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Fretting fatigue strength prediction of dovetail joint and bolted joint by using the generalized tangential stress range–compressive stress range diagram

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ABSTRACT

Stress distribution at the contact edge plays a dominant role in fretting fatigue strength. In the previous studies, based on the stress distribution at the contact edge, a generalized tangential stress range–compressive stress range (TSR–CSR) diagram has been proposed as a fretting fatigue fracture criterion. It has been also confirmed that the proposed diagram would be very useful to predict the fretting fatigue strength regardless of contact geometry, loading condition, material strength, environment, etc. for laboratory-type specimens. In the present study, fretting fatigue strengths of actual components, such as a dovetail joint and a bolted joint, have been predicted based on the generalized TSR–CSR diagram. To verify the effectiveness of the prediction based on the generalized TSR–CSR diagram, the fretting fatigue tests of dovetail joints and bolted joints were carried out. The fretting fatigue strengths of dovetail joints and bolted joints predicted based on the generalized TSR–CSR diagram were in good agreement with the experimental results.

1. Introduction

Fretting fatigue is one of the most severe phenomena for inducing a dramatic reduction of fatigue strength, which often leads to an unexpected failure accident [1]. Fretting fatigue failures are common in engineering applications, especially in automotive, railways, aerospace and power generation [2,3]. Due to the increased demand of high efficiency, high power, light weight, etc., the working conditions become severe and then the fretting fatigue situation becomes unavoidable. However, the fretting fatigue damages should be minimised or completely eliminated by the appropriate fretting fatigue design.

So far a large number of studies have been carried out on fretting fatigue from the mechanical and metallurgical points of view. A lot of researches on fretting fatigue strength prediction have also been reported based on crack nucleation parameters, fracture mechanics approaches, fretting wear approaches and so on. [4–8]. However, due to the involvement of numerous complex factors influencing fretting fatigue phenomena like relative slip amplitude, contact pressure, coefficient of friction, specimen geometry, specimen size, contact material, environment, etc. [9], applicability of the fretting fatigue strength prediction methods proposed has been still in the limited range.

It is well known that in fretting fatigue, the crack always nucleates near the edge of fretting contact region [10]. During fretting fatigue, only two stress components are acting on the fretting contact interface: one is the tangential stress and the other is the compressive stress. So, the intrinsic mechanical parameters controlling the fretting fatigue crack nucleation and propagation are only two stress components which act on the contact surface, as explained in Ref. [11]. Therefore, the fretting fatigue fracture is expected to be controlled by a combination of these two stress components. Based on this, in the previous studies, the tangential stress range–compressive stress range (TSR–CSR) diagram has been proposed as a fretting fatigue design curve for various steels [11,12]. Since the TSR–CSR diagram has given a critical condition for fretting fatigue failure in the wide range of contact size, contact geometry and mean stress, it can be considered as a kind of material property. The above mentioned approach is valid for the particular materials for which the diagrams have been obtained. The TSR–CSR diagrams for various steels at fretting fatigue limit are shown in Ref. [13]. To obtain the TSR–CSR diagram is hard work more than obtaining the *S*–*N* curve. Therefore, the generalized TSR–CSR diagram, which can be applied to wide range of materials, is strongly required to develop. Based on this requirement, the generalized TSR–CSR diagram has been proposed in the previous study [13], where the tangential stress range and the compressive stress range have been normalized by tensile strength of the material. It has been confirmed that the generalized TSR–CSR diagram would be useful to predict fretting fatigue strength

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regardless of contact geometry, loading condition, mean stress and material strength for laboratory type specimen [13,14]. An example of fretting fatigue strength prediction for laboratory-type specimens based on the generalized TSR–CSR diagram has been shown in the previous study [14].

In the present study, fretting fatigue strengths of actual components such as dovetail joint and bolted joint have been predicted based on the generalized TSR–CSR diagram. To confirm the effectiveness of fretting fatigue strength prediction based on the generalized TSR–CSR diagram not only in laboratory-type specimens but also in actual components, fretting fatigue strength tests of dovetail joints and bolted joints have been also carried out. The experimental results have been compared with the predicted fretting fatigue strengths.

2. Generalized TSR–CSR diagram

The generalized TSR–CSR diagram proposed in the previous study [13] to predict fretting fatigue strength is shown in Fig. 1. The generalized TSR–CSR diagram for steels can be expressed in the following equation:

$$\mathrm{NTS}-1.15\mathrm{NCS}=\mathrm{CSP} \quad (1)$$

where, NTS is the normalized tangential stress range (=tangential stress range/tensile strength), NCS the normalized compressive stress range (=compressive stress range/tensile strength) and CSP the critical stress parameter, which is equal to 0.28 at fatigue limit of 10^7 cycles. If the NTS and NCS at the contact edge would be known, it would be possible to predict fretting fatigue strength from Eq. (1).

The procedure for predicting fretting fatigue strength using Eq. (1) is as follows.

(1) For the applied cyclic load, TSR and CSR at the contact edge are evaluated by the finite element analysis (FEA). The procedure for evaluating TSR and CSR are explained in Ref. [11].
(2) Normalize the value of TSR and CSR by tensile strength to obtain the NTS and the NCS.
(3) Substitute the values of NTS and NCS in Eq. (1) to obtain the CSP value.
(4) The CSP values are obtained for various cyclic loads.
(5) A plot is made between CSP and cyclic load (load amplitude). From the plot, the load amplitude corresponding to CSP=0.28 can be identified, which is the critical load amplitude for fretting fatigue failure at 10^7 cycles.

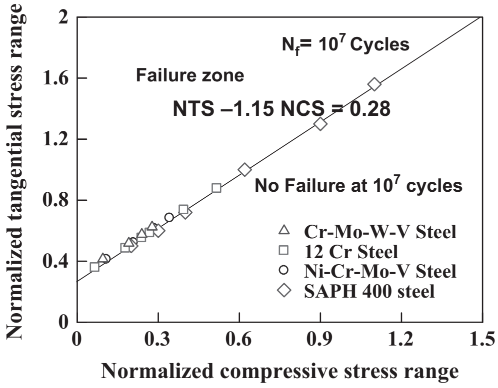

Fig. 1. Generalized TSR–CSR diagram for steels.

3. Fretting fatigue strength prediction based on the generalized TSR–CSR diagram

3.1. Fretting fatigue strength prediction of dovetail joint

Shape and dimensions of the dovetail joint are shown in Fig. 2. The material used for blade side was a 12 Cr steel and for rotor side was a Cr-Mo-W-V steel. Tensile properties of the materials used are given in Table 1. The dovetail joint was constructed by inserting the blade side into the rotor side, as shown in Fig. 3. Two dimensional FEA was carried out by using commercial FEA software MARC. The thickness of blade dovetail and rotor dovetail was 25 mm, which is shown in Fig. 2. The loads applied were well below the elastic limit of the material. The 2D FEA was carried out assuming linear elastic body under plane strain condition to evaluate the stress distribution in the contact region of dovetail joint. A finite element model for the dovetail joint is shown in Fig. 4. The minimum mesh size of 5 μm was used in the contact edge region. The mesh size was selected by performing the trial analysis with models of different mesh sizes, which is given in Ref. [11]. For performing the trial analysis, the same kind of contact geometry as the present analysis and experiments was used. The minimum mesh size was selected based on the result of this trial analysis, which was also in the range of mesh sizes reported [11]. The minimum mesh size will be influenced by the severity of stress singularity at the contact edge. The present minimum mesh size of 5 μm will be effective for plane contact with sharp edge, while the minimum mesh size may become large for cases of plane contact with rounded edge. Contact elements were introduced at the contact interface. The friction coefficient of 0.65 was used for the slip condition of the contact point. The friction coefficient was obtained from the experimental result for a laboratory-type specimen of the 12 Cr steel for the blade material, which is shown in Fig. 5. It can be found from the figure that the

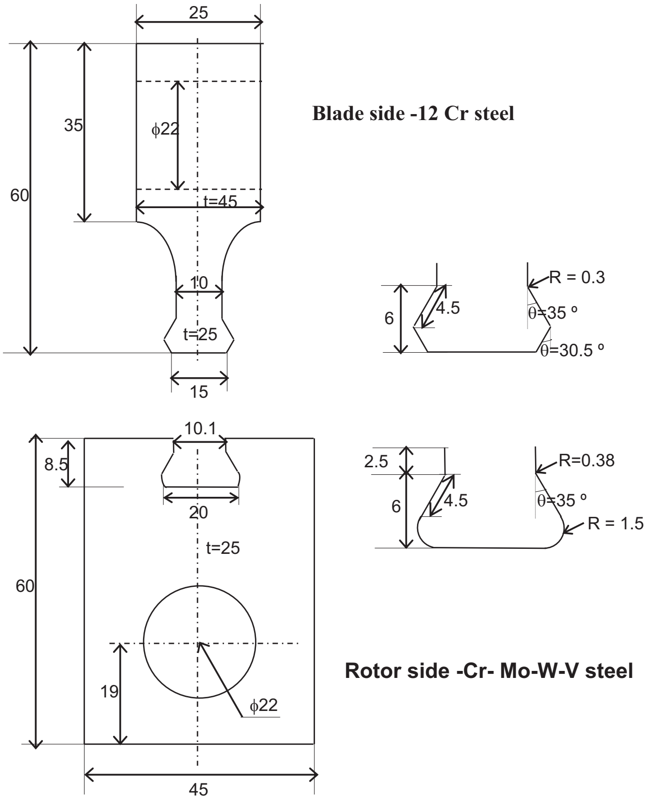

Fig. 2. Shapes and dimensions of dovetail joint specimen.