Fretting fatigue life estimations based on fretting mechanisms

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ABSTRACT

Generally the fretting fatigue S–N curve has two regions: one is the high cycle (low stress) region and the second is the low cycle (high stress) region. In a previous paper we introduced the fretting fatigue life estimation methods in high cycle region by considering the wear process; with this estimation method the fretting fatigue limit can be estimated to be the crack initiation limit at the contact edge. In this paper we estimate the low cycle fretting fatigue life based on a new critical distance theory, modified for a high stress region using ultimate tensile strength $\sigma_u$ and fracture toughness $K_C$. The critical distance for estimating low cycle fretting fatigue strength was calculated by interpolation of the critical distance on the fretting fatigue limit (estimated from $\sigma_u$ and $\Delta K_{IC}$) with critical distance on static strength (estimated from $\sigma_u$ and $K_{IC}$). By unifying this low cycle fretting fatigue life estimation method with the high cycle fretting fatigue life estimation method, which was presented in the previous paper, we can estimate the total fretting life easily. And to confirm the availability of this estimation method we perform the fretting fatigue test using Ni–Mo–V steel.

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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 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 the boundary element method. Methods of estimation of the strength of fretting fatigue have been developed, which use the 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 our previous papers we presented the 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 could not predict the super-high-cycle fretting fatigue problems in the industrial field. For instance, a 660 MW 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 number of loading cycles in just one year was about $1.6 \times 10^6$, and this problem was observed after many years of operation. This very-high-cycle fatigue life cannot be explained using only initial stress analysis results. Then in a previous paper we presented the very-high-cycle fatigue life estimation method considering fretting wear [15] and change in the contact surface [16,17].

In the case of designing rotational machinery such as turbo machinery, we must estimate the low cycle fatigue strength or the life of the blade/disk that connects structures in the start/stop process (as shown in Fig. 2). Here, in this paper we introduced the low cycle fatigue life method using the critical distance theory, and finally we can estimate the $S–N$ curve of the entire process from low cycle fatigue to very high cycle fatigue. To confirm the availability of this estimation method we perform the fretting fatigue test using Ni–Mo–V steel.

2. Fretting fatigue process

In our previous paper [16,17] we presented a 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 slowly especially in a 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, the fretting fatigue life in the low stress amplitude range will be dominated by the propagation of these small cracks that initiate at the contact edge. To estimate the fretting fatigue strength or life in this low stress region, the precise estimation of the fretting wear progress is indispensable. The propagation life of a long crack length region can be estimated using fracture mechanics. In our previous paper [16,17] we discussed the method of estimation of wear extension on contact surfaces near the contact edge, and presented the fretting fatigue crack propagation estimation method considering the fretting wear extension process.

On the other hand, in the case when the stress range is high, the crack initiation will lead to failure easily without wear. In this paper we estimate the fretting fatigue life in this high stress range using the critical distance theory.

3. 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 under each loading condition [16,17], and then the shapes of contact surfaces are modified following the fretting wear amount.

This fretting wear amount is estimated using the classic Archard’s equation as follows [15]:

\[ W = KPS \]

where \( W \) is the wear depth, \( K \) the wear coefficient, \( P \) is the contact pressure and \( S \) the accumulative slippage.

In this equation the slippage \( S \) was calculated from the deformation of each node on the contact surface, and the frictional coefficient on this contact surface was set at 0.7.

Then, the fretting fatigue life under each loading condition, considering the wear process, can be estimated by 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 to be a fretting life, and if the operating $\Delta K$ is lower than the threshold stress intensity factor range $\Delta K_{th}$, the fretting wear amount will be calculated using a new contact pressure and a new relative slippage; these processes will be repeated until operating $\Delta K$ reaches the threshold stress intensity factor range $\Delta K_{th}$. In these comparisons, the threshold stress intensity factor ranges were estimated considering the crack length and stress ratio, derived in the previous paper [7,12,13]. By connecting these fretting threshold conditions we can estimate the fretting fatigue $S$–$N$ curve considering the wear process.

4. Fatigue life analysis using critical distance theory in low cycle region

Even under the fretting conditions, the fretting wear will be neglected in a high stress region. In these cases the fatigue life will be estimated to be the crack initiation condition. In this paper we also estimated the fretting fatigue life using the critical distance stress theory (point method and line method). In this method the fatigue strength limit can be obtained from 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 Figs. 5 and 6. In the case of the point method, the fatigue failure is supposed to occur when the stress range at specific length $r_P$ from the maximum stress point reaches $\Delta \sigma_{w0}$, and in the case of line method the fatigue failure is supposed to occur when the mean stress range between the maximum stress point and specific length point $r_L$ reaches $\Delta \sigma_{w0}(=\sigma_{w0} \times 2)$; $r_P$ and $r_L$ can be derived as follows:

For point method, $r_P = (\Delta K_{th}/\Delta \sigma_{w0})^2 / 2\pi$  \hspace{1cm} (2)

And for line method, $r_L = 2(\Delta K_{th}/\Delta \sigma_{w0})^2 / \pi$  \hspace{1cm} (3)

In this paper we extended this method to the low cycle fatigue regions. First the critical distance in the low cycle fatigue region is derived through the interpolation between the critical distance in the fatigue limit and the 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 Eqs. (4) and (5):

For point method, $r_P = (K_{IC}/\sigma_B)^2 / 2\pi$  \hspace{1cm} (4)

And for line method, $r_L = 2(K_{IC}/\sigma_B)^2 / \pi$  \hspace{1cm} (5)

Fig. 7. Derivation of critical distance in low cycle fatigue region and estimation of low cycle fatigue life.
In this section we illustrate the approach using the point method. The critical distance at each stress level is calculated by interpolation of critical distance on fretting fatigue limit ($r_p$, estimated from $\sigma_{w0}$ and $\Delta K_{th}$) with critical distance on static strength ($r_{p0}$, estimated from $\sigma_B$ and $K_{IC}$) as shown by chain line in Fig. 7(right). The critical distance under objective conditions (structure, load) can be estimated by reflecting the stress distributions of the 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 reference stress $\sigma$ at critical distance $r$ on S–N curve of smooth specimens as shown in Fig. 7(left upper).

5. Application on low cycle fretting fatigue life analysis

The extended critical distance theory will then be applied in the fretting fatigue life prediction. In Fig. 8(left upper) the S–N curve of the Ni–Mo–V steel smooth specimen under complete reversed loading conditions ($R = -1$), and in Fig. 8(left lower) the crack propagation characteristics of the cracked specimen are shown. From these material characteristics we found that the critical distance $r_p$ is 0.011 mm and $r_{p0}$ is 2.13 mm as shown in Fig. 8(right). The stress distributions under the fretting conditions were calculated using the 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 stress $\sigma_a$ in this case are 200 and 100 MPa, respectively.

The critical distance $r$ on each loading condition can be estimated by reflecting these stress distributions in Fig. 8(right) as shown by the dotted line. As an example we can estimate the critical distance $r$ just 2 times higher than that of loading condition shown in Fig. 10. As a cross point of stress distribution (dotted line) with solid line, $r$ and $\sigma$ can be derived as 0.12 mm and 490 MPa, respectively. The low cycle fretting fatigue life in the loading condition, with nominal axial stress $\sigma_a$ 200 MPa, can then be estimated by applying the stress ($\sigma = 490$ MPa) on the S–N curve of smooth specimens as shown in Fig. 8(left upper). By connecting these fretting fatigue life at each stress level we can estimate the fretting fatigue S–N curve as shown in solid line in Fig. 12.
6. Comparison with the experimental results

To confirm the validity of this estimation method we compare the estimated results with the experimental results. The fretting fatigue test apparatus is shown in Fig. 11. The specimen material is Ni-Mo-V steel. The contact pressure between specimen and pads is set to 200 MPa by screw. The contact pressure and crack initiation at the contact edges are monitored by the strain gages A and B, respectively, with calibration.

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

7. Conclusions

1. Low cycle fretting fatigue strength was estimated using critical distance theory.

2. These fretting fatigue strength and life estimated results coincided well with the fretting fatigue test results at each stress and life level, and we can confirm the availability of these fretting fatigue strength and life estimation methods through the standardized fretting fatigue S–N curve estimation method.

References


