Pilot-type scientific experimental device using optical method and computer vision technology

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Digital image and multimedia technology projected in a modified laser shadow spot set-up to guide people to engage in the scientific model of the crack growth has been described. This novel device can be operated automatically, and economically in a participating display. A new method to process the experimental data and predict the fracture time in the PC-based digital signal processing system has been developed. With one video CCD camera and frame grabber analyzing a series of images of laser shadow spot during crack growth, the computer obtain the image size of laser shadow spot to evaluate stress intensity factor in real time. An auto-range finding algorithm is used to find the location of a laser shadow spot. Six special experimental conditions have been considered to improve this scientific model. Participants can operate the model themselves, so that they can observe the change of sizes of the laser shadow spot images and can respond in time to know the status of specimen in tension. It also can remind the attention of the participant with the sign of a speech sound before the break of specimen to achieve the effect during recreation to learn.

I Introduction

The application of the multimedia technology has been spreading widely and constantly due to the improvement on the speed and efficiency of the computers in recent years. The computers have been making a breakthrough from simple calculations to complex displays of internet and multimedia. Here, a novel scientific model is created, experiment of laser shadow spot, by using optical method and multimedia technology (Fig. 1).

![Fig. 1 — The set-up of a pilot-type scientific experimental device](image)

This novel device is also pilot-type and networked multimedia. It means, one who is engaged in the experiment can obtain the assistance from the pilot system of this device and the multimedia information in this experiment can offer communication services at a distance. The following merits have been set-up for this scientific experimental model, in a participating display:

- The participants should be interactive and creative by observing the change of sizes of the laser shadow spot images and comparing the status of specimen in tension.
- The pilot-type system should be flexible and easy to use. Participants can operate the model themselves without any other attendant's help.
- The system should be used to educate the participants or other visitors in an educational situation and improve learning.
- The system should provide access to the internet as a means for presenting real-time experimental information.
- The participants are allowed to squeeze the handlebar to add tensile force and see the breakage of specimen. The crack growth speed in the specimen is larger than 500 m/sec. So, the sudden rupture will bring amazement to the participants. They can realize the importance of precaution and reinforcement of a structure.
- The system can predict the fracture-time, with the sign of a speech sound and keep magical
impression in the visitor's mind.

- The requirements of waste material and operation cost are very low.

Fig. 2 — Material near crack tip forms a circular shape of plastic zone and shrink in thickness under tension

Fig. 3 — The geometry relationship of laser light and shadow spot pattern

Today, many researchers around the world use the method of computer vision and optical technology in problems of stress analysis. The technique of laser shadow spot in fracture analysis has extensively been used for determining stress-intensity factors in crack problems. Material near crack tip forms a circular shape of plastic zone and shrink in thickness, under tension (Fig. 2). When the crack tip of a test specimen is irradiated by a parallel optical beam, the pathway of its reflection and refraction will change from parallel to non-parallel as a result of the influence from variety of pressures generated by the irradiation. The surface of the crack tip in a specimen will slant and produce discontinuous geometric shapes. So, the laser shadow dimension can be derived (diameter) by geometrical optics formulation, which leads to the result that, the light-intensity in the laser shadow spot is zero (Fig. 3). The rays of reflection and refraction, change to an envelope-type of pattern in a three-dimensional space\(^1\). When this envelope pattern is projected on a screen, one bright curve called the caustic curve (a curve surrounded by a dark zone or spot) is produced, as shown in Fig. 4.

Fig. 4 — Light deflection forms the spot

The laser shadow spot's application to fracture studies was originally performed by Manogg\(^6\). He used only the transmitted laser shadow spot, which is sometimes called the laser shadow spot. Theocaris\(^7\) made a big step in the development of the laser shadow spot method and mentioned use of the reflected caustics. A reflected caustic can provide an elementary understanding of how the fracture occurs\(^4\). The reflected caustic includes two pieces of information (front-face caustic and rear-face caustic) concerning the values of the stress-intensity factor \(K_I\). Another type of information provided by the reflected caustic outside the laser shadow spot curve lies in the interference fringes and concerns the thickness variation of the specimen. The application of the laser shadow spot set-up for stress intensity factor
Fig. 5 — Laser shadow spot experimental set-up

Fig. 6 — Six special experimental conditions

$K_i$ and plastic zone measurements has been widely discussed. For example, Gdoutos & Aifantis studied the laser shadow spots around cracks under mixed-mode loading conditions. Kamath & Kim used the laser shadow spot set-up to study three-dimensional deformation fields very near the crack tip. Theocaris has extended the laser shadow spots method in resolving the evaluation of COD and the core region of plane strain. Chang & Lin had done beautiful dynamic $K$ measurements by utilizing only transmitted laser shadow spot set-up.

In a laser shadow spot set-up, a set of suitable apertures and lenses are usually used to achieve the required magnification. The laser beam after a spatial filter can be regarded as a pointed light source. The experimenter here, introduces two lenses, one lens converges the laser light leaving the spatial filter to a parallel beam and the other one converges the light again, to increase the flexibility of the optical method. Many types of laser shadow spot experiments can be arranged by passing the laser light through some advanced optical filtering, but these are not easy to set-up for an experimenter and are unsuitable for scientific model. So here, the above set-up was simplified to use only a diode-pumping laser with divergent lens on its head. In other words, the intention for this device is to design a museum apparatus, and the exhibition clerk need not worry over the moving alignment by experimenter or other factors.

Digital image-processing method was usually used in evaluating the obtained optical pattern,
which is mainly due to the existing singularity at the crack tip. The ray through the crack tip will form a circular envelope known as a caustic surface\(^\text{[16]}\). One can move the screen towards the specimen to see the size of the circular image spot, which assumes a different diameter. As the caustics obtained by a sphere are well defined, so the deviation of the surface of the specimen can be calculated, i.e., the characterization of the deformed surface near the crack tip is achieved by the description of the curve of the caustics. Classical laser shadow spot patterns are easy to be interpreted by the distance from crack tip to the side of spot (Fig. 5). A method to obtain these values is from the distance between respective peaks in the histograms of the image for evaluation of \(K_I\) of the cracks\(^\text{[17]}\). When the direction of the maximum diameter of the laser shadow spot curve is along the \(x\) or \(y\)-axis, this measurement is usually accurate, since the peaks are very sharp. The value of the stress-intensity factor is very sensitive to the measurement of the maximum diameter of the laser shadow spot curve, and the fracture-time can be predicted according to the value of the stress-intensity factor. The width of an ideal crack in the specimen is less than 0.2 mm. It is better to make an artificial crack by a thin metallic disk-cutter. But here, an artificial crack was made by a sawmill for sake of economy. The irregularity of the sawn slit increases the difficulty in fracture prediction. Furthermore, the exact location of laser shadow spot is ambiguous because of optical diffraction effects. Consequently, the exact position of the crack tip is also observed when the variation of the laser shadow spot is too fast. So, new image-processing algorithm must be used to obtain the value of the maximum spot diameter. The author designed an auto-range finding algorithm, to find the location of laser shadow spot. As the participants will operate the model by themselves, six special experimental conditions are considered to improve the reliability of the model.

2 Laser Shadow Spot Theory

Here, a crack in a plate, subjected to in-plane mode I loading is considered. The stress field in the vicinity of the crack tip is governed by the values of the opening-mode \(K_I\) stress-intensity factor. Brown & Srawley\(^\text{[11]}\) derived a stress-intensity factor \(K_I\) as a solution for a single-edge cracks in tension, as follows:

\[
K_I = S \sqrt{a \left( 1.12 \sqrt{a} - 0.41 \left( \frac{a}{W} \right) + 18.7 \left( \frac{a}{W} \right)^{0.7} - 38.48 \left( \frac{a}{W} \right)^{1.7} + 53.85 \left( \frac{a}{W} \right)^{2.7} \right) \}
\]

where the \(K_I\) for a double-edge crack in tension is:

\[
K_I = S \sqrt{a} \left[ 1.98 - 0.36 \left( \frac{2a}{W} \right) + 2.12 \left( \frac{2a}{W} \right)^2 - 3.42 \left( \frac{2a}{W} \right)^3 \right]
\]

and the \(K_I\) for the crack, in pure bending of a beam is:

\[
K_I = \frac{6M}{W^2} \left[ 1.99 - 2.47 \left( \frac{2a}{W} \right) + 12.97 \left( \frac{2a}{W} \right)^2 - 23.47 \left( \frac{2a}{W} \right)^3 + 24.8 \left( \frac{2a}{W} \right)^4 \right]
\]

where \(S\) is the applied stress; \(S = \frac{P}{W}\); \(P\) is the tensile stress; \(t\) is the thickness of the specimen; \(W\) is the width of the specimen; \(M\) is the momentum; and \(a\) is the crack length.

An equation is established by transmission laser shadow spot theory and is expressed by \(K_{Ic}\) as follows:

\[
K_{Ic} = \frac{1.671}{z} \left( \frac{D}{3.16} \right)^{2.5} \left( \frac{z + z_1}{z} \right)^{1.5}
\]

where \(D\) is the transverse diameter of the reflected caustics, \(c_1\) is the stress-optical coefficient and \(t\) is the thickness of specimen. \(z\) and \(z_1\) are constants depending on the characteristic distances (such as in Fig. 5) of the experiment arrangement. By simplifying the above equation, the relation of the value of transverse diameter \(D\) and the stress-intensity factor is given by:

\[
K_{Ic} \propto D^{2.5}
\]

3 Image Processing for Auto-Range Finding

3.1 General description

As mentioned in the beginning of this paper, the computer program has to be connected to a sophisticated learning environment. Here, a new algorithm is developed for processing the laser shadow spot images. There are six special experimental conditions (Fig. 6).
(a) specimen is placed on the frame and crack tip is in ROI (region of interest).

(b) no specimen is placed on the frame.

(c) the force is acting along a wrong direction (that means, one must apply the counter-clockwise moment).

(d) image of crack tip is out of ROI.

(e) the variation of the laser shadow spot is larger than a threshold value.

(f) the crack will be out of image.

3.2 Judgement for each case

Here, many judging algorithms are created to determine what condition the experimental operation is attributed to.

(a) No specimen is placed on the frame

\[ x_{\text{addpix}}(j) = \sum_{i=x_{\text{start}}}^{x_{\text{end}}} \text{darkpix}(i, j) = 0 \]

where

\( x_{\text{start}} \) is the x-axis coordinate of start point of ROI
\( x_{\text{end}} \) is the x-axis coordinate of end point of ROI
\( x_{\text{addpix}}(j) \): the accumulation of dark point in a horizontal line

\[ x_{\text{addpix}}(j) = \sum_{i=x_{\text{start}}}^{x_{\text{end}}} \text{darkpix}(i, j) \]

when \( \text{getpix}(i, j) \geq T \), \( \text{darkpix}(i, j) = 0 \)
\( \text{getpix}(i, j) < T \), \( \text{darkpix}(i, j) = 1 \)

where \( \text{getpix}(i, j) \): get the gray level of pixel \((i, j)\)

\( T \): thresholding value

(b) Specimen is placed on the frame and crack-tip is in ROI

\[ c_{\text{up}} - c_{\text{down}} > c_{\text{wide}} \] \( \ldots (3.2) \)

As shown in Fig. 7,

\( c_{\text{down}} \): the y-axis coordinate of lower boundary in object
\( c_{\text{up}} \): the y-axis coordinate of upper boundary in object
\( c_{\text{wide}} \): the vertical width of object, here the authors set \( c_{\text{wide}} = 5 \)

(b) Specimen is placed on the frame and crack-tip is in ROI

\( c_{\text{up}} - c_{\text{down}} > c_{\text{wide}} \) \( \ldots (3.2) \)

3.3 Shrinkage of ROI

As shown in Fig. 7,

\( x_{\text{end}} > c_{\text{right}} + y_{1} \)
\( y_{\text{start}} < c_{\text{down}} - y_{1} \)
\( y_{\text{end}} > c_{\text{up}} + y_{1} \) \( \ldots (3.3) \)

Otherwise, image of crack tip may be out of ROI (Fig. 8).
As shown in Fig. 9,
y_{start} is the y-axis coordinate of start point of ROI
y_{end} is the y-axis coordinate of end point of ROI
c_{right} is the x-axis coordinate of right boundary of ROI

Fig. 9 — Shrinkage of ROI

As shown in Fig. 10,
x_{start} < c_{right} + y_0
y_{start} > c_{down} - y_0
y_{end} < c_{up} + y_0

Fig. 10 — Minimum distance and maximum distance in ROI

(d) extension in ROI

... (3.4)

As shown in Fig. 10, the value of y_0, y_1 depend on the changing speed of the shadow spot, here the authors set y_0 = 25, y_1 = 40.

(e) The crack tip will be out of image.

Fig. 11 — The crack will be out of image

As shown in Fig. 11,
x_{min} is the x-axis coordinate of the left margin of image
x_{max} is the x-axis coordinate of the right margin of image
y_{min} is the y-axis coordinate of the lower margin of image
y_{max} is the y-axis coordinate of the upper margin of image
x_{bound} and y_{bound} are the safe distance from ROI to the margin of image, here the authors set x_{bound} = 10 and y_{bound} = 10.

3.2 Auto-range finding

Step 1 — define original region, at first a 100 ~ 300 rectangular region is selected as a ROI

set original value x_{start}, y_{start}, y_{end}

Step 2 — if getpix(i,j) < Threshold

then setpix(i,j) = 0, else setpix(i,j) = 255

Step 3 — the accumulation of dark point in a horizontal and vertical line
calculate $y_{accpix}(i)$
calculate $x_{accpix}(j)$

Step 4 — find the edge of object

$c_{down} = \min c_y$
where $x_{accpix}(c_y) > x_{accmin}$

$c_{up} = \max c_y$
where $x_{accpix}(c_y) < x_{accmin}$

$c_{right} = \max c_x$
where $y_{accpix}(c_x) > x_{accmin}$

where $x_{accmin}$ is an adjustable constant and 10 in the system.

Step 5 — judgement for the boundary

If $x_{start} - x_{min} < x_{bound}$
If $x_{max} - x_{end} < x_{bound}$
If $y_{start} - y_{min} < y_{bound}$
If $y_{max} - y_{end} < y_{bound}$
end

Step 6 — extension in boundary, as shown in Fig. 12.

If $x_{start} > c_{down} - y_0$
then $x_{start} = x_{start} + 10$
If $y_{end} > c_{up} + y_0$
then $y_{end} = y_{end} + 10$

Step 7 — shrinkage of boundary

If $y_{start} < c_{down} - y_1$
then $y_{start} = y_{start} - 10$
If $y_{end} > c_{up} + y_1$
then $y_{end} = y_{end} - 10$

Step 8 — set the left margin, as shown in Fig. 13.

$x_{start} = x_{start} - (y_{end} - y_{start})$
goto Step 2

where

$setpix(i,j)$: set the gray level of pixel $(i,j)$
Threshold: thresholding value

$x_{accpix}(j)$: the accumulation of dark point in a horizontal line

$$ x_{accpix}(j) = \sum_{i = \text{start}}^{\text{end}} \text{zeropix}(i, j) $$

when $\text{getpix}(i,j) \neq 0$, $\text{zeropix}(i,j) = 0$
when $\text{getpix}(i,j) = 0$, $\text{zeropix}(i,j) = 1$

$y_{accpix}(i)$: the accumulation of dark point in a vertical line

![Fig. 12 — Extension in boundary](image-url)

![Fig. 13 — The moving of ROI](image-url)
\[ yacpix(i) = \sum_{j=\text{start}}^{\text{end}} \text{zeropix}(i, j) \]

when \( \text{getpix}(i,j) \neq 0, \text{zeropix}(i,j) = 0 \)
when \( \text{getpix}(i,j) = 0, \text{zeropix}(i,j) = 1 \)

\( c_j \) : the vertical coordinate in object
\( c_i \) : the horizontal coordinate in object

3.4 Calculating the diameter of shadow spot

The method of calculation for the diameter of shadow spot \( c_{\text{diameter}} \) is listed as follows:

Step 1 — finding the lower edge of shadow spot
\[ c_{\text{down}} = \min (c_j) \]
where \( xaddpix(j) > d_{\text{min}} \)

Step 2 — finding the upper edge of shadow spot
\[ c_{\text{up}} = \max (c_j) \]
where \( xaddpix(j) > d_{\text{min}} \)

Step 3
\[ c_{\text{diameter}} = (c_{\text{up}} - c_{\text{down}}) \times F \]
where \( F \) is the actual length of a pixel.

The author set the value of \( d_{\text{min}} = 10 \).

4 Experimental Details

In order to get the exact value of a very short time duration, a CCD with electrical trigger is used. The optical set-up consists of a diode-pumping laser, operating at 530 nm wavelength with a lens, producing a divergent light beam. The frame is designed to support tension force and is stationary, fully constrained on the scientific model structures [Fig. 14(a)]. Two hooks are attached on the upper and lower parts of the frame. It is easy for children to load the specimen and perform simple tension test. The specimen was prepared from plexiglas plates (300 × 50 mm and of thickness 2.0 mm), which contained an initial edge crack of a 5 mm length [Fig. 14(b)]. The pointed light source transmitted into the crack tip, forming the laser shadow spot image. In order to obtain an estimation of the laser shadow spot diameter at fracture, the exhibition clerk must take a calibration before normal operation. In the calibration operation, errors introduced by the quality of the lens set and the accuracy in defining the distance between the diode-pumping laser, lens set, specimen and the screen have been taken into account. It was assumed that, the value in measuring the diameter of the laser shadow spot in calibration stage is equal to that of following experimental operation stages because, the dimension of the specimens are all the same. Thus, no precision alignment of the components and no high quality lens set are required. The strain of the specimen can also be calculated by the rounds and the pitch of the frame.

After starting the system, the main graph is displayed (Fig. 15). Participants can select a start-button to process the shadow spot image in real-time, when they place the specimen on the frame. A color-variable progressive bar indicates the status of the tensile test. The green, yellow and red colour bars represent, safety, danger and breakage. One can observe arbitrarily the magnification of the x-y plot shadow spot diameter and stress-intensity factor versus time if they select the \( K_t \) button (Fig. 16). In the left part of the computer screen, the variation of the dimension of shadow spot is plotted and preserved by a group of curves. One can compare these curves to the numerical ray-tracing pattern (Fig. 17), which is simulated by computer.

Fig. 14 — (A) the frame; (B) the specimen
When someone selects the start-button, but no specimen is placed on the frame (Fig. 18), the computer will remind the participants by a digital speech 'Please place the specimen on the frame'. In the mean time, a digital movie file in .AVI format will display on the screen to show how to place the specimen. When someone twists along a wrong direction (Fig. 19), the computer will remind the participants by a digital speech 'Please twist counter-clockwise'. Again, a digital movie will display on the screen to show how to apply the tensile force. In case of wrong direction, the crack tip moves freely and quickly, but the object can still be tracked successfully by using the auto-range finding algorithm. Fig. 20 shows the saturation of the laser shadow spot and this is the time for computer to predict the fracture-time 'Please watch out, the specimen will break'. After a specimen fracture, a digital animation will display the procedures of breakage.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Thickness (mm)</th>
<th>Crack length (mm)</th>
<th>Spot diameter (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lot #1</td>
<td>2.10</td>
<td>1.56</td>
<td>15.35</td>
</tr>
<tr>
<td>Lot #2</td>
<td>2.11</td>
<td>1.55</td>
<td>15.21</td>
</tr>
<tr>
<td>Lot #3</td>
<td>1.94</td>
<td>1.55</td>
<td>13.55</td>
</tr>
<tr>
<td>Lot #4</td>
<td>1.90</td>
<td>1.56</td>
<td>15.15</td>
</tr>
<tr>
<td>Lot #5</td>
<td>2.05</td>
<td>1.56</td>
<td>14.34</td>
</tr>
<tr>
<td>Lot #6</td>
<td>2.02</td>
<td>1.55</td>
<td>14.93</td>
</tr>
<tr>
<td>Lot #7</td>
<td>2.14</td>
<td>1.57</td>
<td>15.55</td>
</tr>
<tr>
<td>Lot #8</td>
<td>2.15</td>
<td>1.55</td>
<td>15.01</td>
</tr>
<tr>
<td>Lot #9</td>
<td>1.92</td>
<td>1.56</td>
<td>13.96</td>
</tr>
</tbody>
</table>

Although, the axis of symmetry of the laser shadow spot should be symmetric to the crack-axis with respect to the axis of loading of the plate, but in the real experiment, there will be small variation in the profile and dimension of the laser shadow spot image in fracture. The main reason is, the thickness of all the specimens are not the same, if the lot number of the plexiglas is different (Table 1). The size and geometry of the extremity of the slit
also influences the size of shadow spot on fracture-time. Indeed, for high values of the applied stress when plastic enclaves are established the length of the laser shadow spot starts to increase more rapidly than its width so that, the shape of the laser shadow spot becomes more and more oblong. So, the judgement of each special condition is 99% accurate but error-ratio of the prediction of fracture-time is 5% (Table 2).

<table>
<thead>
<tr>
<th>Item</th>
<th>Success</th>
<th>Fail</th>
<th>Error-ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>No specimen is placed on the frame</td>
<td>300</td>
<td>0</td>
<td>0%</td>
</tr>
<tr>
<td>The force is acting along wrong direction</td>
<td>298</td>
<td>2</td>
<td>0.6%</td>
</tr>
<tr>
<td>The variation of the laser shadow spot is too fast</td>
<td>298</td>
<td>2</td>
<td>0.6%</td>
</tr>
<tr>
<td>The crack will be out of image</td>
<td>299</td>
<td>1</td>
<td>0.3%</td>
</tr>
<tr>
<td>Prediction in fracture-time</td>
<td>286</td>
<td>14</td>
<td>5%</td>
</tr>
</tbody>
</table>

Fig. 18 — No specimen is placed on the frame

In accordance with the present scientific model, an intelligent system is provided which can interface with a client to guide and analyze the laser shadow spot experiments. In this new scientific model, an audio-video signal can be distributed from one exhibition room to anywhere. People browse the WWW homepage to watch the event. A multimedia presentation process is activated periodically by a 0.5 sec timer-signal to renew the presentation of the next presentation objects. The author adopts automatic document, fetching upon world wide web link activation. However, the documents presented to the users have been synthesized by the world wide web network at the time the request was served (Fig. 21).
5 Conclusion

A combination of the laser shadow spot, online image processing and multimedia technologies as applied to scientific model is made. Although, the method can be only used for a crack which is visible, but, it is still useful in material fracture experiment. From this model, fracture prediction are determined, strain data are computed, and all the operations are guided. Once the data has been collected and entered, the system analyzes and puts the results in the internet server. One of the aims is to promote an interest in the science of electro-optics by encouraging children to participate in the experimental activities. This challenging and interesting experiment will increase scientific knowledge and develop the educational function.

There are four designing key points in the device as follows:

Computer controls the total system and accepts a modest place as a particular aid within a specific educational field; the technologies, including optics, fracture mechanics, digital image-processing, multimedia and internet, are integrated; information is handled digitally; the interface to users, permits interactivity.

Finally, it must be mentioned that, in this experiment, since the diode-pumping laser is adopted as the light source and the simplified lens sets are used to generate laser shadow spot patterns, the value of strain and stress-intensity factor becomes less precise. But, this set-up will be more suitable for scientific exhibition as the light source has long life and the device is easily comprehensive.

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References


