Acta Mech Sin (2009) 25:389–394
DOI 10.1007/s10409-008-0224-4

RESEARCH PAPER

Hole-drilling method using grating rosette and Moiré interferometry

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Received: 5 November 2007 / Revised: 17 October 2008 / Accepted: 17 October 2008 / Published online: 10 January 2009

Abstract The hole-drilling method is one of the most well-known methods for measuring residual stresses. To identify unknown plane stresses in a specimen, a circular hole is first drilled in the infinite plate under plane stress, then the strains resulting from the hole drilling is measured. The strains may be acquired from interpreting the Moiré signature around the hole. In crossed grating Moiré interferometry, the horizontal and vertical displacement fields (u and v) can be obtained to determinate two strain fields and one shearing strain field. In this paper, by means of Moiré interferometry and three directions grating (grating rosette) developed by the authors, three displacement fields (u, v and s) are obtained to acquire three strain fields. As a practical application, the hole–drilling method is adopted to measure the relief strains for aluminum and fiber reinforced composite. It is a step by step method; in each step a single laminate or equivalent depth is drilled to find some relationships between the drilling depth and the residual strains relieved in the fiber reinforced composite materials.

Keywords Grating rosette · Hole-drilling · Moiré interferometry · Residual strain

1 Introduction

Hole-drilling method is one of the most common methods for testing residual stresses. It was widely used to measure the residual stresses in various materials, such as metal and composite materials. In most applications, a strain gauge rosette [1,2] is used to determine the residual stresses. Additionally, various researchers obtained the residual stresses by Moiré hole drilling [3–5], hologram interferometry [6] and digital speckle pattern interferometry [7]. In most case of Moiré interferometry, by means of crossed grating, two directions displacement fields are obtained, i.e., u and v fields, from which two strains and a shearing strain can be acquired. Especially in reference [3,4,8], excellent studies on Moiré hole-drilling method were carried out by using a finite element method based approach and incremental hole-drilling method for residual stresses measurement. It is well known that there are high sensitivity, high contrast fringes and all field displacements test in Moiré interferometry [9]. For residual stresses measurement, it is capable of testing strains in a very small area, just like one point in a specimen. It is more accurate than average strain in the strain gauge method.

In this paper, by means of Moiré interferometry and three directions grating (grating rosette) developed by the authorsé three displacement u, v and s fields are obtained to derive three strain fields, i.e., three directional strains are derived from the horizontal, vertical and 45° displacement fields. Compared with crossed grating Moiré interferometry, three strain fields are always along three certain directions, the specimen can be repositioned accurately by comparing the Moiré patterns after drilling with the one before drilling, it means the Moiré patterns after drilling can be modified according to that before drilling. It can eliminate the errors resulting from the hole drilling.

As a practical application, the hole-drilling method is adopted to measure the relief strains, in which each single laminate or equivalent depth was drilled step by step. Some relationship is found between the depth of drilling and

The project was supported by the National Natural Science Foundation of China (10772117, 10572089).

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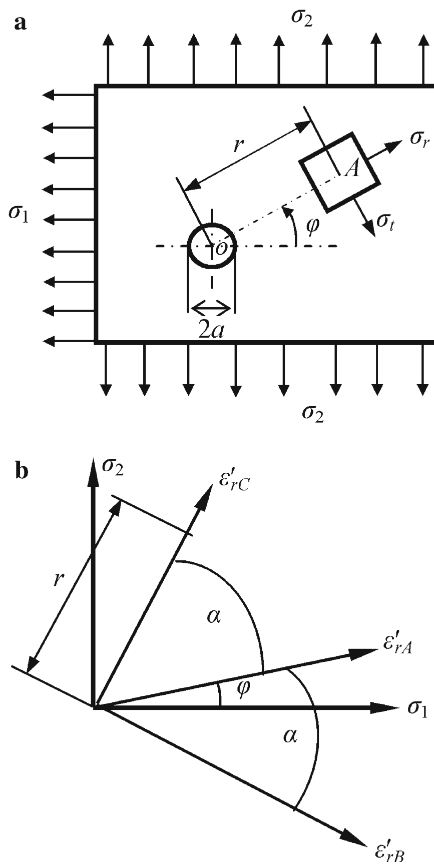


Fig. 1 The principle of drilling-hole

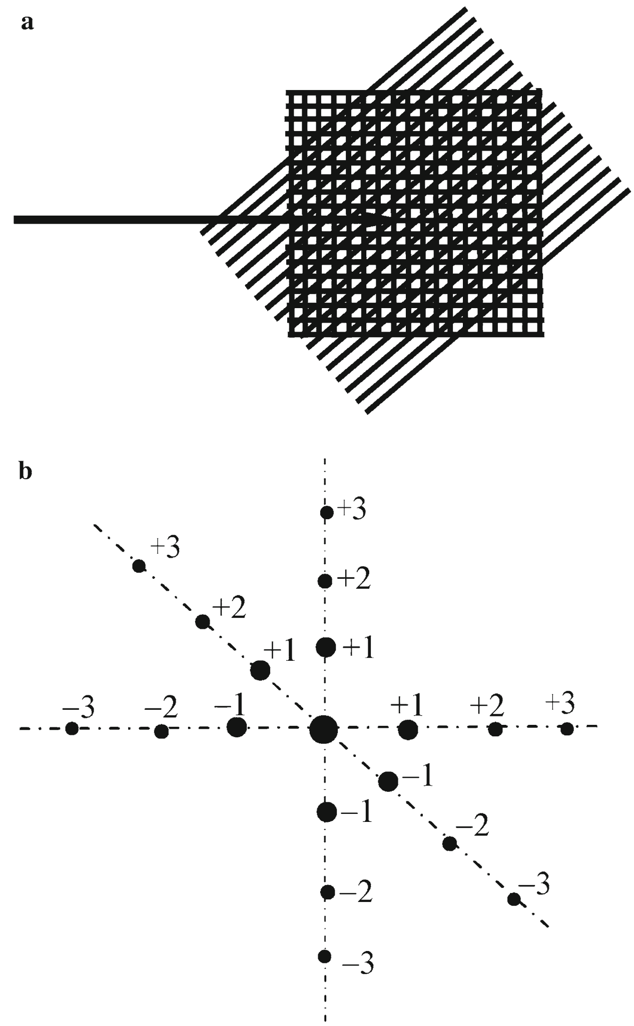


Fig. 2 Grating rosette and its diffraction orders. **a** Grating rosette; **b** Diffraction orders

the residual strain relieved in the fiber reinforced composite materials, and the relief strain within neighboring laminates.

A small area of the surface, which is under plane stress conditions, is investigated as shown in Fig. 1, where components σ_1 and σ_2 denote the principal stress. A hole with diameter $2a$ is drilled at the interested point of the surface. The center O of the hole is a conventional point, where the residual stresses is to be determined, and r is the distance from the center of the hole to point A, or point B or C. The residual strain relieved from the hole drilling at point A, B, C are ε'_{rA}, ε'_{rB}, and ε'_{rC}, respectively.

In crossed grating and Moiré interference method, two perpendicular fringe patterns (u, v field) can be obtained in each test (see Fig. 2), and two strain components ε_x, ε_y and one shear strain γ_{xy} are further determined by comparing fringe patterns before and after loading. It should be noted that in the grating rosette system, three fringe patterns can be obtained to determine three strain components (ε_0, ε_{90} and ε_{45}).

2 Measurement principle

When a hole is drilled on the specimen, the residual stresses in this small area are relieved, which can be determined by detecting deformation on the specimen surface. For measuring the deformation, the grating rosette and Moiré interference method are applied. The directions of the grating rosette are distributed along 0°, 45° and 90°, the corresponding Moiré patterns in each direction before and after the hole drilling can be obtained. Comparing the corresponding Moiré patterns before and after the hole drilling, three strain components ε_0, ε_{45} and ε_{90} can be computed [9] as:

$$\varepsilon_x = \frac{\partial U}{\partial x} = \frac{1}{2f}\frac{N_{x2} - N_{x1}}{\Delta x}, \qquad (1)$$

where ε_x is the normal strain along x axis, x denotes 0°, 90° and 45° directions, f is frequency of the grating, and Δx is a small increment in the distance, N_{x1}, N_{x2} are numbers of Moiré fringes in Δx before and after the hole drilling, respectively.

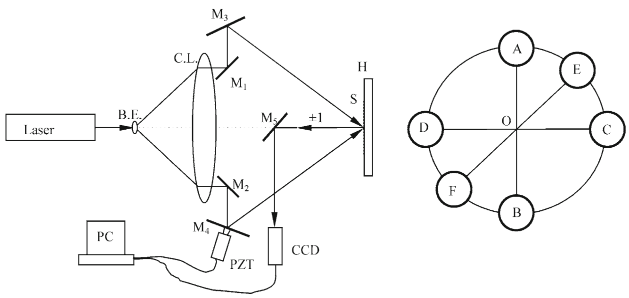


Fig. 3 The basic set-up of grating rosette Moiré interferometry. *L* laser, *B.E.* beam expander, M_1, M_2, M_3, M_4, M_5 mirrors, *C.L.* collimate lens, *S* specimen with grating rosette, and $f = 500$lines/mm in three directions, *H* holder, *PZT* piezoelectric transition, *CCD* video camera, *PC* computer

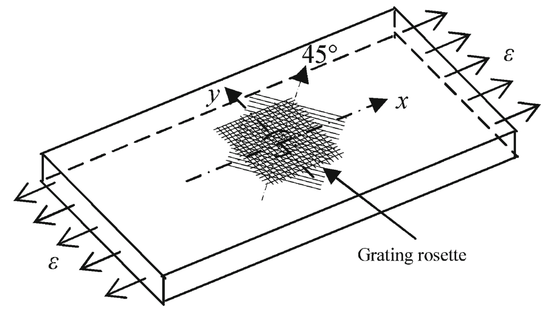


Fig. 4 Schematic of specimen geometry and grating position

3 Experimental set-up and procedure

The basic set-up designed for grating rosette is shown in Fig. 3.

In Fig. 3, the coherent light beam provided by laser is expanded into spherical waves when passing through the beam expander, and then collimates by the collimate lens. Six incident collimated beams (A, B, C, D, E and F) are used to illuminate the desired area of specimen surface with the same angle α (here $\alpha = \arcsin(\lambda f)$, λ is wavelength of the incident beam, f is frequency of the grating rosette). The first order diffraction of all the six beams will intersect at the same point and propagate along the direction normal to the specimen. Each pair of symmetrical diffraction beams—A and B, C and D, and E and F— will interfere and form a virtual grating rosette in the area along 0°, 90° and 45° direction, respectively. Therefore, three displacement fields (u, v and s) will result from superposition of the virtual grating rosette and the specimen grating rosette. By means of CCD camera and computer, the Moiré patterns can be acquired, gathered and stored for analyzing the deformation information.

3.1 Material

The composite laminate specimen is composed of carbon fiber and epoxy and combination with 16 layers, and its size is 150 mm × 100 mm × 2 mm. The forming pressure, temperature and angle of ply are different and expressed in nomenclature. For example, in 20 MPa135°C$[0/90]_{16}$, 20 MPa: pressure, 135°C: temperature during forming, [0/90] : fiber angle of ply, and the subscript 16 is number of layers.

3.2 Testing

The specimen with replicated grating rosette should be installed properly in the holder so that the first order diffraction of all the six beams will intersect at the same point and propagate along the direction normal to the specimen. Each pair of symmetrical diffraction beams will interfere and form a virtual three-directional grating which will superimpose on the specimen grating. The three directional Moiré patterns before the hole drilling were gathered by CCD camera. Secondly, a 1 mm diameter hole is drilled in the first layer and the specimen is re-positioned by comparing this Moiré pattern with the pattern before the hole drilling. This procedure is repeated when drilling the second layer, the third layer. . ., up to the final layer. Finally, all three directional relief strains are calculated by comparing Moiré patterns before and after the hole drilling in each step.

3.3 Calibration test

Figure 4 shows an aluminium alloy calibration specimen of the size of 150 mm × 2 mm × 2 mm. Before hole drilling, a uniform tension was applied in the x direction ($\varepsilon = 930\ \mu\varepsilon$) to fix it in the holding frame. After the strain was almost steady (the movement of strain is no more than 2–3 $\mu\varepsilon$ in two hours), the specimen was regarded as ready for testing.

The experimental data for the aluminium specimen were obtained using the Moiré interferometry system described earlier. The calculations were carried out using the following equations [10]:

$$\sigma_r = \frac{S}{2}\left(1 - \frac{a^2}{r^2}\right) + \frac{S}{2}\left(1 + \frac{3a^4}{r^4} - \frac{4a^2}{r^2}\right)\cos 2\theta, \quad (2)$$

$$\sigma_\theta = \frac{S}{2}\left(1 + \frac{a^2}{r^2}\right) - \frac{S}{2}\left(1 + \frac{3a^4}{r^4}\right)\cos 2\theta, \quad (3)$$

$$\tau_{r\theta} = -\frac{S}{2}\left(1 - \frac{3a^4}{r^4} + \frac{2a^2}{r^2}\right)\sin 2\theta. \quad (4)$$

In this case, we just computed the results along $\theta = 0°$, 45° and 90°, and their comparison is shown in Fig. 5.

Figure 5 shows a good agreement between the experimental data and the calculation results with maximum relative error not more than 15%, and thus this method is found suitable for testing residual stresses.

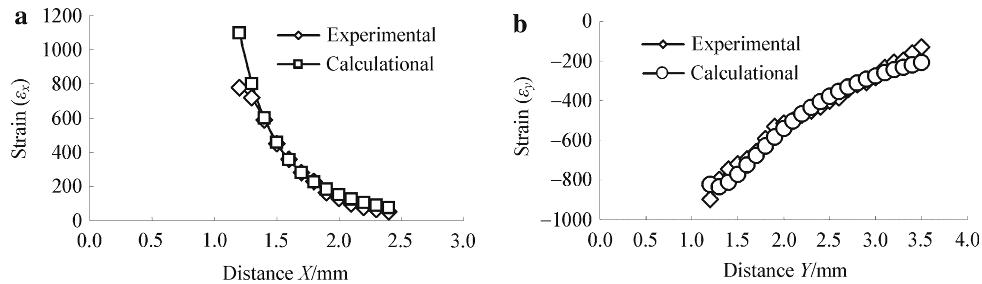


Fig. 5 Comparison experimental data with calculational data

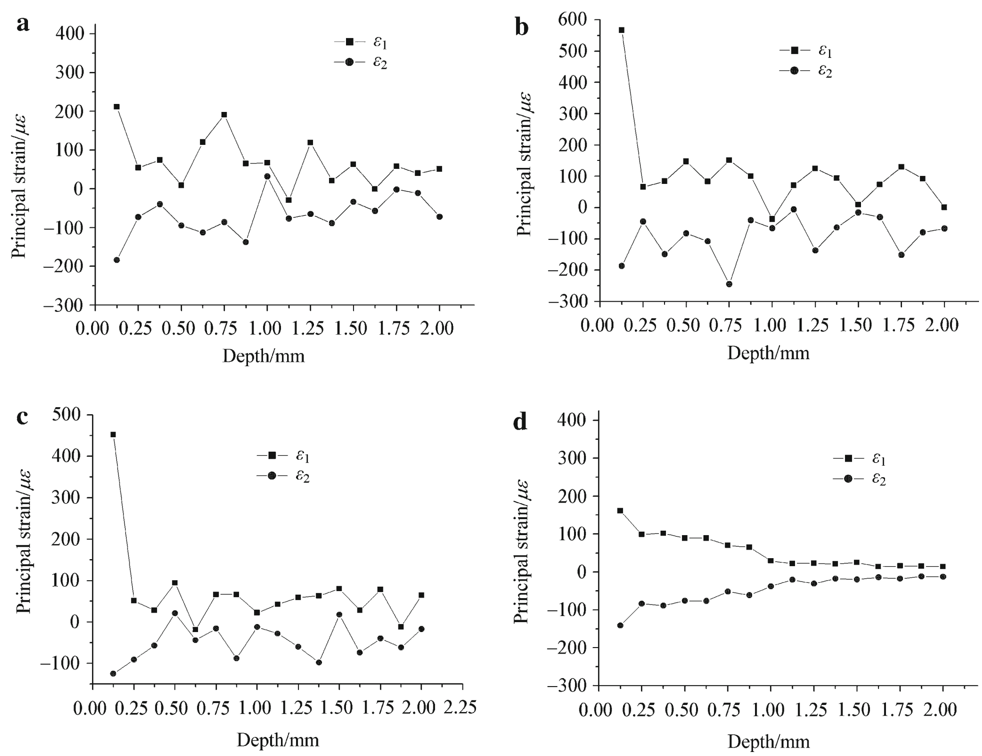


Fig. 6 The relieved residual principal strains between neighboring layers. **a** 20 MPa125°C$[0/0]_{16}$; **b** 20 MPa125°C$[0/0]_{16}$; **c** 27 MPa135°C$[\pm 30]_{16}$; **d** Aluminium alloy

Table 1 Experimental data

Relief strain (με)	Specimen								
	20 MPa125°C$[0/0]_{16}$			20 MPa135°C$[0/90]_{16}$			27 MPa135°C$[30/30]_{16}$		
	H	45°	V	H	45°	V	H	45°	V
1st layer	121	−80	−260	260	−180	120	215	−120	112
Algebraic sum of 16 layers	118	−80	−275	259	−142	74	237	−54	152

4 Results and discussion

Three kind of composite laminate specimen were tested, and the residual principal strains (ε_1, ε_2) are shown in Fig. 6.

For composite materials shown in Figs. 6a–c, the relief strain of the first layer is dominant. For the subsequent layers, the character of relief strains is alternated. From Table 1, we can find that the algebraic sum of relief strains over all 16 layers is nearly equivalent to that of the first layer, especially in the horizontal and vertical direction.

Secondly, the relief strains between neighboring layers vary not only in their magnitude but also in their character, implying that the residual strains between layers in the composite laminate are very complicated.

As shown in Fig. 6d, for aluminium alloy, the relief strains are monotonically increase or decrease with the depth of

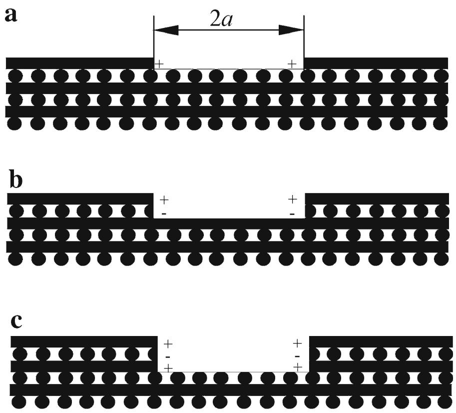


Fig. 7 The residual strains between neighboring layers during drilling. **a** Drilling first layer; **b** Drilling second layer; **c** Drilling third layer

drilling. When the drilling depth is approximately less than the drilling diameter, the relief strain gradient is much more than that when the drilling depth is larger than the drilling diameter. The algebraic sum of relief strain over a drilling depth equal to the drilling diameter is dominant, there is 75% or so residual strain is relieved in this period. But the total relief strain is sizable after the drilling depth exceeds the drilling diameter.

As shown in Fig. 7, when the first layer of composite material $[0/90]_{16}$ is drilled, the relaxed strain is contributed by the stress along certain direction, so it should lead to a specific direction strain. When the second or subsequent layer is drilled, the relief strain is contributed by two or more layers, and thus depends on the combination of different layers, so it is more complicated than the relief strain when a single layer or isotropic materials (aluminium alloy) is drilled.

5 Conclusions

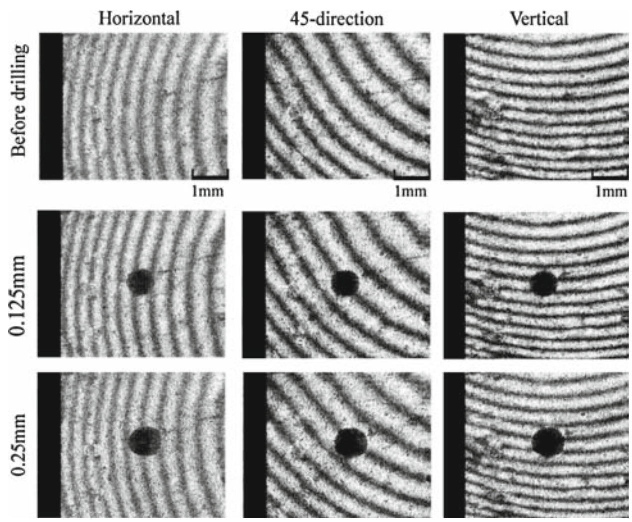
Grating rosette, Moiré interferometry and incremental hole-drilling techniques are used to determine the residual strain relieved in fiber reinforced composites as a function of the depth of drilling. The results show that whereas the residual strain relieved exhibited a systematic variation with the drilling depth in the case of unreinforced aluminium, the behavior was quite complicated in the case of composites, and depended on the residual stresses in neighboring layers.

For composite materials, the relief strain of the first layer is dominant. In other layers, the relief strains are mostly alternated in their character.

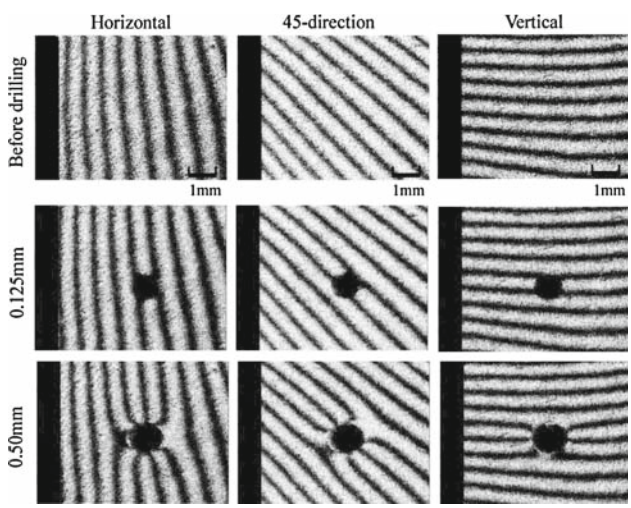
For aluminium alloy, the algebraic sum of relief strain over a drilling depth equal to the drilling diameter is dominant, and the relief strains are monotonically increase or decrease with the drilling depth. But the total relief strain is sizable after the drilling depth exceeds the drilling diameter.

Appendix

1 Step drilling hole, Moiré patterns (20 MPa 135°C$[0/90°]_{16}$)



2 Step drilling hole, Moiré patterns (aluminium alloy)



References

1. ASTM. ASTM E837-95: Standard test method for determining residual stresses by the Hole-Drilling Strain-Gage Method. Annual Book of Standards (1998)
2. Montay, G., Cherouat, A., Garnier, C., Lu, J.: Determining residual stress in spherical components: a new application of the hole-drilling method. J. Test. Eval. **32**(1), 1–7 (2004)
3. Shankar, K., Xie, H.M., Wei, R.Y., Anand, A., Chai, G.B.: A study on residual stresses in polymer composites using moire interferometry. Adv. Compos. Mater. **13**(3/4), 237–254 (2004)

4. Cárdenas-García, J.F., Preidikman, S.: Solution of the Moiré hole drilling method using a finite-element-method-based approach. Int. J. Solids Struct. (43), 6751–6766 (2006)
5. Ya, M., Miao, H., Zhang, X., et al.: Determination of residual stress by use of phase shifting Moiré interferometry and hole-drilling method. Opt. Lasers Eng. (44), 68–79 (2006)
6. Pisarev, V.S., Bondarenko, M.M., Chernov, A.V., et al.: General approach to residual stresses determination in thin-walled structures by combining the hole drilling method and reflection hologram interferometry. Int. J. Mech. Sci. (47), 1350–1376 (2005)
7. Viottia, M.R., Kaufmann, G.H.: Accuracy and sensitivity of a hole drilling and digital speckle pattern interferometry combined technique to measure residual stresses. Opt. Lasers Eng. (41), 297–305 (2004)
8. Zhu, W.U., Guillaume, M., Lu, J.: High sensitivity Moiré interferometry and incremental hole-drilling method for residual stress measurement. C. R. Acad. Sci. Paris, t. 329, Série II *b*, 585–593 (2001)
9. Post, D., Han, B., Ifju, P.: High Sensitivity Moiré. Springer, New York (1994)
10. Timoshenko, S.P.: Theory of Elasticity. McGraw-Hill Book Company, Auckland (1991)