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Effect of material defects on crack initiation under rolling contact fatigue in a bearing ring

Lin Hua*, Song Deng, Xinghui Han, Song Huang

School of Automotive Engineering, Hubei Key Laboratory of Advanced Technology of Automotive Parts, Wuhan University of Technology, Wuhan 430070, China

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ABSTRACT

The effects of material defects such as pores on the crack initiation under rolling contact fatigue (RCF) in a bearing ring are investigated here. First, the main contact position between the ball and the raceway surface is investigated, and the effect of the depth of the pore on the crack initiation is analyzed. Second, several parameters, such as radial load, surface traction and raceway groove curvature radius (RGCR), are varied to evaluate stress intensity factors (SIFs), crack growth rates and crack growth angles. The results provide valuable guidelines for enhanced understanding of RCF in bearings.

1. Introduction

The failure of machine components due to fatigue is of major concern in most engineering applications. In machinery (rolling element bearings, gears, rail-wheel contacts, etc.), RCF is the key aspect of component failure. When two non-conformal bodies roll against each other, alternating stress is induced throughout a very small volume. Under alternating stress, cracks first initiate in the subsurface due to material defects, such as pores and inclusions, and then propagate toward the surface. Next, a chunk of material lifts from the surface, leading to spalling, and RCF failure occurs. This failure can result in significant economic costs, particularly in the area of personal injuries. Therefore, it is of great importance to study the effect of material defects on the crack initiation under RCF in a bearing ring.

Previous work has been carried out on RCF failure mechanism. Some studies [1–4] mainly investigated how material defects induced a very high local increase in stress and strain and the influence of load magnitude, contact geometry, defect location and size on the fatigue impact. Moreover, RCF crack initiation and propagation mechanisms in fluid stress field have been studied [5–8], and the coupled effectiveness between contact pressure, Coulomb friction, crack face friction and traction direction and fluid stress have been emphasized. Additionally, RCF life evaluation [9] is important for predictions of RCF failure. Some criterions, such as the Jiang–Sehitoglu criterion [10], the Brown–Miller strain-life equation [11], the Basquin equation [12] and Pairs' law [13], have been used to calculate fatigue life of crack initiation and propagation. However, it should be noted that on one hand, a majority of the studies above were primarily concentrated on the RCF crack growth in railway wheel steel, based on the conditions of repeated rail/wheel contact, while little attention was paid to the effect of the bearings contact condition on the RCF property of the bearings. However, the contact condition of the bearings is more complex than that of the rail/wheel. Particularly, the contact between the ball and the bearing raceway is elliptical for the ball bearings and the aspect ratio between the two axes of the ellipse is sufficiently high. On the other hand, the RCF crack initiation mechanisms when pores exist below the subsurface remain unclear, because the studies on the influence of material defects on RCF mainly concerned the fatigue impact and fatigue life evaluation. Hence, it is necessary to investigate the effect of pores on fatigue crack initiation, i.e., SIF calculations, crack growth rate and crack growth angle are used to assess the crack initiation modes, the degree of fatigue damage and the crack initiation direction. To date, fracture mechanics also have been used to predict RCF. Based on SIF calculations, the typical fatigue failure mode of rails was revealed during the passage of rail/wheel contact [14]. The subsurface crack propagation when a pore exists below the Hertzian contact centre of the rail was analyzed under rolling contact loading [15]. Correlation of the crack growth rates with various parameters, such as the surface Coulomb friction, the crack inclination, the crack depth and the crack face friction, were investigated to determine the significant conditions that influence RCF [16,17]. However, the studies given above neglected

* Corresponding author. Tel.: +86 15 92645 2706; fax: +86 27 8387 5634.
E-mail address: lhuasvs@yahoo.com.cn (L. Hua).

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Nomenclature

K_{eff}	effective stress intensity factor
dL/dN	crack growth rates
L	half length of the crack
N	number of loading cycles
C	material constant
ΔK	stress intensity factor range
n	slope index
H	pore depth (the distance between the upper face of the pore and the raceway surface)
K_{IU}	mode I stress intensity factor for upper crack front
K_{IIU}	mode II stress intensity factor for upper crack front
K_{IIIU}	mode III stress intensity factor for upper crack front
K_{ID}	mode I stress intensity factor for lower crack front
K_{IID}	mode II stress intensity factor for lower crack front
K_{IIID}	mode III stress intensity factor for lower crack front
β	angle of crack growth along the crack front
M	moment
θ	rotation angle of bearing ring

Table 1
Basic geometrical data of a 6208 deep groove ball bearing inner ring.

Name	Symbol	Value
Bearing bore diameter [mm]	d	40
Bearing width [mm]	B	18
Steel ball diameter [mm]	D_w	12.7
Diameter of ball's centre in the bearing [mm]	D_{pw}	60
Inner raceway groove curvature radius [mm]	r_i	6.54

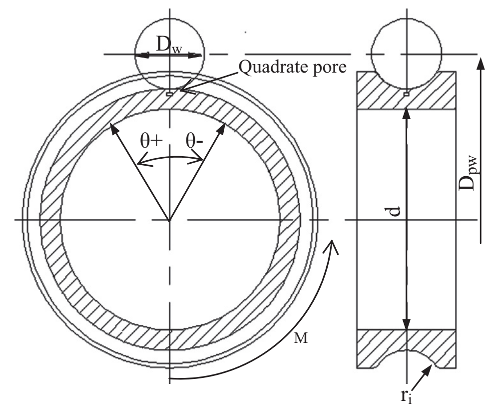

Fig. 1. Plane sketch of a bearing inner ring.

the contribution of mode III SIF to the RCF crack propagation. In reality, crack growth behavior is composed of the three crack modes (model I, II and III). For crack growth rates in particular, mode III cracks play an indispensable role on the RCF crack growth. Therefore, it is of great importance to study the effect of pores on the RCF crack initiation based on SIF calculations by developing an accurate three-dimensional model of the bearing ring.

In this paper, a realistic three-dimensional model of the bearing ring containing a pore below the raceway surface is established using the finite element (FE) software ABAQUS. First, this model is validated according to the Hertzian contact theory. Second, based on this reliable model, the effect of contact position on SIF calculations is investigated and the role of the pore's depth on the RCF crack initiation is analyzed. Second, several parameters, such as radial load, moment and RGCR, are varied to study SIFs, crack growth rates and crack initiation angles. The results are helpful for better understanding the effect of material defects on RCF of bearings.

2. Numerical model development and stress intensity factor calculations

2.1. Numerical model development

In this paper, the inner ring of a 6208 (bearing designation, SKF) deep groove ball bearing is considered as the RCF research object. The basic geometric data are shown in Table 1. A plane sketch of the geometric model used for the RCF analysis is presented in Fig. 1. The material defect is modeled as a quadrate pore located at a depth (0.5 mm) below the raceway surface and its size is assumed to be 0.5 mm. The symbol θ indicates the rotation angle of the inner ring. The rotation angle is defined to be negative when the contact position is to the left of the pore. The moment M is exerted on the inner ring in the anticlockwise direction.

The numerical model was developed as shown in Fig. 2. The material used in this study was AISI 52100 steel, and the main parameters are: Young's modulus $E=2.10\times10^5$ MPa, Poisson's ratio $\nu=0.3$ and material density $\rho'=7.85\times10^3$ kg/m^3. The inner ring was meshed with 20-noded quadratic hexahedron elements. To get accurate stress and strain, the refined mesh was created around the pore. The element size near the pore was an approximately 0.1-mm cube, as shown in Fig. 2(b). The refined meshes above the pore were 10 layers and they were increased with increasing the depth of the pore. The other part of the inner ring was roughly meshed for reducing the computer calculation time. To study the effect of the pore on the crack initiation, it was necessary to define the crack front, crack tip and crack extension direction [18], as shown in Fig. 2(b). The surface of the pore was defined as the crack front, the edge was defined as the crack tip, and the direction parallel to the crack front was assumed as the crack extension direction. To improve the accuracy of the stress intensity factors, the singularity parameter is defined to be 0.25 due to this linear elastic model. Using this method, four crack tips were defined due to the radial load applying to the inner ring, as shown in Fig. 2(c). Tip 1 and 2 were located on the upper crack front, and tip 3 and 4 were located on the lower crack front. The steel ball was defined as a rigid body and its displacement degrees of freedom were constrained. A radial force F_r in the radial direction and a moment M in the circumferential direction were exerted on the inner ring. The surface friction coefficient was 0.15, and the crack face friction coefficient was assumed to be 0.

In a real contact between the steel ball and the inner ring, the pressure distribution is often complex and highly dependent on the exact profiles of the steel ball and inner ring as well as their relative positions. However, a significant amount of previous work on RCF (e.g., [1,4,10]) has employed either a simple representative Hertzian line or elliptical contact. Using the boundary element modeling approach, it is possible to directly simulate the ball contacting the inner ring. Hence, it is convenient to obtain a real pressure distribution on the raceway surface by defining the contact surfaces within the model.