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Fretting fatigue strength of 12% Cr steel under high local contact pressure and its fracture mechanics analysis

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Abstract

Fretting fatigue fractures of industrial machines often occur at the point where high contact pressure occurs due to uneven contact. In this study, fretting fatigue tests were performed under high contact pressure applied in line-contact conditions using 12% Cr steel with parameters of the mean stress, contact pressure, and material strength. The fretting fatigue strength was shown to decrease as contact pressure increased, and minimized when Hertz’s average contact pressure was about 1.5 times 0.2% proof stress $\sigma_{0.2}$, and increased again at higher contact pressure.

Crack propagation behavior was examined using fracture mechanics by observing the detailed crack propagation profile of non-propagating cracks and performing finite element analysis with an inclined elliptical surface crack. Cracks were found to propagate in stage II at the angle where the maximum stress intensity factor range $\Delta K_{\text{max}}$ occurred. Also, test results concerning the fretting fatigue strength could be successfully explained by the micro-crack propagation model in which a micro-crack can propagate when its stress intensity factor range $\Delta K$ is greater than the threshold value $\Delta K_{\text{th}}$ when considering small crack effects and mean stress effects. This model also confirmed the experimental results that showed the length of non-propagating cracks decreased as the mean stress and the material strength increased.

Keywords: Fretting fatigue; Fracture mechanics; Small crack; Crack propagation; Mean stress; Non-propagating crack

1. Introduction

Fretting fatigue fractures of industrial machines often occur at the point where high contact pressure occurs due to uneven contact. Fretting fatigue strength depends on contact pressure; it decreases as contact pressure increases when contact pressure is low and almost saturates over a certain pressure [1-3]. This is due to the trade-off of two effects: increasing tangential force accelerates crack propagation, and compression stress retards crack propagation caused by the contact pressure. However, few studies have been done under high contact pressure, so these findings were mainly obtained under plane-contact conditions where contact pressure is less than yield strength. Therefore, in this study, the author carried out fretting fatigue tests under line-contact conditions where high local contact pressure arose, as schematically shown in Fig. 1. The tests were performed using two 12% Cr steels with different static
strengths, and the effects of the material strength and mean stress were investigated.

To evaluate fretting fatigue strength quantitatively, many researchers have adopted fracture mechanics approaches [4-10]. In these methods, the fretting fatigue limit is predicted by evaluating whether a certain initial crack will propagate or not, i.e., whether stress intensity factor range $\Delta K$ is greater than its threshold value $\Delta K_{th}$ or not. To more accurately evaluate this, the following complex mechanisms characteristic of fretting fatigue have to be considered: 1) mixed modes of tensile and shear $\Delta K$ [4], 2) small crack effect on $\Delta K_{th}$ [6], and 3) mean stress effect on $\Delta K_{th}$ [8] caused by local contact pressure as well as an axial load. In this study, the author evaluated the small crack propagation while considering the above-mentioned three effects and confirmed the effectiveness of the proposed model by observing non-propagating cracks of run-out specimens under various contact pressures and mean stresses.

2. Fretting test method

Test materials were 12% Cr steels that had different static strength, as shown in Table 1. Tensile strength and 0.2% yield strength of steel B are approximately 40% higher than those of steel A. Figure 2 shows shapes of test specimens and a contact pad. Two kinds of tests were undertaken using rectangular-cross-section specimens (5 mm×5 mm) for plane-contact conditions and circular-cross-section specimens (8 mm in diameter) for line-contact conditions. Steel A was used for the contact pad. After first applying an axial mean load, the contact force was applied by cramping bolts, and finally axial alternative loads were applied. The contact force was measured and adjusted by the cylindrical load cell with an uncertainty of 5% to the target value during tests.

Contact pressure was 80 MPa for plane-contact conditions, and line-contact loads were 60, 150, 300, and 450 N/mm, which respectively correspond to 584, 923, 1306, and 1569 MPa of the average elastic contact pressure calculated from Hertz’s formula. Mean stresses were 0 MPa and 400 MPa for all test cases and –100 MPa for plane-contact conditions of steel A. Tests were carried out using an electro-magnetic-resonance machine in air at ambient temperature. The frequencies were about 125 Hz for line-contact and about 110 Hz for plane-contact, which were determined by the stiffness of the test piece and the machine.

The author also carried out plain fatigue tests without contact pads using run-out fretting specimens at $2\times10^7$ cycles, and investigated the size of fretting non-propagating cracks, which were the cause of the plain fatigue fracture in most cases. When the test piece was not broken by the fretting non-propagating crack, its depth was measured by polishing the crack surface until it disappeared. The crack-profile path from the initial point was also measured at the fracture surface by a laser microscope to analyze the behavior of the crack propagation.

Table 1. Mechanical properties of materials

|         | 0.2% proof stress (MPa) | Tensile strength (MPa) | Elongation (%) | Reduction of area (%) | Vickers hardness (Hv) |
|---------|-------------------------|------------------------|----------------|-----------------------|----------------------|
| Steel A | 610                     | 745                    | 26.3           | 65.5                  | 238                  |
| Steel B | 842                     | 1037                   | 15.4           | 51.0                  | 329                  |
3. Fretting fatigue test results

3.1. Fretting fatigue strength

Figure 3 shows the effect of the contact pressure on fretting fatigue strength when mean stresses $\sigma_m$ are 0 MPa and 400 MPa, where break- and not-break-stress amplitudes at $2 \times 10^7$ cycles are indicated. As shown in Fig. 3, fatigue limits for line-contact conditions decreased as the contact pressure increased and minimized at a certain contact pressure. The minimum strength pressure, MSP, when fretting fatigue strength minimizes, depended on the material strength; MSP of steel B (higher static strength) was higher than that of steel A. The average Hertz’s contact pressure at MSP almost corresponded to about 1.5 times 0.2% proof stress $\sigma_{0.2}$ for both steels A and B. Under plane-contact and line-contact conditions at 150 N/mm pressure, steel B exhibited 10-25% higher fretting-
fatigue strength than steel A. On the other hand, the minimum strengths of steels A and B differed little (about 5%) under line-contact conditions; this warns us that a high-static-strength material does not necessarily improve the fretting fatigue strength when local high contact pressure arises. Fretting fatigue strength depended on the mean stress in a high contact pressure region; the strength over $MSP$ increased more drastically at $\sigma_m=0$ MPa than that at $\sigma_m=400$ MPa.

Figure 4 shows an observed contact surface near the contact edge under line-contact conditions at 150N/mm-pressure. The crack edge was located about 0.12 mm inside from the contact edge. The width of wear region was about 0.5 mm, greater than the elastic contact width calculated from Hertz’s formula (about 0.16 mm). This was caused by the plastic deforming at the contact edge under high local pressure.

### 3.2. Dimensions of non-propagating cracks

Figure 5 (a) shows an example of a non-propagation crack at the fracture surface. Its depth $a_0$ and surface length $l$, projected in the plane perpendicular to the axial direction, were read from the fracture surfaces. The value of $a_0/l$ was almost 0.15, as shown in Fig. 5 (b). The relationship between non-propagating crack depth $a_0$ and stress amplitude is summarized in Fig. 6, where top arrows mean the break data corresponding to $a_0\rightarrow\infty$ or off-scale values the depths of which are indicated in parentheses. Figure 6 suggests the following two characteristics:

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Fig. 4. Side view around contact edge of broken specimen. (Steel A: LC, 150N/mm, $\sigma_m=0$MPa, $\sigma_a=130$MPa, $N_f=9.23\times10^6$)

Fig. 5. (a) Example of non-propagating crack and (b) aspect ratio of non-propagating cracks.
• The value of $a_0$ for steel B, the static strength of which is higher than that of A, was smaller than that of steel A on the same $I_a$.
• Higher mean stress lead to the smaller $a_0$ at the fatigue limit.

3.3. Profile path of crack propagation

Figure 7 shows profile paths of crack propagation from the initial crack measured by a laser-microscope, where non-propagating cracks are indicated by O symbols and the stress amplitude is shown in parentheses for each case. According to Mutoh [4], the crack path of fretting fatigue is classified into two stages: stage I is an initial crack stage where a crack inclines greatly against the normal direction, and stage II is where a crack is thought to propagate in a direction perpendicular to the maximum principal stress amplitude. Furthermore, stage II is composed of two regions: a mixed mode region (slant crack) and a mode I region (parallel to normal direction). In this study, the angle of crack inclination against the normal direction was about 50-70° in stage I and about 20° at mixed mode region in stage II, as shown in Fig. 7.

Non-propagating cracks under plane-contact conditions were almost all located in stage II except one case (steel B at 400 MPa-mean stress) when no profile date was obtained because the run-out specimen was not fractured from the fretting non-propagating crack. On the other hand, under line-contact conditions all non-propagating cracks were located near the boundary between stages I and II. The boundary crack depth between stages I and II, $d_1$, depended on the mean stress, contact pressure, and material strength. The following explains why.

- The values of $d_1$ of steel B (higher static strength) were smaller than those of steel A under the same test conditions.
- The values of $d_1$ under plane-contact condition were smaller than those under line-contact conditions at the same mean stress.
- 400 MPa-mean stress lead to lower $d_1$ than 0 MPa-mean stress under line-contact conditions.
- When mean stress was –100 MPa in plane-contact condition, $d_1$ was extremely small (less than 5 μm).

These results regarding $d_1$ are probably to be described by considering the slip range [4], grain size, and crack propagation under mixed modes in stage I, but its details are to be discussed in future work. In this study, the author’s objective is to evaluate the micro-crack propagation in stage II using the data obtained on non-propagation cracks and FE analysis, which is discussed later.
4. Discussion

4.1. Analysis condition of calculating stress intensity factor

By carrying out three-dimensional elastic FE analysis, the relationship between crack depth and stress intensity factor was calculated. Figure 8 shows the analysis models under plane-contact and line-contact conditions where an inclined elliptical surface crack was introduced, the depths of which were 0.03, 0.06, 0.1, and 0.2 mm. The oblique angle against the normal direction, $\alpha$, was 20° on the basis of test results in the mixed region of stage II. Furthermore, to investigate the effect of oblique angle $\alpha$ for a small crack, analysis was done when $\alpha = 0, 20, 50°$ at $a = 0.03$ mm. The aspect ratio (the ratio of crack depth to the surface length) was 0.15 determined from the experiments shown in Fig. 5 (b). The crack was introduced at 0.1 mm inside from the contact edge to avoid the edge effect of the contact analysis and to be consistent with the test results shown in Fig. 4. Local plastic deformation at the contact edge was not considered in this analysis. Friction coefficient was 0.8 determined from the gross slip tests.

Using the extrapolation method of stress distribution from the deepest point of crack, stress intensity factor ranges $\Delta K_I$ and $\Delta K_{II}$ were calculated. Substituting $\Delta K_I$ and $\Delta K_{II}$ into equation (1) [11], tensile $\Delta K_I$ and shear $\Delta K_{c}$ were obtained in the local coordinate system at any evaluation angles $\theta$.

Fig. 7. Non-propagating and propagating crack profiles obtained by fretting fatigue tests: (a) plane-contact (steel A), (b) line-contact (steel A), (c) plane-contact (steel B), (d) line-contact (steel B), and (e) schematic view of fretting crack
4.2. Analysis results on stress intensity factor

Figure 9 shows the variation of $\Delta K_0$ and $\Delta K$ against $\beta$, defined as the angle of the evaluation direction against the normal direction, when a crack is 0.03 mm deep under the plane-contact conditions ($\sigma_p=100$ MPa, and $\sigma_n=0$ MPa). The angle $\beta$ when $\Delta K_0$ maximizes is about 20°, which barely depends on the crack oblique angle $\alpha$. This angle of $\beta$ corresponds well to the inclined crack angle confirmed by tests at the mixed mode in stage II, as shown in Fig. 7; this supports the theory that the fretting fatigue crack propagates in a direction perpendicular to the maximum principal stress amplitude in stage II. When $\beta$ is 50-70°, corresponding to the inclined angle of the initial crack in stage I, $\Delta K$ is not zero; this suggests that both $\Delta K_0$ and $\Delta K$ affect crack propagation in stage I unlike in stage II.

Next, Figs. 10 (a) and (b) show the relationships between crack depth and $\Delta K_{\text{max}}$ and mean value $K_{\text{mean}}$ when $\alpha=20^\circ$ and $\sigma_p=100$ MPa. The value of $\Delta K_{\text{max}}$ is the maximum value of $\Delta K_0$ with the variation of $\beta$ and $K_{\text{mean}}$ is the mean $K_0$ when $\Delta K_0$ is $\Delta K_{\text{max}}$. When the crack is short, $\Delta K_0$ is strongly affected by the contact conditions and, as
a crack grows, it asymptotically reaches the value calculated under the uniform stress distribution without fretting effects. $\Delta K_{\text{max}}$ under uniform stress distribution was confirmed to coincide within 3% of error with the solution by Raju-Newman equation [12].

The value of $K_{\text{max, mean}}$ is negative, and its absolute value increases as the contact force increases, as shown in Fig. 10 (b). The absolute value of $K_{\text{max, mean}}$ decreases as a crack grows because the compression stress caused by the contact force becomes lower as the distance from the surface increases.

4.3. Qualitative evaluation of small crack propagation

Kondo et al. [6] developed the model for evaluating micro-crack propagation schematically shown in Fig. 11 (a). In this model, $\Delta K_{\text{th}}$ is assumed to increase as cracks lengthen in small crack regions and saturates over a certain depth [13]. When $\Delta K$ is lower than $\Delta K_{\text{th}}$ at a certain crack depth, the crack is judged to stop propagation and to remain as a non-propagating crack, indicated by O in Fig. 11(a). On the other hand, when $\Delta K$ is larger than $\Delta K_{\text{th}}$ in a whole crack length, it is judged to propagate to failure. In this section, the author qualitatively evaluates the micro-crack propagation in stage II by considering the effect of the material strength and mean stress under plane-contact conditions. The discussion is made using $\Delta K_{\text{max}}$ calculated at $\theta = 20^\circ$, corresponding to the inclined angle in stage II observed in experiments.

First, Fig. 11(b) shows the schematic view of the material strength’s effect on $\Delta K$. The value of $\Delta K_{\text{th}}$ in the small crack region increases as the material strengthens [13]: $\Delta K_{\text{th}}$ of steel B is higher than that of steel A. On the other hand, $\Delta K$ by the applied stress does not depend on the material strength when the local plastic deformation is ignorable. From this evaluation, the fatigue limit of steel B is higher than that of steel A, which correlates well with the experimental results. Supposing that a crack stops propagating when $\Delta K$ is smaller than $\Delta K_{\text{th}}$, the non-propagating crack depth of steel B is estimated to be smaller than that of steel A under the same stress amplitude. This also agrees well with the experimental results shown in Fig. 6 (a).

Second, Fig. 11(c) schematically shows the effect of mean stress. Because higher mean stress gives rise to smaller $\Delta K_{\text{th}}$ [14], larger $\sigma_m$ leads to the smaller fatigue strength and the smaller non-propagating crack at the fatigue limit from this model. This was also confirmed to correspond well with the experiments shown in Fig. 6(a).

4.4. Quantitative evaluation of small crack propagation
Here, the author quantitatively discusses the micro-crack propagation behavior in stage II using the experimental results and FE analysis under the various contact pressures and the mean stresses. Although non-propagating cracks were located between stages I and II in line-contact conditions, they are assumed to change their direction towards stage II, i.e., $\Delta K_{\text{sh}}$ is applicable for evaluating non-propagation cracks. The values of $\Delta K_{\text{sh}}$ and $K_{\text{sh},\text{mean}}$ for non-propagating cracks were calculated using the observed crack depths and their stress amplitude. As for the propagating data for the target crack depths, 40 $\mu$m and 80 $\mu$m, $\Delta K_{\text{sh}}$ and $K_{\text{sh},\text{mean}}$ were obtained using the minimum stress amplitude over which cracks were confirmed to propagate over the target crack depth.

Calculated data are summarized in Fig. 12, where solid symbols represent non-propagating cracks and open symbols represent propagating crack data. Crack depths used in the evaluation are plotted in parentheses in $\mu$m units. The estimated $\Delta K_{\text{th}}$ for the target crack depths, 40 $\mu$m and 80 $\mu$m, as boundaries between propagating and non-propagating cracks are shown in this figure.

Fig. 11 Schematics of small-crack propagation model at fretting fatigue limit under plane-contact condition: (a) crack depth v.s. $\Delta K$, effects of (b) material strength, and (c) mean stress.

Fig. 12. Quantitative evaluation result of small crack propagation model under various fretting fatigue tests (steel A). Solid symbols represent non-propagating cracks and open symbols represent propagating crack data.
non-propagating data were confirmed to be unified as single curves, as shown in Fig. 12. Furthermore, the estimated results almost correspond well, within 10% error, with $\Delta K_{th}$ at $R = -1$ by Murakami’s equation [13]

$$\Delta K_{th} = 3.3 \times 10^{-3} (HV + 120)^{1/3 \sqrt{area}} \mu m$$

This suggests that fretting fatigue strength can be evaluated by considering the effects of small cracks and mean stress by estimating the initial crack size conservatively. To increase the accuracy, however, the mechanism in stage I must be clarified because the initial crack size depends on the crack initiation and propagation in this stage.

5. Conclusions

Fretting fatigue tests were performed under high contact pressure applied in line-contact conditions as well as plane-contact conditions using 12% Cr steel with parameters of the mean stress, contact pressure, and material strength. The results obtained are as follows.

1. Under line-contact conditions, the fretting fatigue strength decreased as contact pressure increases and minimized when Hertz’s average contact pressure was about 1.5 times 0.2% proof stress $\sigma_{0.2}$. The minimum strengths of steel A and B under line-contact conditions differed very little (about 5%). This warns us that a high-static-strength material does not necessarily increase the fretting fatigue strength when local high contact pressure arises.

2. Test results concerning the fretting fatigue strength can be successfully explained by the micro-crack propagation model in which a micro-crack can propagate when its stress intensity factor range $\Delta K$ is greater than the threshold value $\Delta K_{th}$ when considering small crack effects and mean stress effects. Cracks were confirmed to propagate in stage II at the angle where the maximum stress intensity factor range $\Delta K_{max}$ occurred by observing the propagation profile. This model also confirmed the experimental results that the depth of non-propagating cracks decreased as the mean stress and the material strength increased.

3. The estimated $\Delta K_{th}$ for the target crack depths, 40$\mu m$ and 80 $\mu m$, as a boundary between propagating and non-propagating data were confirmed to be unified as single curves qualitatively.

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