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Procedia Structural Integrity 7 (2017) 453–459

Structural Integrity Procedia

www.elsevier.com/locate/procedia

3rd International Symposium on Fatigue Design and Material Defects, FDMD 2017, 19-22 September 2017, Lecco, Italy

Quantitative Evaluation of the Flaking Strength of Rolling Bearings with Small Defects (Part 1: FEM Analyses of the Stress Intensity Factor, K_{II}, under Rolling Contact)

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Abstract

It has been demonstrated that the rolling contact fatigue (RCF) test, using a specimen with a small drilled hole, is a useful means of evaluating the influence of a minor defect on the flaking strength of steels. In this study, RCF tests were conducted on rolling bearings with small drilled holes. Flaking failure was determined to be caused by the shear-mode fatigue cracks that emanated from the small defects. As a first step to quantifying the crack-growth threshold according to fracture mechanics principles, using the finite element method (FEM), it was necessary to analyze the Mode II stress intensity factor (SIF) range, ΔK_{II}, of a ring-shaped crack, as emanated around the edge of a drilled hole after the passage of a rolling element. Subsequently, the derived values were correlated with the ΔK_{II} values of penny-shaped cracks in an infinite body under uniform shear via a correlation factor, f_{drill}. The SIF of the ring-shaped crack was also uniformly correlated with that of the penny-shaped crack, using the single factor, f_{drill}, irrespective of the hole diameter, d, the depth of the hole-edge, h', and the maximum contact pressure, q_{max}, within the following ranges: $d = 0.05 \sim 0.2$ mm, $h' = 0.05 \sim 0.345$ mm and $q_{max} = 2.0 \sim 3.0$ GPa. The obtained results were later applied towards the quantification of the RCF test results, as detailed in Part 2 of the report on this research.

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10.1016/j.prostr.2017.11.112

Keywords: Rolling contact fatigue ; Flaking ; Stress intensity factor ; Shear-mode crack ; FEM analysis ; Drilled hole

1. Introduction

Flaking-type failure in rolling bearings is a form of fatigue failure produced by cyclic contact stress. A typical mode of failure seen in rolling bearings, sub-surface flaking occurs as a result of the cracking which emanates from the non-metallic inclusions beneath the contact surface (Mitamura, 2008). It has been recognized that bearings fabricated from cleaner steels tend to exhibit a longer flaking-life. However, such a defect-size impact on flaking strength has not yet been quantitatively understood, insofar as the failure mechanism is concerned. In order to obtain such a quantitative evaluation, the following factors need to be further investigated: (i) crack-growth behavior under rolling contact, for which direct observation beneath the contact surface is difficult and, (ii) shear-mode, fatigue crack-growth properties which dominate most of the flaking process.

In the case of hard steels, such as bearing steel, no standard test method exists for the assessment of shear-mode crack properties. Consequently, some research groups developed individual techniques for evaluating shear-mode growth in hard steels (Murakami *et al.,* 1994, 2002, 2003, 2008; Otsuka *et al.,* 1994; Matsunaga *et al.* 2009, 2011; Okazaki *et al.,* 2014, 2017; Endo *et al.,* 2015). Meanwhile, other groups performed rolling contact fatigue (RCF) tests on specimens with artificial defects, thereby investigating the behavior of RCF crack properties (Kida *et al.,* 2004, 2006; Fujimatsu *et al.*, 2015). Komata *et al.* conducted RCF tests using a JIS-SUJ2 plate with small holes drilled at various depths and diameters in the middle of the raceway (Komata *et al.,* 2012, 2013). They demonstrated that flaking strength can consistently be assessed on the basis of fracture mechanics by taking two parameters into account, *i.e.,* shear-stress amplitude at the depth of crack-growth, as well as crack-size dependency on the threshold stress intensity factor (SIF) range of small, shear-mode fatigue cracks.

In this study, in order to evaluate the RCF strength as a crack problem, RCF tests were carried out on rolling bearings with small holes drilled at various diameters and depths along their raceways. As a first step towards fulfilling the research objective of this paper, it was necessary to analyze the Mode II SIF range of a ring-shaped crack originating at the edge of a drilled hole under rolling contact, using the finite element method (FEM). The obtained values were correlated with the SIF ranges for penny-shaped cracks in an infinite body under uniform shear, through the intermediary of a correlation factor. The results were later applied for the quantification of RCF test results, as detailed in Part 2 of this study.

Nomenclature

d	diameter of drilled hole
h'	depth of the edge of drilled hole
a	radius of penny-shaped crack in an infinite body
a'	length of ring-shaped crack emanating around the edge of drilled hole
S_a	semi-major axis of contact ellipse between rolling element and raceway
S_b	semi-minor axis of contact ellipse between rolling element and raceway
F	Applied load on rolling element
q_{max}	Maximum contact pressure
τ_{xz}	Shear stress in *x-z* plane
K_{II}	Mode II stress intensity factor
ΔK_{II}	Mode II stress intensity factor range