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Simple estimation method of fretting fatigue limit considering wear process

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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 of machinery. In previous paper [1,2,3] we present fretting fatigue process model and fretting strength and life estimation using fracture mechanics and wear process approaches. But, the estimation of fretting wear process require a large amount of labor, so this precise wear estimation method is not suitable for actual design site. In this paper we try to present simple fretting fatigue limit estimation method based on the assumption that in the final stage of wear process the contact pressure distributions near contact edges converge to a uniform. And the validity of this estimated result can be confirmed by comparing with experimental results.

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 [4,5], in the shrink-fitted shafts [6,7], in the blade dovetail region of turbo machinery [8,9], etc. During fretting the fatigue strength decreases to less than one-third of that without fretting [10,11]. 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. As shown in Fig. 1(a) the contact pressure on the contact surfaces between ball or round bar/plane can be calculated using Hertzian equation, and in these cases the contact edges doesn't show singularity. But in general industrial fields the curvatures near contact edges change drastically as shown in Fig. 1(b). In these cases the contact pressures at contact edges show singularity behavior. These concentration of contact pressure or stress can be calculated using the finite element method [12] 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 [6,8]. 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 edge [13,14,16], and fretting fatigue limit or life estimation methods using fracture mechanics [10,15,16]. Using these fretting fatigue strength or life estimation method we couldn't estimate the ultra-high-cycle fretting fatigue troubles in industrial field. For instance 660 MW turbogenerator rotor failed in England during the 1970s as a result of fretting fatigue cracking as shown in Fig. 2 [17]. 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. In previous paper [3] we improve these methods on the fretting model in which the wear of the each surface near the contact edge is being considered.

But, the estimation of fretting wear process require a large amount of labor, so this precise wear estimation method is not suitable for actual design site. In this paper we try to present simple fretting fatigue limit estimation method considering wear. In the final stage of wear process the contact pressure distributions near contact edges converge to a uniform. So, we estimate the ultra high cycle fretting fatigue limit as the crack propagation threshold on this uniform contact pressure conditions. And the validity of this estimated result can be confirmed by comparing with experimental results.

2. Fretting fatigue process

Here, 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 [13,14,16]. During this early

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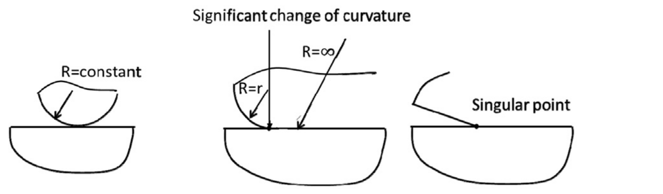

Fig. 1. Stress concentration behavior near contact edges.

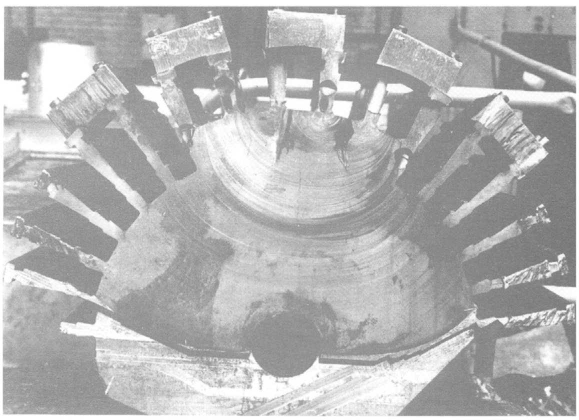

Fig. 2. Fretting fatigue failure example of turbogenerator rotor.

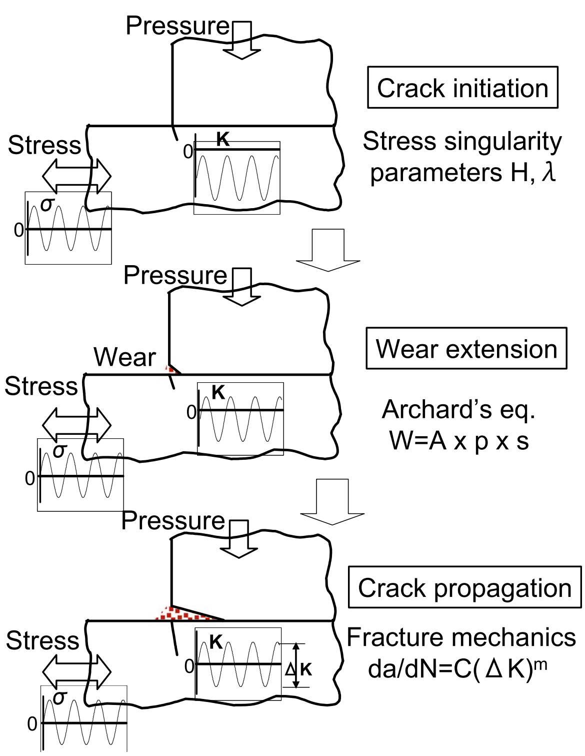

Fig. 3. Fretting fatigue mechanisms.

period, fretting fatigue cracks tend to close and propagate very slow, due to the high contact pressure acting near this contact edge as shown in Fig. 4.

In the case when the substrate is narrow and free from axial deformation the substrate expand in the axial direction as shown in Fig. 4(b). But when substrate is sufficiently large body, axial compression stress occurs near contact edge as shown in Fig. 4(c) by the restraint from outside.

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 on contact surfaces near the contact edge, and present the fretting fatigue crack propagation estimation method considering fretting wear.

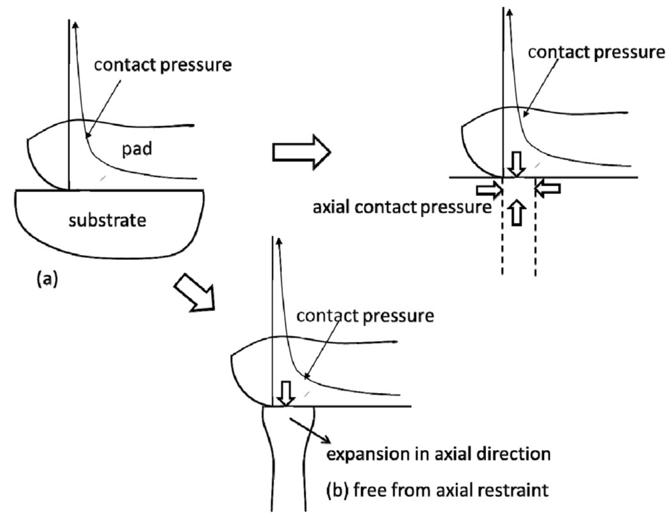

Fig. 4. Schematic illustration of the mechanism of occurrence of axial contact pressure.

3. Fretting wear analysis

3.1. Fundamental equation

Using classic Archard's equation, the wear extension on contact surfaces can be expressed as follows (Fig. 5).

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

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

3.2. Stress and deformation analysis

Firstly we perform the stress and deformation analyses as shown in Fig. 6. In this FEM analysis the minimum mesh size near contact edge is 0.01 mm. And using these calculated results of contact pressure distributions and (see Figs. 7, 9 and 11) and relative slippage we can obtain the wear depth as shown in Figs. 8, 10 and 12. By comparing these calculated results of wear depth distributions on many loading and wear conditions, with experimental results of fretting wear as shown in Fig. 13, the wear coefficient K_w on this material(Ni-Cr-Mo-V Steel) can be estimated as 1.15×10^{-10} [mm^2/N].

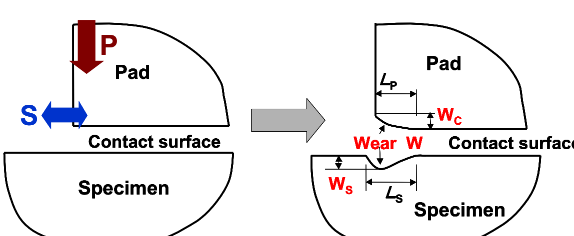

Fig. 5. Wear analysis using contact pressure and slippage.