Effect of heat conduction on rapid evaluation of fatigue limit based on temperature variation measurement

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Abstract

The technique of rapid evaluation of fatigue limit using infrared thermography has been developed and paid attention during the past 30 years. In the thermographic technique, two options are known for evaluating the temperature evolution associated with cyclic loading: one is the mean temperature rise and the other is the second harmonic amplitude of temperature variation. In this paper, numerical simulation is conducted to verify the effect of heat conduction on the rapid evaluation of fatigue limit. First, heat generation due to the thermoelastic effect as well as the energy dissipation caused by plastic deformation is simulated by elasto-plastic finite element analysis of double edge notched specimen of stainless steel. Second, based on this heat generation, both adiabatic and heat conduction analyses are conducted in order to obtain temperature variation under different loading frequencies. Finally, the fatigue limit is evaluated based on the mean temperature rise and the second harmonic amplitude. In conclusion, the mean temperature rise is affected by heat conduction and should not be applied to objects with stress concentration. Furthermore, it is suggested that the fatigue limit should be evaluated based on the second harmonic amplitude with sufficiently high loading frequency.

Keywords: Fatigue limit, Infrared thermography, Dissipated energy, Notch, Finite element analysis

1 Introduction

The technique of rapid evaluation of fatigue limit using infrared thermography has been developed and paid attention during the past 30 years [1]. Although this technique is less reliable than the normal fatigue test, it can be applied to real products easily with low cost. This technique is also beneficial for detecting the location of fatigue damage in real products. In the technique, temperature evolution associated with cyclic loading of the specimen is measured at various load amplitudes and then the fatigue limit is determined based on the relationship between the load amplitude and the temperature evolution.

Two options are known for evaluating the temperature evolution. One is the mean temperature rise associated with cyclic loading and the other is the second harmonic amplitude of temperature variation during cyclic loading. In our previous research, these two options were compared experimentally, and it was found that the mean temperature rise cannot evaluate the fatigue limit accurately [2]. The reason
was considered to be the effect of heat conduction within the specimen but no analytical verification has been conducted yet.

Since the temperature evolution always causes heat transfer, in order to verify the validity of the thermographic technique, it is important to investigate the effect of heat transfer on the evaluation of the fatigue limit. The heat conduction within the specimen should be the most significant compared to heat convection or radiation to the surroundings especially for metallic materials under room temperature. Therefore, in this paper, the effect of heat conduction within the specimen on the rapid evaluation of fatigue limit is assessed by numerical simulation. Two options for evaluating the temperature evolution are compared. The effect of loading frequency on the fatigue limit evaluation is also considered.

2 Simulation method

2.1 Outline

Double edge notched specimen with notch root radius \( R = 5.0 \text{ mm} \) (Fig. 1) was considered. The material assumed is SUS304 stainless steel. The stress concentration factor at the notch root is 1.4 and the “true” fatigue limit evaluated by conducting the standard fatigue test is 3.20 kN [3]. It should be noted that the fatigue limit is evaluated in terms of load amplitude instead of stress amplitude, because the aim of this study is to investigate the applicability of the thermographic technique not to materials but to real structures. In fact, the fatigue limit of materials should be evaluated by the standard fatigue test. Notched specimen was considered as one of the simplest example of real structures in this paper.

Since the specimen is sufficiently thin, two dimensional numerical simulations were conducted in this study. Plane stress elasto-plastic analysis was conducted to obtain heat generation due to the thermoelastic effect and the energy dissipation caused by plastic deformation under different loading frequencies. Based on the heat generation obtained by the elasto-plastic analysis, heat conduction analysis were conducted to determine the temperature variation of the specimen. For simplicity, coupling between the elasto-plastic analysis and the heat conduction analysis was not considered.

![Fig. 1: Double edge notched specimen with 5.0 mm notch (thickness: 3 mm).](image-url)
2.2 Elasto-plastic analysis

Two dimensional elasto-plastic analysis was conducted by using finite element analysis software ABAQUS. The specimen was modelled by four-node linear reduced integration elements. Due to symmetry only one-fourth of the specimen was modelled as shown in Fig. 2. The number of elements is 2,100. Sinusoidal tensile load was applied to the model at one end as shown in the left hand side of Fig. 2 until 1,000 cycles with 40 computational time steps in each cycle (namely 40,000 time steps in total). The load ratio was zero and the loading frequency was 1 Hz or 25 Hz. To simulate ratcheting deformation due to cyclic loading, Chaboche model known as a nonlinear hardening material model was used as in the previous paper [4][5]. Parameters of Chaboche model were determined so as to match the experiment data obtained by Kang et al [6].

Heat generation due to the thermoelastic effect and the energy dissipation caused by plastic deformation was evaluated in the same manner as in the previous paper [4][5]. The three elastic normal strains $\varepsilon_{xx}^e$, $\varepsilon_{yy}^e$, $\varepsilon_{zz}^e$ and the dissipated plastic energy density of all elements were obtained from the elasto-plastic analysis. Heat generation per unit volume due to the thermoelastic effect, $Q_e$, was calculated from the change in volumetric strain by the following equation [7][8]:

$$Q_e = -\frac{T\alpha E}{(1-2\nu)} \delta \varepsilon$$  \hspace{1cm} (1)

where $T$ is the absolute temperature, $\alpha$ is the coefficient of thermal expansion, $E$ is the Young’s modulus, $\delta \varepsilon$ is the change in the volumetric strain and $\nu$ is the Poisson’s ratio. The values of these

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>$\rho$ 7900 kg/m³</td>
</tr>
<tr>
<td>Young’s modulus</td>
<td>$E$ 192 GPa</td>
</tr>
<tr>
<td>Poisson’s ratio</td>
<td>$\nu$ 0.33</td>
</tr>
<tr>
<td>Coefficient of thermal expansion</td>
<td>$\alpha$ $17.8 \times 10^{-6}$ l/K</td>
</tr>
<tr>
<td>Specific heat at constant pressure</td>
<td>$C_p$ 500 J/(kg·K)</td>
</tr>
<tr>
<td>Thermal conductivity</td>
<td>$k$ 16.3 W/(m·K)</td>
</tr>
</tbody>
</table>

Table 1: Material constants of SUS304 stainless steel
constants are shown in Table 1. Heat generation per unit volume due to the plastic energy dissipation, $Q_p$, was calculated based on the dissipated energy density obtained directly by ABAQUS.

### 2.3 Heat conduction analysis

Two dimensional heat conduction equation is expressed as follows:

$$\rho C_p \frac{\partial T}{\partial t} - k \left( \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} \right) = Q_e(t,x,y) + Q_p(t,x,y) \tag{2}$$

where $\rho$ is the density, $C_p$ is the specific heat at the constant pressure and $k$ is the thermal conductivity, whose values are also shown in Table 1. Heat conduction analysis was also conducted by using ABAQUS. The model shown in Fig. 2 was used again with four-node linear heat transfer elements. The heat generation per unit volume, $Q_e + Q_p$, was applied to every elements and the boundary conditions of all of the edges were assumed to be adiabatic. Adiabatic analysis was also conducted by setting thermal conductivity to zero. The initial temperature of model was set to 300 K uniformly.

In addition, in order to simulate the temperature measurement using infrared thermography, the average temperature over the area covered by one pixel was evaluated according to the previous research [5]. The red area shown in the right hand side of Fig. 2 corresponds to the area covered by one pixel of the thermography used in the previous experiment [2]. The average temperature variation over this area was used for evaluating the fatigue limit.

The mean temperature rise per one loading cycle (mean temperature gradient) in the period of 800 to 1,000 cycles instead of the mean temperature rise itself was evaluated because the mean temperature did not always reach equilibrium state. The second harmonic amplitude was evaluated by using Fourier transform of the temperature variation in the same period.

### 3 Results and discussion

Figures 3(a) and 3(b) show the temperature variation determined by adiabatic analysis for the load amplitude 3.0 kN and 3.5 kN, respectively. Although it seems a certain band of temperature in both cases, the temperature is actually oscillating around the mean value due to the thermoelastic effect. When the load amplitude is lower than the fatigue limit (Fig. 3(a)), the mean temperature increases during the early cycles due to the plastic energy dissipation. However, after a sufficient number of cycles, the mean temperature reaches equilibrium because the area of hysteresis loop converges to zero (elastic shakedown). On the other hand, when the load amplitude is higher than the fatigue limit (Fig. 3(b)), the mean temperature keeps increasing because the area of hysteresis loop converges to a constant value (plastic shakedown).
Figures 3(c) –3(f) show the temperature variations determined by heat conduction analysis for the load amplitude 3.0 kN and 3.5 kN and for the loading frequency 25 Hz and 1 Hz. In all cases, the mean temperature decreases due to the effect of heat conduction during the early cycles, which is longer in the case of 25 Hz (Figs 3(c) and 3(d)) while very short in the case of 1 Hz (Figs. 3(e) and 3(f)). After a sufficient number of cycles, the mean temperature reaches equilibrium when the load amplitude is lower than the fatigue limit (Figs. 3(c) and 3(e)), while it slightly increases with loading cycle when the load amplitude is higher than the fatigue limit (Figs. 3(d) and 3(f)).
Figure 4(a) shows the second harmonic amplitude evaluated at load amplitudes from 2.5 kN to 4.0 kN. The second harmonic amplitude is zero or negligibly small at the load amplitude lower than 3.0 kN, which corresponds to the elastic shakedown. On the other hand, at the load amplitude larger than 3.5 kN, the second harmonic amplitude increases with the load amplitude. The increase of the second harmonic amplitude is largest for adiabatic case and becomes smaller as the loading frequency decreases. It was shown that the second harmonic amplitude can evaluate the fatigue limit successfully [4][5]. According to the result shown in Fig. 4(a), it is expected that the second harmonic amplitude can evaluate the fatigue limit even when the heat conduction exists.

Figure 4(b) shows the mean temperature gradient. It is zero or negligibly small at the load amplitude lower than 3.0 kN but increases only in the adiabatic case at the load amplitude larger than 3.5 kN. In fact, as shown in Fig. 4(c), the mean temperature gradient is quite small and difficult to measure in practice when the heat conduction exists. It was shown that the mean temperature rise can evaluate the fatigue limit successfully in adiabatic case [4][5]. However, it seems difficult to evaluate the fatigue limit from the mean temperature gradient when the heat conduction exists.

Fig. 4: Temperature evolution against load amplitude
In the thermographic technique, the fatigue limit is determined by detecting the change of increasing rate of the temperature evolution against the load amplitude. In order to detect this “knee point” appropriately, the temperature evolutions below and above the knee point were curve fitted by linear functions, respectively. The best knee point was determined uniquely by the least squares concept and the fatigue limit was evaluated as the load amplitude at the knee point [9].

Figure 5 shows comparison between the fatigue limits evaluated. The green line indicates the “true” fatigue limit. The fatigue limit evaluated in the adiabatic case coincides well with the true value. Similarly, the fatigue limit evaluated by the second harmonic amplitude determined by the heat conduction analysis for the loading frequency 25 Hz is in good agreement with the true value. On the other hand, the fatigue limit evaluated by other cases are much larger than the true fatigue limit. Since heat is generated by energy dissipation associated with cyclic loading only in the vicinity of the notch root, heat conduction occurs due to the temperature gradient between the notch root and the surrounding area. Consequently, the temperature evolution at the notch root decreases and does not increase linearly but in a curved manner against the load amplitude as shown in Figs. 4(a) and (c). Furthermore, if the notch root radius becomes smaller, the heat generation becomes larger and more localized even if the load amplitude is unchanged and hence the heat conduction becomes more remarkable. As a result, the mean temperature rise and the second harmonic amplitude with low loading frequency are much affected by the effect of heat conduction within the specimen and, therefore, should not be applied to high stress concentrated part.

Fig. 5: Fatigue limit evaluated by the second harmonic amplitude (A) and the mean temperature gradient (B)
4 Conclusion

In this paper, heat conduction analyses were conducted to verify the effect of heat conduction on rapid evaluation of fatigue limit. The following conclusions are obtained.

(1) The mean temperature rise is affected by the heat conduction and should not be used to evaluate the fatigue limit of objects that have stress concentration parts.

(2) The fatigue limit should be evaluated by the second harmonic amplitude with sufficiently high loading frequency.

References


