Application of the Digital Image Correlation Method to Micro Hole Drilling

S.H. Tung¹, M.H. Shih² and J.C. Kuo³
¹ Department of Civil and Environmental Engineering
Department of Civil and Environmental Engineering
National University of Kaohsiung, Taiwan
National Chi Nan University, Nantou, Taiwan
² Department of Civil Engineering
³ Department of Materials Science and Engineering
National Cheng-Kung University, Tainan, Taiwan

Abstract

Due to hot forging during the production process or the cyclic deformation, there may be residual stress in structural or mechanical components. Residual stress will reduce the strength or service life of the component. The hole drilling method described in ASTM-E837-01 is a semi-destructive measurement method, which can be used to measure the residual stress. The smaller the hole is, the less damage the specimen has and the closer this method is to the non-destructive testing.

However, if the hole is too small, the strain gauge can no more be used to measure the strain around the hole. This research applies the digital image correlation method to measure the strain in the micro-scale hole drilling method. The result shows that the trend and values of the measured strain are consistent with the theoretical values of ASTM and the determined residual stresses and direction are close to the theoretical values.

Keywords: digital image correlation, hole drilling method, residual stress.

1 Introduction

Due to hot forging during the production process or the cyclic deformation, there may be residual stress in structural or mechanical components. Residual stress will reduce the strength or service life of the component. Therefore, the measurement of residual stress is very important to ensure the usage safety of structures or machinery.

The hole drilling method described in ASTM-E837-01 [1] is a semi-destructive measurement method. Strain gauges are attached around the hole to measure the surface strain at various drilling depths. As the hole diameter decreases, the damage degree of the specimen will also be reduced and this makes this method more and more close to the non-destructive testing.
However, if the hole is so small that the strain gauge can no more attached around the hole, it can not meet the requirement of the ASTM standard. Therefore, we can not use the strain gauge to measure the strain. DIC [2-4] is a non-contact and multi-scale measurement technology. It can determine the displacement and strain field by comparing the grayscale of images before and after deformation. The feasibility of using DIC to measure the strain in the hole drilling method is studied in this research.

2 Analysis methods

2.1 Hole drilling method

According to ASTM-E837-01, hole drilling method can only be applied to the residual stress measurement on the surface of isotropic and linear elastic material. [1] However, this method is not suitable as the stress exceeds half of the specimen’s yield strength.

In the hole drilling method, at least three strain gauges are needed to measure the strain around the hole. The strain gauges are attached around the hole as shown in Figure 1. The distance \( D \) between the strain gauge and the center of hole is equal to three times the hole diameter. The drilling depth is up to 0.4\( D \). For example, the drill bit used in this experiment has a diameter of 1 mm, which is one third of \( D \) according to the ASTM standard. It means that \( D \) is about 3mm and the drilling depth (0.4\( D \)) is 1.2 mm. After the drilling, the relaxation of stress induces the deformation around the hole. This deformation can be measured using the strain gauges. The relationship between the surface strain and the principal stresses is shown in Equation (1) and Figure 2. [5] The values of \( \bar{a} \) and \( \bar{b} \) can be obtained from Table 1. [1]

\[
\varepsilon_r = (A + B \cos 2\beta)\sigma_{\text{max}} + (A - B \cos 2\beta)\sigma_{\text{min}}
\]

\[
A = -\bar{a}(1 + \nu) / (2E)
\]

\[
B = -\bar{b} / (2E)
\]

Where \( \sigma_{\text{max}}, \sigma_{\text{min}} \) express the major and minor principal stresses separately, \( \varepsilon_r \) is the measured strain around the hole, \( \beta \) is the angle from the direction of major principal stress to the line from hole center to the strain gauge, \( D_0 \) is the diameter of the hole, \( D \) is the diameter of the circle on which the strain gauges locate, \( E \) is the Young’s modulus and \( \nu \) is the Poisson’s ratio. \( \sigma_{\text{max}}, \sigma_{\text{min}} \) and \( \beta \) in Equation (1) are unknowns. The measured strains in different directions can then be used to solve these unknowns.

The traditional drilling method uses strain gauge to measure the strain. It has the following disadvantages:

1. Before the test, strain gauges must be calibrated per stable and repeated tests to ensure the achievement of a measurement accuracy of \( \pm 2 \times 10^{-6} \).
2. Before attaching the strain gauge to the specimen, the contact surface should be cleaned thoroughly, to avoid separation of the strain gauge from the specimen.
3. The strain gauge can be damaged during the drilling process and the measurement accuracy will decline. Therefore, the drilling should be proceeded carefully.

4. It is difficult to make sure that the strain gauge is completely attached to the specimen surface. This can induce the measurement error.

5. A strain gauge can only measure the strain of a single point. To measure the strain of many points, we need a lot of strain gauges. This will raise the cost of the test. Besides, the surface of the specimen may not hold so many strain gauges.

6. It is impossible to comply with ASTM specification to attach the strain gauges around the hole while its diameter is only 1 mm.

<table>
<thead>
<tr>
<th>Rosette A</th>
<th>( \bar{\sigma} )</th>
<th>( \bar{\varepsilon} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blazed hole</td>
<td>Hole Diameter, ( D/D )</td>
<td></td>
</tr>
<tr>
<td>0.30</td>
<td>0.30</td>
<td>0.30</td>
</tr>
<tr>
<td>0.35</td>
<td>0.35</td>
<td>0.35</td>
</tr>
<tr>
<td>0.40</td>
<td>0.40</td>
<td>0.40</td>
</tr>
<tr>
<td>0.45</td>
<td>0.45</td>
<td>0.45</td>
</tr>
<tr>
<td>0.50</td>
<td>0.50</td>
<td>0.50</td>
</tr>
</tbody>
</table>

Table 1: \( \bar{\sigma}, \bar{\varepsilon} \) values according to ASTM-E837-01 [1]

2.2 Digital Image Correlation Method

Because the traditional hole drilling method has many restricts, especially there are many factors that can easily lead to errors while we use strain gauge to measure the strain. Instead of strain gauge, this study used digital image correlation method to measure the strain. The principle of DIC is to determine the correlation between the
images before and after deformation [2-4]. The corresponding positions of both images before and after deformation can be obtained, and then the displacement and strain fields can also be calculated. Suppose that the subimage before deformation is $A$, after deformation is $B$, the relationship between these two subimages can be expressed as follows [2-4]:

$$
COF = \frac{\sum g_{ij} \tilde{g}_{ij}}{\sqrt{\sum g_{ij}^2 \cdot \sum \tilde{g}_{ij}^2}}
$$

(2)

Where $g_{ij}$, $\tilde{g}_{ij}$ are the grayscale values of coordinates $(i, j)$ on image $A$ and $(\tilde{i}, \tilde{j})$ on image $B$ separately. Greater correlation coefficient means greater relevance. As the correlation coefficient equal to 1, the image $B$ will be exactly the image $A$ after deformation.

For the analyzing purpose, random speckles have to be marked on the specimen surface before the test begins.

3 Experiment

3.1 Material of specimen

The strain can not be too small when using strain gauge or DIC to measure the deformation. Because most metallic materials have quite high stiffness, a larger loading is needed to induce a measurable deformation. However, only a low capacity load cell is available in the laboratory. Instead of metallic material, the polyoxymethylene (abbreviated POM), which is also known as acetal, is chosen to be the material of specimen in this study.

To obtain the mechanical properties of the material, a uniaxial compression test is carried out. The maximum loading is limited to 350 kgf/cm$^2$ and the DIC method is used to measure the strain parallel and perpendicular to the loading direction. The stress-strain relationship is shown in Figure 3. The calculated Young's modulus is about 22335 kgf/cm$^2$ and Poisson ratio is 0.5.

![Figure 3: Stress-strain relationship of uniaxial compression test](image)
3.2 Experimental equipments

The experimental equipments are listed below:

1. Canon EOS 7D DSLR camera
2. Canon Macro Lens EF-S 60mm 1:2.8 USM
3. Computer with DIC software
4. Milling machine
5. 1 mm drill
6. Ring light source
7. Specimen - 2×2×2 cm³ cube
8. Load cell
9. Data logger

3.3 Experimental procedures

1. Mount the Canon EOS 7D camera, Canon Macro Lens EF-S 60mm 1:2.8 USM lens and ring light on the milling machine as shown in Figure 4, and adjust the position of the camera and focus.
2. Place the specimen in a customized fixture, and install the load cell before the fixture as shown in Figure 5. It can apply the needed loading on the specimen. The applied loading is controlled at 1400 kgf.
3. Register the locations for drilling and photographing in the milling machine. These two locations are shown in Figure 6.
4. The specimen is drilled with a 1 mm diameter drill. The drill depth will increase 0.15 mm each time until the total depth reaches 1.2 mm. After each drilling, the specimen will be move to the photographing location and take an image. Then the specimen will be move back for next drilling.
5. Analyze the captured images using the digital image correlation method. The surface displacement field and strain field variation at different drilling depth can then be obtained.

Figure 4: Arrangement of image capture device
Figure 5: Arrangement of Fixture, specimen and load cell

Figure 6: Locations of drilling and photographing

4 Results and discussions

4.1 Experimental results
The radial strain calculated according to ASTM theory and the analyzed results of DIC with the grid size of 64, 48 and 32 pixels are shown in Figure 7. The following points can be observed from Figure 7.

1. It can be found that the results obtained using various grid sizes have the same trends. The strain in the loading direction is negative, and positive in the perpendicular direction. This shows that analyzing using the DIC method can obtain the correct trend of strain variation, but the selected grid size can affect the accuracy of analyzed strain.
2. The analyzed strain with the grid size of 48 (Figure 7(c)) is most similar to the results calculated using ASTM empirical solution (Figure 7(a)) in both the trend and the magnitude. So adopting an appropriate grid size can yield quite accurate results.

3. Due to the larger grid size, the strain field around the hole can be strongly influenced by the existence of hole when the grid size is 64 pixels. (As shown in Figure 7(b)) So using a large grid size to analyze, the strain filed at the strain concentration area will be less accurate. Observing Figure 7(d) can find that the error will be enlarged when a small grid is used in the analysis.

4.2 Released residual stress

After obtaining the strain in x- and y-direction using DIC, the radial strain defined according to the ASTM standard can be calculated. The radial strain can then be used to calculate the released residual stress of the material. The relationship between released stress and strain is shown as Equation (3).

\[
\varepsilon_r = \frac{1}{E} \left( \Delta \sigma_r - \nu \Delta \sigma_\theta \right)
\]

\[
\varepsilon_\theta = \frac{1}{E} \left( \Delta \sigma_\theta - \nu \Delta \sigma_r \right)
\]
It has been mentioned in the literature that the tangential strain $\varepsilon_\theta$ can be ignored and it has little effect on the results. [6] The released stress can be calculated using Equation (3) and the strain from ASTM standard and DIC. The results are shown in Figure 8.

Figure 8: Released residual stress

It can be found from Figure 8 that the released stresses calculated from the ASTM standard and the DIC analysis have similar trend, but the values are slightly different. Many reasons could induce the deviation. To begin with, there are errors when we drill the hole and measure the strain using DIC. However, these errors should not induce such an obvious deviation. Secondly, there is plastic deformation occurred during the test. This plastic deformation will not be recovered as the loading removed. So the measured strain is smaller than expected and the released stress is underestimated.

4.3 Evaluation of residual stress

When the drilling depth reaches 1.2 mm, the surface strain of the specimen induced by drilling should keep constant. Therefore, the strain can be substituted into the solution of elasticity theory to calculate the residual stress.

$$\sigma_{\text{max, min}} = \frac{\varepsilon_1 + \varepsilon_3}{4A} \pm \frac{1}{4B} \sqrt{(\varepsilon_1 - \varepsilon_3)^2 + (\varepsilon_1 + \varepsilon_3 - 2\varepsilon_2)^2}$$

(4)

$$\tan 2\beta = \frac{\varepsilon_1 + \varepsilon_3 - 2\varepsilon_2}{\varepsilon_1 - \varepsilon_3}$$

(5)

Where $\varepsilon_1$, $\varepsilon_2$ and $\varepsilon_3$ are the radial strains at the coordinates of $(x_0, y_0 + D)$, $(x_0 - D \times \cos(45^\circ), y_0 - D \times \sin(45^\circ))$ and $(x_0 + D, y_0)$ respectively. $A = \frac{1 + \nu}{2E} \left(\frac{D_0}{D^2}\right)$, $B = \frac{1 + \nu}{2E} \left(\frac{4}{1 + \nu} \frac{D_0^2}{D^3} - 3 \frac{D_0^4}{D^4}\right)$. 


After transferring the measured strains into the radial strains $\varepsilon_1$, $\varepsilon_2$, and $\varepsilon_3$, the magnitude and direction of the residual stress can be evaluated in accordance with Equation (4) and (5). The strain varies when its distance to the hole center changes. Nevertheless, the obtained residual stress will remain the same so long as the measurement locations of these three radial strains lies on the same circle centered at the drilling center.

Figure 9: Theoretical strain and residual stress

(a) Theoretical strain in 0 degree
(b) Theoretical strain in 90 degree
(c) Theoretical strain in 45 degree
(d) Theoretical residual stress

The variations of radial strains with respect to the distance to the hole center are displayed in Figure 9. The strains are in 0 degree, 90 degree and 45 degree direction according to the major principal stress. Polynomial regression equations are used to model these variations. (As shown in Figure 9(a) ~ 9(c)) It can be found that the quadratic equations can quite accurately approximate the strain variations in each direction. The strains at various distance to the hole center can be calculated using the regression equations. The residual stress can then be calculated with these predicted strain values. The results are shown in Figure 9(d), the major principal stress is -350 kgf/cm² and the minor principal stress is -175 kgf/cm². They are exactly equal to the exerted loading during the test. Thus, this method and the results measured by DIC analysis will be applied to calculate the residual stress.
First, the regression equations are used fit the strains in 0 degree, 90 degree and 45 degree direction. The results are shown in Figure 10(a) ~ 10(c). The strain calculated from the regression equation can then be substituted into Equation (4) to calculate the residual stress. The results are shown in Figure 10(d).

Figure 10: Measured strain and residual stress
Due to the measurement error, the measured strain curves shown Figure 10(a) ~ (c) are not so smooth as the curves of theoretical solution (Figure 9(a) ~ (c)). Because most of the measurement errors are random, in theory, the regression approach can filter out random errors. Figure 10(d) shows that the obtained residual stresses are very close to each other. However, the value is not identical to the applied loading, and x- and y-axis are not perfectly parallel with the principal stresses (Figure 10(e)). As described in Section 4.2, the plastic deformation should be the main reason to result this situation. Therefore, the regression can really reduce the influence of measurement errors. After regression, the strain measured using DIC can be applied to calculate the residual stress.

5 Conclusions

Hole drilling method is a semi-destructive measurement method. However, the smaller the drill hole is, then the less damage the original structure or part will have. This makes this method closer to a non-destructive testing method as well. The following conclusions can be drawn according to the analysis results:

1. Instead of strain gauge, DIC can be applied to measure strain in a micro-scale experiment.
2. A proper grid size should be selected in the DIC analysis in order to obtain a precise strain.
3. Using regression approach can reduce the influence of measurement error. The strain obtained from the regression model can be substituted into the theoretical solution to solve the residual stress. A consistent residual stress can always be solved with the strain inside the influence area. This shows that DIC method can successfully applied to the micro hole drilling method to measure the residual stress.

Acknowledgement

The authors would like to acknowledge the support of Taiwan National Science Council through grant No. NSC 99-2625-M-390-001 and NSC 99-2625-M-260-003.

References
