Theoretical and Applied Fracture Mechanics 73 (2014) 161–169

Contents lists available at ScienceDirect

Theoretical and Applied Fracture Mechanics

journal homepage: www.elsevier.com/locate/tafmec

A practical expression for evaluating the small shear-mode fatigue crack threshold in bearing steel

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ARTICLE INFO

Article history:
Available online 1 August 2014

Keywords:
Shear-mode fatigue crack
Small crack
Threshold stress intensity factor range
$\sqrt{area}$ parameter model
Bearing steel

ABSTRACT

The ranges of the threshold stress intensity factor (SIF), ΔK_{IIth} and ΔK_{IIIth}, for small shear-mode cracks in bearing steel are measured using torsional fatigue testing under static compression. The threshold values are described as a function of the crack size and the crack-face interference. In addition, to simplify the evaluation of the shear-mode threshold, a single parameter, K_τ, is introduced to represent the SIF of shear-mode cracks. Moreover, a practical expression for approximating K_τ is proposed on the basis of the $\sqrt{area}$ parameter model. Finally, the threshold SIF range $\Delta K_{\tau th}$ is found to exhibit a dependence on the crack size similar to that of small mode I cracks, i.e., $\Delta K_{\tau th} \propto (\sqrt{area})^{1/3}$, for the regime of small shear-mode cracks with $\sqrt{area}$ values ranging from 0.01 to 1 mm.

1. Introduction

Flaking, a typical fracture mode in rolling contact fatigue (RCF) of rolling bearings, is known to be associated with shear-mode (modes II and III) fatigue crack growth [1–22]. Therefore, it would be desirable to handle the flaking strength as a crack problem in a manner similar to the methodology used to solve many metal fatigue problems with mode I crack growth. To quantitatively evaluate the flaking strength based on fracture mechanics, a basic understanding of the behavior of shear-mode cracks and their threshold condition for propagation should be established. The flaking strength associated with subsurface cracking is strongly influenced by the size of the defect at the fracture origin (e.g., non-metallic inclusion), where the flaking strength decreases with an increase in the defect size. In fact, in the quality control of bearing steels, a great deal of effort has been made to improve the cleanliness of the material in the manufacturing process [23]. The dependence of the RCF strength on inclusion size implies that the strength is determined by a local fracture process at/near the inclusion (i.e., crack initiation and early-stage growth). When performing a fracture mechanics-based evaluation, the fracture process must be addressed as a *small crack problem* [1–3,24–32]. However, although significant progress has occurred over the last two decades [4–17], the shear-mode growth behavior of a crack in hard steel is still not fully understood, especially for small cracks. Recently, under these circumstances, Matsunaga et al. [1,2] performed torsional fatigue tests with static compression to measure the ranges of the threshold stress intensity factor (SIF), ΔK_{IIth} and ΔK_{IIIth}, for the shear-mode growth of small surface cracks between approximately 0.01 and 1 mm in length in a bearing steel. Consequently, these authors noted a crack size dependence for ΔK_{IIth} and ΔK_{IIIth}.

In this study, the threshold SIF ranges for small shear-mode cracks, ΔK_{IIth} and ΔK_{IIIth}, in bearing steel are measured using the above testing method with a newly developed testing machine [33]. The threshold values are described as a function of the crack size and the crack-face interference. In addition, the SIFs are represented by a single parameter, K_τ, to simplify the evaluation of the shear-mode threshold. Moreover, a practical expression for approximating K_τ is proposed on the basis of the $\sqrt{area}$ parameter model [23]. Finally, the threshold SIF range $\Delta K_{\tau th}$ is found to exhibit a crack size dependence similar to that of mode I cracks, i.e., $\Delta K_{\tau th} \propto (\sqrt{area})^{1/3}$, in the small crack regime for $\sqrt{area}$ values of 0.01–1 mm.

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http://dx.doi.org/10.1016/j.tafmec.2014.07.016
0167-8442/

Nomenclature

a	half crack length at the specimen surface
$area_{defect}$	projected area of an artificial defect
$area_{crack}$	area of an interfering crack face
b	crack depth
$E(k_1)$, $E(k_3)$	complete elliptic integral of the second kind
k_1	$(1-b^2/a^2)^{1/2}$
k_2	aspect ratio of a crack = b/a
k_3	$(1-a^2/b^2)^{1/2}$
k_4	a/b
$K(k_1)$, $K(k_3)$	complete elliptic integral of the first kind
K_{II}, K_{III}	stress intensity factors for modes II and III
K_τ	stress intensity factor of a shear-mode crack
f	fraction of the interfering crack area over the total areas of the defect and crack = $area_{crack}/(area_{defect} + area_{crack})$
HV	Vickers hardness
N	number of cycles
N_{total}	total number of cycles applied
ΔK_{II}, ΔK_{III}	stress intensity factor ranges for modes II and III
ΔK_{IIth}, ΔK_{IIIth}	threshold stress intensity factor ranges for modes II and III
$\Delta K_{\tau th}$	threshold SIF range for shear-mode fatigue cracks
ν	Poisson's ratio
σ	normal stress
σ_s	static compressive stress applied in the axial direction
τ	shear stress
τ_a	shear stress amplitude at the specimen surface
$\tau_{a\ np}$	shear stress amplitude at which a crack becomes non-propagating
φ	angle from the surface along the crack front of a semi-elliptical crack
$\sqrt{area}$	square root of the area of a crack
$\sqrt{area_i}$	square root of the area of an internal crack
$\sqrt{area_s}$	square root of the area of a surface crack

2. Threshold SIF ranges (ΔK_{IIth} and ΔK_{IIIth}) for small shear-mode cracks

Firstly, in this chapter, a testing method for the growth of small shear-mode fatigue cracks is described. Then, based on the experimental results, the crack size dependence of the threshold SIF ranges for shear-mode growth is discussed.

2.1. Experimental

2.1.1. Material and specimen

The material investigated in the present study was a commercial grade SAE52100 bearing steel. The chemical composition in mass % was 1.01 C, 0.25 Si, 0.34 Mn, 0.017 P, 0.007 S, 0.10 Cu, 0.05 Ni, 1.41 Cr, 0.03 Mo and bal. Fe. The steel was heat-treated at 840 °C for 30 min in a deoxidizing gas followed by oil quenching and tempering at 170 °C for 2 h. The average Vickers hardness, HV, measured under a load of 9.8 N was 749.

Fig. 1 shows the shape and dimensions of the fatigue specimen. The specimen surface was finished by polishing the surface with an emery paper and then buffing the surface with a diamond paste. The following two types of artificial defects were introduced to the specimen surface: (i) two adjacent, shallow drilled holes with crack-like thin slits produced by the focused ion beam (FIB) technique at both ends and (ii) a semi-circular slit created by an electrical discharge between the FIB slits at both ends. Fig. 2 shows the shapes and dimensions of these defects, which are hereafter designated as the Type A defect and Type B defect.

2.1.2. Fatigue test

Fully reversed cyclic torsion tests were conducted using a newly developed fatigue testing machine [33] operating at a test frequency of 50 Hz in ambient air. In the experiments, an axial static compressive stress, σ_s, of −1200 MPa was superposed on the cyclic torsion to suppress the tendency of mode I crack branching. This test condition was previously demonstrated as an appropriate condition for attaining stable growth of a shear-mode fatigue crack in very hard bearing steel [1,2]. During the test, the shear stress amplitude was varied in a stepwise fashion to obtain a non-propagating crack. If the crack did not propagate over an additional 10^7 cycles after a decrease in τ_a, the crack was considered to be a non-propagating crack, and the corresponding stress amplitude was considered to be the threshold stress. The tests were periodically halted for replica observation of the crack initiation and growth behaviors.

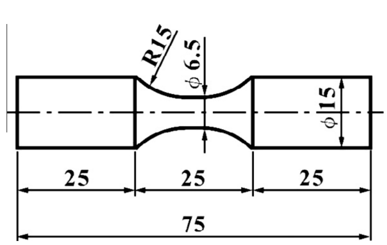

Fig. 1. Shape and dimensions of test specimen, in mm.

2.2. Influential factors for the crack growth threshold

2.2.1. Results of fatigue tests

Fig. 3 shows the growth curves of shear-mode cracks propagating in the axial direction for the two types of defects. Both cracks grew from an edge of the defect and finally became non-propagating cracks as the shear stress amplitude decreased. Fig. 4 shows optical micrographs of the non-propagating cracks. Fig. 5 shows the shape and dimensions of the non-propagating cracks obtained by the successive polishing method, in which the crack was observed after every removal of 3–10 μm-thick layer. In a shear-mode semi-elliptical crack, such as the cracks in Fig. 5, the crack propagates in mode III at the crack depth, whereas in the vicinity of the free surface, the propagation is dominated by mode II [34–37]. Mode I crack branching was not observed along the surface or internal fronts of the non-propagating cracks; hence, these cracks were concluded to have propagated in the shear-mode.

From the shapes and dimensions of the non-propagating cracks, the threshold SIF ranges, ΔK_{IIth} and ΔK_{IIIth}, were calculated using the solution of Kassir and Sih (*cf.* Eqs. (8)–(11) in Section 3.1) [38]. In the calculations, the half-length, a, and depth, b, of a surface crack were regarded as the major and minor radii of an elliptical crack, respectively. The Poisson's ratio of the material, ν, was assumed to be 0.3. Table 1 lists the dimensions of the non-propagating cracks together with the test conditions. In the specimen with a Type A defect, ΔK_{IIIth} could not be determined, as no crack existed at the notch depth (*cf.* Fig. 5(a)). In Table 1, the experimental data for the JIS-SUJ2 bearing steel obtained by Matsunaga et al. [1] are also listed.