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Accuracy improvement in dissipated energy measurement by using phase information

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Abstract. In this paper, a technique for improving the accuracy of a dissipated energy measurement based on the phase information—called the phase $2f$ lock-in infrared method—is proposed. In the conventional $2f$ lock-in infrared method, the dissipated energy is obtained as the double frequency component of the measured temperature change. In this work, a phase analysis of the double frequency component has been conducted. It is found that the double frequency component includes the influence of the energy dissipation and harmonic vibration of the fatigue testing machine, and the phase difference between the thermoelastic temperature change and the double frequency component is a specific value. The phase $2f$ lock-in method utilizes a specific phase of the dissipated energy and is effective for removing the noise component such as the thermoelastic temperature change due to the harmonic vibration of fatigue testing machine. This method provides an improvement in the accuracy of the fatigue-limit estimate and the detection of future crack initiation points based on the dissipated energy.

Key words: Infrared thermography, Fatigue-limit estimation, Fatigue, Dissipated energy

1. Introduction

Nondestructive testing (NDT) and nondestructive evaluation (NDE) using infrared thermography has been developed for the maintenance of steel bridges through their life cycles [1]. The first sign of deterioration in aging steel bridges is the initiation of fatigue cracks. Therefore, it would be beneficial to preempt this phase by predicting the occurrence of fatigue crack initiation. In particular, the increase in the temperature or thermal sources are related to the fatigue behavior of a material and can be used to find the occurrence and location of a fatigue crack and to assess the fatigue limit [2-16]. Thermal sources are considered to be caused by the irreversible energy dissipation due to the local plasticity, and this temperature change is called the “dissipated energy.” The dissipated energy can be used to estimate the fatigue limit and to predict the fatigue life [18, 19].

Fatigue-limit estimation based on the dissipated energy measurement using infrared thermography has received increasing attention in various industries, and there are two main methods for obtaining the dissipated energy. One method is to obtain a measurement of the surface temperature of a specimen that is subjected to cyclic loading [2-5, 18-19]. When the stress amplitudes are gradually increased and become higher than the fatigue limit, the surface temperature of the specimen increases. The increase in the surface temperature is related to the energy dissipation during the fatigue test. Therefore, the fatigue limit of a material can be assessed considering the heating rate or the magnitude of the increase in the temperature. This measurement method requires a large number of cycles to measure a sufficient increase in the temperature; thus, it is affected by the environmental temperature such as room-temperature fluctuations and the temperature of the grips of the fatigue testing machine. Another method is lock-in infrared thermography [6-17], which is widely used to improve the accuracy of a thermoelastic stress analysis (TSA). The existence of local plasticity influences the results of the TSA measurement. In the work of Sakagami [17], the temperature signal was analyzed in the frequency domain, and the double frequency component is used to describe the energy dissipation due to the local plasticity. This measurement method is called the $2f$ lock-in infrared method, which uses the reference signal of the double frequencies. Palumbo and Galietti [15-16] evaluated the phase of the thermoelastic signal related to the influence of the local plasticity (TPA method).

In previous works, the authors applied the $2f$ lock-in infrared method to estimate the fatigue limits of types 304 and 316L austenitic stainless steels and showed that it is possible to estimate the fatigue limit of a material [11-12]. To investigate the relationship between the dissipated energy and the crack initiation for austenitic stainless steel, slip-band growth was observed using atomic force microscopy (AFM) along with the measurement of the dissipated energy during the fatigue test [14]. In the $2f$ lock-in infrared method, the environmental temperature has a very small influence on the measurement of the temperature signal, but the $2f$ lock-in infrared method requires a high-sensitivity and high-speed detector to analyze the temperature signal in the frequency domain. The importance of a high-precision measurement could become significant for low heat sources produced by the fatigue damage phenomenon, as in a high-fatigue-strength material with low deformation. In this study, the phase information of the energy dissipation was investigated and was applied to improve the accuracy of the dissipated energy measurement for fatigue-limit estimation.

2. Measurement and phase analysis of the dissipated energy

A reversible temperature change is observed for a specimen subjected to cyclic loading. This phenomenon is called the thermoelastic effect, and the thermoelastic temperature change ΔT_E can be expressed by the thermoelastic coefficient k , the absolute temperature T , and the sum of the principal stresses $\Delta\sigma$ as follows:

$$\Delta T_E = -kT\Delta\sigma \quad (1)$$

In reality, the increase in the temperature due to irreversible energy dissipation ΔT_D occurs at the maximum tensile stress and maximum compressive stress. Thus, the measured temperature change $T(t)$ on the surface includes ΔT_E and ΔT_D , as shown in Fig. 1. The thermoelastic temperature change ΔT_E is obtained as follows:

$$\Delta T_{E,\sin} = \frac{2}{N} \sum_{t=1}^N T(t) \sin(t) \quad (2)$$

$$\Delta T_{E,\cos} = \frac{2}{N} \sum_{t=1}^N T(t) \cos(t) \quad (3)$$

$$\Delta T_E = \sqrt{\Delta T_{E,\sin}^2 + \Delta T_{E,\cos}^2} \quad (4)$$

where $\sin(t)$ is the reference signal from the cyclic load, and $\Delta T_{E,\sin}$ is the amplitude of the temperature change that is synchronized with the reference signal. $\Delta T_{E,\cos}$ is the amplitude of the temperature change that has a phase that is opposite to that of the reference signal. The phase lag between the thermoelastic temperature change and the cyclic load θ_E is caused by thermal diffusion. θ_E is calculated as follows:

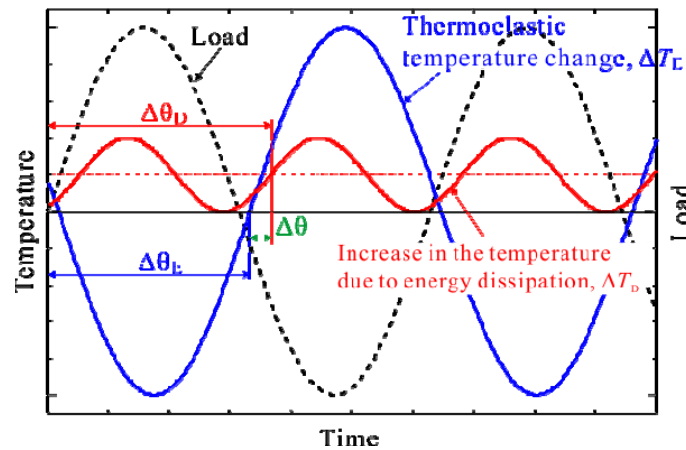


Fig. 1 Schematic of the temperature changes due to thermoelasticity and energy dissipation and the load signal.

$$\theta_E = \tan^{-1} \left(-\frac{\Delta T_{E,\cos}}{\Delta T_{E,\sin}} \right) \quad (5)$$

Palumbo and Galietti used the phase of the thermoelastic signal to monitor the fatigue damage in a material [15]. ΔT_D can be obtained as the component having a double frequency of the reference signal by a lock-in algorithm as follows [17]:

$$\Delta T_{D,\sin 2f} = \frac{2}{N} \sum_{t=1}^N T(t) \sin(2t) \quad (6)$$

$$\Delta T_{D,\cos 2f} = \frac{2}{N} \sum_{t=1}^N T(t) \cos(2t) \quad (7)$$

$$\Delta T_D = 2\sqrt{\Delta T_{D,\sin 2f}^2 + \Delta T_{D,\cos 2f}^2} \quad (8)$$

where $\sin(2t)$ and $\cos(2t)$ represent the double frequency reference signal based on the cyclic loading signal. ΔT_D is presented as a range of temperature changes. The dissipated energy q is calculated from ΔT_D , the density ρ , and the specific heat c of the material as follows:

$$q = \rho c \Delta T_D \quad (9)$$

The phase lag between the temperature change due to the energy dissipation and the double frequency reference signal is calculated as follows:

$$\theta_D = \tan^{-1} \left(-\frac{\Delta T_{D,\cos 2f}}{\Delta T_{D,\sin 2f}} \right) \quad (10)$$

where θ_D includes the influence of thermal diffusion. To remove this influence on the phase information of the energy dissipation, the phase difference $\Delta\theta$ is defined as follows:

$$\Delta\theta = \frac{1}{2} \theta_D - \theta_E \quad (11)$$

$\Delta\theta$ is based on the phase space of the reference signal frequency f ; thus, it has value from 0° to 180° . Further, $\Delta\theta$ also indicates the phase lag between the temperature change due to the energy dissipation and the double frequency reference signal based on the thermoelastic temperature change, as shown in Fig. 1.

3. Experimental setup

The material under test is a JIS-type 316L austenitic stainless steel. The geometry of the specimen is shown in Fig. 2. The specimen has a smooth notch with a stress concentration factor α of 1.03. Cyclic-axis loading with a frequency of 5 Hz and a stress ratio $R = -1.0$ was applied to the specimen by an electrohydraulic fatigue testing machine. The temperature change on the specimen surface was measured by infrared thermography with an MCT array detector (CEDIP Inc., Titanium530L). The specifications of this infrared camera are listed in Table 1. In the staircase-like stress level test [2], the applied stress amplitude was increased from 200 MPa to 280 MPa step-by-step. The number of cycles for each step is 3100 cycles, and each temperature measurement is performed after 1000 cycle loadings. The values of c and ρ of the type 316L steel are 503 J/(kg·K) and 8060 kg/m³, respectively.

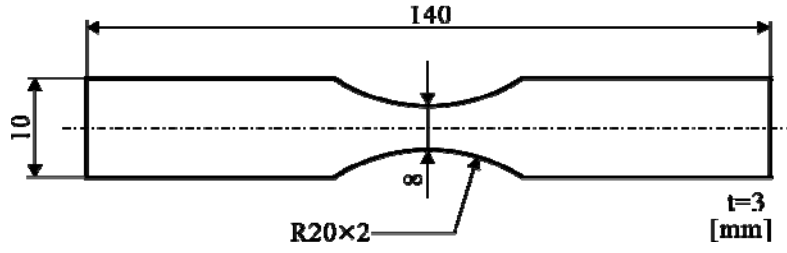


Fig. 2 Geometry of the specimen.

Table 1. Properties and specifications of the infrared thermography camera

Infrared detector	MCT
Number of detectors	190 × 254
Wavelength	7.7–9.3 μm
Frame rate	311 frames/s
Temperature resolution (NETD)	25 mK

4. Results and discussion

4.1 Dissipated energy and phase information

The S – N curve obtained by the conventional fatigue test is shown in Fig. 3. In this study, the run-out number of cycles is defined as 2.0×10^6 cycles. The fatigue limit of type 316L stainless steel is around 250 MPa. The change in the dissipated energy and the phase difference in the staircase-like stress-level test are shown in Fig. 4. The values of the dissipated energy and phase difference indicate the mean value of a square evaluation area of 1 mm × 1 mm at the center of the specimen. From Fig. 3, it is found that q significantly increases at $\sigma_a = 255$ MPa. In addition, $\Delta\theta$ is unstable at low stress levels from 200 to 250 MPa. On the other hand, the phase difference is constant (approximately 57°) at high stress levels, where the change in the dissipated energy is increasing. The standard deviation in the phase difference are 39.6 and 1.14 degrees for low and high stress levels, respectively. The experiments were carried out at least four times, and the results show good repeatability.

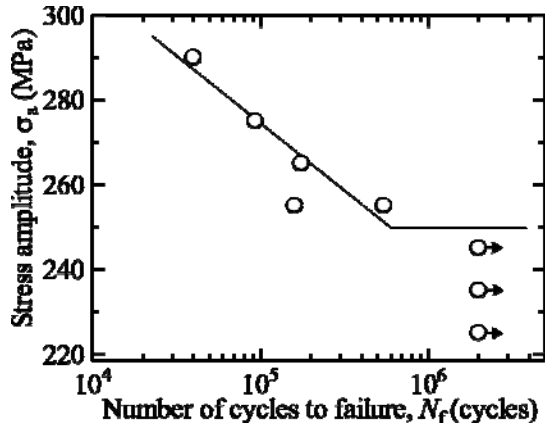


Fig. 3 S – N curve.

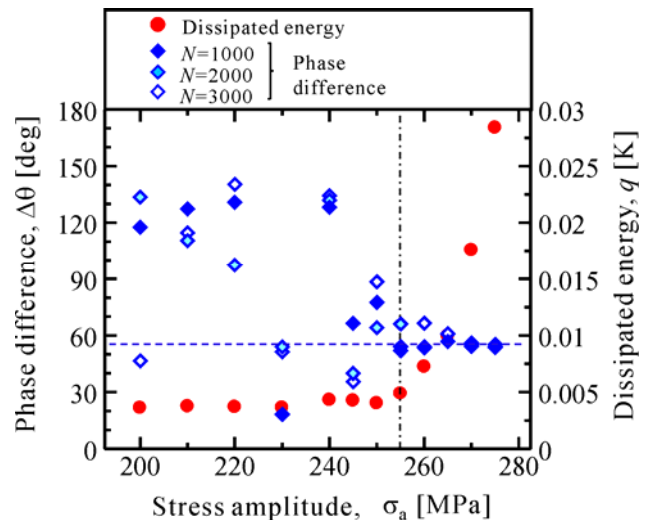


Fig. 4 Change in the dissipated energy and the phase difference of the energy dissipation for a cyclic load.

In fatigue-limit estimation based on the dissipated energy, the data are divided in two different series: high- and low-energy groups. Grouping is carried out by minimizing the sum of the squared error between an approximate straight line for each series. The intersection of the straight lines gives the estimated fatigue limit. The estimated fatigue limit based on the dissipated energy ($\sigma'_w = 254$ MPa) coincided with the fatigue limit obtained by the S – N curve ($\sigma_w = 250$ MPa).

The distributions of the dissipated energy and phase difference at $\sigma_a = 265$ MPa are shown in Fig. 5. The area where the dissipated energy exhibits a high value coincides with the area where the phase difference is approximately 60° . To investigate the relationship between the dissipated energy and the phase difference, a histogram of the phase difference is obtained. The relationship between the histograms of the phase difference in the evaluation area and the applied stress amplitude is shown in Fig. 6. The relative frequency F in a square evaluation area is plotted along the vertical axis. The histograms for a low stress level from 200 to 250 MPa have two peaks at 60° and 140° . On the other hand, those for a high stress level, which is above the fatigue limit of the material, have a peak at 60° . As a result of analyzing the load signal measured from the load cell in the frequency domain, it is clear that the measured load signal includes a nonlinear load component, except for the target frequency component of the load signal. **The result of spectrum analysis for load signal is shown in Fig. 7. The value of the nonlinear load component and the value obtained by the conventional lock-in method change according to a parameter of the fatigue testing system controller (which is called the “response value” or “gain”). An increase in the gain will speed up the motor’s response to servo update errors. However, if the gain is too large, the system will overshoot its desired position and eventually become unstable.** This nonlinear component is considered to be caused by the harmonic vibration of the electrohydraulic testing machine. Further, the double frequency component of the temperature change having a phase difference of 140° is considered to be the thermoelastic temperature change due to the harmonic vibration of the fatigue testing machine; therefore, it is not an energy dissipation component. The double frequency component of the temperature change having a phase difference of 60° becomes dominant when the applied stress is above the fatigue limit. Therefore, this

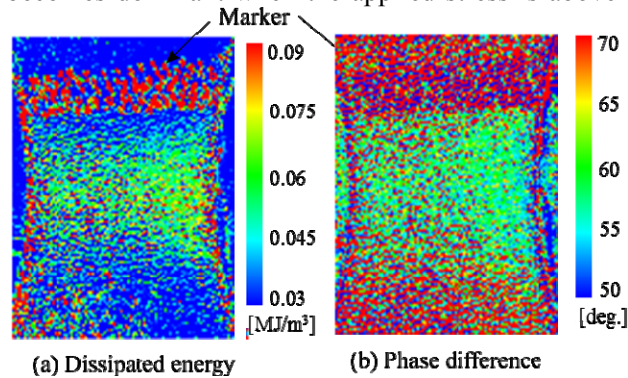


Fig. 5 Relationship between the dissipated energy and the phase difference. ($\sigma_a = 265$ MPa, $N = 3000$ cycles).

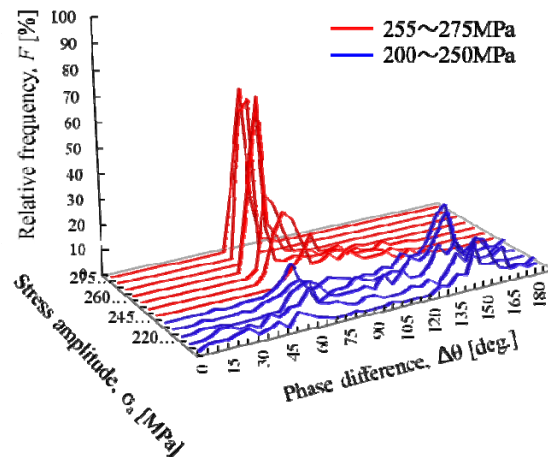


Fig. 6 Histograms of the phase difference.

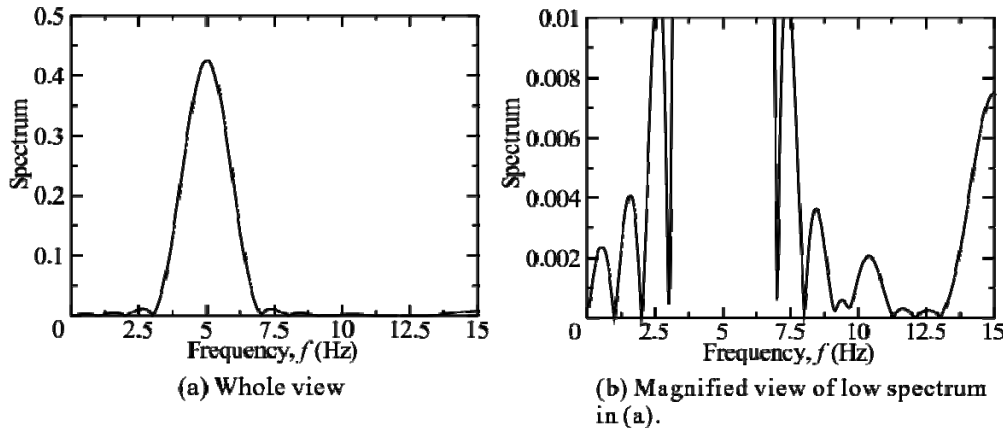


Fig. 7 Spectrum analysis of load signal measured by load cell ($\sigma_a = 280\text{MPa}$, $N = 3000$ cycles, sampling frequency = 2kHz)

component is considered to indicate the temperature change due to the energy dissipation related to the fatigue damage. It is found that the temperature change due to the energy dissipation has a specific phase difference, which is thought to indicate the behavior of the local plasticity, such as slip movement [14]. It is necessary to study the relationship between the phase of dissipated energy and the fatigue damage.

The conventional lock-in method ($2f$ lock-in infrared method) obtains the component of the temperature change having a double frequency, which includes two main components—a thermoelastic temperature change due to the harmonic vibration of the fatigue testing machine and the dissipated energy related to the fatigue damage. A new evaluation technique is suggested by using the specific phase difference of the temperature change due to the energy dissipation. In this technique—called the phase $2f$ lock-in infrared method—a staircase-like stress-level test is conducted, and the phase difference is measured. When the change in the phase difference is constant and the dissipated energy increases, this phase difference is determined as the specific phase difference of the energy dissipation $\Delta\hat{\theta}$. The correlation between $T(t)$ and the modified reference signal, which is shifted by $\Delta\hat{\theta}$ and the phase lag of the thermoelastic temperature change θ_E , is calculated as follows:

$$\Delta\hat{T}_D = \frac{2}{N} \sum_{t=0}^N T(t) \cdot \sin \left\{ 2 \cdot \left(2\pi \cdot t \cdot \frac{f_{\text{load}}}{f_{\text{meas}}} - (\theta_E + \Delta\hat{\theta}) \right) \right\} \quad (12)$$

where f_{load} and f_{meas} are the load frequency and the measurement frequency of the thermal camera, respectively. A correlation with a negative value is set to zero. The phase $2f$ lock-in infrared method can separate the components related to the energy dissipation and the thermoelastic temperature change due to the harmonic vibration of the fatigue testing machine.

The change in the dissipated energy obtained by both methods for a staircase-like stress-level test is shown in Fig. 8. In this analysis, $\Delta\hat{\theta}$ was set to 57° . It is found that the dissipated energy obtained by the phase $2f$ lock-in infrared method at a low stress level is smaller than that obtained by the conventional $2f$ lock-in infrared method. The estimated fatigue limits are 254 and 251 MPa for the conventional and phase $2f$ lock-in methods, respectively. The fatigue limit estimated by the phase $2f$ lock-in method coincides with the fatigue limit from the S - N curve with a good accuracy.

The distributions of the dissipated energy obtained by both methods are shown in Fig. 9. The applied stress amplitude is 255 MPa for this measurement and is above and near fatigue limit. It is found that the concentration of the dissipated energy obtained by the phase $2f$ lock-in infrared method at the notch root is clearer than that obtained by the conventional $2f$ lock-in infrared method. The relationship between the phase difference and the dissipated energy from the evaluation of the specimen is shown in Fig. 9(c). The components have a phase difference of 140° , which indicates the thermoelastic temperature change due to harmonic vibration, and this component is removed by the phase $2f$ lock-in method.

5. Conclusions

Fatigue-limit estimation based on the dissipated energy measurement using infrared thermography has received an increasing amount of attention in various industries. Two methods—measurement of the increase in the surface temperature and the $2f$ lock-in infrared method—are mainly applied to obtain the dissipated energy. An improvement in the dissipated energy measurement is needed to estimate the fatigue limit in a high-fatigue-strength material.

It is found that the $2f$ lock-in method can obtain the component of the temperature change that has a double frequency, which includes two main components—the thermoelastic temperature change due to the harmonic vibration of the fatigue testing machine and the dissipated energy related to the fatigue damage. The phase difference of the dissipated energy exhibits a specific value when the dissipated energy sharply increases at a certain stress level, which coincides with the fatigue limit of the material.

To improve the accuracy of the dissipated energy measurement, the use of the phase information of the dissipated energy with the phase $2f$ lock-in infrared method is proposed. The phase $2f$ lock-in method utilizes

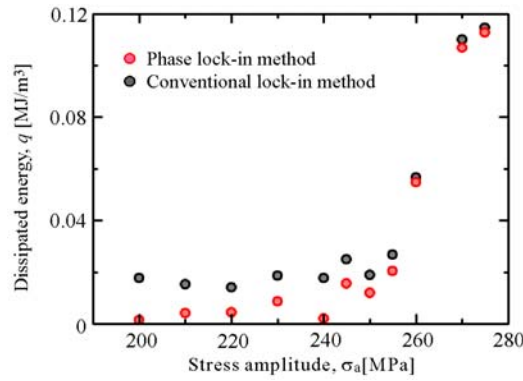


Fig. 8 Comparison between the phase and conventional lock-in methods for the measurement of the dissipated energy in a staircase-like stress-level test.

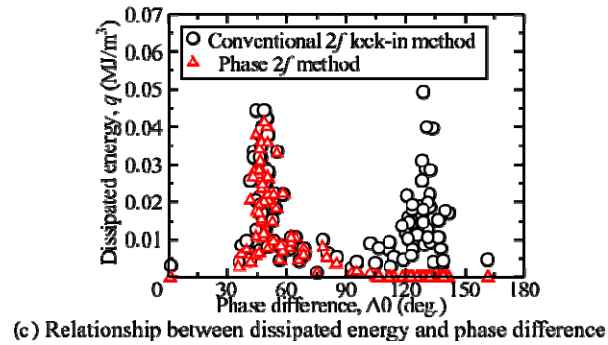
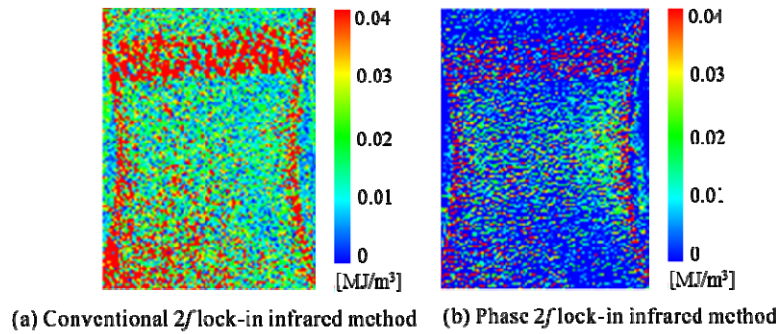


Fig. 9 Effect of the phase $2f$ lock-in infrared method on the distribution of the dissipated energy ($\sigma_a = 255$ MPa).

this specific phase difference so that it can obtain the double frequency component due to the energy dissipation from the measured temperature signal. The phase lock-in method is effective for removing noise components such as the thermoelastic temperature change due to the harmonic vibration of the fatigue testing machine. The proposed method exhibits an improvement in the accuracy of the fatigue-limit estimate and the detection of future crack initiation points.

Future work will focus on studying the mechanisms of the phase information of the dissipated energy.

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