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Effect of non-metallic inclusions on butterfly wing initiation, crack formation, and spall geometry in bearing steels

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A B S T R A C T

Non-metallic inclusions such as sulfides and oxides are byproducts of the bearing steel manufacturing process. Stress concentrations due to such inclusions can originate cracks that lead to final failure. This paper proposes a model to simulate subsurface crack formation in bearing steel from butterfly-wing origination around non-metallic inclusions until final failure. A 2D finite element model was developed to obtain the stress distribution in a domain subjected to Hertzian loading with an embedded non-metallic inclusion. Continuum Damage Mechanics (CDM) was used to introduce a new variable called Butterfly Formation Index (BFI) that manifests the dependence of wing formation on depth. The value of critical damage inside the butterfly wings was obtained experimentally and was used to simulate damage evolution. Voronoi tessellation was used to develop the FEM domains to capture the effect of microstructural randomness on butterfly wing formation, crack initiation and crack propagation. Then, the effects of different inclusion characteristics such as size, depth, and stiffness on RCF life are studied. The results show that stiffness of an inclusion and its location have a significant effect on the RCF life: stiffer inclusions and inclusions located at the depth of maximum shear stress reversal are more detrimental to the RCF life. Stress concentrations are not significantly affected by inclusion size for the cases investigated; however, a stereology study showed that larger inclusions have a higher chance to be located at the critical depth and cause failure. Crack maps were recorded and compared to spall geometries observed experimentally. The results show that crack initiation locations and final spall shapes are similar to what has been observed in failed bearings.

1. Introduction

Ball and rolling element bearings are crucial parts of all machinery which have rotary and relative motion. Because of their geometry, these elements usually function under large stresses. Bearings can fail because of environmental debris, improper lubrication systems, excessive loading, or bad installation. If a bearing is properly installed and maintained, the main mode of failure will be due to material fatigue. It has been observed that a loaded rotating element has a limited life because of the probability of the surface or subsurface initiated fatigue damage. Failure due to this phenomenon is commonly referred to as rolling contact fatigue (RCF).

In general, rolling contact fatigue happens due to two different phenomena: surface originated pitting and subsurface originated spalling [1]. Fig. 1 shows two typical cracks due to surface and subsurface failure. As can be seen, the depths at which the cracks initiate are different. Hence, these two phenomena commonly can act separately; however, they might interfere in the Propagation stage and cooperate to fail the material. While surface initiated fatigue can be hindered by employing better lubricants and more efficient lubrication techniques, there are not actually many ways to stop subsurface initiated fatigue *after* the bearing is manufactured and installed. So, it is important to understand the mechanisms leading to this type of failure in order to improve the bearing design and manufacturing process.

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Nomenclature

b	half-contact width	N	number of cycles
BFI	butterfly formation index	ε	strain tensor
C	stiffness tensor	σ	stress tensor
D	damage variable	σ_r	resistance stress
$D_{c\text{-}Butterfly}$	critical damage for butterfly formation	$\tau_{alternating}$	amplitude of shear stress
$D_{c\text{-}Crack}$	critical damage for crack formation	τ_{mean}	mean shear stress
E	modulus of elasticity		
m	damage law exponent		

Subsurface cracks mostly occur at stress concentration sites such as material defects, voids, and non-metallic inclusions [2]. Non-metallic inclusions are byproducts of steel manufacturing process and can cause stress concentrations in the matrix due to different material properties. Many researchers have investigated the effect of inclusions on fatigue crack initiation in hardened bearing steels. These works can generally be divided into experimental and analytical research.

Experimental investigation of fatigue crack initiation in bearing steels has mostly been conducted in two main categories: uniaxial tensile fatigue tests [2–7] and RCF tests with a set up similar to actual bearings, i.e. with rolling elements [8–12]. Uniaxial fatigue tests have their own pros and cons. The advantage of such tests is that a large volume of material (including many inclusions) is subjected to the critical stress level, so the failure is almost always due to the presence of the inclusion, and it is easy to spot the initiation point due to fish-eye phenomenon. However, there is an issue with this approach. In uniaxial tests, the failure is due to tensile loading, but RCF occurs due to reversal of shear stress [1]. As can be observed in Fig. 2 for a point located at 0.5b, shear stress is the only stress component which experiences a reversal during each load pass. So, the crack initiation and development mechanisms as well as fatigue life assessment with uniaxial fatigue tests may be inaccurate. As a new approach, some researchers [13,14] have recently used torsion fatigue as an analogy to RCF because the failure is shear dominated in both cases. However, in torsion fatigue tests only the outer layer of the shaft is subjected to the critical shear stress value and the probability of crack initiation due to inclusions and defects is less. Tests on rolling elements have been conducted by a number of investigators [15–19] and many more to study the effect of inclusions on RCF. The drawback of current test set up is that crack initiation is hard to detect as it occurs in subsurface of the material. Moreover, it is hard to find an exact correlation between the inclusion presence and final failure, because in most cases, the inclusion itself is removed from the matrix with the spall. Recently, non-destructive methods such as ultrasonic detection [4,20–23] have provided the ability to detect inclusions and monitor the crack development inside the material before the failure.

It has been frequently observed that crack initiation in the vicinity of inclusions is accompanied by microstructural changes which are commonly referred to as “butterfly wings”. In these regions, the material microstructure alters from martensite to ultrafine ferritic grains [24,25]. A butterfly formation can serve as a crack initiation site which may culminate in the final failure. Experiments suggest that after the wing formation, cracks commonly form on top of the upper wing and bottom of the lower wing as shown in Fig. 3 in a pair of typical butterfly wings [19,26]. Despite the extensive amount of experimental research on butterflies, there are very few models suggested for butterfly wing formation. In 1992, Salehizadeh and Saka [27] used an elastic-linear plastic model to calculate residual stress evolution around a circular inclusion. In 1996, Melander [28–30] used fracture mechanics to investigate the propagation of cracks that were already initiated adjacent to the inclusions. Two years later, Vincent et al. [31], suggested that

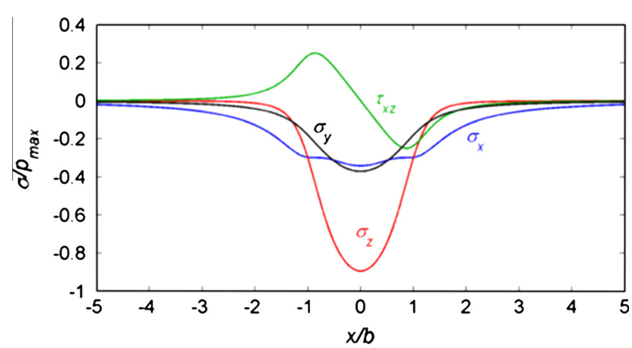

Fig. 2. Stress history for a point located at 0.5b as a function of distance from the center of a moving Hertzian contact.

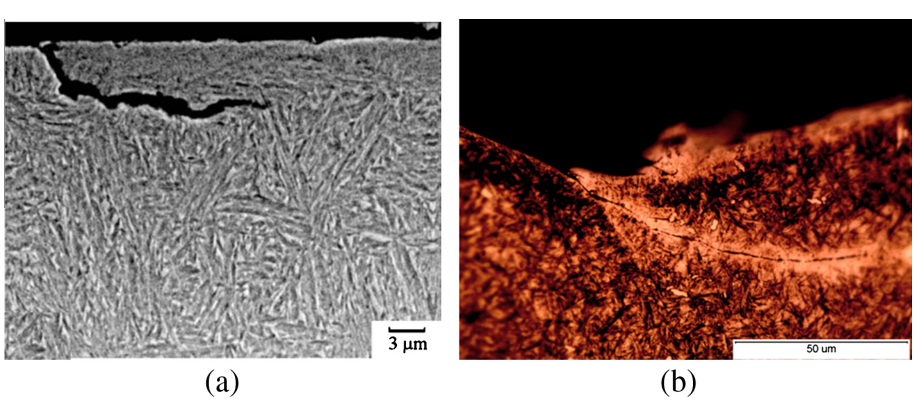

Fig. 1. Failure due to surface pitting (a) [62] as opposed to subsurface spalling (b) (note the depth of the cracks).