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High strain gradient measurements using modified automated grid technique

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ABSTRACT

The automated grid technique, which was constantly used to measure strain field mapping, is a full field optical technique with the character of high efficiency, good adaptability and simple applicability. Due to the limitation of the spot pattern preparation, it was restricted for the measurement of strain distribution in regions of high strain gradient. In this paper, an modified automated grid technique, in which the grid spots were made by using the lithography technique, was applied for the measurement of the high strain gradient. To validate the modified automated grid technique, aluminum specimens with circular holes were employed as the test specimens and the deformation behaviors in the regions of stress concentration were investigated. The testing results agreed well with the analytical and numerical analysis. In comparison with the traditional automated grid technique, the modified method is more accurate. All the results indicate that the high strain gradient test method based on the modified automated grid technique is reliable and appropriate.

1. Introduction

During the designation, mechanical parts and structural elements often have features that cause sudden changes in geometry. Under the action of loads, these changes in geometry significantly increase the local stress fields of the parts and they usually represent locations from which parts start to fail. This localization of high stresses is called stress concentration [1]. In this area, the largest stress may be several times larger than the remote stresses, thus more attentions should be attracted to this area because the failure mostly originates from such places with stress concentration [2]. A dimensionless factor, known as stress concentration factor (SCF) *K*, is used to quantify how “concentrated” the stress is. It is traditionally defined as the ratio of the hot-spot stress in the area of a discontinuity or other stress raiser to the corresponding nominal stress [1]

$$K = \frac{\sigma_{hot}}{\sigma_{nom}} \tag{1}$$

The stress concentration factor is an indicator of the effect of stress concentration on structural components.

Because of the close relation between the stress concentration and the structure strength designing, the investigation of the mechanical properties for stress concentration has attracted increasing attentions. In the past years, a number of studies have been conducted on the determination of SCF by means of theoretical analysis, numerical analysis, and experimental measurements [3,4]. However, the stress measurement is difficult. An indirect method is to measure the strain, and then the stress can be calculated by using Hooke's law. Thus, the strain analysis is always instead of stress analysis. For traditional experimental investigation, the strain field of the stress concentration area is usually measured by the strain gage [3]. Unfortunately, this method was highly limited in regions of high strain gradient, because the use of strain gages cannot provide accurate results, particularly at distances close to the field where the maximum stress concentration is expected. In addition, the attachment of strain gages near a stress concentration site is an intrusive methodology, which often effects the measurement.

To solve these problems, non-contact displacement measurement technique were developed to provide information at the microscopic level. The non-contact measurement methods mainly refer to all kinds of optical methods, such as the moiré method [5,6], moiré interferometry [7], photoelasticimetry method [8], holography interferometry [9] and digital image correlation [10,11]. The displacements and the strains of the interest region can be determined by a numerical analysis of the reference and deformed images. Recently, these methods have been widely applied in measuring the strain field of the stress concentration area. In 1967, Flynn and Roll studied the stress concentration in hyperbolic and u-shaped grooves by using the photoelasticimetry method [12]. Livieri and Nicoletto used the moiré interferometry

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method to obtain the strain concentration factors in finite thickness plates in 2003 [13]. By using a dual magnification digital image correlation method, Wang et al. measured the deformation on the front and side faces of the specimen with a circular hole [14]. However, the photoelasticimetry method requires a birefringent material, which is stuck on the studied sample or replaces the actual prototype. Holographic technique is attractive because of its high sensitivity but it needs an extreme environmental stability. The moiré method can be used in several experimental configurations. Through the geometric phase technique on the basis of the digital moiré method, the deformation is evaluated in micro scale [5,15,16]. However, this method is inconvenient to arrange the optical setups and prepare the samples. The digital image correlation method is an effective technique to measure the deformation but the calculation is time consuming.

Different from the grid method based on the moiré interferometry method [17], the automated grid method [18,19] has been actively and successfully used in strain analysis, and it is a non-interferometric full field measurement optical technique. In comparison to other optical methods, the optical system and sample preparation for this technique are simpler. The grid consisting of circles, dots or other shapes is applied on the specimen's surface before test. The measuring principle is to track each spot of the undeformed and deformed images, and to calculate the displacements and the strains according to the differences of the spots. The computational efficiency of the programmed algorithm of the automated grid method is very high, so it can be used as a real-time measurement. Moreover, the measurement is hardly effected by the vibration and the accuracy is high, thus it can be used for accurate measurement. Moreover, this technique can be applied under high temperature, which highly extends the application range of the automated grid technique. In recent years, this technique forwards to be practically applied in various field, such as measuring the longitudinal Young's modulus and Poisson's coefficient of small bones [20] and the mechanical properties of 3D carbon/carbon composite [21]. However, for the measurement of strain distribution in regions of high strain gradient such as the stress concentration area, the automated grid technique is still restricted. In this area, the strain field is nonuniform and varies violently. If the calculation area is not small enough, the strain results would be averaged seriously. In order to dispel the average effect, grid spots with small size and dense distribution are needed. The lithography technique is technical feasible to produce appropriate grid spots (small, dense enough and high-quality). However, this technique has not been applied to make grid spots for modifying the automated grid method.

In this paper, an modified automated grid technique is developed to measure the strain distribution in high strain gradient regions, in which the lithography technique was introduced to produce appropriate grid spots. The quality and the precision between the traditional grid and the new grid were compared and evaluated. To validate the modified automated grid technique based on the grids of small-scale made through lithography technique, the deformation behaviors in the regions of stress concentration of aluminum specimens with circular holes were investigated. The results obtained by this method were compared with the ones obtained from the traditional grid method, analytical and numerical analysis.

2. Experimental

2.1. Automated grid technique

The automated grid technique measurement system consists of a CCD video camera and a personal-computer-based image-processing system, tracking the spot locations through the automatic pattern recognition of the reference and deformed images, and yielding the displacement vectors. The full field displacement distribution can be calculated according to the differences for the centroid of each spot. The implementation process of the automated grid method mainly includes segmentation, calculation of the centroid coordinates, pattern recognition, and motion analysis.

Segmentation, consisting of identifying regions and boundaries of interest in the image, is processed by considering a threshold, which is determined according to the Ostu threshold method [22]. The level below the threshold is considered as black, so the spot boundary can be defined, and then the centroid coordinates can be calculated [23]. Each spot's context is uniquely determined by its position relative to its neighbors. After the context mapping, the motion analysis is continued by the centroid coordinate of each spot.

2.2. Preparation of spot pattern

The quality of the grid seriously affects the precision of the automated grid technique. In order to extend the application range of the automated grid technique to the high strain gradient measurement, making appropriate grid spots becomes the most important task.

Traditionally, the painting method is adopted to prepare spot pattern. Both the background color and the grid spots are made by paint. This method can be divided into the following steps: firstly, make piercing grid template; secondly, paint the specimen with black paint and flat base on the surface; thirdly, align the template with the specimen closely; finally, paint the specimen with white paint. However, the grid cannot be made small and dense enough, because the grid will be seamlessly fused by this method.

In order to get more detailed results, the lithography technique is introduced to produce appropriate grid spots. The lithography technique is a process used in microfabrication to pattern parts of a thin film or the bulk of a substrate. The geometric pattern of a photomask can be transferred to the surface of the processed object through the light-sensitive chemical photoresist on the substrate [24]. In this work, the grid manufacturing process is as follows: firstly, make appropriate photomask of grid spots; secondly, coat aluminum on the surface of a tape and then coat it with the photoresist; thirdly, expose the coated tape to ultraviolet light through the photomask, changing the chemical structure of the photoresist where exposure takes place; fourthly, remove the exposed areas (for photoresist) by development process, leaving windows of the bare underlying material; Fifthly, remove the bare underlying material by wet etching with acid; finally, remove the rest of photoresist by resist stripper. The grid manufacturing process is schematically shown in Fig. 1.

By this method, the small spots can be obtained (micron dimension if necessary). The thicknesses of the tape and the aluminum coating are about 20 μm and 200 nm, respectively. Because the tape and the grain coating are thin enough, they hardly affect the strain field of the sample. Besides, the tape can be easily pasted and well fixed on the surface of any flat specimen by instantaneous strong adhesive, which leads to a convenient way to measure the deformation of flat structures.

Here, the sizes of the traditional grid (made by paint) and the new grid (made by lithography technique) are listed in Table 1.

2.3. Comparison of grid

The precision of automated grid method, based on the traditional grid and the new grid, should be calculated and compared. The similar images of 3×4 spot pattern of the two kinds of grids were used for calculating the precision of the automated grid

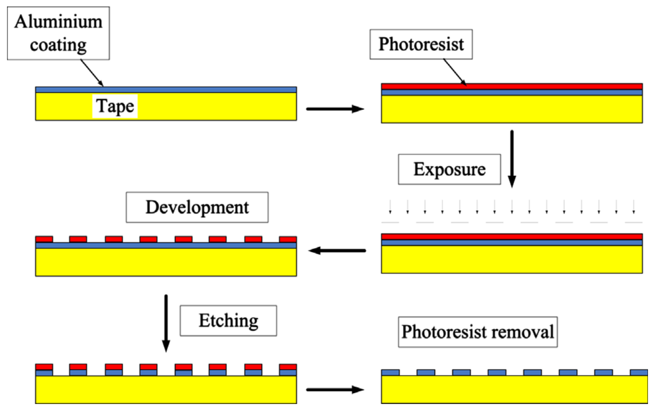

Fig. 1. Grid manufacturing process by lithography technique.

Table 1
Sizes of the grid spots.

Grid type	Radius of the grid spot (mm)	Bullseye distance between two grid spots (mm)
Traditional grid	1.5	2.5
New grid	0.2	0.4

Table 2
Comparison of the grids.

Grid type	Maximum displacement error (pixel)	Variance (pixel^2)
Traditional grid	0.052	0.0110
New grid	0.048	0.0118

technique. The pictures of spot pattern were stretched quantitatively by computer, generating a certain displacement for each spot, and then the displacements were calculated by the computer program.

Table 2 shows the maximum displacement errors and the variances of the two kinds of grids, which indicates the grid obtained through lithography technique has an analogous quality compared with traditional grid made by paint, even though the spot size is much smaller.

The conversion relation of the precision between the pixel and displacement is as follows:

$$\Delta l = \frac{\Delta p}{p} l \tag{2}$$

where l is the gauge length, p is the pixel of the gauge length in the picture and Δp is the precision of automated grid method. In this work, the actual length of 1 mm is equal to 50 pixels in the picture. So the precision of the displacement can be calculated as follows:

$$\Delta l \approx \frac{0.05}{50} \times 1\ mm = 1\ \mu m \tag{3}$$

Through lithography technique, the grid combing the high precision and appropriate size for high strain gradient measurement can be obtained.

2.4. Stress concentration of a plate with a circular hole

Holes in structural components will create stress concentrations, and hence reduce the mechanical properties. The majority of service cracks nucleate in the area of stress concentration at the edge of the hole. So knowledge of stress in the vicinity of a hole should be required for reliable design of structural components. In the past years, the problem of determining the stresses in a plate under tension when the material is pierced by a circular hole is both theoretically interesting and practically important.

Provided that the plate of isotropic materials can be regarded as infinitely extended in two dimensions, the presence of the hole leads to the occurrence of stress equal to 3 times the tension at infinity. These maximum stress occur at the edge of the hole and on the diameter perpendicular to the direction of the applied tension. Complicating matter is the stress concentration of a limited width plate with a circular center-hole. A number of studies had been conducted on the determination of SCF of a limited width plate with a circular center-hole under tension by means of theoretical analysis, finite element analysis, and experimental measurements [25–27]. Based on these results, Heywood presented the empirical formula to estimate the stress concentration factor as follows [28]:

$$K = \frac{2 + (1 - (2R/L))^2}{1 - (2R/L)} \tag{4}$$

where R is the radius of the circular center-hole, L is the width of the plate. For isotropic material, this formula is of high accuracy.

In this investigation, aluminum specimens with circular center-holes were tested under tension to validate the modified automated grid technique using the grids of small-scale made through lithography technique (tape-lithography method).

2.5. Procedure

Six specimens with the center-holes of two dimensions are tested in the tension experiment. The specimen configuration is shown in Fig. 2.

The painting method and the tape-lithography method are used to prepare the grids in the vicinity of the holes in order to get the strain information in the x, y directions. The x and y are responding to the loading direction and width direction, respectively. The complete information of specimens is listed in Table 3.

The tensile testing is conducted on the MTS 809 universal testing machine (MTS Systems Corporation, USA), at a constant cross-head rate of 0.015 mm/min. The sample should be fixed on the MTS, perpendicularly to the ground. An optical setup is established in front of the texture. The optical setup included a computer, a 1 Megapixels CCD, a telecentric lens, and a set of fixing device. The lens axis is perpendicular to the sample's surface. A uniform light is ensured by lamps. When the loading is applied, pictures of the specimen in the front are recorded.

3. Validation and analysis

In the field of stress concentration area, the strain calculation is complicated because the distribution of the strain is uneven. In the present paper, the separate fitting method is adopted. Firstly, the displacements of the separate area are quadratic fitted, and then the function of strain could be calculated through derivating the displacement function. Finally, the strain can be calculated.

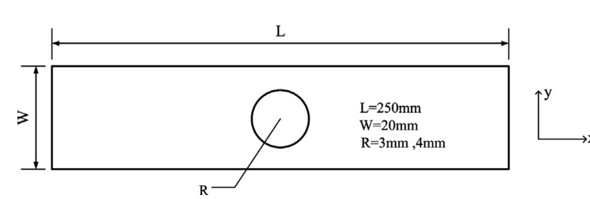

Fig. 2. Configuration of the specimens.

Table 3
Specimen information.

Specimen number	Radius of the center-hole (mm)	Method for preparation of spot pattern
1#1	3	Painting method
1#2	3	Tape-lithography method
1#3	3	Tape-lithography method
2#1	4	Painting method
2#2	4	Tape-lithography method
2#3	4	Tape-lithography method

Table 4
Stress concentration factor of each specimen.

Specimen number	Stress concentration factor		Error (%)
	Empirical value	Experimental value	
1#1	3.347	2.126	36.5
1#2	3.347	3.287	1.8
1#3	3.347	3.131	6.5
2#1	3.693	2.532	31.4
2#2	3.693	3.751	1.6
2#3	3.693	3.417	7.5

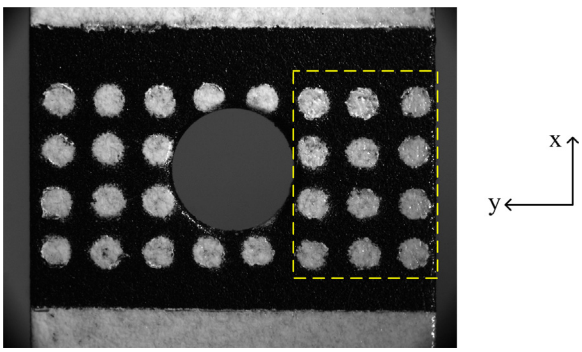

Fig. 3. Tensile specimen with traditional grid.

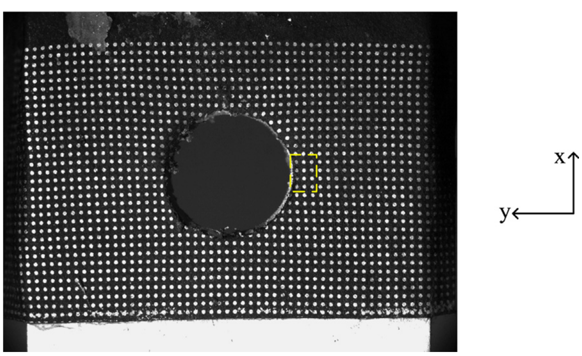

Fig. 4. Tensile specimen with new grid.

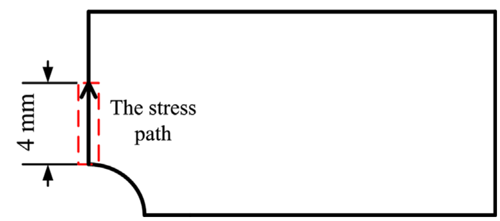

Fig. 5. Stress path selected.

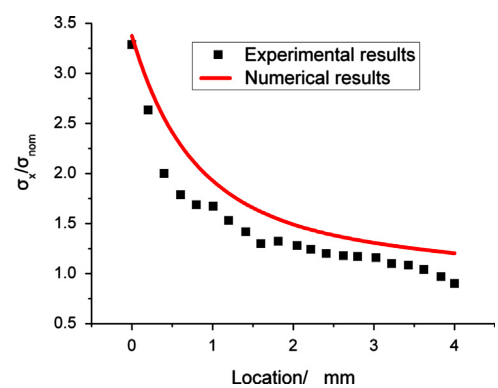

Fig. 6. Stress distribution of the numerical and the experimental method.

For quadratic fitted method, more than 6 spots are need for fitting. In this investigation, the separate areas in the vicinity of the circular holes with 3×4 spot pattern (1×1.4 mm for small-scale grids, 6.5×9 mm for traditional grids) are used for calculating the maximum tensile strain (before the plastic deformation occurred), then the stress concentration factors can be calculated by Eq. (1). The separate areas for calculating the stress concentration factors are schematically shown in Figs. 3 and 4.

Table 4 lists the stress concentration factor of each specimen calculated through the empirical formula (Eq. (4)) and obtained by the tension experiment of each specimen.

It can be seen that the SCFs obtained through the tension experiment based on the modified automated grid technique, whose grid is made by the tape-lithography method, agrees well with the results calculated by the empirical formula. The maximum error is 7.5%, less than 10%. The results obtained through the experiment whose grid is made by the painting method show bigger errors. All the results mean that the application range of the automated grid technique can be extended to the measurement of strain distribution in regions of high strain gradient, by using the lithography technique to make spots.

In order to assess the stress concentration test method based on the modified automated grid technique, the finite element analysis for a plate with a circular hole of 6 mm aperture is performed to determine the tensile stress or strain distribution near the stress concentration area. Then the numerical results are compared with the experimental results of 1#2 specimen.

The finite element analysis is completed using commercial FEM package code ABAQUS. Due to the geometric symmetry, only a quarter of the sample is modeled. In order to simulate the same conditions with the experiment, appropriate boundary conditions and loading conditions are applied.

The stress path selected is schematically shown in Fig. 5. For comparison's sake, the stresses are divided by nominal stress to get the dimensionless values.

Fig. 6 shows the stress distribution in the selected path of the numerical and the experimental method. It can be seen that the dimensionless tensile stress distribution of experimental results have the same trend with the distribution of the numerical results, which indicates that the stress concentration test method based on the modified automated grid technique is reliable. However, the experimental values are slightly less than the numerical results. This is un-surprising because of the average effect. Furthermore, the experimental values of the stress concentration factor are also less than the empirical values (except for 2#2 specimen because of experimental errors). The difference is increased with the increase of the spot size. This phenomenon also indicates that the average effect cannot be avoided completely. In order to get more accurate results, grid spots of smaller size and denser distribution should be made through the lithography technique.

4. Conclusions

The measurement of the deformation in regions of stress concentration is important for evaluating the structure strength. The automated grid technique is widely used for measuring the in-plane displacement in homogeneous strain field. In this work, the lithography technique is introduced to make appropriate grid spots, the as-modified automated grid technique combining the high precision and appropriate size for high strain gradient measurement, which enable it be suitable for the measurement of strain distribution in regions of stress concentration.

The deformation behaviors in the regions of stress concentration of aluminum specimens with circular holes are investigated to validate the stress concentration test method based on the modified automated grid technique. The results agree well with the analytical calculation and the numerical analysis. In comparison with the traditional automated grid technique, the modified automated grid technique is more accurate. All the results indicate that the stress concentration test method based on the modified automated grid technique is reliable and appropriate, and the modified automated grid technique is capable of capturing the local deformation in regions of high strain gradient.

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