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Fretting-contact-induced crack opening/closure behaviour in fretting fatigue

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ABSTRACT

Fretting fatigue experiments and finite element analysis of stainless steel (SUS316L) were performed to investigate the crack opening/closure behaviour of a fretting fatigue crack. The crack nucleated at the location of the maximum shear stress range and then propagated in the maximum tangential stress range direction. The crack path could be successfully predicted based on the criterion of the maximum tangential stress range. A crack opening under compressive bulk stress was found in both the experiment and finite element analysis. The crack opening was induced by the restraint of deformation of one side of the crack surface due to the fretting contact. The predicted fatigue lives without consideration of crack opening were significantly longer than those of the experimental results, while the predicted fatigue lives with consideration of crack opening were in good agreement with the experimental results.

1. Introduction

Fretting fatigue is a fatigue with the contribution of fretting at the contact of combined components. The fretting fatigue strength is significantly lower than that of plain fatigue [1,2]. The fretting fatigue life (N_f) depends on both contact conditions (contact pressure, geometry, etc.) and cyclic loading conditions (axial, bending, etc.). According to previous studies [3–6], a fretting fatigue crack is likely to nucleate at a location of maximum shear strain range. After crack nucleation, it propagates in the maximum tangential stress range direction under the influence of contact pressure, tangential stress on the contact surface, and bulk alternating stress. The length of the initial propagating crack could be assumed as the critical smallest crack length [3,7]. The influence of tangential stress decreases as the crack propagates away from the contact surface. Eventually, the propagating crack is under the domination of bulk alternating stress. At this stage, the crack propagates in the direction perpendicular to the bulk alternating stress. It is also known that a fretting fatigue crack nucleates at the very early stage of N_f and that N_f is dominated by the fatigue crack growth (FCG) process. Therefore, by assuming that N_f is equal to the fretting fatigue crack propagation life, fretting fatigue life predictions have been carried out based on the linear-elastic fracture mechanics (LEFM) approach [3–6,8–12].

In the LEFM approach, the stress intensity factor range (ΔK) is defined to characterize the severity of the stress state near the crack tip, as well as the FCG behaviour. However, the FCG behaviour may be influenced by the crack opening/closure behaviour. For crack propagation with the crack opening/closure behaviour, the effective stress intensity factor range (ΔK_{eff}) is known as the driving force of FCG [13]. ΔK_{eff} is defined as K_{max}–K_{op}, where K_{max} is the maximum stress intensity factor and K_{op} is the stress intensity factor at the crack opening point (F_{op}). Various crack opening/closure mechanisms have been proposed: plasticity-induced crack closure, oxide-induced crack closure, roughness-induced crack closure, viscous fluid-induced crack closure, and phase transformation-induced crack closure [14].

Although ΔK has been applied to the prediction of N_f in the previous fretting fatigue research works [3–6,8–12], almost all of them were made without consideration of the crack opening/closure phenomena. For fretting fatigue, crack opening/closure may be possible under the effects of bulk alternating stress, contact pressure, and tangential stress. Noraphaiphipaksa et al. [15] found the crack opening/closure behaviour under fretting fatigue, denoted as the fretting-contact-induced crack closure. Unfortunately, research works on crack opening/closure behaviour in

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fretting fatigue have rarely been reported; thus, the understanding of it is far from complete. Further detailed investigation is therefore required to clarify the crack opening/closure behaviour and to predict more accurate fretting fatigue life.

In the present work, it is assumed that N_f is equal to the fretting fatigue crack propagation life. The crack paths are predicted by using finite element analysis (FEA) with the maximum tangential stress (MTS) range criterion and compared with those from fretting fatigue experiments. The crack opening/closure behaviour is also estimated by using FEA and compared with that from a fretting fatigue experiment using an elastic compliance method. N_f is predicted by combining the FCG curve (ΔK_{eff} – da/dN) obtained in the experiment and the effective stress intensity factor range (ΔK_{eff}) evaluated by FEA. The predicted N_f with and without consideration of the fretting-contact-induced crack opening behaviour is compared with the experimental results. The effect of fretting-contact-induced crack opening/closure on fretting fatigue behaviour is then discussed.

2. Materials and experimental procedures

2.1. Materials

Materials used in the present study were the same materials used in the previous study [15], i.e., an SUS316L rod (12-mm diameter) for fretting fatigue specimens and an SUS316L plate (12-mm thickness) for contact pads. The materials were annealed at 1100 °C for 90 min. Tensile properties of the annealed SUS316L plate and rod were almost identical; thus, it was assumed that these properties were the same. They are σ_Y = 251 MPa, σ_U = 602 MPa, E = 210 GPa and ν = 0.3.

The cyclic stress–strain relationship of the annealed SUS316L rod was determined using the incremental-step test (IST) method [16], i.e., applying progressive fully-reversed cyclic strain on the same specimen. During the IST method, a fully-reversed cyclic strain with a frequency of 20 Hz was applied to the specimen until the cyclic flow stress reached the quasi-steady state or saturation. Then, the fully-reversed cyclic strain was increased to obtain another saturation of flow stress. The increasing of the fully-reversed cyclic strain was continued until the specimen fractured. A plot of the peak flow stresses at saturation as a function of peak strains gives the cyclic stress–strain relationship. The cyclic stress–strain properties of the annealed SUS316L rod (σ_Y = 280 MPa, σ_U = 590 MPa, E = 210 GPa and ν = 0.3) were used for the present FEA.

A single-edge notch bending (SENB) specimen, machined from the SUS316L plate, was used for the FCG experiment. Because the tensile properties of the annealed plate and annealed rod were almost identical, the FCG curve of the annealed plate was assumed to be similar to that of the annealed rod. The geometry of the specimen and experimental procedure were in accordance with the ASTM standard [17]. The FCG experiment was performed using a servo-hydraulic fatigue-testing machine (Instron 8872 with 25-kN load cell). The testing was carried out in air, with a temperature of 25 ± 2 °C and relative humidity of 60 ± 5%. A sinusoidal waveform with a frequency of 20 Hz and stress ratio (R) of 0.1 was used for the FCG experiment. The effective stress intensity factor range (ΔK_{eff}) is defined as K_{max}–K_{op}, where K_{max} is the maximum stress intensity factor and K_{op} is the stress intensity factor at the crack opening point (F_{op}). The FCG curve (ΔK_{eff}–da/dN) is shown in Fig. 1. Although the FCG experiment was conducted under R = 0.1, the FCG curve was arranged by ΔK_{eff} and could be applied to the fretting fatigue life prediction under any stress ratio. Details of the FCG experiment and result can be found in the previous work [18].

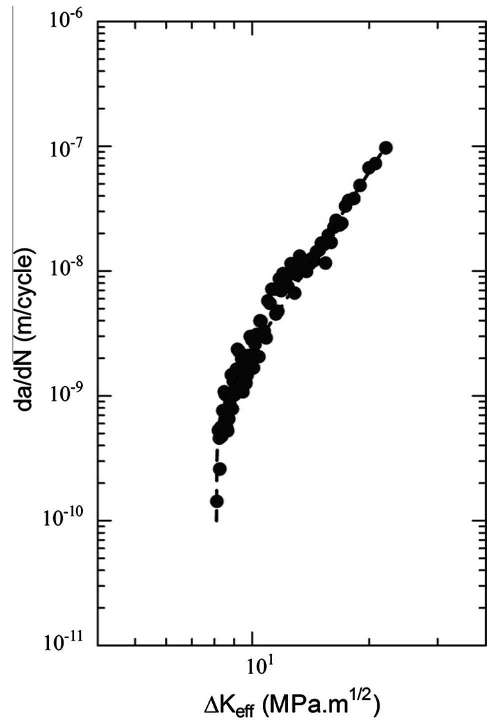

Fig. 1. Fatigue crack growth curve [18].

2.2. Fretting fatigue experiment

Fretting fatigue experiments with bridge-type contact pads were performed in accordance with the JSME standard [19]. The shape and dimensions of the fretting fatigue specimen and contact pad are shown in Fig. 2. The set-up of the fretting fatigue test is shown in Fig. 3. A pair of contact pads was clamped to the gage part of the specimen using clamping screws and a proving ring. The ball joints were used at the interface between the clamping screw and contact pad. To maintain the alignment between contact pads, the proving ring, clamping screws, contact pads and specimen were carefully machined and assembled. The clamping axis, which passes through the clamping screws, was placed at the middle of the specimen. The edges of the contact pads were placed in the direction perpendicular to the longitudinal axis of the specimen. The pad alignment was assured by the observation of contact marks after the fretting fatigue experiment, i.e., (i) the differences between the widths of four contact marks and the average width should be within ±10%, and (ii) the perpendicular angles between

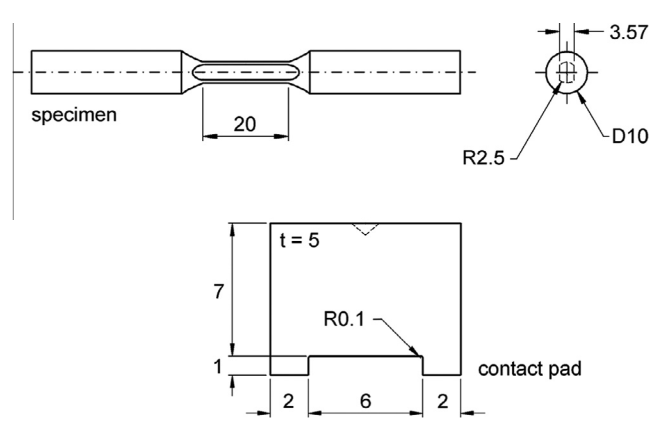

Fig. 2. Fretting fatigue specimen and contact pad (dimensions in mm).