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Cohesive zone modeling of intergranular fatigue damage in rolling contacts

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ABSTRACT

Fatigue lives of rolling element bearings exhibit much scatter due to the statistical nature of the failure process. The localized character of contact stresses enhances the effects of microstructural features on fatigue life. In this paper, the growth of intergranular fatigue damage in rolling contacts is investigated. An explicit finite element model is developed which models the grain boundaries using an irreversible cohesive zone approach. The effects that the grain boundary properties play in fatigue life scatter and final spall patterns are presented and discussed. The predicted fatigue lives and spall patterns were found to be similar to experimental results.

1. Introduction

One of the leading causes of failure of rolling contacts is a process known as rolling contact fatigue (RCF). An RCF manifests itself through the removal of a small piece of material from the contacting surface. An RCF develops through a variety of mechanisms with the most dominant being surface initiated pitting and subsurface initiated spalling [1]. Subsurface spalling is the dominant failure mode for rolling contacts, which are well lubricated and properly maintained. Subsurface spalling is characterized by the initiation of a crack below the surface of the contact, which propagates to the surface forming a relatively large spall. These cracks are often found to initiate near defects such as non-metallic inclusions in the region of maximum shear stress, which occurs below the surface.

Predicting RCF failures is challenging due to the complexity of the highly localized, multi-axial stress distribution, which occurs in the contact region. The nature of these stresses result in a particular material point experiencing a stress history with out of phase stress components. These stresses cause both the principal axes and the planes of maximum shear stress to continuously change orientation during a load pass. This makes it difficult to identify planes in the material on which the maximum fatigue damage is likely to occur. The localized nature of the contact stresses results in an enhanced effect of microstructural features, such as grain size distribution, grain boundaries, crystallographic orientation, initial defects and material inclusions on fatigue life and fatigue life scatter.

For rolling element bearing applications, a large number of models, both empirical and mechanistic, have been developed to predict an RCF life [2]. In general, the life predictions of the empirical models are based on using solutions of the elastic stress field, while directly inputting scatter into the model, using a Weibull probability distribution function. The mechanistic models assume an initial crack of a given length and orientation and use fracture mechanics to predict the spall shape and fatigue life. Both types of models typically do not directly include microstructural features in their life predictions.

Recent modeling has been undertaken to incorporate microstructural features in an RCF life predictions [3–5]. The modeling approach utilizes a randomly generated simulated material microstructure and uses continuum damage mechanics to capture the fatigue induced damage. The approach captures both the initiation and propagation of fatigue induced material degradation and has been used to obtain both Weibull slopes of simulated life data and final spall crack patterns that compare well with experimental results [3–5]. The models have been developed assuming either an intergranular [3,4] or transgranular [5] damage propagation mechanism. The intergranular failure mechanism has been implemented using both discrete element [3] and finite element methods [4]. Using the discrete element method [3] the grains of the material are rigid and are interconnected through a network of elastic springs. The properties of the springs are calibrated such that global behavior of the spring element network approaches that of a continuum. Damage propagates in the model by breaking springs between the grains. Using the finite element approach [4], the grains of the material are meshed using finite elements. The finite element mesh is

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continuous across the grain boundaries and damage propagates by releasing nodes of the elements along these boundaries. Neither approach directly models the material properties and behavior of the grain boundaries.

The focus of the present paper is on investigating the role that grain boundary material properties play in the rolling contact fatigue damage accumulation process. A two-dimensional explicit finite element model is developed which directly models the grain boundaries, using a cohesive zone approach. Fatigue damage is assumed to be restricted to the grain boundaries and is captured by introducing a continuum damaged mechanics based damage variable to the irreversible cohesive zone law. The effects that the grain boundary properties play in fatigue life scatter and the final spall pattern is presented.

2. Grain scale material model

The grain scale material model used in this investigation is developed by representing the contacting bodies by a two-dimensional elastic half-space under plane strain conditions as depicted in Fig. 1. Based upon the geometry of the contacting bodies and the load transmitted through them, an equivalent Hertzian pressure distribution of half-width b and maximum pressure $p_{\max}$ can be determined. The theoretically infinite domain is truncated to a rectangular domain of width 10b and height 7b. These dimensions are chosen so as to allow the stresses to diminish to zero away from the contact region, while allowing for a reasonable computational time. In the contact region of the half-space, the material microstructure is simulated using a Voronoi tessellation of randomly distributed initial seed points. The Voronoi tessellation has been shown to represent the grains of a polycrystalline material to a good degree of accuracy [6,7] and by constructing it from randomly distributed points a non-unique material microstructure is generated for each simulation. The microstructure is only simulated for a width of 4b and a depth of 4b of the half-space to reduce the computational effort. The elastic half-space is meshed using constant strain finite elements. Isotropic linear elastic material properties are assumed.

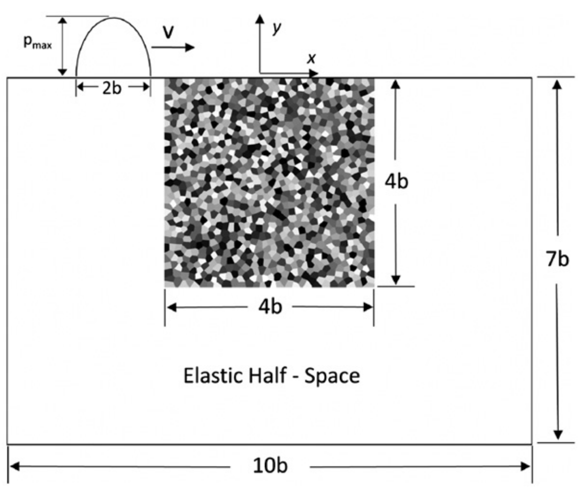

Fig. 1. Computational domain.

The behavior of the grain boundaries of the material is captured using cohesive zone elements. A cohesive zone element is an element with zero initial thickness, which describes the behavior of an interface through a constitutive relationship based upon the relative opening displacement, Δ, which develops in the element. Many different types of traction-separation laws have been developed [8] and cohesive zone elements have been used to model grain boundaries in the past [7,9]. In this study, the grain boundaries are modeled using four-noded cohesive zone elements, which are inserted between the finite elements on the grain boundaries, as shown in Fig. 2.

To investigate the effects of grain boundary properties, two cohesive laws will be considered. The first law assumes that the normal and tangential tractions, (T_n, T_t), are linear functions of the normal and tangential displacements, (Δ_n, Δ_t). The relationships are given by

$$T_n = k_n \Delta_n T_t = k_t \Delta_t \tag{1}$$

where k_n and k_t are the stiffness of the cohesive zone in the normal and tangential directions. The second cohesive law assumes that the normal traction remains linear, but assumes that the tangential displacement is a bilinear function of the tangential displacement. This will allow inelastic sliding to occur at the grain boundaries. The behavior in the normal direction remains as given in Eq. (1). The behavior in the tangential direction is given by

$$T_t = \frac{\tau_{\max}}{\delta_{t,\max}} \Delta_t \quad \text{when} \quad \Delta_t < \delta_{t,\max}$$
$$T_t = \tau_{\max} \frac{\delta_{t,crit} - \Delta_t}{\delta_{t,crit} - \delta_{t,\max}} \quad \text{when} \quad \Delta_t > \delta_{t,\max} \tag{2}$$

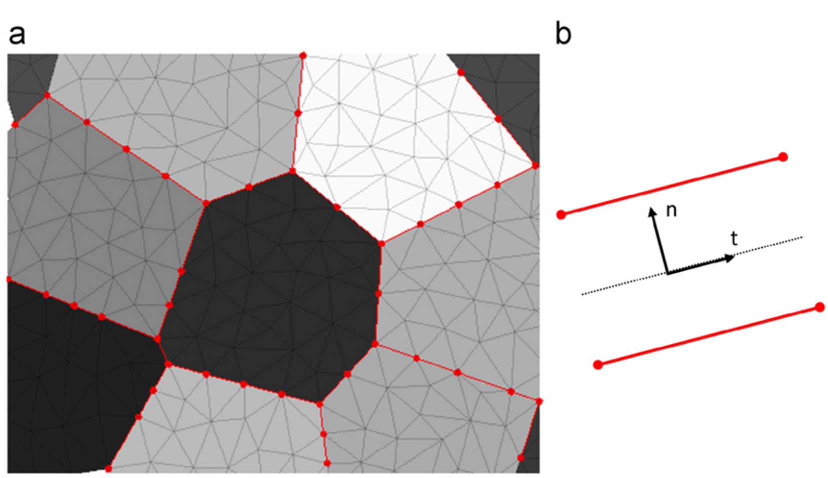

Fig. 2. (a) Finite element and cohesive zone element mesh of the material microstructure and (b) local coordinate system of the cohesive zone element.