Fretting fatigue strength and life estimation considering the fretting wear process

T. Hattori, M. Yamashita & N. Nishimura
Department of Mechanical and System Engineering, Gifu University, Japan

Abstract

In this paper we present the estimation methods of fretting wear process and fretting fatigue life using this wear process. Firstly the fretting-wear process was estimated using contact pressure and relative slippage. And then the stress intensity factor for cracking due to fretting fatigue was calculated by using contact pressure and frictional stress distributions, which were analyzed by the finite element method. The S-N curves of fretting fatigue were predicted by using the relationship between the calculated stress intensity factor range (ΔK) with the threshold stress intensity factor range (ΔKth) and the crack propagation rate (da/dN) obtained using CT specimens of the material. Finally fretting fatigue tests were conducted on Ni-Cr-Mo-V steel specimens. The S-N curves of our experimental results were in good agreement with the analytical results obtained by considering fretting wear process. Using these estimation methods we can explain many fretting troubles in industrial fields.
Key words: fretting fatigue, fretting wear, contact pressure, fracture mechanics, threshold stress intensity factor range, crack propagation rate, crack initiation, stress singularity parameters.

1 Introduction

Fretting can occur when a pair of structural elements are in contact under a normal load while cyclic stress and relative displacement are forced along the contact surface. This condition can be seen in bolted or riveted joints [1,2], in the shrink-fitted shafts [3,4], in the blade dovetail region of turbo machinery [5,6], etc. During fretting the fatigue strength decreases to less than one-third of that without fretting [7,8]. The strength is reduced because of concentrations of contact stresses such as contact pressure and tangential stress at the contact edge, where fretting fatigue cracks initiate and propagate.

This concentration of stress can be calculated using the finite element method [9] or boundary element method. Methods for estimating the strength of fretting fatigue have been developed that use values of this stress concentration on a contact surface [3,5]. However, the stress fields near the contact edges show singularity behavior, where the stress at contact edges is infinite. Thus, maximum stresses cannot be used to evaluate fretting fatigue strength. So, in previous papers we present fretting crack initiation estimation method using stress singularity parameters at contact edge [10,11,13], and fretting fatigue limit or life estimation methods using fracture mechanics [7,12,13]. Using this fretting fatigue strength or life estimation method we couldn't estimate the ultra-high-cycle fretting fatigue troubles in industrial field. For instance 660MW turbogenerator rotor failed in England during the 1970s as a result of fretting fatigue cracking as shown in Fig. 1 [14]. In this case the loading cycles in just one year is about 1.6×10^9 and this trouble was observed after many years operation. These ultra high cycle fatigue life can't be explained using only initial stress analysis results. In above mentioned methods we neglect the wear of the contact surfaces near contact edge and change of contact pressure in accordance with the progress of wear. Here, in this paper we improve these methods on the fretting model in which the wear of the each surface near the contact edge is being considered. And finally we can estimate the S-N curve in ultra-high cycle fretting fatigue.

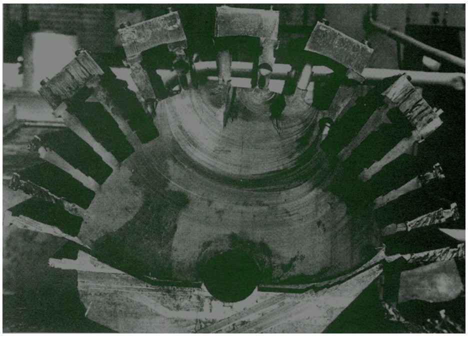


Figure 1: Fretting fatigue failure example of turbogenerator rotor. After Lindley and Nix (1991) [14].

2 Fretting fatigue process

Here, we present fretting fatigue process model as illustrated in Fig. 2. Cracking due to fretting fatigue starts very early in fretting fatigue life. We used stress singularity parameters at the contact edge to estimate the initiation of these cracks [10,11,13]. During this early period, fretting fatigue cracks tend to close and propagate very slow, due to the high contact pressure acting near this contact edge. But wear on the contact surface reduces the contact pressure near the contact edge, and cracks gradually start to propagate. Hence, fretting fatigue life will be dominated by the propagation of this small cracks initiated at the contact edge. So to estimate the fretting fatigue strength or life, the precise estimation of the fretting wear progress is indispensable. The propagation life in long crack length region can be estimate using ordinal fracture mechanics. In this paper we discuss the estimation method of wear extension on contact surfaces near the contact edge, and present the fretting fatigue crack propagation estimation method considering fretting wear extension

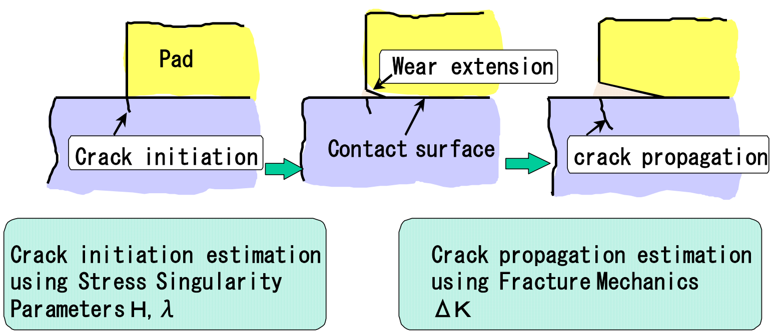


Figure 2: Fretting fatigue mechanisms in various processes.

3 Fretting fatigue life analysis considering fretting wear

In Fig. 3 the flow of fretting fatigue life analysis considering the extension of fretting wear. Firstly the fretting wear amount is estimated using contact pressure and relative slippage on each loading condition. Then the shapes of contact surfaces are modified following the fretting wear amount. And finally fretting crack extension or arrest evaluation is performed using fracture mechanics, if the operating ΔK is higher than the threshold stress intensity factor range ΔK_{th} we can estimate this load cycle as fretting life, and if the operating ΔK is lower than the threshold stress intensity factor range ΔK_{th} fretting wear amount is estimated using new contact pressure and new relative slippage and repeat these process until operating ΔK reach to the threshold stress intensity factor range ΔK_{th}.

4 Fretting wear analysis

4.1 Fundamental equation

Using classic Archard's equation, the wear extension on contact surfaces can be expressed as follows (Fig. 4).

$$W = K \times P \times S \tag{1}$$

W; wear depth, K; wear coefficient, P; contact pressure, S; slippage

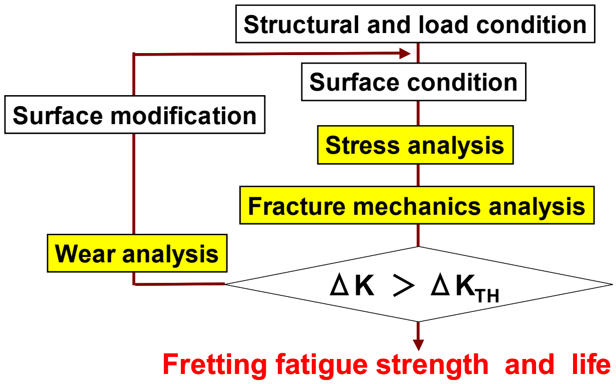


Figure 3: Flow chart of fretting fatigue life analysis.

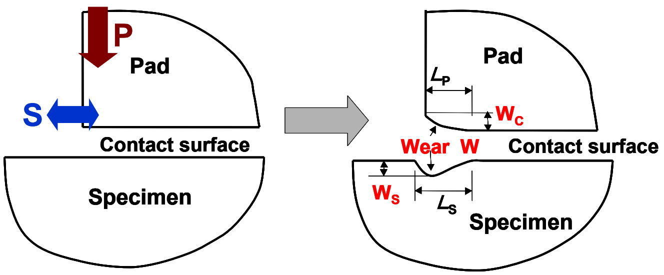


Figure 4: Wear analysis using contact pressure and slippage.

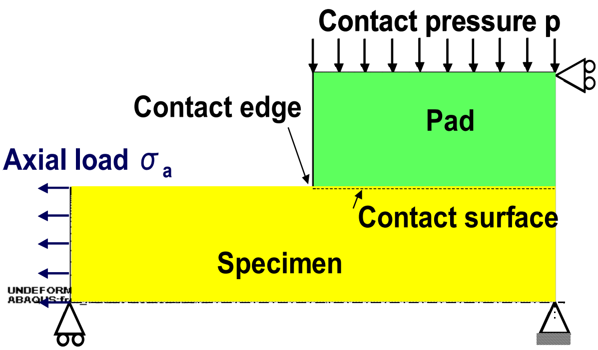


Figure 5: Fretting model for stress and deformation analyses.

4.2 Stress and deformation analysis

Firstly we perform the stress and deformation analyses as shown in Fig. 5. And using these calculated results of contact pressure distributions and slippage distributions on contact surfaces and Eq. (1), we can calculate the wear depth distributions. By comparing these calculated results of contact pressure and slippage distributions on many loading and wear conditions, with experimental results of fretting wear (example is shown in Fig. 6), the wear coefficient on this material (Ni-Cr-Mo-V Steel) can be estimated as 1.15×10^{-10} [mm^2/N].

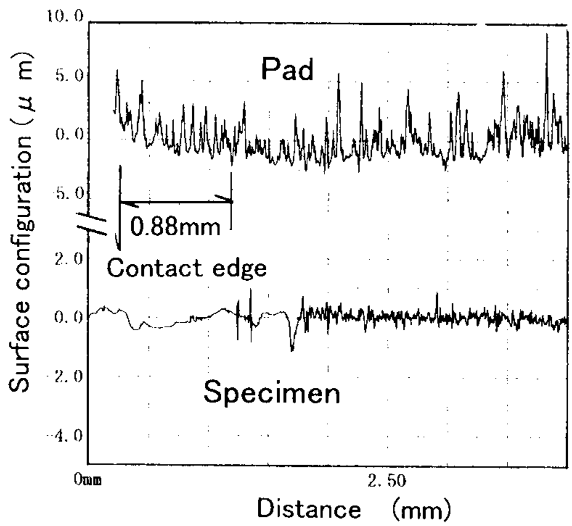
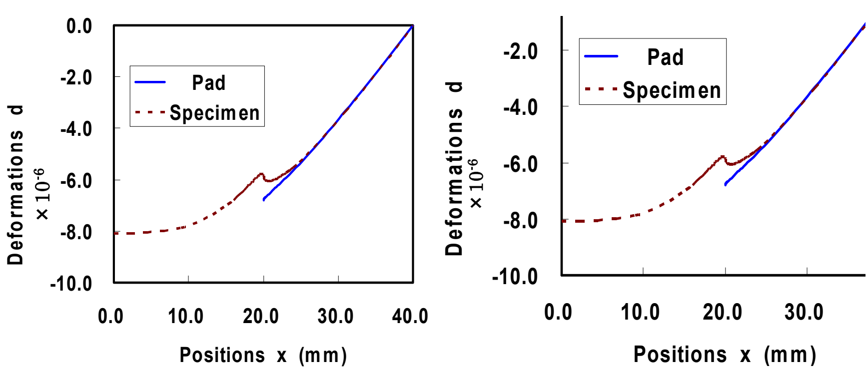


Figure 6: Experimental results of fretting wear. (ó$_a$=110Mpa, N=2×10^7 , Ni-Mo-V Steel).



(a) Axial stress +50MPa (b) Axial stress -50MPa

Figure 7: Calculated results of deformations on contact surfaces.

4.3 Calculation examples of contact pressure, slippage and wear

Then the calculation examples of contact pressure, slippage and wear are shown. Fig. 7 shows the calculated results of deformations on contact surfaces of pad and specimen in initial condition (without wear). The slippage of this fretting model in half loading cycle (-50MPa ▶ +50MPa) can be calculated as the difference of both deformations as shown in Fig. 8. And by multiplying this slippage and contact pressure (shown in Fig. 9) the wear depth in this half loading cycle can be calculated as Fig. 10.

The modifications of contact surfaces of specimens and pad are performed using the calculated results of these wear extension. And the stress and deformation analyses are performed using these new shape models repeatedly as shown in Fig. 3. In Figs.11–14 we will show the repeatedly calculated examples of contact pressure distributions and cumulative wear depths with loading condition of σ_a=62MPa, and repeated cycles of 3.6×10^7 and 1.6×10^8 respectively.

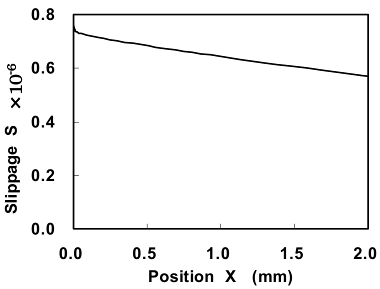


Figure 8: Calculated results of slippage in half loading cycle. (-50Mpa ➔ +50MPa).

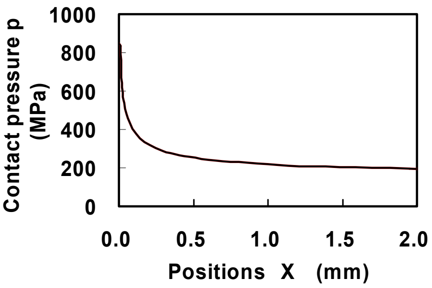


Figure 9: Calculated result of contact pressure distributions near contact edge.

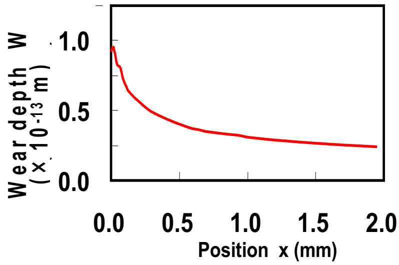


Figure 10: Calculated result of wear in loading cycle. (-50Mpa➔+50Mpa).

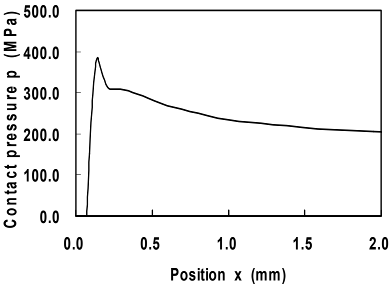


Figure 11: Calculated result of half contact pressure. (σ_a=62Mpa, N=3.6×10^7).

5 Fracture mechanics analysis

Then the fracture mechanics analyses are performed for each wear condition with small fretting cracks at contact edges. In Fig. 15 the calculated examples of stress intensity factors with each wear depth (0m, 5×10^{-6}m, 10×10^{-6}m) are shown.

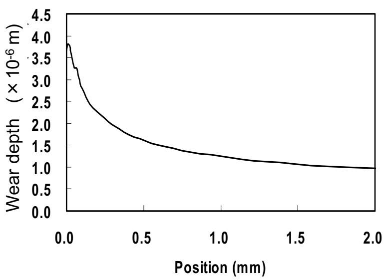


Figure 12: Calculated result of wear (σ_a=62MPa, N=3.6×10^7).

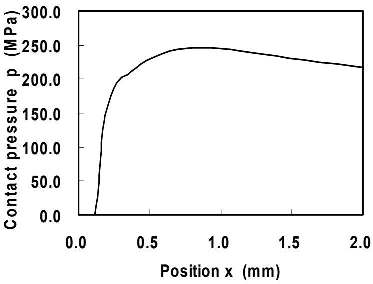


Figure 13: Calculated result of contact pressure. (σ_a=62MPa, N=1.6×10^8).

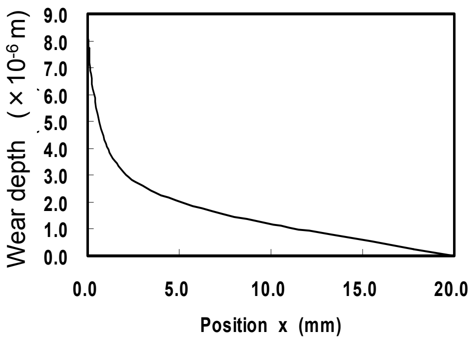


Figure 14: Calculated result of wear. (σ_a=62MPa, N=1.6×10^8).

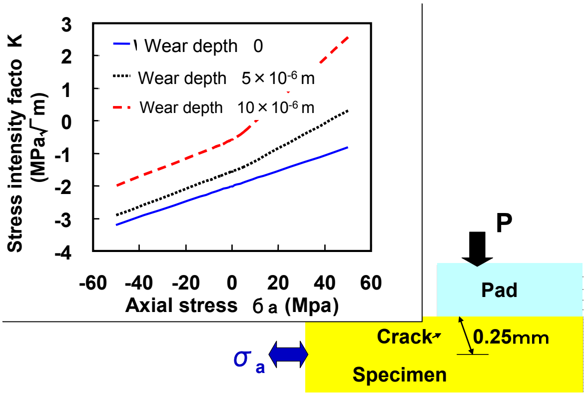


Figure 15: Calculated result of stress intensity factor for each wear depth.

In this model initial crack length is set as 50×10^{-6}m and crack inclination is set as 30 degrees, which is estimated from the maximum stress amplitude direction. The validity of this estimation was confirmed by the experimental results [13].

6 Fretting fatigue life analysis

Finally, the fretting fatigue life for each loading conditions can be estimated comparing the operating stress intensity factor range ΔK with the threshold stress intensity factor range ΔK_{th} of the material (Ni-Cr-Mo-V Steel). In Figs. 16–18 the comparisons of operating stress intensity factor ranges with the threshold stress intensity factor ranges for each loading condition. In this comparison, the threshold stress intensity factor ranges were estimated considering crack length and stress ratio as derived in previous paper [7,12,13]. If I'm limited the estimation of fretting S-N curve just on ultra high cycle region ($N>10^8$), I can ignore the fretting fatigue crack propagation life.

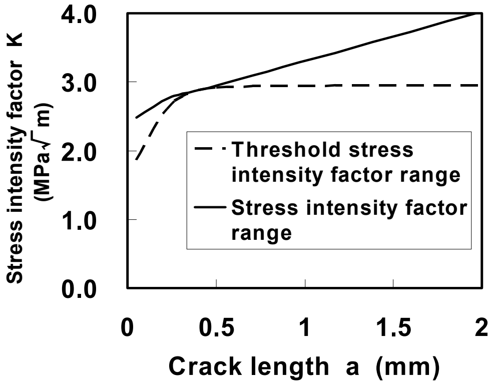


Figure 16: Comparison of operating stress intensity factor range with threshold stress intensity factor range. (σ_a=140MPa, N=1×10^7, without fretting wear).

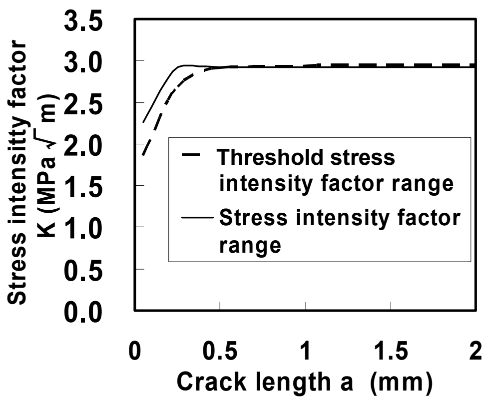


Figure 17: Comparison of operating stress intensity factor range with threshold stress intensity factor range. (σ_a=110MPa, N=2×10^7, wear depth 4μm).

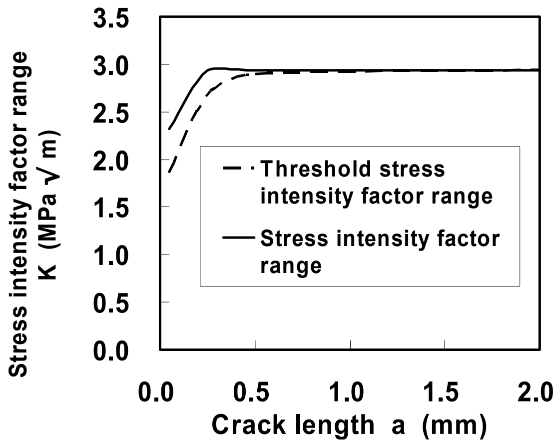


Figure 18: Comparison of operating stress intensity factor range with threshold stress intensity factor range. (σ_a=62MPa, N=1.6×10^8, wear depth 10μm).

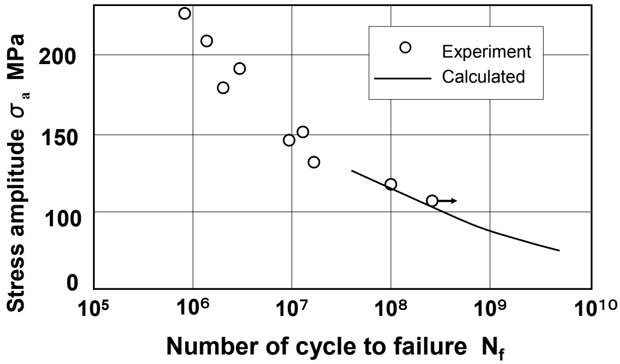


Figure 19: Estimated and experimental fretting fatigue S-N curves.

And so, by connecting these fretting threshold conditions I can estimate the fretting fatigue S-N curve considering the wear process. This estimated S-N curves especially in ultra high cycle region are compared with the experimental results as shown in Fig. 19. Both results coincide well and this tendency of decrease of fretting fatigue strength especially in ultra high cycle region can explain many fretting troubles in industrial fields.

7 Conclusions

1.Fretting fatigue strength and life was estimated considering the wear process.
2.Wear process was estimated using classical Archard's equation.

3.Fretting fatigue strength decreased in accordance with the increase of wear, and this tendency coincided well with the fretting trouble in industrial fields.
4.Estimated fretting fatigue S-N curve coincided well with the experimental results.

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