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Effects of crystal elasticity on rolling contact fatigue

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ABSTRACT

Rolling contact fatigue (RCF) is one of the primary damage modes for properly installed and lubricated rolling element bearings. Historically, because RCF is a stochastic process, extensive testing with subsequent statistical analysis is required to calibrate models that enable confident prediction of expected bearing service life. Recent research has focused on using computational models of microstructure topology to simulate the scatter in bearing life results. In this study, the anisotropy of the grain crystals and the grain texture of the microstructure are taken into account in addition to the explicit representation of the microstructure topology. Starting with a topological microstructure of Voronoi elements representing the material grains, each grain is assigned a cubic material definition and a set of random Euler angles to define the orientation. This microstructure is then converted into a 2D finite element model and a Hertzian contact is passed over the surface of the polycrystalline microstructure to simulate a roller bearing loading cycle. The maximum shear stress reversal and its location are calculated. Due to mismatch in the orientations of grains, stress concentrations develop on the grain boundaries leading to higher shear stress ranges than those calculated for an isotropic material. Depths of the maximum shear stress range show good agreement with experimental observations of crack initiation locations. The shear stress range and location are used to calculate the relative life of the bearing; evaluating many microstructural domains demonstrates that the life scatter produced by various microstructures relates well to the experimentally observed scatter in bearing life.

1. Introduction

In properly installed, lubricated and maintained rolling element bearings, rolling contact fatigue (RCF) is a predominant damage mode [1]. RCF is typically categorized into surface and subsurface initiated spalling. Surface initiated spalling has been shown to occur when high friction, surface dents or other surface defects cause stress to rise to the surface of the material and lead to the formation of surface cracks. In subsurface initiated spalling (SIS), microcracks initiate and grow below the surface before eventually propagating to the surface and forming a spall. Subsurface initiated spalling is of particular interest because unlike other forms of surface damage which are caused by non-ideal operating conditions, SIS damage is predominant when bearings are operated under ideal conditions, i.e., well lubricated and free of surface defects.

Similar to classical fatigue, RCF has been divided into stages [2]. The initial stage consists of crack initiation when the first cracks occur under the surface of the material. In the latter stages, the subsurface initiated cracks propagate growing towards the surface to form a subsurface spall. Fatigue cracks are thought to nucleate along grain slip bands in well oriented grains making the crack initiation strongly dependent on the microstructure [3]. However, not all well oriented grains initiate cracks, recent research [4] has pointed to the elastic anisotropy as the driving force that initiates cracks in the well oriented grains. In the current study, the effect of elastic anisotropy in stress is considered on initiation of rolling contact fatigue cracks.

Experimental bearing life tests for SIS, similar to most fatigue failure data, have shown a stochastic distribution of lives for identical loading conditions and bearing geometry [5]. The experimental life data closely follows a Weibull distribution [6], which is the basis of the empirical life formula proposed by Lundberg and Palmgren [7]. They postulated that the driving force behind the formation of microcracks and eventual surface spalling damage must be a critical stress in the bearing, which led them to include a critical stress in the bearing life equation. Given that microcracks initiate at the critical stress, the cracks in Hertzian contacts must then travel to the surface before a spall is formed, therefore the depth of the critical stress is related to the life of the bearing as deeper initiation cracks will lead to longer crack propagation lives before material removal by surface spalling. Finally, the volume of

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material in the critically stressed region is taken into account since the microcracks are assumed to initiate at weak points of the material. Combining these factors, Lundberg–Palmgren proposed the bearing life equation as:

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

where τ_0, z_0, and V are the critical shear stress, the depth of the critical shear stress below the surface, and the volume of the critically stressed material. N and S are the number of bearing stress cycles and the probability of survivability, respectively. c, k, and e are experimentally obtained exponents for a given bearing material. From the seminal work of Lundberg and Palmgren [7], RCF research has proceeded in two general directions. In the first, probabilistic engineering life models were created using the experimental measurements of life scatter [8]. Lundberg and Palmgren's work would fall into this category as well as the ISO standard for rolling bearing life [9]. The second direction of research developed deterministic life models based on mechanics of fatigue failure [10]; however, these models do not capture the stochastic nature of rolling contact fatigue. Recently a new approach to bearing models was proposed by Raje et al. [11] in which the stochastic nature of rolling contact fatigue is characterized as a function of the random microstructure in the bearing. Using this approach, a given microstructure has a deterministic life; however, when a large set of random microstructures are considered the stochastic nature of RCF life is captured. Further developments of this model have addressed 3D microstructural definitions [12–14], carbide inclusions [15], and plasticity effects in RCF [16,17].

Previous studies investigating the microstructure of bearing steels assumed the grains were isotropic and grain boundaries were weak planes in the material where cracks could form [11,12,18,19]. However, bearing steels are polycrystalline materials consisting of a large number of crystalline grains each randomly orientated in the domain. When many grains form an aggregate with random orientation, such as in steel, the macroscopic properties of the material become isotropic which has been shown by Bohlke and Bertram [20] and Nygårds [21]. The Hertzian contact in a rolling element bearing acts on an extremely small volume of material on a similar order to the grain size. Therefore, in order to conduct detailed stress evaluations at the roller contact, the material should not be classified as an isotropic material and an explicit representation of the grains is required [22].

In the current study, a fatigue life model with explicit definition of microstructural elements was developed to determine RCF life of rolling element bearings. Unlike previous research that focused on the microstructural topology and failure along grain boundaries as the primary cause of RCF, in this investigation, the effects of topology, anisotropy and crystal orientation are incorporated to gain a more complete understanding of the effects of microstructure on RCF. Differences in the crystal orientations cause stress concentrations at the grain boundaries increasing the stresses in the material. The results obtained using the fatigue life model, which incorporates the life equation shown in Eq. (1), are found to be in excellent agreement with experimental life scatter results published by Miller [3] for rolling element bearings.

2. Modeling approach

2.1. Microstructure topology model

Steel is a complex microstructure consisting of a multiple phases of variable size and shape grains. Previous research [11,18,19,23] has simplified the complex microstructure into a polycrystalline aggregate of individual grains and grain boundaries, reminiscent of an austenitic microstructure prior to any quenching. This simplified microstructure retains the effects of topological randomness which can be computationally represented using Voronoi tessellations [24–27]. A Voronoi tessellation divides a Euclidean space into regions with the criterion that all points in a particular region are closer to the generating point of that region than any other member of the generating set. This is similar to metal solidification where grains grow from a nucleation site until they impinge on neighboring grains. The topological randomness of a microstructure is captured by Voronoi tessellations. Voronoi microstructures are created by a randomly generated set of seed points in a domain. The regions resulting from the tessellations, known as Voronoi cells, are associated with generating points or seed points representing the grains in a material. Based on the density of the randomly generated seed points, the average size of a Voronoi cell can be determined and therefore a certain grain size can be simulated. The minimum Voronoi cell size is also set by specifying a minimum distance between seed points assuring a more uniform grain size. For this analysis, the spacing between the generating points was maintained such that the average size of the Voronoi cell was 10 μm which corresponds to the grain size of bearing steel [28].

Previous studies employing Voronoi tessellations to represent polycrystalline materials used a Voronoi centroid method to discretize the Voronoi polygons for finite element analysis [18]. Fig. 1A depicts the Voronoi centroid discretization method wherein, finite element triangles are defined by joining each Voronoi edge to the Voronoi centroid; therefore, an N sided Voronoi polygon is discretized into N finite element triangles. The advantage of this method is a minimum number of finite elements. However, with very few elements inside each grain, it is best suited for homogeneous, isotropic material models which do not experience strong stress gradients inside the grain. The anisotropy of a material, however, causes significant stress gradients on the interior of the individual grains; therefore, an alternative method allowing for a finer discretization of the Voronoi polygons was developed for this investigation. Fig. 1B illustrates the new method wherein, the Voronoi cell boundaries are discretized into several triangles with a meshing program (Triangle [29]). Note that area constraints are specified to ensure a sufficient number of elements inside each grain. The area constraints were tested in the material model validation described in Section 2.2 and that same area constraint was used for all the RCF models. The quality of the elements was also ensured by limiting the minimum angle of the elements to above 20°. The new meshing procedure thereby eliminates the problems created by short sided Voronoi polygons [23] in addition to addressing the stress gradients inside the Voronoi polygons. Each triangle was represented as a linear strain triangle and all the elements contained in a Voronoi cell were grouped to allow specific material properties for each grain to be assigned.

2.2. Polycrystal elasticity model

On the microstructural scale, steel is a composition of anisotropic crystal grains which are randomly oriented with respect to one another. On the macroscale, where stresses are evaluated over millions of grains, the individual random grain orientations become insignificant to the global stiffness of the material resulting in isotropic material behavior. However, since critical bearing stresses operate on the microstructural scale in rolling contact fatigue, it is important to take into account how the anisotropy of the grains affects the stresses in the material. In this investigation, in order to account for grain orientations, a cubic anisotropy model was employed similar to the approach adopted by Alley and Neu [22].