Tribology International 59 (2013) 210–221

Contents lists available at SciVerse ScienceDirect

Tribology International

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

Numerical modeling of sub-surface initiated spalling in rolling contacts

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ARTICLE INFO

Article history:
Received 5 August 2011
Received in revised form
30 December 2011
Accepted 14 March 2012
Available online 27 March 2012

Keywords:
Rolling contact fatigue
Finite element
Damage mechanics

ABSTRACT

A 3D finite element model was developed to investigate the influence of microstructure topology on the stochastic nature of rolling contact fatigue. Grains of the material microstructure are modeled with random Voronoi tessellations. Continuum damage mechanics and mesh partitioning are implemented to capture the initiation and propagation phases of fatigue damage that lead to spalling. Simulated fatigue spalling is shown to progress similarly to experimental observations of rolling contact fatigue. The fatigue lives obtained with the model exhibit scatter on par with empirical measures and are fit well by 2 and 3-parameter Weibull distributions.

1. Introduction

Material fatigue is the leading cause of failure in rolling element bearings (REBs) that are properly maintained and operate under conditions of elastohydrodynamic lubrication. As bearing elements roll between the raceway surfaces of the inner and outer rings, the ring material is fatigued by repeated exposure to non-conformal contact stresses. Hence, the phenomenon of material fatigue in REBs is commonly called rolling contact fatigue (RCF). It manifests through various mechanisms, but surface and subsurface initiated spalling are dominant [1,2]. Both mechanisms are characterized by fatigue cracks that propagate through the critically stressed volume to liberate material from the raceway surfaces [3] as shown in Fig. 1 [4]. However, with low frictional forces, clean lubrication, and good surface finishes, the operating conditions are favorable for subsurface initiated spalling.

RCF is distinguished from classical fatigue in several ways that make it a challenging topic of research. The non-conformal contact between a rolling element and raceway produces a complex, multi-axial state of stress that diminishes as a function of distance from the contact site. Due to the rolling action, the directions of the principal stresses are not fixed for a given material point during the load cycle and the loading is non-proportional, i.e., the stress components do not rise and fall in succession together. The localized nature of the contact precludes bulk failures and enhances the effects that heterogeneous micro-scale features such as grain size and distribution, inclusions, carbides, etc., have on the RCF process. Random variation of these inhomogeneities between otherwise identical bearings leads to scatter in their fatigue lives.

Numerous empirical and research models have been developed to predict the fatigue lives of REBs [5]. Early efforts were focused on developing formulae to compute the "safe loads" and service lives of REBs from extensive full-scale fatigue tests [6,7]. Lundberg and Palmgren later formulated a more unified theory [8,9] that has since served as the basis for other models and ANSI/ABMA and ISO standard load-life equations [10]. In general, fatigue life predictions of empirical models have their foundation in the stress solution of elastic contact and incorporate scatter through an assumed Weibull probability distribution function. On the other hand, research models provide deterministic life predictions by addressing the underlying physical mechanisms responsible for RCF. Typically, research models account for either the crack initiation or propagation phase but rarely both.

An emerging class of numerical models of RCF provides an alternative to the conventional approaches that captures the stochastic nature of the phenomenon without relying on Weibull regression parameters obtained from full-scale bearing fatigue test data [11–14]. This new type of model utilizes randomly generated microstructure models and applies damage mechanics to simulate the fatigue induced material degradation. They capture both the initiation and propagation phases of RCF and have been used to obtain fatigue life estimates and spalling profiles that compare well with experimental results. These models have been formulated as discrete element (DEM) [11] and finite element (FEM) [12–14] models. The DEMs consider intergranular fatigue failure and treat the material grains as rigid

Abbreviations: AD, Anderson–Darling statistic; CVD, Carbon vacuum degassed; DEM, Discrete element model; FEM, Finite element model; FIB, Focused ion beam; JIC, Jump-in-cycles; LST, Linear strain tetrahedral; MP, Mesh partitioning; OSL, Observed significance level; RCF, Rolling contact fatigue; REB, Rolling element bearing

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0301-679X/$ - see front matter
http://dx.doi.org/10.1016/j.triboint.2012.03.006

Nomenclature

C	stiffness tensor [N/m^2]
D	damage tensor or scalar [dimensionless]
E	modulus of elasticity [N/m^2]
F	failure probability [dimensionless]
I	identity tensor [dimensionless]
N	number of stress cycles elapsed [dimensionless]
R_v	triaxiality function [dimensionless]
T	traction vector acting on grain boundary [N/m^2]
V	element volume [m^3]
Y	damage rate of strain energy release [N m]
a	Hertzian contact half-width in the rolling direction [m]
b	fatigue strength exponent [dimensionless]
d_g	grain diameter [m]
e	shape parameter of Weibull distribution [dimensionless]
f	ratio of minimum strain energy release increment to total [dimensionless]
k	sample size [dimensionless]
l	Hertzian contact length transverse to the rolling direction [m]
m	material parameter in damage rate law [dimensionless]
n	grain boundary normal vector, number of elements [dimensionless]
$p_{[\max]}$	[maximum] pressure in the contact region [N/m^2]
t_x, t_z	shear, normal surface tractions [N/m^2]
x	surface coordinate where tractions are calculated [m]
x_c	surface coordinate defining center of pressure distribution [m]
z	depth below contact surface [m]
ΔN	increment in elapsed stress cycles [dimensionless]
$\Delta\sigma$	stress range [N/m^2]
$\Delta\tau_{\text{critical}}$	critical shear stress reversal acting on a grain boundary [N/m^2]
$\Delta\varphi_D$	increment in strain energy released by damage growth [N m]
φ_D	total strain energy released by damage growth [N m]
α	location parameter of Weibull distribution [dimensionless]
β	scale parameter of Weibull distribution [dimensionless]
ε	strain tensor [dimensionless]
ν	Poisson's ratio [dimensionless]
σ	stress tensor or scalar [N/m^2]
τ	shear stress [N/m^2]
τ_f'	shear fatigue strength coefficient [dimensionless]
μ	coefficient of friction [dimensionless]

Subscripts

H	hydrostatic
c	contact
e, i, j, k, l, m, n	indices
eq	equivalent (von Mises)
r	fatigue resistance
s	surface
D	portion of ΔN attributable to required damage increment
φ	portion of ΔN attributable to required strain energy release increment

particles interconnected through a spring network [11]. The spring properties are calibrated such that the homogenized macro scale behavior simulates a continuum, and fatigue damage is propagated through the model by weakening and breaking the springs. Using the FEM approach, the material grains are deformable and damage may propagate along intergranular or transgranular pathways.

A common simplification used in models for RCF is a 2D representation of the material. Though the contact loading may warrant such a simplification, the 3D internal geometry of the material should be considered for its role in the formation and propagation of fatigue damage. Spall surface topologies,.e.g., Fig. 1, and reconstructions of sub-surface fatigue cracks from focused ion beam (FIB) images [15] are evidence of this process.

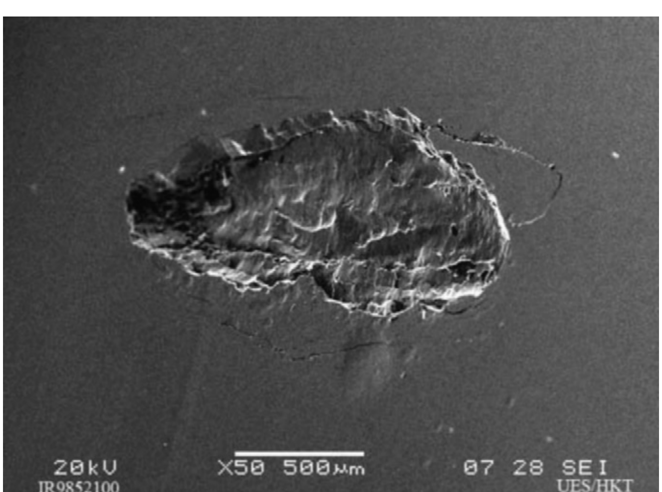

Fig. 1. Typical fatigue spall in AISI 52100 (from [4]).

This work presents a numerical model of RCF developed in a 3D finite element framework that explicitly considers the microstructure topology for its stochastic influence on the fatigue of REBs. Grains of the material microstructure are modeled using randomly generated Voronoi tessellations, and damage mechanics is incorporated to account for the gradual material degradation due to the cyclic contact fatigue loading. The model uses a mesh partitioning procedure to simulate the initiation, propagation, and coalescence of fatigue damage in the form of intergranular cracks. Simulation times are significantly expedited by an integration algorithm that considers the strain energy released through damage formation and growth. The spalling patterns generated by the model for rolling line contact loading originate under the raceway and propagate to the surface with three-dimensional characteristics that are unobtainable with plane strain/stress models. Examination of sequential crack patterns reveals the influence of the 3D microstructure topology on the failure progression. The topological effect on fatigue lives is discussed and the results are compared with empirical observations.

2. Simulation of a contact stress cycle in a roller bearing

The rolling contact fatigue model presented in this investigation was developed to simulate subsurface initiated spalling in cylindrical roller bearings. The normal contact between a roller and a raceway can be modeled as an equivalent contact between