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Numerical investigation of the spall opening angle of surface initiated rolling contact fatigue

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ABSTRACT

The spall opening angle was studied for surface initiated rolling contact fatigue with the purpose to allow assessment of the volume of detached material. The influence of friction and the crack inclination angle on the damage spread in the contact surface was investigated with the asperity point load mechanism and a simplified three-dimensional rolling contact fatigue load. Crack arrest due to crack closure was proposed as explaining mechanism for the spall opening angle of the typical v-shaped or arrowhead crack configurations. A new three-dimensional crack geometry was presented allowing the study of the spalling surface morphology in a gear application. Stress intensity factors along the crack front were computed using the eXtended Finite Element Method (XFEM) implemented in Abaqus (6.12). Both low crack inclination angles and increased friction resulted in larger spall opening angles. For cracks with small inclination angles the effects of increased friction on the spall opening angle appeared however very little. The findings increase understanding of the surface morphology and the damage process and further motivate the asperity point load mechanism as an important source for surface initiated RCF damage.

1. Introduction

Rolling contact fatigue (RCF) is encountered on mechanical components subjected recurrently to high contact loads in combination with small relative sliding motion. Gears, bearings or cam wheels are only some structural components that commonly suffer from cracks or craters in the contact surfaces due to RCF as illustrated in Fig. 1(a) for a gear application. One can distinguish between micro-scale and macro-scale damage: surface distress designates damage with dimensions comparable to surface roughness, whereas macro-scale damage is referred to as spalling, following the nomenclature by Tallian [1]. In the literature however RCF damage is also referred to as surface fatigue, pitting or flaking. RCF damage may induce dysfunctionality of structural components and even result in final failure. RCF may therefore become a life limiting factor for a mechanical component.

1.1. Experimental observations

The RCF initiation site may be situated below or on the contact surface. The former case is designated as sub-surface RCF with initiation sites at sub-surface defects resulting in fairly irregular shaped craters or spalls in the contact surface. The

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Nomenclature

a	total crack length in symmetry plane
a_c, a_β	cylindrical crack length, planar crack length in symmetry plane
a_l, a_p	cylinder contact half-width, asperity contact radius
c	half surface crack length
c_β	half planar crack length in y-direction
E	Young's modulus
i	dummy index or subscript referring to a contour
f	geometric shape factor
k	dummy index referring to a calculation point
K_I, K_{II}, K_{III}	mode I, II and III stress intensity factors (SIFs)
$K_{I,cl}$	crack closure limit
m	superelliptical exponent
n_c	first accounted contour in Eq. (A.1)
N	gear life
N_c	total number of contours in Eq. (A.1)
N_k	total number of calculation points in Eq. (A.2)
p_l, p_p	normal cylindrical and spherical Hertzian pressure distribution
p_{0l}	maximum cylindrical Hertzian pressure
p_{0p}	maximum spherical Hertzian pressure
q_l, q_p	tangential cylindrical and spherical Hertzian traction distribution
q_{0l}	maximum cylindrical Hertzian tangential traction
q_{0p}	maximum spherical Hertzian tangential traction
r_c	cylindrical crack radius
r_e	enrichment radius
s_β	curvilinear coordinate along crack front
S	sum of squared residuals in Eq. (A.2)
t	thickness of FE model
x_c	surface position of crack
x_d	distance defining position of cylindrical load
x, y, z	global cartesian coordinates with origo at centre of spherical load
x_β, y_β, z_β	local cartesian coordinates with origo at O_β
α	spall opening angle
β	crack inclination angle relative to contact surface
μ	cylindrical coefficient of friction
ν	Poisson's ratio
σ_0	uniform tension
θ	cylindrical angular coordinate
$\mathbf{\Phi}$	normal level set, signed distance to crack face
$\mathbf{\Psi}$	tangent level set, signed distance to crack front plane
$\bullet^0$	reference solution
$\bar{\bullet}$	average value
$\bullet_{max}$	maximum value

angle between the contact surface and the spall wall is then typically more than 45° [1]. For surface initiated RCF the entry angle, β, is more shallow, typically less than 30° [1–3]. Another essential characteristic of surface initiated spalling damage is the arrowhead shape with opening in the rolling direction and crack initiation at the apex [1]. This typical configuration or damage morphology has also been described in the literature as a triangular, v-shaped, sea-shell shaped or fan-shaped crack. Multiple studies have investigated or reported the typical v-shaped surface damage for both bearing and gear applications [4,5,2,6–10]. The angle at the apex of the spall or crater, α in Fig. 1(b), is referred to as spall opening angle or crack spread angle.

Bastias et al. [2] measured the spall opening angle during an experimental study on 440C bearing steel and found α to be situated in the range 50–60°. Murakami et al. [11] report experimental results from various studies in the range 70–140°. Olsson [7] reported spall opening angles in the range 85–115° measured on gear flanks. The currently investigated gear wheels in Fig. 1(c) were part of the study by Olsson [7]. The spall opening angles of typical v-shaped spalls were measured on three gear wheels. For each gear wheel the black square marker at the centre of the black line in Fig. 1(c) represented the average spall opening angle. The total length of the black vertical line corresponded to two standard deviations. The average spall opening angle was close to 100°, which was also indicated by the horizontal bar graph to the right in Fig. 1(c).