represent the large deformations. However, the higher-order expansions in both geometric and physical interpretations are complicated, and there are situations where even these approaches fail. Similarly, we should pay special attentions to the interferograms reflecting inhomogeneous deformations, especially to the large deformation zones, such as in the measurement of K-dominance during the punch test [13], the measurement of stress field in the contact problems [14], or the measurement of stress intensity factor in a stress concentration test [15]. All the experiment results in previous studies show that CGS method is not valid for accurately measuring large deformations although there are fringes with high quality in the large deformation zones. In other words, the interference fringes in large deformation zones are incorrect for characterizing the specimen deformations.

Therefore, the deformation measuring scale of CGS method should be investigated. It is necessary to develop a method to obtain the 'true' interferogram which can accurately reflect the corresponding section deformations. Moreover, a universal criterion to distinguish the boundaries between small and large deformations should be proposed in measuring inhomogeneous deformations using CGS method.

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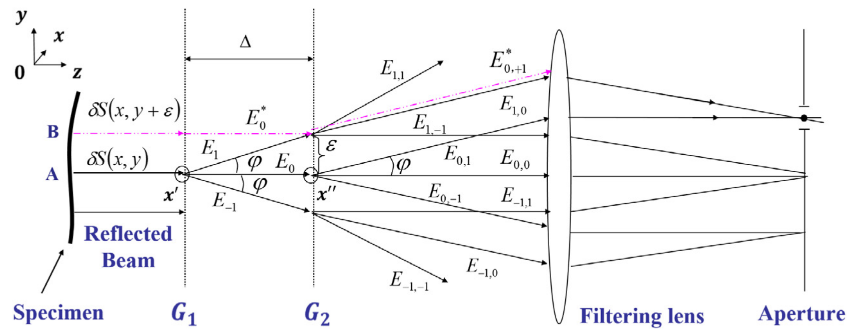

Fig. 1. Principle of reflective CGS method.

In this study, the instrumented indentation is used to obtain an inhomogeneous deformation field of Ni–Cr alloy. The pile-up phenomenon around the indentation is observed. The interferograms obtained by reflective CGS method are directly used to obtain the specimen surface shape, which is proved incorrect. To analyze the contradiction between the experiment results and the actual conditions, some interesting phenomena of interference fringes are observed and discussed by experimental investigation. The effects of grating distance, collimation property of incident beams, camera lens focal length, screen and specimen location are analyzed. As a result, the measuring scale of reflective CGS method for large deformation is obtained. The method to obtain the 'true' interferogram which contains both small and large deformations is developed. In addition, a criterion to distinguish the boundaries between small and large deformations is proposed in measuring inhomogeneous deformations using CGS method.

2. Experiment and phenomena

2.1. The principle of phase-shifted reflective CGS method

Fig. 1 shows the principle of reflective CGS method. The object wave, reflected from the specimen surface, passes through two Ronchi gratings G_1 and G_2. The grating distance is Δ, and the principle grating direction is on y axis. Light beam A and B represent two incident beams with a separation distance of ε. E_1 represents the +1 order diffraction beam of A diffracted from G_1, while E_0^* represents the 0 order diffraction beam of B diffracted from G_1. E_1 and E_0^* will converge on G_2 if $\varepsilon = \Delta \cdot \tan\varphi$, where φ is the grating first order diffraction angle. Each of these diffracted beams diffract again at G_2. $E^*_{0,+1}$ represents the +1 order diffraction beam of E_0^* diffracted from G_2, while $E_{1,0}$ represents the 0 order diffraction beam of E_1 diffracted from G_2. The subscripts correspond to diffraction orders at two gratings. The intensities and directions of $E^*_{0,+1}$ and $E_{1,0}$ are the same and as a result, there are interference fringes of $E^*_{0,+1}$ and $E_{1,0}$ on the right side of G_2. The wavefronts $E^*_{0,\pm 1}$ and $E_{\pm 1,0}$ contribute to the ±1 diffraction spot on the focal plane, while the wavefronts $E_{0,0}$ and $E^*_{1,-1}$ contribute to the zero order. All the diffraction beams and their interference fringes can be observed on the right side of G_2. Therefore, a filtering lens and aperture are implemented to filtering out all but +1 diffraction order, which is usually used in CGS method [15].

In this study, the grating pitch is $p = 25$ μm, and the laser wavelength is $\lambda = 532$ nm, so the grating first order diffraction angle is $\varphi = \sin^{-1}\lambda/p \approx \lambda/p = 1.22°$. The commonly used grating distance is 20–50 mm. The two beam light path difference between G_1 and G_2 is ignored as shown in Eq. (1):

$$\Delta \cdot \left(\frac{1}{\cos\varphi} - 1\right) = \frac{\Delta}{\cos\varphi} \cdot \left[1 - 1 + \frac{\varphi^2}{2} + O\left(\varphi^4\right)\right] = O\left(\varphi^2\right). \quad (1)$$

Therefore, the interference fringes reflect the light path difference between A and B on the left side of G_1, which only comes from the specimen surface. The fringes represent the out-of-plane displacement gradient contours of reflective surfaces as shown in Eq. (2):

$$\frac{\partial w}{\partial y} = \frac{Np}{2\Delta} \quad (2)$$

where w is the out-of-plane displacement, N is the fringe order [1,2]. In addition, the grating principle direction is on y axis in Eq. (2). When the grating principle direction is on x axis, the surface slopes on x axis can be obtained, which is similar to Eq. (2).

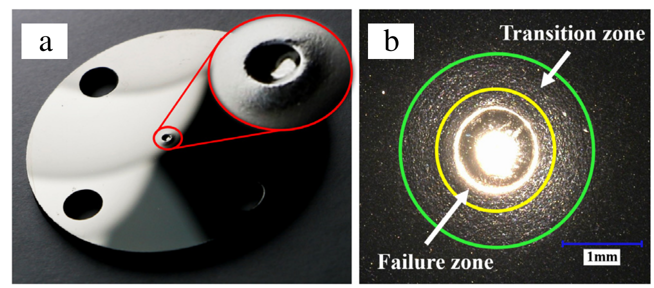

Fig. 2. Specimen with an indentation in the center: (a) observed by regular digital camera; (b) observed by digital microscope. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

In the reflection mode, it should be noticed that the object wave is perpendicular to the optical axis, or the incident beam should be a collimated beam at least [5]. Otherwise the reflection angle varies at different specimen locations and the fringes appear in the wrong places. In other words, there might be interference fringes in some zones although there are no deformations. The fringes can reflect the deformations of other zones if the deformations are large enough to produce a decollimated beam. As a result, the interference fringes cannot characterize the corresponding location deformations when measuring large deformations, which might be the reason of the contradiction in Refs. [3,6–8].

In previous work, a phase shifting technology (Plane-parallel plate rotating method) was developed and proved to be effective for CGS method [10]. The phase shifting can be introduced by rotating a plane-parallel plate between two gratings. The governing equation of this modified CGS method is:

$$\frac{\partial w}{\partial y} = \frac{p}{2\Delta}\left[N - K\left(\alpha, n, d, \Delta, p, \lambda\right)\right] \quad (3)$$

where $K(\alpha, n, d, \Delta, p, \lambda)$ is related to the rotation angle α, plate refractive index n, plate thickness d, grating distance Δ, grating pitch p and laser wavelength λ. The $K(\alpha, n, d, \Delta, p, \lambda)$ factor can be solved by numerical method as introduced in Ref. [10]. In addition, the parameters of the phase shifter are the same with those in Ref. [10]. In this study, the phase-shifted reflective CGS method is used for its convenience of automatic fringe treatment and high accuracy.