International Journal of Fatigue 106 (2018) 92–102

Contents lists available at ScienceDirect

International Journal of Fatigue

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

A 3D finite element modelling of crystalline anisotropy in rolling contact fatigue

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ARTICLE INFO

Keywords:
Rolling contact fatigue
Crystal anisotropy
Finite elements

ABSTRACT

Rolling contact fatigue (RCF) is one of the primary modes of failure in bearings and in this study it is hypothesized and demonstrated that RCF is strongly influenced by inhomogeneity in polycrystalline material microstructure. This paper presents a three-dimensional modeling approach to include the effects of microstructure topology and material anisotropy in a polycrystalline microstructural bearing steel subject to RCF loading. A randomly generated 3D Voronoi tessellation is used to represent the microstructural topology of the material. A cubic material definition with random spatial orientation is specified for the material grains to simulate the polycrystalline anisotropy. The size of the RVE was chosen such that it represented the macroscopic linear elastic material properties of a polycrystalline aggregate. The semi-infinite domain is then subjected to a moving Hertzian pressure to simulate a load cycle. Due to inhomogeneity in the polycrystalline material local stress risers occur at the grain boundaries, however, in general, the locations of the maximum shear stresses compare well to the experimental RCF results readily available in literature. Elemental shear stresses averaging scheme was employed to illustrate that the finite element model is mesh independent. The estimated fatigue life scatter obtained from the inhomogeneous polycrystalline material model corroborates well with the fatigue life scatter obtained from the RCF experiments.

1. Introduction

Rolling element bearings (REBs) are precision engineered mechanical components that permit rotary motion between machine elements while providing load support to the system. For REBs and other non-conformal machine elements operating under elastohydrodynamic lubrication (EHL) regime, one of the primary modes of failure is rolling contact fatigue (RCF) [1]. RCF differs from the classical fatigue since there is a complex multiaxial state of stress between the non-conformal contacts, governed by Hertz contact theory. Also the load history and the stress variation over the duration of the load cycle is not proportional at locations below the surface [2].

Surface and subsurface initiated spalling are the prevalent damage mechanisms observed in rolling contact fatigue [3]. It is commonly observed that subsurface initiated spalling dominates over surface initiated spalling for defect free surfaces with good surface finish under well lubricated operating conditions. Subsurface initiated spalling occurs due to the development of micro cracks below the surface and propagation to the surface to form a surface spall. The micro crack formation was found to occur at a depth which corresponds to the region of maximum shear stress reversal below the surface [4]. Due to localized nature of the RCF, inhomogeneity in microstructure plays a significant role in micro crack formation [5]. Thus, features such as grain size distribution, nonmetallic inclusions and carbides can play an important role in fatigue life of non-conformal contacts.

Numerous empirical and analytical research models have been developed to determine fatigue life estimate of REBs [2]. The early work aimed at developing empirical life formulations of REBs from full scale fatigue testing [6,7]. The experimental fatigue results were found to closely follow the Weibull Distribution. This led Lundberg and Palmgren [8] to develop their seminal work to estimate fatigue life of REBs using the Weibull weakest link theory. They postulated that the most probable location of crack initiation is at the maximum orthogonal shear stress zone and the probability of such weak link locations increases with the volume of the material under loading. These factors were combined to develop the Lundberg-Palmgren bearing life equation [8]:

$$\ln\left(\frac{1}{S}\right) \propto \frac{\tau_0^c V}{z_0^k} N^e \tag{1}$$

where τ_0, z_0 and V are the critical orthogonal shear stress, the location of the orthogonal shear stress below the surface and the volume of the

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http://dx.doi.org/10.1016/j.ijfatigue.2017.09.016
Received 28 June 2017; Received in revised form 22 September 2017; Accepted 23 September 2017
Available online 25 September 2017

critically stressed material respectively. *N* and *S* are the number of bearing stress cycles and the probability of survivability, while *c*, *k*, and *e* are experimentally obtained exponents for a given bearing material. Lundberg-Palmgren theory [8] has since served as the basis for other probabilistic models and the American National Institute of Standards, the American Bearing Manufacturers Association and ISO standard for rolling bearing life [9].

Deterministic approaches have also been adopted by several researchers and are based on the mechanics of the fatigue failure process. Keer and Bryant [10] used a two dimensional fracture mechanics approach to model fatigue failure in Hertzian contacts and assumed the initiation life to be short compared to propagation life. The deterministic models can be broadly classified as crack initiation and/or crack propagation models. Models which account for both crack initiation and propagation are rare. Deterministic models also do not include the stochastic nature of REB fatigue life.

Raje et al. [11] proposed a new approach where an explicit representation of the polycrystalline microstructure using Voronoi tessellations was used to capture the fatigue initiation and propagation phases in RCF. Instead of assuming an explicit Weibull distribution of fatigue life, the stochastic nature of fatigue life is captured by considering a large number of randomly generated microstructural domains. This approach has been extended to study carbide inclusions, fretting fatigue, 3D microstructural domains [12,13] and plasticity effects in RCF [14]. These studies however assumed that the microstructure possess isotropic material properties.

Bearing steels are found to have a granular microstructure with average grain sizes in the order of 1–10 μm [2]. Hence it can be effectively treated as polycrystalline aggregates with nonhomogeneous microstructure at the micron level with the grain boundaries acting as weak planes for crack initiation [11–13,15]. It has been shown that polycrystalline aggregates with random crystallographic and morphologic texture will have effective isotropic and homogenous material properties at the macro level [16,17]. Alley and Neu [18] developed a crystal plasticity model to analyze plastic strain accumulation near inclusions. Paulson et al. [15] studied the combined effects of topology, anisotropy and crystal orientation at the grain level using a 2D finite element model. They showed that inclusion of crystalline anisotropy into a microstructural based model provides a good description of measured experimental scatter in fatigue life than isotropic models. Crystalline anisotropy creates stress concentrations in the grain boundaries between adjacent grains and can create stress singularities at triple grain junctions [19]. However the average value of the shear stress along the grain boundary is bounded and this approach was used by Noyel et al. [20] in a cohesive element approach to model RCF.

Although a 2D representation of microstructure is commonly used as a simplification in modelling of RCF life, this approach does not appropriately characterize the grain geometry. In a 2D model, the grains have randomness in topology in only two directions with a uniform thickness in the third direction which can be considered as columns in a 3D space. A 3D Voronoi model accounts for randomness in microstructure in three directions. The bias in stress fields introduced by a columnar approach to microstructure is discussed by Zeghadi [21,22]. A 2D RCF finite element simulation typically assumes that the grains have infinite dimension in the direction perpendicular to the direction of the rolling motion. While this simplification is an efficient approach in simulating rolling contact fatigue, inclusion and other heterogeneities in the bearing microstructures are not infinitely wide. Also RCF effects such as butterfly wings are captured more accurately by a 3D finite element model as discussed by Moghaddam et al. [23]. Since the stress strain behavior of an anisotropic grain along the rolling and transverse direction is dependent on its orientation in space, a 3D finite element approach is more representative of the material microstructure.

The current work presents a 3D finite element model to simulate the effect of crystalline anisotropy on RCF life. The representative microstructural model was developed using Voronoi tessellations to represent microstructural grain topology. The model uses a cubic material definition with a unique material orientation for each tessellation in a polycrystalline aggregate that has isotropic material properties at the macroscopic level. The grains are then meshed with quadratic tetrahedral elements for finite element analysis. The current investigation describes in detail the identification of a representative volume element (RVE) which effectively characterizes a polycrystalline microstructure that maps macroscopic behavior of the constituent material. A Hertzian line pressure is moved over the contact surface to simulate a rolling pass over the domain. The grain boundaries are found to exhibit significant stress concentrations compared to the stresses within the grain. The stress concentration magnitudes vary with the level of mesh refinement in the finite element method. Hence, a grain boundary stress averaging scheme was used for removing the mesh dependence of the stress solution. The average grain boundary shear stress reversal is used for estimation of the probability of failure. The fatigue life scatter estimated from the current model correlates well with results from RCF life experiments available in literature.

Table 1
Cubic elasticity constants for steel.

Elastic constant	Stress (GPa)
C11	204.6
C12	137.7
C44	126.2

2. Modeling approach

2.1. Modeling of material microstructure

The bearing steels are found to exhibit a granular microstructure [24]. The contact area in REBs and other non-conformal contacts are extremely small (usually of the order of hundreds of microns), which is comparable to tens of grains in bearing steels. Hence it is important to employ a realistic representation of microstructure for modelling RCF phenomena. Voronoi tessellation can be employed for a geometric representation of a granular microstructure in bearing steel [25–28]. Ito and Fuller [29] showed that Voronoi tessellations represent the grains of a polycrystalline material to a good degree of accuracy. Voronoi tessellation involves partitioning a Euclidean space based on a set of seed points such that all points inside a partition are closer to the generating seed point than any other seed point in the domain. By using randomly placed seeds points in the given Euclidean space, an arbitrary microstructural topology can be generated for each tessellation simulation. The average grain size is controlled using the density of seed point distribution. Voronoi tessellations have been extensively used in RCF simulations [11–13,15,30,31] to account for geometric randomness in the material microstructure topology. In the current study, the average Voronoi grain size was chosen to be 10 μm which is a reasonable estimate for the grain size of bearing steel [32].

Although most RCF models available in open literature employ an isotropic material definition for steels, the individual grains of a steel matrix exhibit elastic anisotropy. For any mesoscale simulation of RCF at a grain level, an anisotropic material definition is necessary for a more representative analysis of stress evolution in rolling contact loading. A cubic material definition as shown in Eq. (2) is used to characterize the crystalline elasticity in this model.