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Rolling contact fatigue crack path prediction by the asperity point load mechanism

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ABSTRACT

The crack path of surface initiated rolling contact fatigue was investigated numerically based on the asperity point load mechanism. Data for the simulation was captured from a gear contact with surface initiated rolling contact fatigue. The evolvement of contact parameters was derived from an FE contact model where the gear contact had been transferred to an equivalent contact of a cylinder against a plane with an asperity. Five crack propagation criteria were evaluated with practically identical crack path predictions. It was noted that the trajectory of largest principal stress in the uncracked material could be used for the path prediction. Different load types were investigated. The simplified versions added some understanding but the full description with cylinder and asperity pressures was required for accurate results. The mode I fracture mechanism was applicable to the investigated rolling contact fatigue cracks. The simulated path agreed with the spall profile both in the entry details as in the overall shape, which suggested that the point load mechanism was valid not only for initiation but also for rolling contact fatigue crack growth.

1. Introduction

Many mechanical applications contain components that interact repeatedly with pure rolling or rolling with small relative sliding. Some examples are gears, bearing, cams or even the wheel-rail contact of trains. When the rolling contact loads are high, rolling contact fatigue (RCF) may become life limiting for the structural components.

RCF damage is characterized by cracks and small craters in the contact surfaces. Typical examples are presented in Fig. 1 [1]. Depending on the damage size one can distinguish between micro- and macro-scale contact fatigue. Surface distress (SD) is widely used to designate micro-scale contact fatigue. The damage has then a size comparable to the dimensions of asperities on the contacting surfaces. Macro-scale contact fatigue is commonly designated as spalling or pitting. Here the nomenclature of spalling by Tallian [2] is used. It may be noticed that a spall is the chipped off material, which by removal leaves the spalling craters. However, the crater may also be referred to as a spall. The overall gear picture in Fig. 1a shows spalls in pinion or driving teeth flanks. The spalls are located along the pitch line or roll circle with initiation points at approximately the same longitudinal position in the dedendum. Fig. 1b and c shows top and cross-sectional views of typical spalls. Talysurf measurements were performed on three spalls on the gear wheel, see Fig. 1d, where the x-axis indicated the rolling direction. In order to compare the spall profiles with numerically predicted crack paths, the curvature of the gear wheel was substracted and the spall profiles were translated to a common initiation point.

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Nomenclature

a	crack length
a_l, a_p	contact half-width, contact radius
c	crack size in y-direction
E	Young's modulus
h_{asp}	asperity height
K_I, K_{II}	mode I and II stress intensity factors
$K_{I,cl}$	closure limit
$p_{0\,l}$	cylindrical maximum Hertzian pressure
p_{0p}	spherical maximum Hertzian pressure
p_{FE}, p_{Hertz}	FE and Hertzian contact pressure
P_l, P_p	normal line force, normal point force
q_{FE}, q_{Hertz}	FE and Hertzian traction
q_{0p}	spherical maximum Hertzian tangential traction
Q_p	tangential point force
r, r_{asp}, r_{pl}	sphere radius, asperity radius, plastic zone size
R	radius of curvature or R load ratio
R_a	average roughness
R_p, R_v	maximum profile peak height and valley depth
t	thickness of FE model
T	T-stress
x_c, x_d	position of initial crack, position of cylindrical load
x, y, z	cartesian coordinates
β, β_{entry}	crack angle, entry angle relative to contact surface
β_{SD}	surface distress crack angle
ΔK_I	mode I stress intensity factor range
$\Delta K_{I,eff}$	mode I effective stress intensity factor range
ΔK_{th}	fatigue threshold value
λ_q	root mean square wavelength
ν	Poisson's ratio
μ_{asp}	asperity coefficient of friction
σ_x, σ_z, τ_{xz}	cartesian stresses
σ_N, σ_C, σ_T	stress normal, colinear and tangential to crack faces
σ_R	residual surface stress
$\sigma_{Y,mt}$, $\sigma_{Y,mc}$	monotonic tension and compression yield stresses
$\sigma_{Y,cycl}$	cyclic yield stress
σ_θ	hoop stress
$\tau_{Y,cycl}$	cyclic yield stress in simple shear
$\bar{\bullet}$	average value
$\bullet_0$	initial value
$\bullet_{max}$, $\bullet_{min}$	maximum and minimum value

1.1. Mechanisms – previous work

The literature contains numerous observations on the RCF damage process and the influence of interacting parameters. The early work by Way [3] in 1935 introduces the damage and the failure atlas by Tallian [2] displays examples of intermediate damage stages. Ding and Rieger [4] have published scanning electron micrographs of cracks and craters. The damage process consists of three stages. Firstly, inclined surface micro-cracks initiate. Secondly, some of these grow into the material, gradually turning towards a surface parallel path. The depth of this spalling bottom often corresponds to the depth with maximum effective stress. Finally, a piece of material separates from the surface giving the craters in Fig. 1. Further examination reveals two different mechanisms, which differ by initiation at the surface or below it. Both mechanisms lead to surface craters and agree in the later part of crack propagation. Surface initiated craters often display a v- or sea-shell shape, Fig. 1b, with the apex directed against the rolling direction. According to Tallian [2] the entry angle, $\beta_{entry} < 30°$. Smaller ranges were reported by Bastias et al. [5], $\beta_{entry} = 20–24°$ and by Dahlberg and Alfredsson [1], $\beta_{entry} = 25–30°$. The crack profiles in Fig. 1d have $\beta_{entry} = 23–30°$. The sub-surface initiated craters are however irregular in shape and lack the shallow entry angle of the surface initiated spall. Here Tallian [2] reports $\beta_{entry} > 45°$.