

# Fretting Fatigue Strength/Life Estimation Considering Wear Process and Critical Distance Stress Theory

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**ABSTRACT.** *Fretting fatigue process have many features such as early stage crack initiation at contact edge, very slow crack propagation and fatigue failure after very long life operation. In this paper firstly we present fretting fatigue model in high cycle region, which is considering the wear process near contact edge. And then we present fretting fatigue life estimation method in low cycle fatigue region using critical distance stress theory. By using these fretting fatigue strength/life estimation methods we can estimate the full range fretting S-N curve. And we can confirm the validity of these estimated results by comparing with the experimental results. Finally by using these estimations, we try to explain other many fretting features such as fretting fatigue strength and life dependence on contact pressure, contact edge shapes.*

## 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 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 stresses at contact edges are 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 edges [10,11,13], and fretting fatigue limit or life estimation methods using fracture mechanics [7,12,13]. Using these fretting fatigue

strength or life estimation methods we couldn't estimate the super-high-cycle fretting fatigue troubles in industrial field. For instance 660MW turbo-generator 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  $1.6 \times 10^9$  and this trouble was observed after many years operation. These very-high-cycle fatigue life can't be explained using only initial stress analysis results. In above mentioned method we neglect the wear of the contact surfaces near contact edge and change of contact pressure in accordance with the progress of wear.

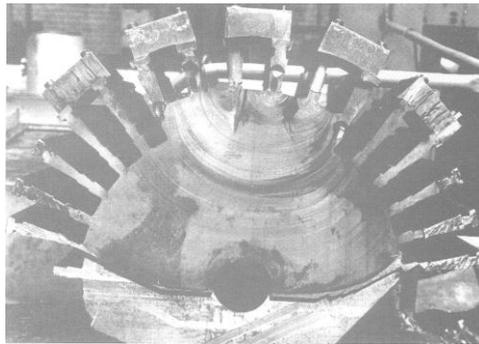


Fig. 1. Fretting fatigue failure example of turbogenerator rotor[14 ]

Here in this paper at first we improve fretting model by considering the wear process on contacted surfaces, and estimate the S-N curve in very high cycle region. And then we extend fretting fatigue strength evaluation method on the low cycle fatigue region. In the case of designing the turbo machinery, we must estimate the low cycle fatigue strength or life of blade/disk connecting structures in start/stop process (as shown in Fig. 2). Here, in this paper we introduced the low cycle fatigue life using critical distance theory. And finally we can estimate the S-N curve thorough the whole processes from low cycle fatigue to very high cycle fatigue. And to confirm the availability of this estimation method we perform the fretting fatigue test using Ni—Mo-V steel.

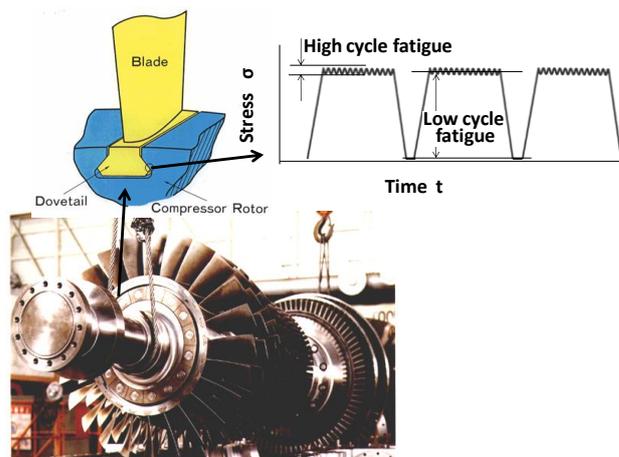


Fig. 2. Assembled gas-turbine compressor rotor and blade dovetail joint

### FRETTING FATIGUE PROCESS

In Previous paper [15,16] we present fretting fatigue process model as illustrated in Fig. 3. 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 especially in low stress amplitude range, 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 in low stress amplitude range will be dominated by the propagation of this small cracks initiated at the contact edge. So to estimate the fretting fatigue strength or life in these low stress region, the precise estimation of the fretting wear progress is indispensable. The propagation life in long crack length region can be estimate using ordinary fracture mechanics. On the other hand, in the case when the stress range is high, the crack initiation will lead the failure easily without wear. In this paper we also estimate the fretting fatigue life in these high stress range using critical distance theory.

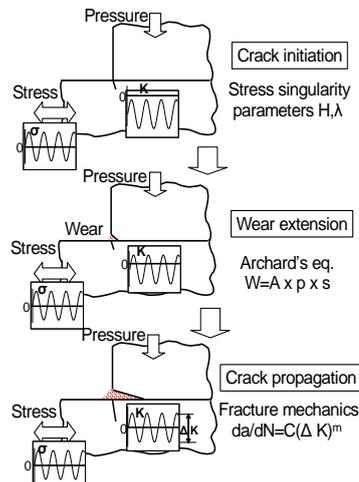


Fig. 3. Fretting fatigue mechanisms in various processes

### FRETTING FATIGUE LIFE ANALYSIS CONSIDERING FRETTING WEAR IN HIGH CYCLE REGION

In Fig. 4 the flow of fretting fatigue life analysis considering the extension of fretting wear is shown. Firstly the fretting wear amount is estimated using contact pressure and relative slippage on each loading condition [15, 16]. Then the shapes of contact surfaces are modified following the fretting wear amount. This fretting wear amount is estimated using classic Archard's equation as follows[15].

$$W = K \times P \times S \quad \text{--- (1)}$$

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

Then, the fretting fatigue life for each loading conditions considering the wear process can be estimated comparing the operating stress intensity factor range  $\Delta K$  with the

threshold stress intensity factor range  $\Delta K_{th}$ . If the operating  $\Delta K$  is higher than the threshold stress intensity factor range  $\Delta K_{th}$  we can estimate this load cycle as fretting life, and if the operating  $\Delta K$  is lower than the threshold stress intensity factor range  $\Delta K_{th}$  fretting wear amount will be calculated using new contact pressure and new relative slippage and repeat these process until operating  $\Delta K$  reach to the threshold stress intensity factor range  $\Delta K_{th}$ . In these comparison, the threshold stress intensity factor ranges were estimated considering crack length and stress ratio as derived in previous paper [7,12,13]. By connecting these fretting threshold conditions we can estimate the fretting fatigue S-N curve considering the wear process as shown in dash line in Fig.11 .

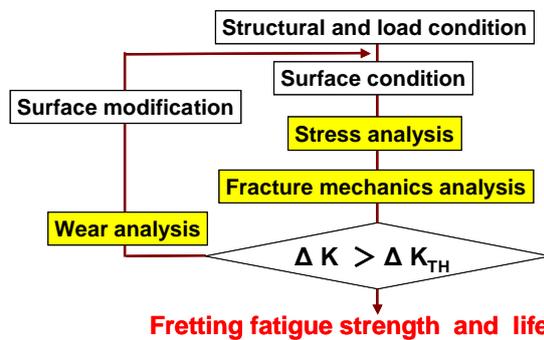


Fig. 4 Flow chart of fretting fatigue life analysis

### FATIGUE LIFE ANALYSIS USING CRITICAL DISTANCE THEORY IN LOW CYCLE REGION

Even if in the fretting conditions, the fretting wear will be neglected in high stress region. In these cases the fatigue life will be estimated as the crack initiation conditions. Then in this paper we estimated the fretting fatigue life using critical distance stress theory (point method and line method). In this method the fatigue strength limit can be obtained typical material strength parameters such as the fatigue limit of smooth specimens  $\sigma_{w0}$  and the threshold stress intensity factor range  $\Delta K_{th}$  of the cracked specimens as shown in Fig. 5,6. In the case of point method, the fatigue failure

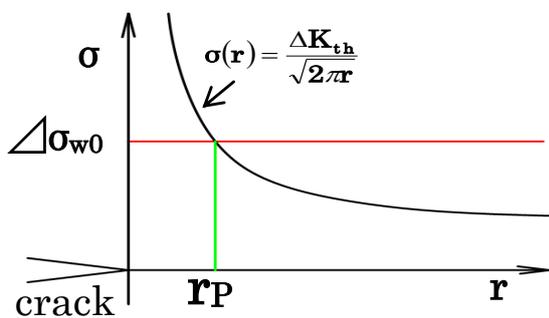


Fig. 5 Derivation of critical distance  $r_P$  (point method)

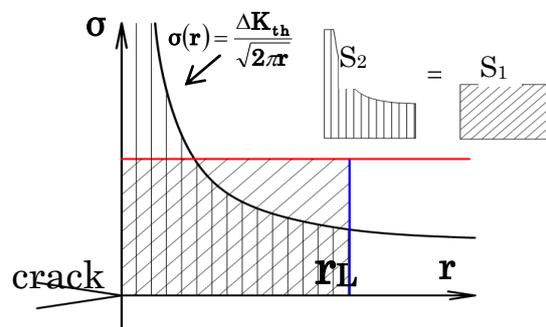


Fig. 6 Derivation of critical distance  $r_L$  (line method)

supposed to occur when the stress range at specific length  $r_p$  from maximum stress point reach  $\Delta\sigma_{w0}$ , and in the case of line method the fatigue failure supposed to occur when the mean stress range between maximum stress point and specific length point  $r_L$  reach  $\Delta\sigma_{w0}$ . Each  $r_p$  and  $r_L$  can be derived as follows.

For point method, 
$$r_p = (\Delta K_{th} / \Delta\sigma_{w0})^2 / 2\pi \quad (2)$$

And for line method, 
$$r_L = 2(\Delta K_{th} / \Delta\sigma_{w0})^2 / \pi \quad (3)$$

In this paper we extended this method to the low cycle fatigue regions. Then we will explain this development in detail. Firstly the critical distance in low cycle fatigue region is derived by interpolating between critical distance in fatigue limit as shown in above and critical distance in static strength. This static strength critical distance can be derived using ultimate strength of smooth specimen  $\sigma_B$  and the fracture toughness  $K_{IC}$  of the cracked specimen as shown in Eq. (4),(5).

For point method, 
$$r_p' = (K_{IC} / \sigma_B)^2 / 2\pi \quad (4)$$

And for line method, 
$$r_L' = 2(K_{IC} / \sigma_B)^2 / \pi \quad (5)$$

In this section we use only the point method.

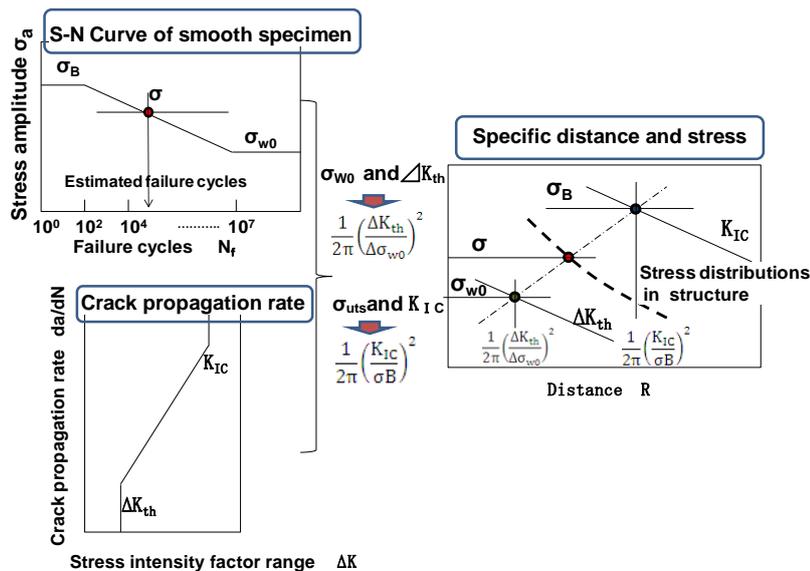


Fig.7 Derivation of specific distance in low cycle fatigue region and estimation of low cycle fatigue life

The critical distance in each stress level is calculated by interpolation of critical distance on fatigue limit ( $r_p$ , estimated from  $\sigma_{w0}$  and  $\Delta K_{th}$ ) with critical distance on static strength ( $r_p'$ , estimated from  $\sigma_B$  and  $K_{IC}$ ) as shown by chain line in Fig. 7(right). The critical distance on objective conditions (structure, load) can be estimated by reflecting the stress distributions of objective structure as shown by dotted line in Fig. 7(right). The low cycle fatigue life in this objective condition can be estimated by applying this stress level at critical distance on S-N curve of smooth specimens as shown in Fig. 7(left upper).

### APPLICATION ON LOW CYCLE FRETTING FATIGUE LIFE ANALYSIS

Then we will apply this extended critical distance theory on the fretting fatigue life prediction. In Fig. 8 (left upper) the S-N curve of Ni-Mo-V steel smooth specimen in complete reversed loading conditions (R=-1), and in Fig. 8 (left under) the crack propagation characteristic of cracked specimen is shown. From these material characteristics we can obtain the critical distance  $r_p$  is 0.011mm and  $r_p'$  is 2.13mm as shown in Fig. 8 (right). The stress distributions in fretting conditions were calculated using FEM model as shown in Fig. 9. The calculated example of stress distribution near the contact edge is shown in Fig. 10. The mean contact pressure  $\sigma_p$  and mean axial

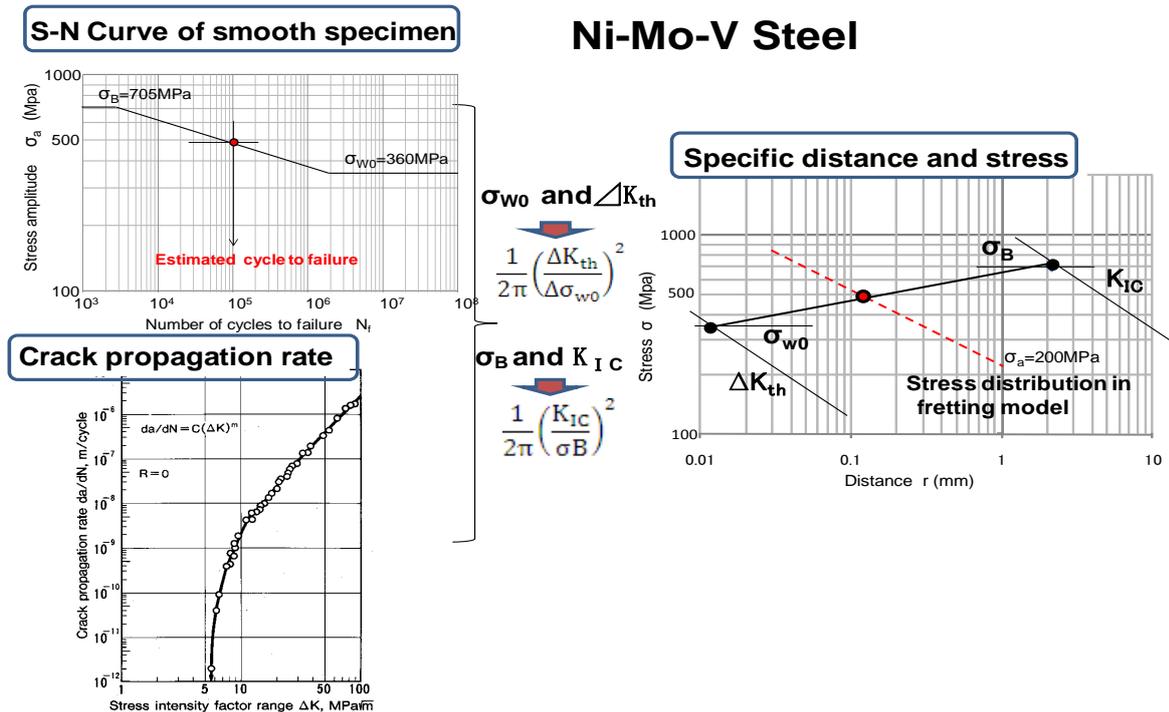


Fig.8 Derivation of specific distance in low cycle fatigue region and estimation of low cycle fretting fatigue life

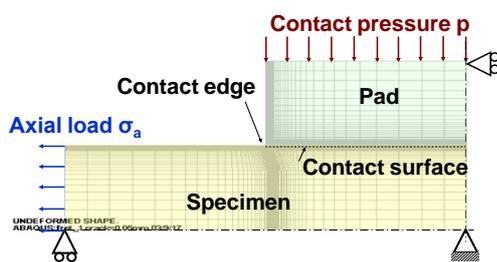


Fig.9 FEM Fretting model

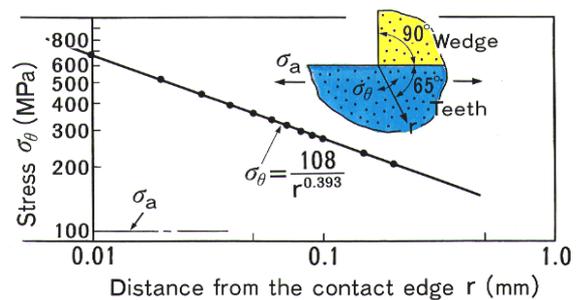


Fig. 10 Calculated result of stress distributions

stress  $\sigma_a$  in this case are 200MPa and 100MPa respectively.

The critical distance on each loading conditions can be estimated by reflecting these stress distributions on Fig. 8 (right) as shown by dotted line. The low cycle fretting

fatigue life in this loading condition ( $\sigma_a$  is 200MPa) can be estimated by applying this stress level at critical distance (490MPa) on S-N curve of smooth specimens as shown in Fig. 8(left upper). By connecting these fretting fatigue life on each stress level we can estimate the fretting fatigue S-N curve as shown in solid line in Fig.11 .

### COMPARISON WITH THE EXPERIMENTAL RESULTS

To confirm the validity of this estimation method we compare the estimated results with the experimental results. The experimental results of fretting fatigue tests are shown in Fig. 11 by symbol  $\circ$  .

The estimated results of low cycle fretting fatigue life using critical distance theory is shown by dotted line in Fig. 11. The estimated results of high cycle fretting fatigue life considering fretting wear process which was presented in previous paper [16, 17] is shown by dash line in Fig. 11. And the estimated fretting fatigue limit (142MPa) without considering fretting wear which was presented in previous paper[12, 13] is shown by two points of dot-dash line in Fig. 11. We can see that these three kinds of fretting fatigue strength and life prediction results coincided well with the experimental results in each stress and life level. And we can confirm the validity of these fretting fatigue strength and life estimation methods.

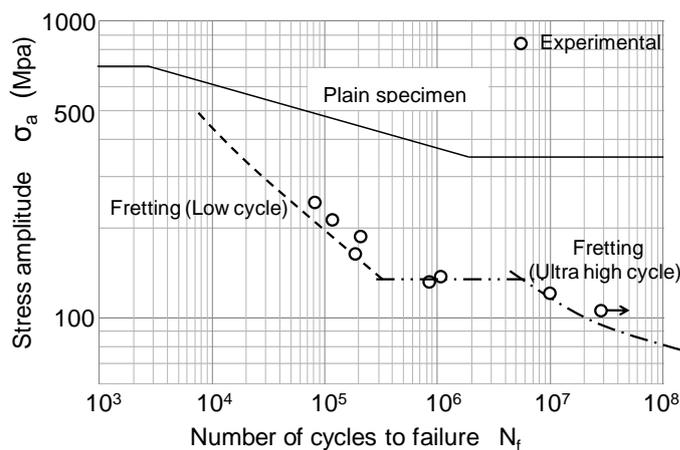


Fig.11 Estimated and experimental fretting fatigue S-N curves

### CONCLUSIONS

1. Low cycle fretting fatigue strength was estimated using critical distance theory.
2. This estimated results and other two kinds of fretting fatigue strength and life prediction results, fretting fatigue limit without considering the fretting wear process and high cycle fretting fatigue life prediction considering fretting wear process are compared with the experimental results.
3. These fretting fatigue strength and life estimated results coincided well with the fretting fatigue test results in each stress and life level. And we can confirm the availability of these fretting fatigue strength and life estimation methods as the standardized fretting fatigue S-N curve estimation method.

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