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Experimental validation of a fracture-mechanics model for evaluating fretting-fatigue strength by focusing on non-propagating cracks

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ABSTRACT

Fretting-fatigue strengths of 12%-chromium steel with different static strengths were evaluated quantitatively by applying fracture mechanics considering the effects of small crack and mean stress on the threshold value of stress-intensity factor range, ΔK_{th}. Crack-propagation behavior was investigated by obtaining non-propagating crack lengths of run-out specimens and ΔK_{th} from fretting pre-cracks under several stress ratio, *R* values, including negative mean stress. It was confirmed that test results concerning fretting fatigue strength can be successfully explained by applying maximum-tangential-stress theory. Cracks were confirmed to propagate in stage II at an angle at which the maximum stress-intensity factor range occurred. This model also confirmed the experimental result that the depth of non-propagating cracks decreases as mean stress and material strength increase.

1. Introduction

Fretting-fatigue strength is mostly determined by whether small cracks propagate when cracks are easily initiated in a local high-stress area. Hence, applying fracture mechanics is expected to be effective for evaluating fretting fatigue strength [1–7]. By means of these methods, the fretting fatigue limit is predicted by evaluating whether the stress-intensity factor range, ΔK, is greater than its threshold value, ΔK_{th}. A model for evaluating micro-crack propagation, which is shown in Fig. 1, was developed by Kondo [4]. According to this model, when ΔK is lower than ΔK_{th} at a certain crack depth, the crack is thought to stop propagating and remain as a non-propagating crack (marked by "O" symbol in the figure). On the other hand, when ΔK is larger than ΔK_{th} along the entire crack length, the crack is thought to propagate to failure. The objective of this study is to evaluate fretting-fatigue strength quantitatively by using this model under various test conditions, including different material strengths and mean stresses.

The following two major difficulties need to be addressed when quantitatively applying the micro-crack propagation model:

(1) Effects of small crack size and mean stress on ΔK_{th},
(2) Mixed modes of (tensile and shear) ΔK.

Regarding the effect of small crack size on ΔK_{th}, El Haddad [8] proposed a correlation factor, a_0, for crack length, a, and a threshold for ΔK of a long crack, $\Delta K_{th,\ l}$, expressed as

$$\Delta K_{th} = \Delta K_{th,\ l}\sqrt{a/(a+a_0)} \qquad (1)$$

The empirical rule proposed by Murakami [9], namely, ΔK_{th} is proportional to the one-third power of the square root of the micro-crack surface area is also well known. Although these approaches are effective in estimating ΔK_{th} for micro cracks, there are few data on the effect of mean stress on micro-crack ΔK_{th} [10], especially under a high negative stress ratio (*R*), which is indispensable in evaluating the fretting fatigue strength.

Mixed-mode (tensile and shear) ΔK should be considered because most fretting-fatigue cracks incline under multi-axial stress fields caused by the contact pressure and tangential force [11–13]. According to Mutoh [14], as shown in Fig. 2, the crack path of fretting fatigue is classified into two stages (called "I" and "II"). Stage I is the initial crack stage, in which a crack inclines greatly against the normal direction, and stage II is the crack-propagation stage, in which the crack propagates in the direction perpendicular to the maximum principal stress.

As many researchers have stated [15–17], maximum-tangential-stress theory is considered to be effective for expressing the crack propagation in stage II; hence, one problem is how to model crack propagation in stage I. To solve this problem, Pook's failure-mechanism map [18] in the $\Delta K_{I}-\Delta K_{II}$ plane can effectively separate crack propagation patterns into shear and tensile modes. Although it was proposed to define equivalent stress-intensity factors, such as $(\Delta K_{I}^{2}+8\Delta K_{II}^{2})^{1/2}$ based on the strain-energy release rate, and $(\Delta K_{I}^{4}+8\Delta K_{II}^{4})^{1/4}$ from Tanaka [19], no unified model applicable to various test results [20] has been developed. In summary, regarding the studies on mixed modes, it is difficult to explain the crack

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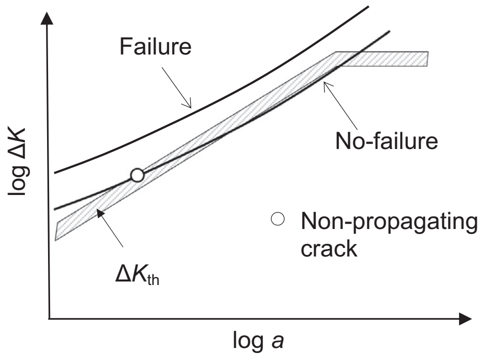

Fig. 1. Schematic of small-crack propagation model at fretting fatigue.

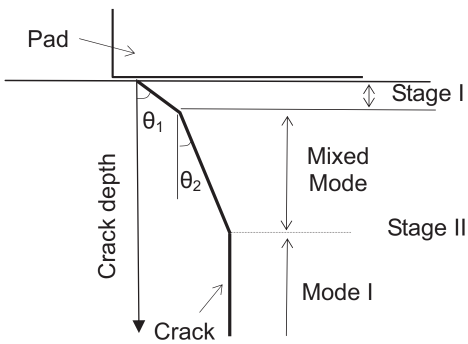

Fig. 2. Schematic view of fretting crack propagation.

Table 1
Mechanical properties of materials.

	0.2% Proof stress (MPa)	Tensile strength (MPa)	Elongation (%)	Reduction of area (%)	Vickers hardness (Hv)
Sample A	610	745	26.3	65.5	238
Sample B	842	1037	15.4	51.0	329

propagation in stage I because it is difficult to experimentally obtain the mode II thresholds [21] and quantitatively estimate the actual ΔK_{II} in consideration of crack-surface-friction effects [22].

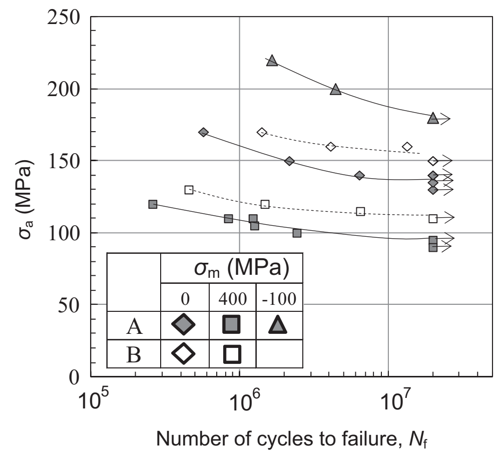

Fig. 4. S–N diagram of fretting fatigue tests.

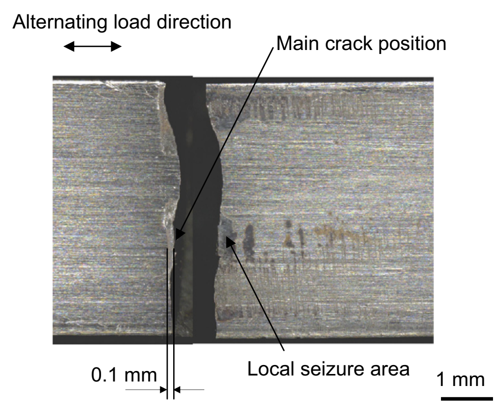

Fig. 5. Side view near contact edge of failure specimen. (Sample A: $\sigma_m = 0$ MPa, $\sigma_a = 150$ MPa).

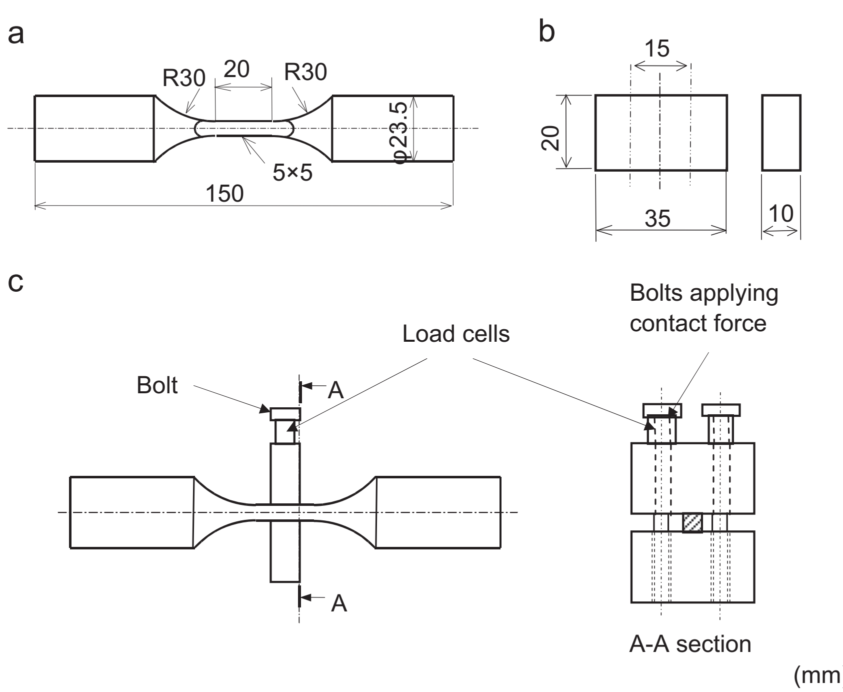

Fig. 3. Shapes of specimens and test apparatus: (a) specimen, (b) contact pad, and (c) test apparatus.