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A continuum damage mechanics based approach to damage evolution of M50 bearing steel considering residual stress induced by shot peening

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ABSTRACT

The damage evolution induced by three types of carbides in M50 bearing steel is studied in this paper. Stress distribution in the micro-domain is initially obtained to calculate the damage accumulation of the elements. Subsequently, the process of the butterfly generation is simulated. It can be seen that the butterfly wings are generated at the sites where maximum stress appears. The irregular shape carbide seems to be most harmful to the bearing material. Finally, the effect of residual stress on damage evolution induced by the carbides is investigated. The result shows that higher temperature, smaller balls and ion implantation are beneficial for the strengthening of residual stress and hence damage accumulation rate is reduced.

1. Introduction

As crucial components of high-end machinery, rolling bearings often work under the condition of heavy load and high speed. Stress concentration is generated under the contact surface due to the existence of inhomogeneities within the bearing material. Failures of bearings occur due to the severe working conditions. Rolling contact fatigue (RCF) is the main mode of failure for rolling bearings and affects the life of rolling bearings [1]. For some advanced applications, i.e., aerospace engines, wind turbines, high-speed railways, the fatigue life of the bearing is required to be in excess of 30,000 h or 100 billion (10^{11}) contact cycles [2]. Conventional bearing steels such as AISI 52100 and SAE 4118 cannot meet the requirements. Nowadays, case hardened M50 steel is widely used in the above advanced applications due to its excellent performance [3]. The fatigue behavior of M50 bearing steel under severe working condition remains unclear.

It is well known that non-metallic inclusions act as stress raisers in bearing material. The problem of an inclusion in the matrix has been initially investigated by Melander [4,5]. The work completed by Melander [4,5] applied energy release criterion to study crack initiation and propagation induced by the inclusion and the results show that crack propagation is influenced by the type of inclusion. A number of investigations about inclusions have been conducted since the pioneering work of Melander. The effect of inclusion characters, such as shape [6–8], elastic modulus [9–12], size [1,11,12], depth [1,11,12], distribution of inclusions [13,14] have been studied. Many simulation and experimental results demonstrate that inclusions with irregular shape could cause higher stress concentration and are more harmful to bearing material. Stiénon et al. [15] established the finite element model of a real inclusion and found that stress concentration is strongly influenced by the orientation of inclusion-cavities system. Zhang et al. [16], Mohamed et al. [17] extracted the morphology of inclusions based on the Scanning Electron Microscope (SEM) images. The results indicated that inclusion shape and interaction of inclusions determine the stress distribution. Jiang et al. [18–20] applied electron backscatter diffraction (EBSD) technique to reconstruct the geometry of the inclusion. Initial crack is observed at the corner of the inclusion where maximum stress appears. There are several numerical methods to analyze the inclusion problems, such as finite element method [21–23], molecular dynamics method [24,25], convergent iterative algorithm [26–29]. Finite element method is most widely used for the inclusion problems and relatively accurate results could be obtained; molecular dynamics method is beneficial for mechanism analysis, however it is not fit for macroscale computation; the time consumption and memory occupation required by convergent iterative algorithm decrease obviously, but this method is not applicable when the domain is complicated.

In recent years, the idea of damage accumulation has been introduced to numerical methodology of rolling contact fatigue. In the perspective of damage mechanics, damage accumulation in bearing steels results in the final fatigue failure. Evans, et al. [30–32] acquired the surface profiles of helical test gears and accomplished the micro-

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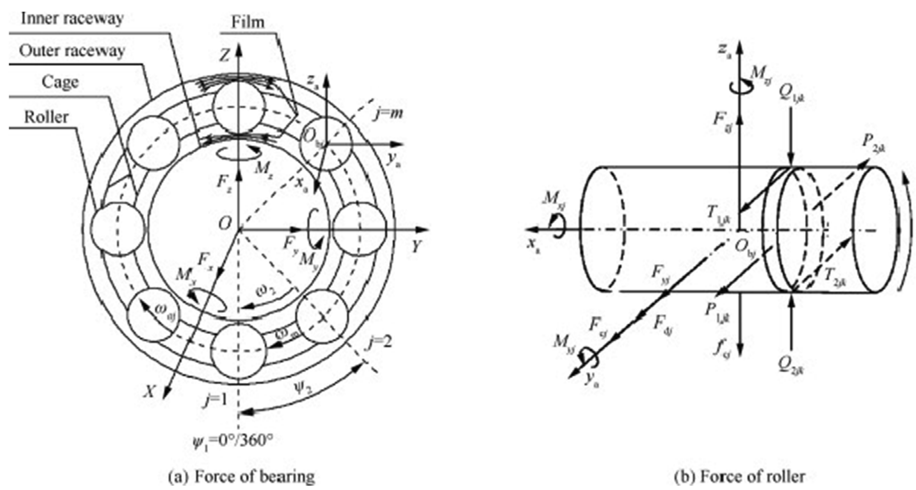

Fig. 1. Force equilibrium of the bearing and the rollers [41].

EHL simulations considering the real contact surfaces. Palmgren-Miner rule was adopted to calculate damage accumulation. The results showed that fatigue damage is closely related to surface topography. Ali and M.M. Khonsari [33,34] applied continuum damage mechanics to predict damage accumulation and crack initiation. The loading sequence effect on fatigue behavior is studied. Researchers in Purdue [1,10,11,35] incorporated the continuum damage mechanics into finite element model to simulate the subsurface spalling in bearing steel. The results are in good agreement with that observed in tests.

Surface treatment such as shot peening and heat treatment will induce compressive residual stress in the steel material. A number of investigations have shown that certain level of compressive residual stress can prolong the fatigue life of bearing steel. R.C. Dommarco, et al. [36] analyzed the evolution of residual stress and retained austenite during rolling process for SAE 52100 steel. Their results clearly revealed that compressive residual stress makes contribution to improve the fatigue life of the steel. Bryan, et al. [37] conducted rolling contact fatigue experiments on AISI M50 bearing balls and they found that initial residual stress in bearing balls inhibits the change of material properties and microstructure after RCF loadings. In other words, the initial residual stress in bearing balls is beneficial for reducing the severity of RCF loading. Youngsik [38] investigated the effect of residual stress on rolling contact fatigue in view of crack initiation life and crack propagation life. It should be noted that the fatigue life is enhanced by more than 40%. Y.B. Guo [39] concluded that residual stress would affect near-surface initiated RCF rather than subsurface initiated RCF. Yi Shen, et al. [40] developed a numerical model to calculate the fatigue damage accumulation of steel material by continuum damage mechanics (CDM). It has been found that damage accumulation rate decreases in the case of compressive residual stress which improves the fatigue life of bearing steel.

Developing an understanding of the damage accumulation induced by carbides is essential for investigating the fatigue behavior of M50 bearing steel. To address the damage accumulation in M50 bearing steel, the damage initiation and growth process is necessary to be studied. Previous literature mainly focused on the stress concentration and damage accumulation induced by inclusion with regular shape. There is no doubt that the sharp edge of inclusion with irregular shape will cause high stress concentration and initial fatigue crack, thus more attention should be paid on it. Meanwhile, studies on the effect of residual stress on damage accumulation in M50 bearing steel are urgently needed. The studies are necessary for enhancing the surface strengthen technology.

The purpose of this paper is to develop a numerical method based on the Voronoi finite element method and continuum damage mechanics to solve fatigue problems of M50 bearing steel in the presence of carbides. The stress concentration and damage accumulation in M50 bearing steel which contains carbides with irregular shape could be investigated by this method. Afterwards, the effect of residual stress on damage evolution will be studied. It should also be noted that the procedure could be extended to other bearing steels. The Voronoi finite element method was successfully employed by Sina Mobasher et al. [1] and the simulation results are very close to that obtained in experiments.

2. Description of the numerical model

This paper aims to establish the numerical calculation system from macroscopic to microcosmic. Initially, the contact load between rollers and raceway is obtained by quasi-dynamic method. Then, elastohydrodynamic lubrication theory is employed to calculate the contact pressure between the friction pairs. Secondary peak stress emerges in the condition of elastohydrodynamic lubrication condition. Finally, the damage evolution of M50 bearing material is investigated by the combination of Voronoi finite element method and continuum damage mechanics.

2.1. Governing equations for quasi-dynamic method

The quasi-dynamic method is adopted for force and motion analysis of rolling bearings. The method is widely used for solving rolling bearing's mechanics and motion problems due to its high accuracy and applicability. Fig. 1 describes the force equilibrium of the bearing and the rollers. In Fig. 1, *OXYZ* represents the fixed coordinate system of the roller bearing and $O_{bj}x_ay_az_a$ represents the relative coordinate of the roller. j is the jth roller and k represents the kth slice of the roller. The quasi-dynamic method is based on the following assumptions: 1) the loading of the rollers is completed instantaneously; 2) the effect of gyroscopic moment is neglected; 3) the friction between the roller and the raceway flange is neglected.

The force and moment equilibrium equations of the rollers, cage and raceway are given in equation (1). In the equations, T_{1jk} and T_{2jk} are the traction force; P_{1jk} and P_{2jk} mean the film pressure; Q_{1jk} and Q_{2jk} are the contact loads between rollers and raceway; F_{cj} and f_{cj} stand for the normal and tangential forces of the cage; F_{yj} and F_{zj} mean the initial forces; F_{dj} refers to the resistance of gas–oil mixture; M_{xj}, M_{yj} and M_{zj} are the initial moments.

Newton-Raphson iterative method is adopted to solve the equation (1) to obtain the contact loads between rollers and raceway. A thorough description of the quasi-dynamic method can be found in the reference by Cui, et al. [41]. The working condition for the roller bearing is shown in Table 1. The maximum contact load between the rollers and