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A fracture mechanical life prediction method for rolling contact fatigue based on the asperity point load mechanism

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ABSTRACT

The purpose was to develop a fracture mechanics based method for determining the life of surface initiated rolling contact fatigue or spalling. The life simulations were based on the asperity point load mechanism, a mode I crack growth assumption and LEFM. The life prediction was verified against the spalling life in some gear teeth, which had been measured for the simulation data. The computational tool required an equivalent mixed-mode life parameter. Such are suggested in the literature and some of these were evaluated. Also, the work required material properties for crack growth at stress cycles with highly compressive minimum loads. An experimental series was performed for crack growth at $R < 0$. Negative crack closure limits $K_{I,cl}$ were suggested by the compliance but not the crack growth rate. Simulations with small negative closure limits ($K_{I,cl} = -0.1\ \mathrm{MPa}\sqrt{\mathrm{m}}$) predicted the spalling life in the gears. It was however noted that the life predictions depended more on $K_{I,cl}$ than the equivalent mixed-mode life parameter.

1. Introduction

Gears, bearings and even the wheel-rail contact of trains are examples of applications that contain highly loaded rolling contacts. If other failure modes are avoided, then they eventually will suffer from rolling contact fatigue (RCF). The damage is characterized by cracks and craters in the contact surfaces, see the typical example in Fig. 1a. Following Tallian [1], the nomenclature spall was used for the crater and the chipped off material. The damage process was named spalling. Another common notation is pit and pitting [2].

The overall gear picture in Fig. 1a shows spalls in the teeth flanks of a pinion or driving gear wheel. The individual spalls are located in bands along the roll-circle of each tooth. One typical spall is magnified in Fig. 1b. Rolling was from the bottom of Fig. 1b or from the root to the tip of the teeth in Fig. 1a. The overall contours display v- or sea-shell shapes with the apex directed against the rolling direction. The damage started at the apex, in the area below the roll-circle, where contact movement or slip was negative, *i.e.* with friction on the pinion teeth acting against the rolling direction. All spalls grew in the forward rolling direction and at a shallow start angle to the surface.

The first comprehensive description on RCF was presented in 1935 by Way [2]. Way finds that lubricants with high viscosity and highly polished surfaces could prevent spalling. Also, surface hardening delays spalling and results in smaller spalls. Since then numerous researchers have investigated the damage process. Tallian [1] displays examples of intermediate stages and summarizes the process. Firstly, surface micro-cracks initiate, these are typically 10–30 μm long, inclined to the contact surface and pointing in the forward rolling direction. Secondly, some of these cracks continue to grow forward into

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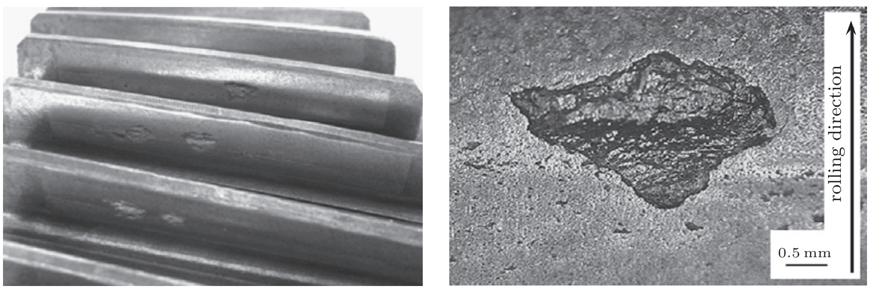
Nomenclature

a	crack length
a_l, a_p	cylinder contact half-width, asperity contact radius
b	Paris' law fatigue exponent
C	Paris' law fatigue coefficient
$CMOD$	crack mouth opening displacement
E	Young's modulus
h_{asp}	asperity height
K_I, K_{II}	mode I and II stress intensity factors (SIFs)
$K_{I,cl}$	crack closure limit
K_{II}^{cl}	mode II SIF at onset of crack closure
N	fatigue life
p	contact pressure
p_{0l}	maximum cylindrical Hertzian pressure
p_{0p}	maximum spherical Hertzian pressure
P	load at crack growth experiment
q	contact traction
q_{0p}	maximum spherical Hertzian tangential traction
r_{asp}	asperity radius
R	radius of curvature or load ratio
x_c, x_d	positions of initial crack and cylindrical load
x, y, z	cartesian coordinates
β	crack angle relative to contact surface
ΔK_I, ΔK_{II}	mode I and II (effective) SIF ranges
ΔK_{eq}, ΔK_{th}	equivalent SIF range, fatigue threshold value
α	material parameter in Eq. (5d)
μ_{asp}	asperity coefficient of friction
ν	Poisson's ratio
ξ	normalized curvilinear crack length coordinate
σ_N, σ_T	stress normal and tangential to crack faces
σ_{Yc}	monotonic yield stress in compression
σ_x	stress in x-direction
σ_θ	hoop stress
$\bar{\bullet}$	normalized value
$\bullet_0$	initial value
$\bullet_{max}$, $\bullet_{min}$	maximum and minimum value

the material. Finally, a piece of material separates from the surface giving a crater similar to the one in Fig. 1b. Alternatively the RCF crack may initiate below the surface, typically at an inclusion. These sub-surface initiated spalls lack the shallow entry angle and display an irregular overall shape with steep exit angles around the spall.

The rolling contacts in gears and bearings can often be regarded as rolling cylinders, which suggest a two-dimensional description. A two-dimensional model could explain line damage across the complete contact width but not individual spalls as in Fig. 1. Also, the normal line contact does not give any tensile crack opening stress. Olsson [4] proposes an asperity point



(a) Pinion or driving gear wheel with separate spalls on the flanks.

(b) Characteristic v- or sea-shell shaped surface initiated spall [3].

Fig. 1. Surface initiated RCF damage in a gear wheel after 5.17 Mcycles at 2.27 GPa maximum Hertzian contact pressure.