Damage Monitoring of Metal Materials by Laser Speckle Assisted by Image Processing Technique* (Basic Experiment)

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This paper presents a method to detect damage of metals with no contact using a laser speckle technique. This method is based on observations of the change of the laser speckle pattern depending on the surface roughness and texture change of the material caused by slip bands due to plastic deformation. The laser speckle pattern was analyzed automatically and quantitatively using an image processing system in this experiment. A new parameter, c_k , was derived to statistically express the features of the speckle pattern. It was found that this parameter can express the features of the speckle pattern accurately and has excellent reproducibility. Also, it allows an accurate measurement of plastic strain. The experiment was carried out for cases of both static tensile and fatigue loading using aluminum alloy as the material.

Key Words: Nondestructive Inspection, Laser Speckle Method, Image Processing, Plastic Deformation, Fatigue

1. Introduction

Both static plastic deformation and fatigue damage of metal materials are accompanied with plastic strain, producing slip bands on the material surface. Therefore, the surface roughness and surface profile change with the progress of plastic deformation or fatigue damage. The laser speckle pattern changes with the change of surface roughness and profile. If the relationship between the laser speckle pattern and the amount of plastic deformation or fatigue damage is known in advance, we can estimate the damage of metal materials based on the speckle pattern.

Measurement of plastic deformation by the laser or white-light speckle technique has been reported by several researchers^{(1)~(4)}. Those papers investigated the method to estimate plastic strain based on the speckle pattern change depending on the surface texture change induced by slip bands. However, the data

obtained in those experiments scatter slightly, and the results are not sufficiently reliable. It is essential in this kind of experiment to analyze the laser speckle pattern quantitatively and to find a parameter that can express the features of speckle pattern change accurately. In this investigation, an image processing system was employed to analyze the laser speckle pattern automatically and quantitatively. As the distribution of the light intensity of the laser speckle varies drastically, we considered a new statistical parameter to express the features of the laser speckle pattern. The reproducibility of this parameter was examined and the accuracy of the measurement was investigated.

In the earlier stage of fatigue, slip bands generate on the metal surface, microscopic shear strain is stored in the slip bands and the slip bands become dense. The surface texture changes and surface roughness becomes marked with the progress of fatigue damage^{(5),(6)}. If we use the laser speckle technique, there is a possibility of detecting the fatigue damage of metals in the early stage of fatigue before initiation of cracks. In this study, we observed the change of the speckle pattern during fatigue cycles under operation

* Received 2nd October, 1990

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of a testing machine and the possibility of fatigue monitoring by the laser speckle technique was investigated.

2. Experimental Procedure

2.1 Experimental system

The material used in this experiment is 6061 aluminum alloy. The initial roughness and directional feature of the specimen surface has a large influence on the speckle pattern. If the surface texture is directional, the speckle pattern is directional and not axisymmetrical. Also, if the initial surface roughness is large, speckle pattern change is small in the range of small plastic strain. Therefore, if it is required to detect a small change of speckle pattern, the specimen surface should initially be smooth and nondirectional. In this experiment, the specimens were polished finally with aluminum dioxide powder in random directions so that the surface texture became macroscopically isotropic and uniform. The initial surface roughness was about $0.1\text{ }\mu\text{m Ra}$ for every specimen.

Figure 1 shows the layout of the experimental system. He-Ne laser was illuminated on the specimen surface and the laser speckle pattern was formed on the ground glass placed in front of the specimen. The diameter of the laser beam was about 1 mm. The image of the speckle pattern was input into the image processing system (Hamamatsu C1000) through a TV camera and then A/D converted. Resolution of the image memory was 256×256 and the gray scale of one pixel was 256. The brightness of the laser speckle was

Fig. 1 Configuration of experimental system

expressed by a numerical value from 0 to 255 in the image memory. The digital image data were transferred to the main memory of a minicomputer (VAX 11/730) and then stored in its magnetic tape. Software to analyze the speckle image was developed on the minicomputer.

2.2 Data analysis

Figure 2 shows examples of the gray level distribution of the speckle patterns obtained from the image processing system for different magnitudes of plastic strain caused by uniform tension. These figures show that the speckle pattern changes clearly with the magnitude of plastic strain. The peak gray level at the center of the speckle image decreases and the gray level distribution spreads out with the increase of plastic strain.

Figure 3 shows the relationship between the ratio of $M_{\min}/M_{\max}$ and plastic strain. Here, $M_{\min}$ and $M_{\max}$ are the minimum and maximum values, respectively, among second-order moments of inertia of the gray level distribution around the four different axes shown in the chart of Fig. 3. If the ratio $M_{\min}/M_{\max}$ is close to 1, it means that the second-order moments of inertia around the four axes take almost the same value; that is, the gray level distribution of the speckle pattern is round and axisymmetrical. From the figure, this ratio is smaller than 1 when plastic strain is small, but it approaches 1 with the increase of plastic strain. This means that the gray level distribution is slightly directional initially, but it becomes nondirectional and axisymmetrical around the centroid of the gray level distribution when plastic deformation becomes large. Hence we considered the following parameter to express the spread of the gray level distribution around the centroid of the distribution.

First, the image of the speckle pattern was smoothed to reduce the noise. We used a moving averaging method of 3×3 pixels for smoothing. Then the centroid, $O(x_0, y_0)$, of the gray level distribution was obtained (Fig. 4(a)), and the average gray level, $g(r)$, of pixels on a circle c with the center O and the radius of r was obtained (Fig. 4(b)). The average gray level $g(r)$ is expressed by the following expression,

$$g(r) = \frac{\sum_c g(x, y)}{n_c}, \quad (1)$$

where $g(x, y)$ is the gray level at a point (x, y) on circle c of the speckle image. Then $\sum_c g(x, y)$ is the summation of the gray level of pixels on circle c and n_c is the number of pixels on the same circle. Also,

$$r = \sqrt{(x - x_0)^2 + (y - y_0)^2}.$$

Consequently, the function $g(r)$ expresses the gray level distribution in the radial direction around the

(a) Initial ($\epsilon_p = 0\%$) (b) $\epsilon_p = 1.55\%$ (c) $\epsilon_p = 3.16\%$ (d) $\epsilon_p = 5.20\%$ (e) $\epsilon_p = 6.60\%$

Fig. 2 Speckle pattern for different plastic strains

(a) Gray level distribution

Fig. 3 Relationship between M_{min}/M_{max} and plastic strain

(b) Image plane

Fig. 4 Procedure for obtaining $g(r)$

centroid O (Fig. 5(a)).

Then $g(r)$ was normalized to reduce the error induced by the difference of speckle brightness. We used the following linear mapping function for normalization:

$$g'(r) = \frac{255(g(r) - g_{\min})}{g_{\max} - g_{\min}} \quad (2)$$

This function makes the maximum gray level in $g(r)$, $g_{\max}$, to be 255 and the minimum value, $g_{\min}$, to be 0. The normalized gray level distribution is shown in Fig. 5(b). Figure 6 shows the difference in the normalized gray level distribution depending on the plastic strain. The gray level distribution, $g'(r)$, is found to spread with the increase of plastic strain. Hence, we considered the following parameter that can express the feature of the gray level distribution:

(a) $g(r)$

(b) $g'(r)$ (Normalized)

Fig. 5 Normalization of $g(r)$

Fig. 6 Difference in gray level distribution $g'(r)$

$$c_k = \frac{\sum_{r=0}^{N_r} g'(r)r^2}{\sum_{r=0}^{N_r} g'(r)} \quad (3)$$

where N_r is the limit of r , which was taken as 110 in this analysis.

Next, we examined the influence of brightness of the laser speckle on the c_k parameter. Figure 7 shows the relationship between c_k and $g_{\max}$ when the speckle pattern was obtained at the same point of a specimen with different brightness of the laser speckle. The speckle brightness was changed by two methods. One is that the aperture of the lens of the TV camera was changed under a constant intensity of the laser light and the other is that the intensity of the laser light was changed with an ND filter under a constant aperture of the lens. This figure shows that the c_k parameter is almost constant in the wide range of $g_{\max}$ (from 20 to 160) and takes almost the same value in both cases. This means that the c_k parameter is not significantly influenced by the brightness of the laser speckle, and both the change of aperture and the change of light intensity have almost the same effect on the c_k parameter.

3. Measurement of Plastic Strain

First we applied this method to the measurement of plastic strain. Here the aluminum specimens were loaded by uniaxial tension. Plastic strain was measured by the moiré method. Figure 8 shows the relationship between the surface roughness (R_a) and the magnitude of plastic strain. It is found that the surface roughness increases with the increase of plastic strain. Figure 9 shows the relationship between the c_k parameter of the laser speckle pattern and the magnitude of plastic strain ϵ_p . The experiment was conducted under four different testing conditions of speckle brightness. The first one was that the aperture of the TV camera was constant but the light intensity of the laser light was adjusted with an ND filter so that the

Fig. 7 Relationship between c_k and $g_{\max}$

average gray level of the speckle image became approximately constant. The others were that the aperture of the lens of the TV camera was fixed at three different values, i. e., $f/32$, $f/16$ and $f/8$, under a constant light intensity. It is found that the values of c_k obtained under different conditions of speckle brightness coincide very well and the c_k parameter is not influenced by speckle brightness in all cases of plastic strain. The parameter c_k increases with ϵ_p and has a tendency similar to the surface roughness shown in Fig. 8.

Figure 10 shows the relationship between c_k and ϵ_p obtained from two specimens under the same experimental condition. In the figure, the data of specimen A are the averages of values shown in Fig. 9. The values of c_k obtained from the two different specimens coincide very well. This shows that the c_k parameter has a very good reproducibility and that there is a fixed relationship between c_k and plastic strain ϵ_p . Figure 10 shows that there is a linear relationship between $\log(c_k)$ and $\log(\epsilon_p)$. This relation can be expressed by the following equation:

$$\log(c_k) = a + b \log(\epsilon_p). \quad (4)$$

Alternatively, it can be expressed by

Fig. 8 Relationship between surface roughness and ϵ_p

Fig. 9 Relationship between c_k and ϵ_p

$$\epsilon_p = c(c_k)^d. \quad (5)$$

Here, $\log(c) = -a/b$ and $d = 1/b$. The values of c and d were obtained by the least squares method; $c = 3.99 \times 10^{-4}$ and $d = 0.74$. Therefore, we can estimate the magnitude of plastic strain from the value of the c_k parameter using this equation. It was found that this parameter c_k is not influenced significantly by the brightness of the laser speckle and that it has a very good reproducibility. It can be concluded that this parameter will allow us to make an accurate measurement of plastic strain.

4. Fatigue Test

In the fatigue test, we used the notched specimens shown in Fig. 11. The laser light was illuminated on the edge at the notch root of the specimen, as shown in the figure. The testing machine used was a servo-hydraulic fatigue testing machine (Instron). The specimens were subjected to uniaxial tensile fatigue load. The specimen was set in the testing machine and the laser light was illuminated on the specimen surface. The experimental layout is almost the same as in Fig. 1 except that we used a high-speed camera (SP2000, Kodak) to obtain the speckle image and a personal computer (IBM PS/2) to analyze the image data. The image of the speckle pattern was taken using the high-speed camera during fatigue loading without stopping the testing machine or unloading the specimen. This high-speed camera can obtain images up to 2000 frames/sec. This equipment performs A/D conversion

Fig. 10 Relationship of c_k - ϵ_p for two specimens

Fig. 11 Test specimen for fatigue test

of the image signal and stores the digital image in its memory as well as on the magnetic tape. The resolution of this image memory is 238×192 and the gray scale is 64. As the frequency of the cyclic loading was set at 6 Hz, which was not so high, we used the high-speed camera with the speed of 200 frames/sec. During the fatigue test, an image of the laser speckle pattern was taken at a certain interval of fatigue cycles. The image data of the speckle pattern were transferred to the personal computer, and the same analysis as that in the static tensile test was made.

We observed the speckle pattern change with the progress of fatigue damage under several kinds of stress amplitude. We used specimens with a notch radius of 6.4 mm. As the notch radius is rather large, the stress concentration factor due to the notch can be considered to be 1. The conditions of fatigue stress at the notch root were as follows: the mean stress was fixed to $\sigma_m = 217$ MPa and the stress amplitude was changed as $\sigma_a = 155, 167, 186, 205$ and 217 MPa. Figure 12 shows the relationship between stress amplitude and fatigue life, N_f . Figure 13 shows the relationship between the c_k parameter of the laser speckle pattern and N/N_f . Here, N is the number of stress cycles. It is normalized by fatigue life, N_f , for the corresponding stress amplitude shown in Fig. 12. The value of c_k is very small compared to that in the case of static plastic deformation, especially when σ_a is small. Also, the change of the c_k value is very small when σ_a is smaller than 186 MPa. However, the c_k value increases monotonously with N/N_f . The c_k value becomes large with the increase of σ_a , and the change of the c_k parameter with N/N_f becomes perceptible. It is found that the c_k value changes markedly during the earlier cycles of fatigue and is saturated for larger N .

As the plastic strain induced by fatigue loading is very small compared to that of the static tensile test, the change of the speckle pattern is small and the c_k value does not change so markedly in the fatigue test.

Fig. 12 Relationship between stress amplitude and fatigue life

However, as shown in Fig. 13, the c_k value changes appreciably with the increase of fatigue cycle when stress amplitude is rather large and it may be concluded that damage detection is possible in the early stage of fatigue by observing the change of the c_k parameter.

5. Conclusions

The laser speckle technique was applied to the measurement of plastic strain and the detection of fatigue damage, assisted by an image processing system in this study. The image processing system was found to be very effective in analyzing the speckle pattern quantitatively. The c_k parameter which we derived in this study expresses the features of the laser speckle pattern numerically and has a very good reproducibility. The relation between c_k and plastic strain is expressed by a simple equation in the range of plastic strain ($\epsilon_p < 10\%$) where we made experiments. Then, plastic strain can be estimated easily using this equation. It is concluded that the magnitude of plastic strain can be estimated accurately by the laser speckle technique.

The speckle pattern did not change so dramatically with fatigue loading, and the change of the c_k parameter was very small. Also, the fluctuation of the c_k parameter was not as distinctive as that of static tensile test. Therefore, detection of fatigue damage will not be as accurate. However, the c_k parameter changed appreciably when the stress amplitude was rather large. It can be concluded that there is a possibility of detecting fatigue damage by this method.

Fig. 13 Relationship between c_k and N/N_f under different stress amplitudes

Acknowledgments

Financial support for the work reported has been provided in part by U.S. Army Research Office, Engineering Science Division, through contract No. DAA0388K033. The major part of the work was done when A. Kato was a visiting scholar at SUNY at Stony Brook.

References

- (1) Miyagawa M. and Azushima A., "Measurement of Plastic Deformation by Means of a Laser Beam", Proc. of Ninth World Conference on Non-Destructive Testing (1979), p. 1.
- (2) Azushima A., Miyagawa M., Ohira T. and Kishi T., "Measurement of the Plastic Zone around a Fatigue Crack of a Stainless Steel Structure Member with a Laser Beam", Proc. of the 1982 SESA-JSME Joint Conference on Experimental Mechanics (1982), p. 709.
- (3) Lee C., Chao Y. J., Peters W. H. and Sutton M. A., "Surface Texture and Plastic Deformation", Proc. of the Southeastern Conference on Theoretical and Applied Mechanics (1986), p. 275.
- (4) Lee C., Chao Y. J., Sutton M. A., Peters W. H. and Ranson W. F., "Determination of Plastic Strains at Notches by Image-Processing Methods", Experimental Mechanics, Vol. 27, No. 2 (1989), p. 214.
- (5) Mughrabi H., Wang R., Differt K. and Essmann U., "Fatigue Crack Initiation by Cyclic Slip Irreversibilities in High-Cycle Fatigue", ASTM STP811 (1983), p. 5.
- (6) Lin T. H., Lin S. R. and Wu X. Q., "Micromechanics of an Extrusion in High-Cycle Fatigue", Proc XVII International Congress on Applied Mechanics, Grenoble, France (1988).