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Rolling–sliding contact fatigue of surfaces with sinusoidal roughness

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ABSTRACT

Surfaces of mechanical components under combined rolling and sliding motions may be subjected to accelerated contact fatigue failure due to increased number of microscopic stress cycles and pressure peak heights caused by rough-surface asperity contacts. Available rolling contact fatigue (RCF) theories were developed mainly for rolling element bearings, for which the effect of sliding is usually insignificant. In various types of gears, however, considerable sliding exist in the critical tooth contact area below the pitch line, where excessive wear and severe pitting failures originate. Ignorance of sliding is most likely the reason why the conventional RCF models often overestimate gear fatigue life. This paper studies the effect of sliding motion on the contact fatigue life of surfaces with sinusoidal roughness that mimicks the topography from certain manufacturing processes. A set of simple equations for stress cycle counting is derived. Mixed elastohydrodynamic lubrication simulations are executed with the considerations of normal loading and frictional shear. Relative fatigue life evaluations based on a subsurface stress analysis is conducted, taking into account the two sliding-induced mechanisms, which are the greatly increased number of stress cycles and the pressure peak heights due to surface interactions. Obtained results indicate that sliding leads to a significant reduction of contact fatigue life, and rough surface asperity contacts result in accelerated pitting failure that needs to be considered in life predictions for various mechanical components.

1. Introduction

Power transmission is often accomplished through contact of component surfaces under combined rolling and sliding motions. Pure rolling contact, often found in rolling element bearings, can be considered as a special case of rolling–sliding contacts. It is well known that surface pitting due to contact fatigue is a major failure mode for many mechanical components subjected to counterformal contacts, such as various types of gears, rolling element bearings, cam and follower systems, continuously variable speed transmissions, and some metal-forming tools. Available rolling contact fatigue (RCF) theories (see [1–5], for example) have been developed mainly for rolling element bearings, where sliding motion is usually insignificant. In various types of gears, however, considerable sliding can be found in critical tooth contact areas below the pitch line, where excessive wear and severe pitting failures originate. Testing results obtained from two-disc experiments have indicated that, under otherwise the same conditions, the reduction of relative sliding from 25% to 10%, and then down to 0% may result in a great increase in contact fatigue life by two orders of magnitude, as reported by Bujold et al. [6]. Most recently studies presented by Govindarajan et al. [7], Oksanen et al. [8], Ramalho et al. [9], Lee et al. [10], and Seo et al. [11], all indicate that sliding appears to have a significant influence on contact fatigue behaviors. Exclusion of the sliding effect is most likely a major reason why the conventional RCF models often overestimate gear pitting life.

It is well known that engineering surfaces are not ideally smooth, and different surface topographic features may lead to different responses to rolling and sliding. In a pure-rolling contact, the number of stress cycles experienced by a certain piece of material on a surface is basically the same as that of the rolling cycles. With the presence of sliding, however, the number of stress cycles may be significantly higher because many asperities of one surface can pass over a given point in the mating surface during each rolling cycle. Apparently, the number of stress cycles should be, in general, a function of slide-to-roll ratio, S, defined as $S = 2(U_2 - U_1)/(U_1 + U_2)$, where U_1 and U_2 are the surface velocities of the two rollers, and the properties of rough surface topography.

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Nomenclature

a	radius of Hertzian contact circle
A, $\mathscr{A}$	amplitude and dimensionless amplitude of sinusoidal waves, $\mathscr{A} = AR_x/a^2$
c	stress exponent
e	Weibull slope
E'	effective elastic modulus
f_1, f_2	asperity densities of Surfaces 1 and 2, respectively
G^*	$\alpha E'$, dimensionless material parameter
h	local film thickness
h_0	normal approach between two bodies
L	surface interaction zone
M	number of stress cycles
N	number of loading cycles
n	number of asperity contacts per loading cycle
$\dot{n}$	rate of asperity contacts in the interaction zone
p, P	pressure and dimensionless pressure, $P = p/p_h$
p_h	maximum Hertzian pressure
P_{max}	maximum relative pressure, defined as the maximum EHL pressure minus p_h then divided by p_h
P_S	probability of survival
f	friction coefficient
R_q	RMS roughness
R_x, R_y	local radii of curvature in the x- and y-directions, respectively
S	$(U_2 - U_1)/U$, slide-to-roll ratio
t	time
T	duration of surface interaction
U	$(U_1 + U_2)/2$, rolling velocity
U^*	$\eta_o U/(E'R_x)$, dimensionless speed parameter
U_1, U_2	surface velocities of Body 1 and Body 2, respectively
u^p	elastic deformation caused by pressure
u^s	elastic deformation caused by frictional shear
v	elastic surface deformation
V	stress-affected volume
w	load
W^*	$w/(E'R_x{}^2)$, dimensionless load parameter
W_x, W_y	wavelengths in the x- and y-directions, respectively
x	coordinate in the rolling direction
y	coordinate perpendicular to the rolling direction
α	pressure–viscosity exponent
δ	relative sliding
Δ	$=U\Delta t/a$, dimensionless time step length
δ_1, δ_2	roughness amplitudes of Surfaces 1 and 2, respectively
η	lubricant viscosity
η_0	ambient viscosity at inlet temperature
η^*	effective viscosity
ρ	lubricant density
ρ_0	ambient lubricant density at inlet temperature
σ_{eff}	effective stress
τ_0	reference shear stress
τ_1	shear stress on Surface 1

The fundamental theories for predicting the limiting number of cycles to fatigue under a certain probability were developed by Weibull [1,2], Bakharev [3], Lundberg and Palmgren [4] and others. More recent phenomenological fatigue models, such as those by Ioannides and Harris [5], and Zaretsky et al. [12], have been used to predict the lifetime of rolling elements with an improved accuracy. Furthermore, extensive lifetime data for well-characterized systems are available in the literature. The effects of sliding have received some attention [13–16] through analyzing surface shear and stress histories under the influence of sliding. In addition, the damage-cumulative approach by Ai [17] adopted a variable to modify the probability that the material at a location experiences a certain stress level.

It should be mentioned that the detailed pressure distribution should be obtained from a mixed elastohydrodynamic lubrication (EHL) analysis in order to obtain accurate pressure distributions subjected to rolling–sliding, asperity contact, and interfacial frictional shear, before any one of the above-mentioned life models is used. This is because that, in engineering practice, surface roughness is often of the same order of magnitude as, or even greater than, the average EHL film thickness. Therefore, most mechanical components operate in the mixed EHL regime, in which localized pressure peak heights due to surface asperities may be much higher than the Hertzian pressure, causing significantly increased subsurface stresses and number of stress cycles. Great efforts have been made in order to develop mixed EHL models for rough surface lubrication. Representative studies include those by Xu and Sadeghi [18], Zhu and Ai [19], Jiang et al. [20], Holmes et al. [21,22], Zhu et al. [23], and others. The first unified mixed EHL model for point contact problems with 3-dimensional (3D) machined roughness was presented by Zhu and Hu, 1999 [24], Hu and Zhu [25], and Zhu et al. [26], which has been demonstrated to be capable of simulating the entire transition from the full-film and mixed lubrication all the way down to the boundary lubrication and dry contact. This mixed EHL model and the subsurface-stress-based fatigue-life model by Zaretsky [12] have resulted in effective approaches for pitting life predictions by Epstein et al. [27], Zhu et al. [28], Greco et al. [29], and others. However, no sliding effect was considered in these studies.

The present study aims to investigate the critical effect of relative sliding motion on contact fatigue life, due to the increased number of stress cycles and the high asperity contact pressure, for concentrated contacts in mixed lubrication without considering wear. This paper reports the development of an equation set for stress cycle counting, the execution of mixed EHL simulations, and the comparative analyses of near-surface fatigue under 50% possibility. The variations of the mixed EHL pressure distribution and asperity stress cycle as a result of the S increase are analyzed. The effects of sliding on pressure distribution, friction, subsurface stress cycles, and fatigue life of surfaces with sinusoid-like roughness are numerically investigated.

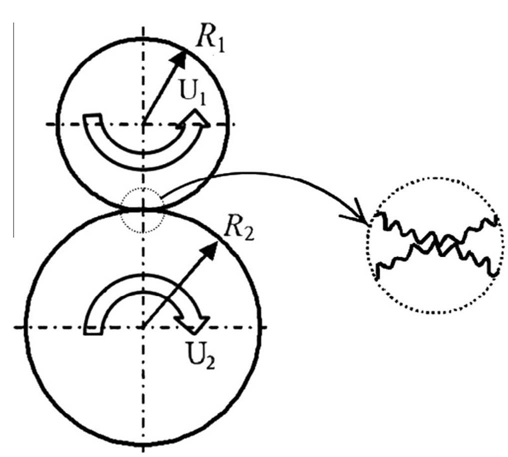

Fig. 1. Contact of equivalent cylindrical (or spherical, or elliptical) rollers.