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A novel experimental device with modified laser shadow spot and optical strain gauge set-up

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Abstract

A new device, which combines the technologies of laser shadow spot and optical strain gauge with image processing, computer voice, and WWW software for detecting the broken procedure of different materials, has been presented in this paper. The whole testing experiments are monitored by an imaging system and guided by the computer voice to predict the crack step by step. The system generates a laser shadow spot or diffraction image on a screen when the laser beam passes through a lens as well as the crack gap of a specimen. The mechanical shelf changed the strength of the specimen and a CCD camera grabbed the variant images of the specimen under strength. The computer calculated each image for guiding the operator how to install the specimen and added the proper strength. Our proposed algorithm calculated the radius of the crash gap, the factors of the strength intensity and the strain value. In the experiment of optical strain gauge, the change in diffraction pattern and strain is caused by the applied force change. In the laser shadow spot experiment, the more the stress on the specimen causes the more the strain intensity factor and the later turns to saturation gradually, which means the specimen will be broken.

Keywords: Laser shadow spot; Optical strain gauge; Image processing; Strain intensity factor

1. Introduction

This paper is an application in mechanics and materials for training users to understand the variation of the crack tip and the breaking procedure of a material to know what the terminologies of

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strain, the characterization of the centralized stress, and Poisson's ratio are. In optics [1–3], this experiment involves geometrical optics, physical optics, and caustic theorem. Laser beam goes straight with high coherence, high power density and can be focused in a small focus area. We have simplified the set up of traditional laser projection spot by modifying some complicate devices. The crack tip has a plasticity distorted area, and how this area changed is impossible to see with our eyes but all the variations of the crack tip can be shown apparently by using the laser shadow spot method. Hence, for an observer, this experiment should be a marvelous work.

An observer who operates the system, is allowed to add strength to the specimen, watches the monitor to see the laser spot, and follows the instruction of computer voice until the specimen is broken. When the laser spot is large enough and reaches the limit, the computer continues to analyze the image obtained from CCD and informs the observer that the specimen is broken. Here, the specimen is allowed to be destroyed, so the observer is able to feel the whole variation of the laser spot before and after breaking the specimen.

The testing set-up is easy to modify as an optical strain gauge [4,5], which needs only to reverse the installation of the lens and let the laser beam diverse to a wide parallel ray, and the specimen changes to an open gap type for versatile function. All the experimental procedures have been created in a WWW homepage as an open learning environment. A tiny crack of a rigid body which is not detected by eyes does not feel break but after a period of time, the length and the depth of the crack are increased and the intensity of strength will be over the threshold. In the meantime, the crack grows very fast just like a broadcasting stress wave and the speed of the growth is faster than that of the sound speed. Hence, the specimen is broken promptly [6].

2. The concepts of fracture theory

A crack of a tenacity material is possible to be broken, when the crack is increased by increasing the stress. Three possible cracks caused by stress are shown as in Fig. 1. The first type of crack is the opening mode caused by a right stress and the direction of the crack is along the y-axis as a pair of lips of an open mouth. The second type of the crack is the sliding mode caused by an inside shear stress, two sides of the crack sliding along x-axis. The third type of the crack is the tearing mode caused by a plain shear stress with two sides of the crack grows along the z-axis just like torn off. Most cracks can be described by these three modes and usually the first is the common type for a crack body. Hence, the first type will be discussed in the next section.

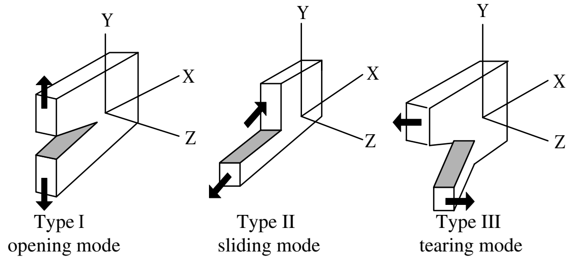

Fig. 1. The three types of the crack.

The technology of laser shadow spot is easily described by caustic phenomena as shown in Fig. 2. Caustic phenomena are due to the spherical aberration in a lens. When a bundle of parallel rays is incident on a lens normally, they should

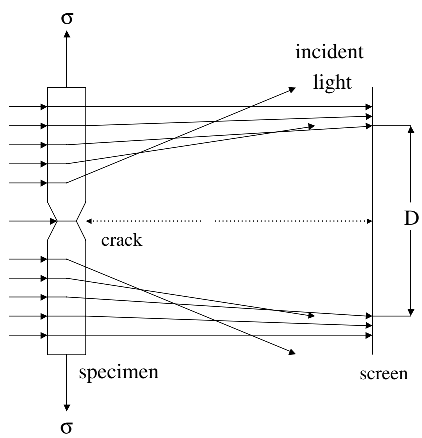

Fig. 2. The laser shadow spot.

focus on the same point according to geometric optic theorem. In real word, the focal point is not a point but is much larger due spherical aberration and caustic phenomena describes the focal divergence. The thickness of the crack tip shrinks with the extension of stress. The shrinking is so tiny and not possible to be seen by naked eyes. The laser shadow spot will amplify the distortion and show the variance.

The crack tip has a plasticity distorted area, and the change in this area is also difficult to see with our eyes but all the variations of the crack tip can be shown apparently by using the laser shadow spot method. An observer, who is allowed to add strength to the specimen, operates this system and watches the size change of the spot to monitor the growth of the crack. The growth of the crack has three stages. The first stage shows a clear laser spot. During the second stage, the more the stress added, the wider the spot diameter with slow growth. The third stage shows a promptly broken crack as in Fig. 3.

3. Laser spot (caustic) experiments

The set-up of a caustic experiment includes a laser source, specimen, lens, screen, and pressure shelf. There are two kinds of caustic experiments that can be adapted. One is transmission type and the other is the reflection type.

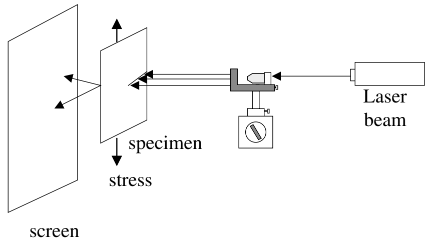

Fig. 4. The set-up of a transmission type caustic.

An optical set-up of transmission type caustic experiment is shown as in Fig. 4 [7]. A specimen is put behind the laser source and the spatial filter. The laser is aimed to the crack tip and added stress on the specimen lightly. The screen shows the variance of the laser spot, which can be changed by adding different stress on the specimen. The more the stress added the wider the spot diameter. This is because the thickness and index of refraction of the distorted area are variant. The spot image of this type is very clear as shown in Fig. 5. The lens is a device to diverge or converge the laser beam. The beam goes through the crack tip of the specimen and generates the spot image on the screen. When user puts stress on the specimen, an algorithm solves the diameter of the laser spot, the factors of the strength intensity and the strain value. The more the stress added the more the factors of the strength intensity until saturation, which means the stage approaches where the material breaks [8]. The diameter has direct relation with

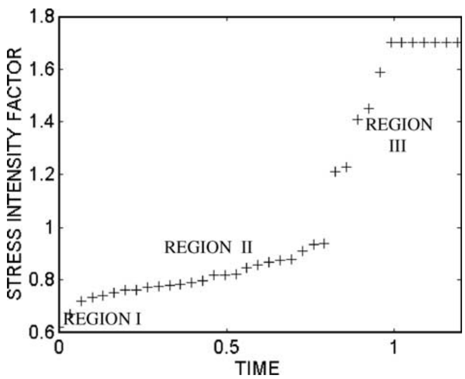

Fig. 3. The relation between time and stress intensity factor in the growth of crack.

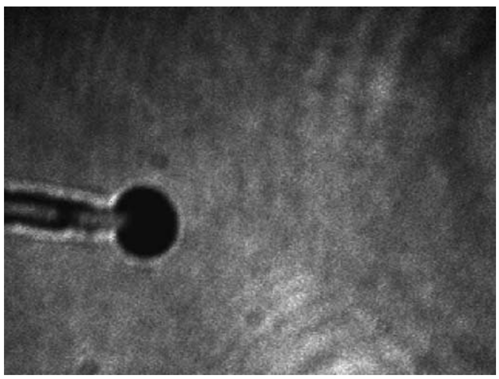

Fig. 5. The transmission type caustic image of a transparent specimen (a crack shown on the image).

the added stress. Hence, a laser shadow spot set up is good for testing the strength or broken tolerance of a material. In the experiment, if the incident angle of the laser beam or the image distort on the screen is smaller, there is less error in the experiment. Therefore, the whole set up of the optical system must be very careful. Even the clapping process of the specimen is done step by step from upper to bottom to the clap on the clapping shelf [9].

The relative K_I (represented by K_C), got from the laser spot experiments.

The transmission type caustic:

$$K_C = E\frac{1.671}{z_0 t c_t} \times \frac{1}{\lambda^{1.5}}\left(\frac{D_{t\lambda}}{3.16}\right)^{2.5} \tag{1}$$

The reflection type caustic:

$$K_C = \frac{E(2\pi^{0.5})\left(\frac{D_{t\lambda}}{3.1702}\right)^{2.5}}{C_1^{1.5} dv C_3 \frac{3}{2}} \tag{2}$$

$D_{t\lambda} = 3.16\lambda r_0 =$ the diameter of caustic

where E is the density of the optical field, v is the speed of laser beam, C_1 and C_3 are the distance constants of the experiment.

$$r_0 = \left(\frac{3C}{2\lambda}\right)^{\frac{2}{5}}$$

where

$$C = \frac{z_0 t c_t K_I}{\sqrt{2\pi}}$$

$$\lambda = \frac{z_i}{z_0 + z_i}$$

z_0 is the distance between the specimen and the screen, t is the thickness of the specimen, c_t is the optic stress factor of the incident beam, and z_i is the distance between screen and the CCD camera as shown in Fig. 6.

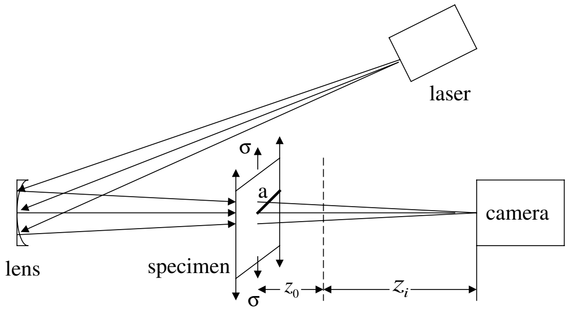

Fig. 6. The ray path of a caustic.

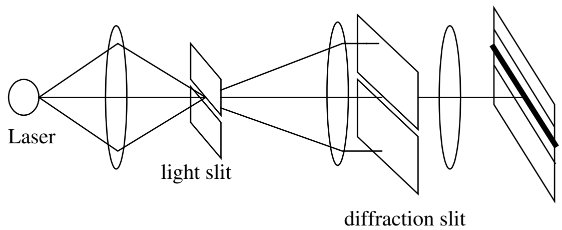

Fig. 7. The set-up of single slit diffraction.

4. Optical strain gauge

Since 1956, the coherence characteristic of the laser beam has been making the development of optic strain gauge possible [10]. Some experiments used single slit diffraction (Fig. 7) technology such as Tuckerman's optical strain gauge which is a good example as shown in Fig. 8.

Usually, the width of a slit is only a few micrometers. When the plate of slit is distorted by putting some stress, the width of the slit will be increased. A laser spot is generated on the screen when the laser beam goes through the slit. The more the stress increases the wider the slit and closer the laser spots are. This is the concept for the strain measurement of a specimen.

Assume b is the slit width of a copper specimen, then

$$b = \frac{\lambda R_n}{y} \tag{3}$$

where n is the number of dark points counted from the spot image center, y is the distance between the nth dark point and the image center. The width difference of the slit is represented as Δb.

$$\Delta b = \varepsilon l \tag{4}$$

Assume y is the distance from the dark point to the image center before distortion. When the spec-

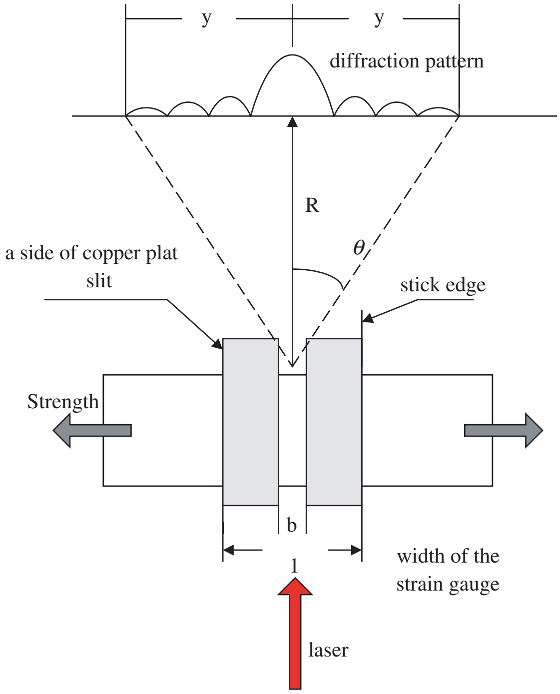

Fig. 8. The optical strain gauge.

imen is under stress causing elongation, the elongation length is Δb.

$$b + \Delta b = \frac{\lambda R_n}{y_1} \tag{5}$$

Before adding the stress, the relation between b and y is:

$$b = \frac{\lambda R_n}{y} \tag{6}$$

Subtracting Eq. (5) from (6), the average strain amount ε could be derived as:

$$\varepsilon = \frac{\Delta b}{l} = \frac{\lambda R_n (y - y_1)}{l y_1 y} \tag{7}$$

The diffraction image is composed of a vertical line of bright or dark spots. Optical strain gauge is calculated by measuring the distance change of those spots. Here the image process procedure is described. The whole image is calculated by gray level to find the binarization threshold and then binarized the image. All the bright spots and the coordinates of the maximum bright spot are found.

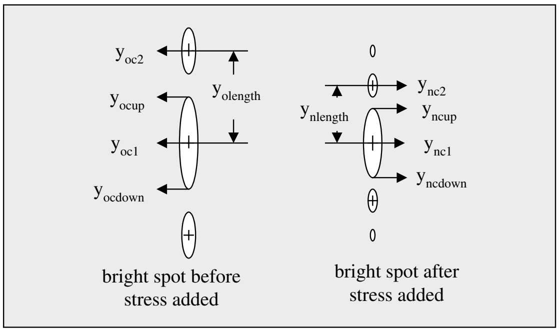

Fig. 9. The distance change before and after the addition of stress.

Upon searching vertically up and down, two edges of this bright spots are observed. The average of the coordinates of these edges would be the coordinate of the center. The same algorithm is used to find the center coordinates of the second order as well as the third order. This procedure must process before and after the stress added on the specimen to find the coordinate difference for the strain measurement. Fig. 9 is the position change of each bright spot before and after the stress added.

The algorithm of the optical strain gauge:

Step 1. Find the horizontal coordinate of the brightest spot.
max yaddpix(x) store x to x_c

Step 2. Count the average gray scale of those bright spots to find binarization threshold value.
$\mathrm{gray}(g) = \sum_{i=x-\mathrm{wide}}^{x+\mathrm{wide}} \sum_{j=0}^{240} \mathrm{pixel}(i,j)$

Step 3. Assume the threshold of binarization.
$\mathrm{gray}_1 = \sum_0^{255} \mathrm{peak}(g)$
$\mathrm{gray}_2 = \sum_{255}^{0} \mathrm{peak}(g)$
$\mathrm{Threshold} = \frac{\mathrm{gray}_1 + \mathrm{gray}_2}{2}$

Step 4. if getpix(i,j) < Threshold
then setpix(i,j) = 0, else setpix(i,j) = 255

Step 5. Find the vertical coordinate of the brightest spot.
max xaddpix(y) store y to y_c

Step 6. Find the vertical coordinates of each bright spot before adding stress.
Find y_{ocup}, y_{ocdown}
Get y_{oc1}
The same procedure to find y_{oc2}
$y_{\mathrm{olength}} = y_{\mathrm{oc1}} - y_{\mathrm{oc2}}$. The distance between center and edge of a bright spot.

Step 7. Find the vertical coordinates of each bright spot after adding stress.
Find y_{ncup}, y_{ncdown}
Get y_{nc1}
the same procedure to find y_{nc2}
$y_{\mathrm{nlength}} = y_{\mathrm{nc1}} - y_{\mathrm{nc2}}$

Step 8. Use $y_{\mathrm{olength}} - y_{\mathrm{nlength}}$ to calculate stress goto Step 1.

Symbol Table & Instruction:

gray(g): The average of the gray scale.
When getpix(i,j) = gthen pixel(i,j) = 1 or pixel(i,j) = 0, g is the range of gray scale from 0 to 255.

wide: The width of the image for the calculation of average gray scale.
peak(g): The peak value of the gray scale.

gray$_1$: The first peak value of the gray scale.
gray$_2$: The second peak value of the gray scale.
x_c: The horizontal coordinate of the largest gray scale in the vertical line.
y_c: The vertical coordinate of the largest gray scale in the horizontal line.
y_{ocup}: The edge vertical coordinate of the central bright spot before adding stress.

$$\sum_{j=y_c}^{240} \mathrm{getpix}(i,j) < d_{\mathrm{limit}} \text{ store } y_{\mathrm{ocup}}$$

y_{ocdown}: The bottom edge vertical coordinate of the central bright spot before adding stress.

$$\sum_{j=y_c}^{1} \mathrm{getpix}(i,j) < d_{\mathrm{limit}} \text{ store } y_{\mathrm{ocdown}}$$

y_{oc1}: The location of the central bright spot before adding the stress.

$$y_{\mathrm{oc1}} = \frac{y_{\mathrm{ocup}} + y_{\mathrm{ocdown}}}{2}$$

y_{oc2}: The location of the second central bright spot before adding the stress.

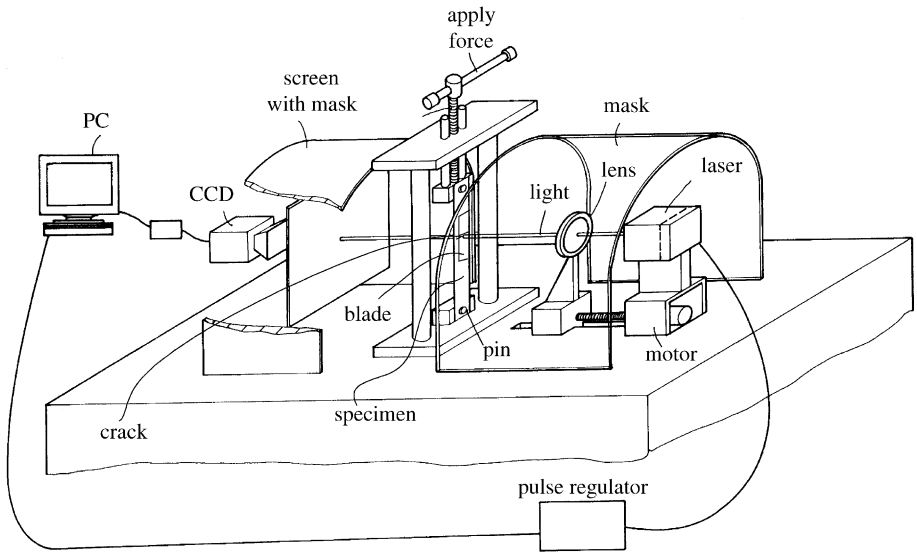

Fig. 10. The novel experimental device with modified laser shadow spot and optical strain gauge set-up.

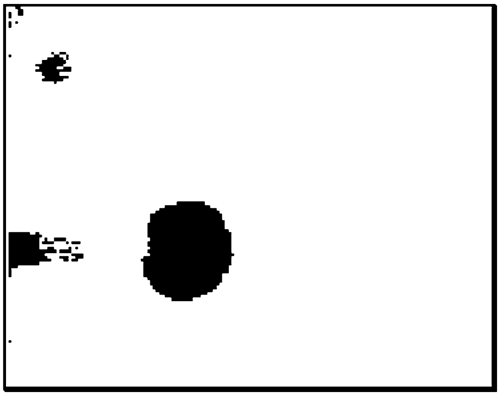

Fig. 11. The binarization of images.

y_{nc1}: The location of the central bright spot after adding the stress.
y_{ncup}: The upper edge vertical coordinate of the central bright spot after adding stress.
y_{ncdown}: The bottom edge vertical coordinate of the central bright spot after adding stress.
y_{nc2}: The location of the second central bright spot after adding the stress.
$y_{olength}$: The distance of two bright spots before adding stress.
$y_{nlength}$: The distance of two bright spots after adding stress.

5. Experiments

We adopt a novel scientific experimental device in the modified laser shadow spot and optical strain gauge set-up. The light source is a laser diode with red light, which is fixed on the terminal of the system controlled by an electric pulse regulator (Fig. 10). A lens diverges the laser light to a wider beam. The diversion angle is about 6×30 degrees. The lens is put on a suitable place with the laser source. A stepping motor adjusts the distance between the lens and the laser source to control the laser beam width as a parallel beam or a diverged beam. When the lens is located on the front part then the laser beam is a parallel beam,

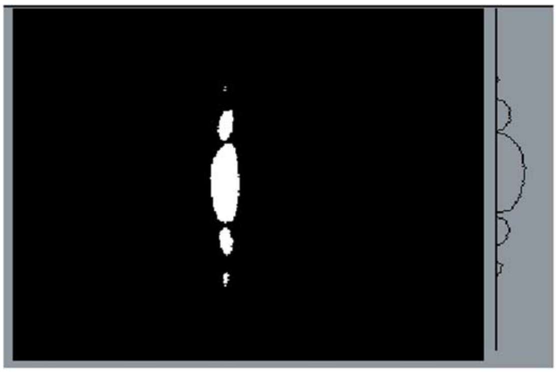

Fig. 12. The statistical diagram of horizontal bright spots.

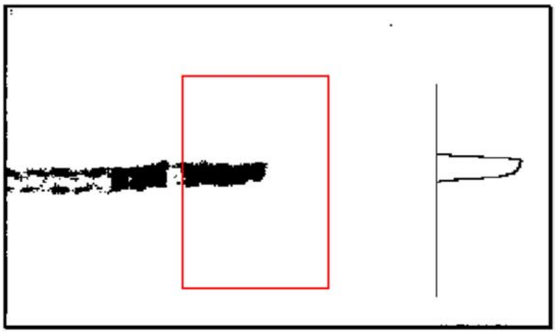

Fig. 13. The statistical diagram of horizontal dark spots.

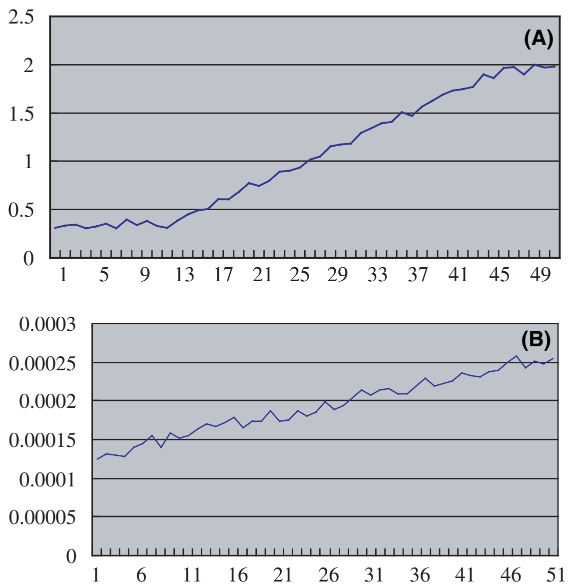

Fig. 14. (A) The testing result of an acrylic specimen(I) (the result is calculated from a diffraction image). (B) The testing result of an acrylic specimen(I) (the result is calculated from a diffraction image).

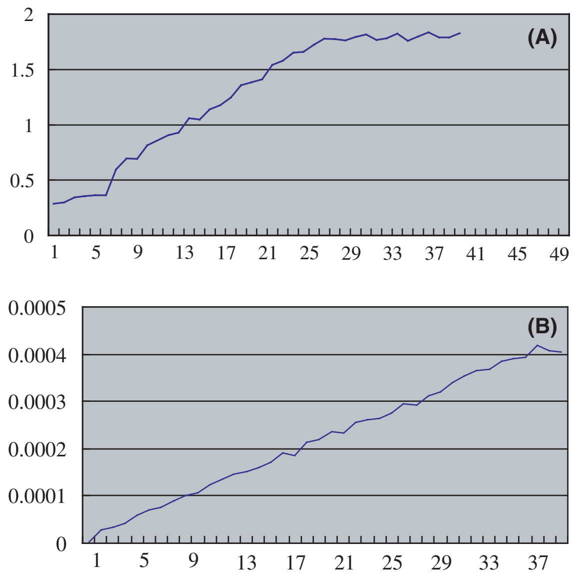

Fig. 15. (A) The testing result of an acrylic specimen(II) (the result is calculated from a diffraction image). (B) The testing result of an acrylic specimen(II) (the result is calculated from a diffraction image).

whereas when the lens is located on the back the laser beam gets diverged.

When an operator rotates the arm, the specimen is extended gradually. It changes the shadow projected on the glass screen. The operator will be guided by computer voice to know each step of the specimen change until it is broken and to understand the principle of these experiments.

The laser source has been modulated to generate 10 light pulse per second. A stepping motor carried the lens back and forth 5 times per second and made the laser beam parallel or broaden. The laser source went through the crack of specimen and the slit of the copper shelf that generated 10 images on the screen with images of five laser shadow spots and five diffraction patterns.

The specimen was put under stress by a stress shelf. A CCD camera grabbed the image change. A computer solved the radius of the crack and the factor of strength intensity or the strain value by our algorithm.

In the experiment of optical strain gauge, the strength change causes a strain change. In the laser shadow spot experiment, the more the applied force on the specimen, the more the strain intensity factor and the later turns to saturation gradually. The saturation of the strain intensity factor means that the specimen will be broken. The thickness of the image screen is a ground glass of less than 2mm in size. This screen is kept clean. For better image quality, the screen should be coated with oil before experiments.

The grabbed image should be processed as a binarization image consisting dark and bright pixels. If the gray scale of a pixel has larger threshold than the pixel set to bright (gray scale 255) or the pixel set to dark (gray scale 0), the purpose of the binarization is to distinguish the image of object and the background as shown in Fig. 11. Two kinds of pixels were in the image, dark and bright, after binarization. Therefore, it is easy to get the statistical amount of dark points or bright points. The histogram for the calculation of the horizontal

Fig. 16. The binarization image and the statistic diagram of horizontal dark spots.

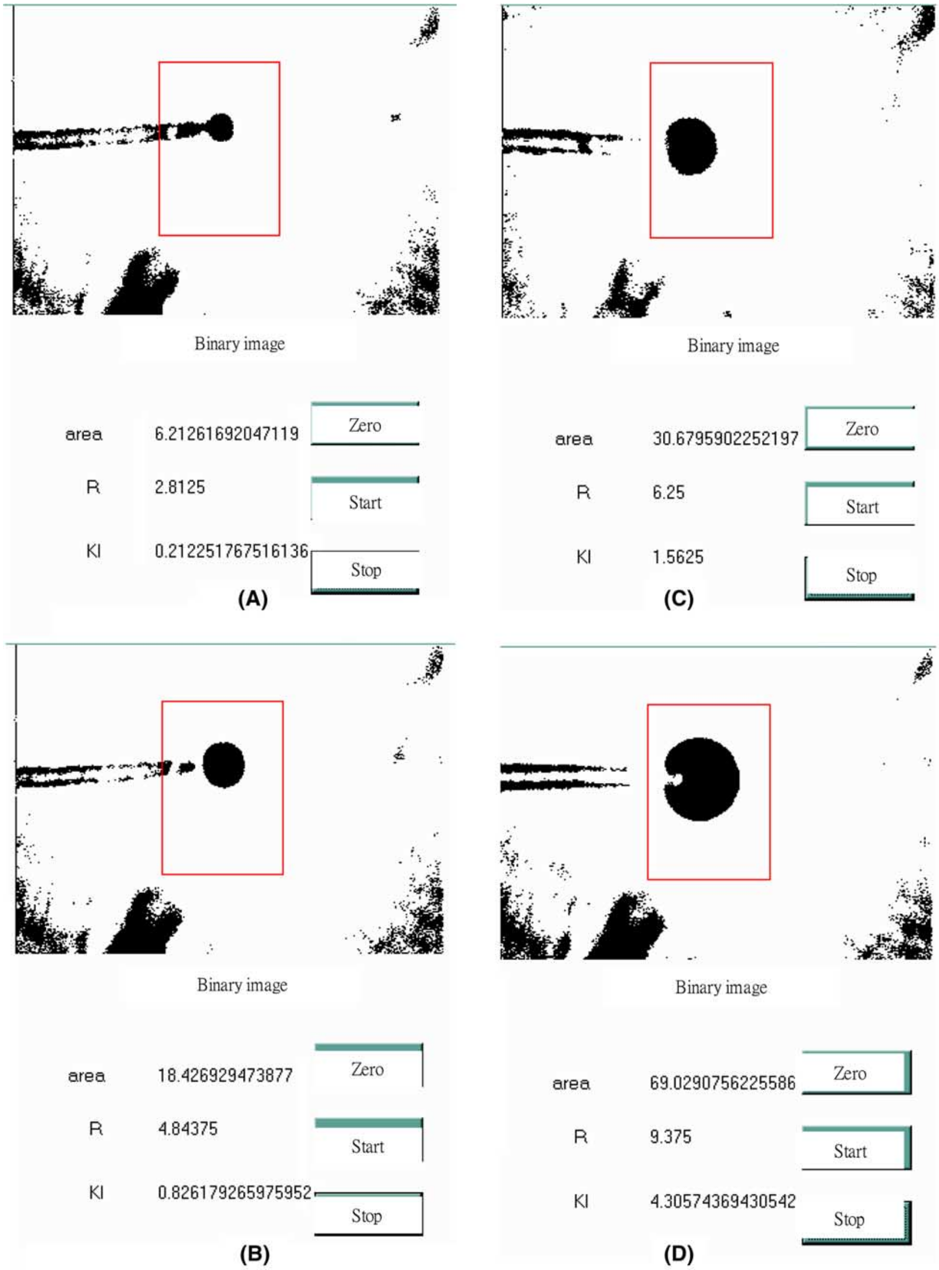

Fig. 17. (A)–(D) The images changed with the increasing of strain on an acrylic specimen.

bright spot is shown as in Fig. 12. We can derive the vertical coordinate from the histogram of the bright spots horizontal projection. Also, We can derive the vertical coordinate from the histogram of the horizontal projection of dark sports as shown in Fig. 13.

Figs. 14 and 15 are the test result of extension strain rate for an acrylic specimen. Fig. 14(A) is the K_I curve of an acrylic specimen, and Fig. 14(B) is the test curve of the strain rate about $2.5 \times 10^{-5}\,s^{-1}$. Fig. 14(A) is the K_I cure of an acrylic specimen, and Fig. 14(B) is the test curve of the

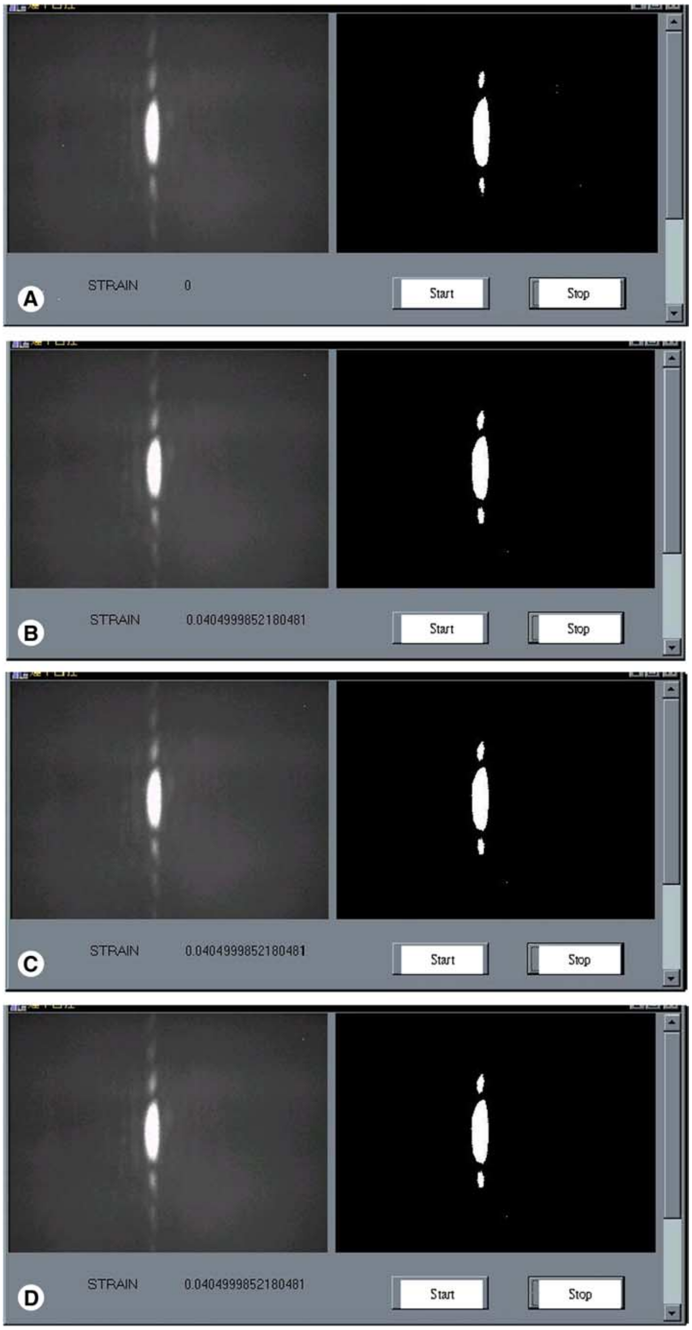

Fig. 18. (A)–(D) The recorded images and the strain change in the testing stage.

extension strain rate about $1 \times 10^{-4}\,\mathrm{s}^{-1}$. Fig. 16 shows the binarization image and the statistic diagram of horizontal dark spots. Fig. 17(A)–(D) is the images changed of the extension strain on an acrylic specimen. From the monitoring system, we can observe the diameter of the laser shadow spot and value of the stress intensity. Fig. 18(A)–(D) is the recorded images and the strain change in testing stage.

6. Conclusion

We hope that these novel experiments will help people in the laser shadow spot and optical strain gauge for the crack detection. Recently, lots of engineering had defects inside the construction such as the crack of the main pillars. Some cracks have existed for a certain time without any danger happened and people may be careless in it. However, from this experiment we know that if we cannot fix the crack in advance, it may grow and the growth speed becomes too fast that we will not get any chance to avoid the collapse of a structure. That told us the importance of the prevention. We hope this experiment reminds us to find out and care the engineering safety around us.

Acknowledgement

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References

[1] K. Karmas, B.R. Pramod, Digital image processing of fringe patterns in photomechanics, Optical Engineering 31 (1992) 1487–1498.

[2] F.A. Jenkins, H.E. White, Fundamentals of Optics, 4th ed., McGraw-Hill, Singapore, 1981, pp. 274–417 (Chapters 13 and 19).

[3] J. Dyson, Interferometer as a Measuring Tool, Machinery Publish, 1984, pp. 33–45 (Chapter 4).

[4] S.B. Brown, Polychromatic Optical Strain Gauge, US patent 4,939,368, 1990.

[5] W.H. Glenn, G. Meltz, E. Snitzer, Method For Impressing Gratings Within Fiber Optics, US patent 4,725,110, 1988.

[6] C.S. Lin, A pilot type scientific experimental device using optical method and computer vision technology, Indian Journal of Pure and Applied Physics 40 (2002) 816–827.

[7] C.S. Lin, R.S. Chang, Image processing in crack growths using a caustic method, Journal of Nondestructive Evaluation 15 (2) (1995) 61–70.

[8] T.Y. Chen, C.E. Taylor, Computerized fringe analysis in photomechanics, Experimental Mechanics 29 (1989) 323–329.

[9] C.S. Lin, A novel scientific experimental device in modified laser shadow spot and optical strain gauge set-up, Chinese patent 351452, 1999.

[10] C.S. Lin, W.C. Ke, An image processing system and method in optical experiment, Chinese patent 372271, 2000.