IDENTIFICATION OF PLASTIC-ZONE BASED ON DOUBLE FREQUENCY LOCK-IN THERMOGRAPHIC TEMPERATURE MEASUREMENT

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ABSTRACT

Lock-in infrared thermography was applied for the evaluation of stress distribution and local plasticity in the stress concentration area of the plate specimen with a circular hole. For evaluating the local plasticity, $2f$ lock-in infrared measurement using a reference signal of double frequencies was newly proposed. Under loading conditions with no local plasticity, no significant change appeared in the distribution of $2f$ lock-in measurement values. On the other hand, under loading conditions where local plasticity was expected to exist near the hole edge, remarkable increase was found in the distribution of $2f$ lock-in measurement values. It was found that the result of $2f$ lock-in measurement was effectively used for the estimation of local plasticity in the stress concentration area.

1. INTRODUCTION

Numerical stress analysis techniques such as the finite element method (FEM) and the boundary element method (BEM) enabled us to evaluate stress distribution of structural components even with complicated shapes. However, we often encounter difficulties in conducting numerical stress analyses in actual components, because loading conditions or boundary conditions of the objective components cannot be easily prescribed. Experimental techniques of stress evaluation are then very important. Thermoelastic stress analysis (TSA) has been widely used as full-field experimental stress evaluation method. Especially it is employed as a useful tool for the evaluation of stress concentration at notches or welding parts in the components. At the highly stress concentrated area in the component, however, local stress exceeds yield point resulting a local plasticity. The existence of the local plasticity may influence on the result of TSA measurement. In this study, the identification technique of the local plasticity using infrared thermography is newly proposed. The feasibility of the proposed technique is investigated for evaluating the local plasticity and stress distribution in the stress concentrated area around a circular hole in a steel plate.

2. THERMOELASTIC STRESS ANALYSIS (TSA)

2-1 Thermoelasticity

Dynamic stress change causes very small temperature change under the adiabatic condition in solid. This phenomenon is called thermoelastic effect and is described by the following equation that relates temperature change (ΔT) to a change in the sum of the principal stresses ($\Delta\sigma$) under cyclic loading.

$$\Delta T = -\frac{\alpha}{\rho\, C_p} T\, \Delta\sigma \qquad (1)$$

α : Coefficient of thermal expansion

ρ : Mass density

C_p : Specific heat at constant pressure

T : Absolute temperature

The lock-in thermography correlates the load-induced infrared signal with the reference-loading signal enabling the noise reduction and the measurement of very small temperature changes due to the thermoelastic effect. As the lock-in thermography system, the infrared thermography with In-Sb array sensor was employed with the lock-in data processor.

2-2 Experiment

Steel plate specimen with a circular hole (diameter 10mm) was made from 590MPa class hot rolled steel. The width and thickness of the plate were 30mm and 3mm, respectively. Fully reversed tension and compression cyclic load (stress ratio R=-1) was applied to the specimen. Loading amplitude P_a was increased from 6kN to 18kN. Stress distribution and local plasticity were evaluated at every additional 1kN in the increasing loading amplitude. Loading frequency f was set to be 10Hz. Calibration relation between the sum of the principal stresses and the infrared radiation is required for experimentally obtaining the thermoelastic coefficient k for the measurement of the absolute stress values in TSA. In this experiment, stress values measured by strain gages were calibrated with the values of infrared intensity in the plate specimen.

3. IDENTIFICATION OF LOCAL PLASTICITY

Sequential data on transient temperature distribution near the notch root was measured under the loading condition, in which local plasticity appeared in the highly stress concentrated region. The waveform of the transient temperature change reflects both of the thermoelastic effect and the heat generation due to plastic deformation. Based on the investigation of this result, an identification method of the local plasticity is newly proposed in this paragraph.

3.1 Waveform analysis

Measured waveform of the transient temperature change near the notch root under the loading amplitude P_a=18kN is shown by solid square mark in Fig. 1. This waveform was reconstructed from sequential temperature data in 10 cycles. Infrared intensity values in 256x256 pixels were digitally captured at every 1/140s. Under this loading amplitude, stress values in the vicinity of the notch root exceeded the yield stress and the local plasticity seemed to be found.

The solid line in Fig. 1 indicates the estimated sinusoidal waveform, if no plastic deformation is generated and thermoelastic effect indicated by Eq.(1) is satisfied. This waveform was constructed by doubling the experimentally obtained waveform under P_a=9kN, in which the maximum stress value at the notch root did not exceed yield stress.

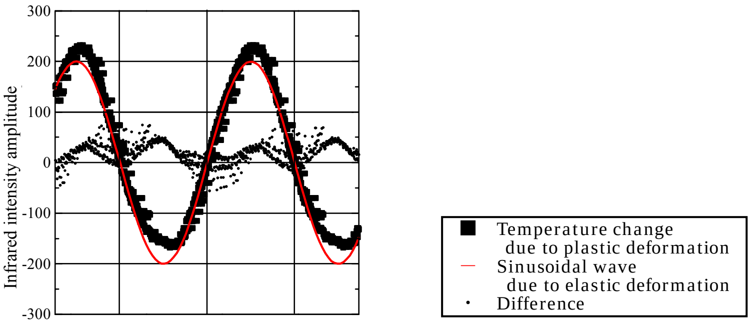


Fig. 1 Waveform of infrared intensity observed near circular hole under P_a=18kN

It is found that the measured waveform affected by the plastic deformation deviates from sinusoidal waveform estimated under the assumption of complete elasticity. The elastic waveform was subtracted from the waveform affected by the plastic deformation, and the result was plotted by dotted symbol in the figure. It is found that the subtracted waveform has two peaks in one loading cycle. This means that the effect of local plasticity appears in the waveform of double frequency, 2*f*. This seems to be the effect of local thermal generation due to the local plastic deformation which occurs at the maximum tensile stress and at the maximum compressive stress.

3.2 Identification method of local plasticity

Based on the investigation in the foregoing paragraph, it was found that the frequency of the waveform affected by the local plasticity was double of the loading frequency. Therefore it seems to be possible that the thermal effect due to the local plasticity is separately measured from the data on temperature change, if the double frequency, i.e., $2f$ is employed as the frequency of the reference signal of the lock-in measurement. We term this technique as "$2f$ method".

4. RESULTS OF LOCAL PLASTICITY IDENTIFICATION

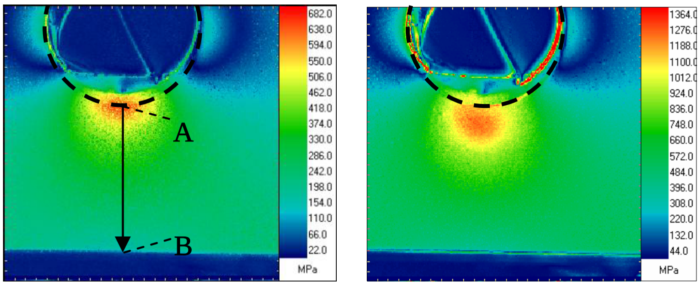
4.1 Distribution of $\Delta\sigma$

The distributions of sum of the principal stresses $\Delta\sigma$ measured by TSA for load amplitude P_a=9kN and 18kN are shown in Fig. 2. The broken line in the figure indicates the edge of the circular hole. As described in the above sections, no plastic deformation was found under P_a=9kN, on the other hand local plastic deformation was found under P_a=18kN. Stress distribution on the line AB in Fig. 2 is shown in Fig. 3. The stress distribution computed by the elastic-plastic FEM analyses was also shown by the broken line in Fig. 3.

It is found from the both figures that stress concentrated area was observed near the notch root. It is found in Fig. 3 that stress distribution measured under P_a=9kN shows very good correspondence with that obtained by FEM analysis. However in the stress distribution measured under P_a=18kN, measured stress values are higher than those obtained by FEM analysis. The similar tendency was found under the loading condition $P_a > 15$kN, in which local plasticity was observed near the notch root. It can be concluded that the thermal effects due to the existence of local plasticity affects the results by the thermoelastic stress measurement.

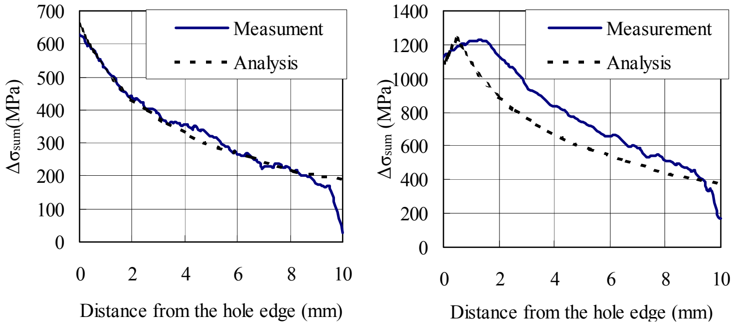
4.2 Results of 2f measurement

The results of the $2f$ measurement are shown in Fig. 4. Distribution of $2f$ synchronized infrared intensity values measured under P_a=9kN and 18kN are shown in Figs. 4(a) and (b), respectively. It is found in Fig. 4(a) that the $2f$ synchronized infrared values are almost constant near the notch root under P_a=9kN. It is found in Fig. 4(b), on the other hand, highly concentration in the the $2f$ synchronized infrared values is observed in the vicinity of the notch root under P_a=18kN. This result shows the feasibility of the proposed $2f$ lock-in measurement technique for the identification of the local plasticity.



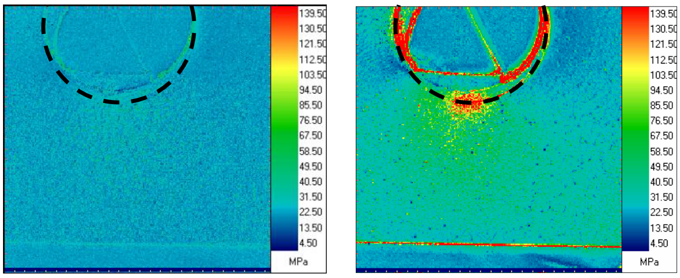
(a) under P_a =9kN (b) under P_a =18kN

Fig. 2 Distribution of sum of principal stresses by TSA measurement.



(a) under P_a =9kN (b) under P_a =18kN

Fig. 3 Line profile of distribution of sum of principal stresses by TSA measurement



(a) under P_a =9kN (b) under P_a =18kN

Fig. 4 Distribution of $2f$ synchronized infrared intensity values.

4.3 Estimation of the region of plastic deformation

In order to confirm the relation between plastic deformation and the $2f$ synchronized infrared values, experimental results were compared with numerical results, for loading amplitude in which local plasticity appears at the notch root.

The maximum values of the 2*f* synchronized infrared values measured for several loading conditions are plotted against the loading amplitude P_a. The results are shown in Fig. 5. It is found in Fig. 5 that the 2*f* synchronized infrared values shows a steep increase when the loading amplitude P_a exceeds 15kN. In the FEM analysis, it was found that the local plasticity was observed at the notch root under the loading condition $P_a > 15$kN. Therefore it can be concluded that the plastic deformation affects the 2*f* synchronized infrared values.

Based on the above result, the plastic region can be identified as the region in which the 2*f* synchronized infrared values shows a steep increase compared with the surrounding region (hatching area in Fig. 5). Plastic deformation was identified by the 2*f* synchronized infrared values based on the relation in Fig. 5, and size of the plastic zone was estimated. The result is shown in Fig. 6 comparing with that by FEM analysis. It is found that the sizes of the plastic zone estimated by the 2*f* method are relatively larger than those obtained by the FEM analysis. Further studies are required to investigate the cause of this discrepancy. The intensity of heat generation due to the local plasticity and the effect of thermal diffusion should be investigated. The accuracy of FEM analyses should be also checked, because the FEM results shown in this study were obtained under a static loading condition.

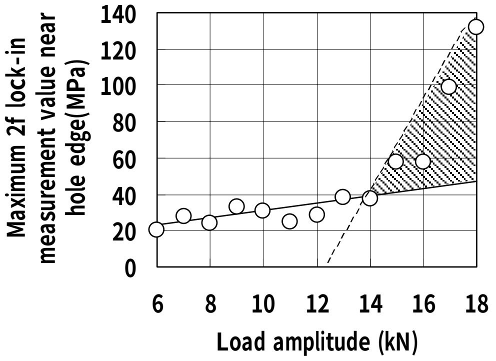


Fig. 5 Relationship between 2*f* synchronized infrared intensity and loading amplitude.

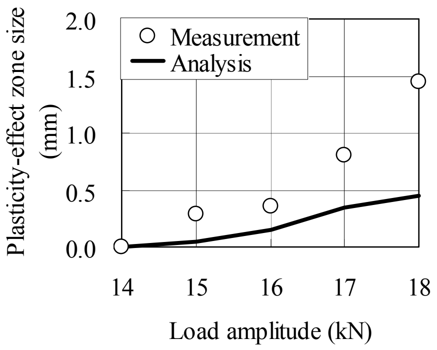


Fig. 6 Estimated size of plastic zone.

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