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EHL modeling of nonhomogeneous materials: The effects of polycrystalline anisotropy on RCF

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ABSTRACT

Bearing steel is comprised of a polycrystalline aggregate of anisotropic crystals which affects the stress distribution and subsurface fatigue crack formation. In the present investigation an approach is proposed to determine the contact pressure, film thickness and subsurface stresses in a polycrystalline anisotropic aggregate material operating under elastohydrodynamic lubrication (EHL). The approach is based on a fully coupled finite element EHL model which uses 1D finite elements to solve the Reynolds equation and 2D finite elements to resolve the deformations for a line contact EHL problem. The polycrystalline material is simulated using a Voronoi polygon discretization with each Voronoi polygon receiving a unique crystallographic orientation. The anisotropic material definition used for this model has a cubic crystal structure. Results from the FE Voronoi EHL model show that the contact pressures vary due to crystallographic orientation and stress concentrations occur at the polycrystalline grain boundaries. EHL film thickness profiles were not significantly affected by the addition of crystal anisotropy effects to the microstructural model. However, relative life prediction obtained from the model with the anisotropic stress profiles showed that significant life scatter is generated by the addition of crystal anisotropy into the microstructural model. The results obtained from the FE Voronoi EHL model show much closer agreement to experimental results than models that assume isotropic material models.

1. Introduction

Subsurface spalling occurs in bearing materials when rolling contact fatigue cracks initiated in the bulk of the material propagate to the surface removing a flake of material. The initiation of subsurface fatigue cracks is known to be influenced by material inhomogeneities contained in the materials [1,2]. While nonmetallic inclusions have received the most focus of all inhomogeneities, alternative sources of material variation also affect rolling contact fatigue (RCF). Nonmetallic inclusions in bearing materials have decreased significantly by vacuum degassing and other manufacturing processes [3]; however, one source of inhomogeneity that is intrinsic to bearing steels is polycrystalline anisotropy. Bearing steels are formed by an aggregate of individual crystalline grains each with a unique grain orientation. When a sufficiently large aggregate of grains is considered the steel will behave as a homogenous, isotropic material [4,5]. However, because EHL contacts act on a volume of material comparable to the size of few a hundred microns or grains, the homogeneous, isotropic assumption is not realistic and the polycrystalline grain structure needs to be considered to determine the stresses and pressures generated in the contact.

Recent research in rolling contact fatigue has focused on the effects of grain microstructures on the fatigue process. The effect of microstructure topology has been investigated at length as a method of introducing microstructural variation into previously explicit fatigue models [6–10]. Topology variations have been shown to predict the stochastic variation observed in rolling contact fatigue. While some life variations are captured using microstructural topology modeling it typically under predicts the scatter observed in experimental RCF lives [7,11]. To address the under prediction of life variation, additional forms of microstructural variation have been incorporated into RCF models. One of the most promising additions to the microstructural model has been the addition of anisotropic material properties and crystallographic orientation to the individual material grains. Paulson et al. [12] have shown that the addition of anisotropy material creates a Weibull slope much closer to experimental results than models considering only microstructure topology. A similar anisotropic model has also been proposed which incorporated cohesive elements between the grains and evaluated the effect of anisotropic properties on crack propagation in rolling contact fatigue [13]. Alley and Neu [14] recently investigated microstructure sensitivity of models that included both elastic and plastic anisotropic material models around inclusions.

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Nomenclature

b	Hertzian half contact width
C	material compliance matrix
F	nondimensional force per unit width (f/p_h)
H	nondimensional film thickness (hr/b^2)
H_0	nondimensional rigid body film thickness (h_0r/b^2)
P	nondimensional pressure (p/p_h)
p_h	Hertzian pressure
r	equivalent radius of curvature
R	rotation matrix
U	nondimensional displacement (ur/b^2)
u_m	mean entrainment velocity
W	finite element weighting function
X	nondimensional distance (x/b)
y	depth dimension
α	pressure-viscosity coefficient
ϵ	strain
$\bar{\mu}$	nondimensional viscosity (μ/μ_0)
μ_0	ambient temperature zero-pressure viscosity
ξ	penalty term parameter
$\bar{\rho}$	nondimensional density (ρ/ρ_0)
ρ_0	ambient temperature zero-pressure density
σ	stress

While research using microstructural sensitivity has shown great promise in analytically modeling the variations observed in RCF, nearly all of the models proposed assume the rolling contact pressure is Hertzian. This assumption is accurate for unlubricated contacts; however, this is not the general operating condition for lubricated rolling contact machine elements [15]. The difference between EHL and Hertzian pressure profiles on RCF stresses has shown that EHL pressure profiles causes lower stresses and therefore predict longer lives [16]. Material inhomogeneity effects on EHL pressure and subsurface stress profiles was first studies by Slack et al. [17] using a discrete element model with inclusions coupled with an elastohydrodynamic solver. This work was extended to address multiple inclusion shapes and sizes [18,19]. Recently, Paulson et al. [20] developed a fully coupled finite element EHL model to determine the effect of subsurface damage accumulation on EHL pressure profiles and RCF damage propagation. Material inhomogeneities in all of the models described here have shown significant alterations to the EHL pressure and subsurface stress profiles causing a significant effect on RCF lives.

The current work develops a fully coupled polycrystalline anisotropic EHL model to investigate rolling contact fatigue of heavily loaded lubricated machine components. The approach developed within uses a 1D finite element method to discretize the Reynolds equation and a 2D FE method to resolve deformations and stresses in the polycrystalline domain. By combining these elements into a fully coupled linearize FE model the line contact EHL problem is solved for anisotropic material definitions. The contacting bodies' computational domain was discretized using Voronoi polygons of unique crystallographic orientation in order to simulate polycrystalline structured material. The coupled anisotropic EHL model was used to determine the contact pressure profiles, film thickness profiles as well as subsurface stress distributions within the material. The contact pressures show significant variation due to the crystallographic orientations of the material which lead to stress concentrations along the Voronoi boundaries. Similarly subsurface stresses show increased magnitudes at the intersection of Voronoi elements. Due to the variable nature of the microstructure topology and crystallographic orientations significant variations are observed in the internal stress distributions. Applying the relative life prediction model to a collection of microstructural domains predicts life scatter which is consistent with experimental results.

2. Modeling approach

In order to determine the effects of anisotropic polycrystalline microstructures on elastohydrodynamic lubrication, a model was developed that couples the hydrodynamic lubrication, elastic deformation and anisotropic material properties of contacting surfaces. The model was developed by coupling the finite element formulation of the Reynolds and elasticity equations of a polycrystalline material model including the microstructure of the material. Voronoi tessellations were used to simulate the anisotropic polycrystalline microstructure of the material. The Voronoi tessellation allows for unique orientation angle of each individual grain in the microstructure of the polycrystalline material being modeled. The discretized Voronoi domain is then input into the FE EHL model with the appropriate anisotropic material definition to calculate the contact pressure, film thickness and internal stresses.

2.1. EHL finite element model

The FE EHL model implemented is an extension of the formulation proposed by Habchi et al. [21] which has been used as alternative to finite difference formulations [22–25]. The EHL model proposed for this study assumes steady-state smooth isothermal Newtonian operation of the bearing components. In the extended formulation anisotropic material properties can be specified by using an anisotropic stiffness matrix in the elastic element definitions. The fundamental equations used in the EHL model are provided below however for more details the reader is referred to [20,21].

2.1.1. Reynolds equation

Solving the EHL problem requires solving three equations simultaneously. The first of these is the line contact Reynolds equation [26].

$$\frac{\partial}{\partial X}\left(\epsilon\frac{\partial P}{\partial X}\right) - \frac{\partial(\bar{\rho}H)}{\partial X} = 0 \qquad (1)$$

where

$$\epsilon = \frac{\bar{\rho}H^3}{\bar{\mu}\lambda}, \qquad \lambda = \frac{12u_m\mu_0 r^2}{b^3 p_h}$$

In the current investigation, the fluid is assumed to behave Newtonian and thermal effects are neglected. These assumptions have been shown to be accurate for low slide to roll ratios [27] like those experienced in rolling contact fatigue machine components. While Eq. (1) is the standard form of the Reynolds equation, an additional term must be added to address the free boundary condition at the outlet of the contact. Wu [28] proposed that a penalty term can be used to drive the negative pressures to zero in the outlet region solving this free boundary problem. This results in a Reynolds equation of:

$$\frac{\partial}{\partial X}\left(\epsilon\frac{\partial P}{\partial X}\right) - \frac{\partial(\bar{\rho}H)}{\partial X} - \xi\min(P,0) = 0 \qquad (2)$$

ξ in Eq. (2) is set to an arbitrarily large constant to drive the pressure to zero in negative pressure regions. The Reynolds equation is solved along the contacting surfaces of the upper and lower bodies and the resulting pressure distribution is used to define the boundary conditions for the anisotropic elastic deformation. The film thickness H is defined by:

$$H = H_0 + \frac{X^2}{2} - U_{y,1} + U_{y,2} \qquad (3)$$