Modelling of surface initiated rolling contact fatigue crack growth using the asperity point load mechanism

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Even the strongest have their moments of fatigue.

Friedrich Nietzsche
Preface

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In addition, I would like to mention my fellow PhD students and other colleagues for the nice and stimulating work environment. It is really a pleasure to spend time with friends at work.

I am also extremely thankful towards my family for all their sacrifices and for allowing me to pursue a higher education. Their never ending support and encouragements have pushed me forward.

Finally, I would like to extend my gratitude to Sara, who has brought balance in my life. Thank you for your understanding, patience and love.

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List of appended papers

**Paper A:** Rolling contact fatigue crack path prediction by the asperity point load mechanism
Dave Hannes and Bo Alfredsson
*Report 507, Department of Solid Mechanics, Engineering Sciences, KTH Royal Institute of Technology, Stockholm, Sweden*

**Paper B:** A fracture mechanical life prediction method for rolling contact fatigue based on the asperity point load mechanism
Dave Hannes and Bo Alfredsson
*Report 508, Department of Solid Mechanics, Engineering Sciences, KTH Royal Institute of Technology, Stockholm, Sweden*

In addition to the appended papers, the work has resulted in the following publications and presentations:

**Prediction of rolling contact fatigue crack paths**
D. Hannes and B. Alfredsson
Presented at Svenska Mekanikdagar, Södertälje, 2009 (P)

**Spricktillväxt vid rullande kontaktutmattning**
D. Hannes and B. Alfredsson
Presented at UTMIS, Sandviken, 2011 (P)

**Life prediction for rolling contact fatigue based on the asperity point load mechanism**
D. Hannes and B. Alfredsson
To be presented at Svenska Mekanikdagar, Göteborg, 2011 (P)

**Rolling contact fatigue crack growth prediction by the asperity point load mechanism**
D. Hannes and B. Alfredsson
To be presented at 10th *International Conference on Fracture and Damage Mechanics*, Dubrovnik, 2011 (A,P)

\(^1\text{A = Extended abstract, P = Presentation}\)
Introduction

Many applications or machine components have interacting surfaces, where due to repeatedly high contact loads, contact or surface fatigue could initiate. When moreover relatively little slip is involved, one speaks of rolling contact fatigue (RCF). This type of fatigue can lead to non-functionality of machine components, increase noise and vibrations or even result in total failure of the component.

The present thesis contains both experimental and numerical work on surface initiated rolling contact fatigue in case hardened gear wheels. The purpose is to estimate the fatigue life of gears that suffered from surface initiated RCF using the asperity point load mechanism. Before estimating fatigue life, the fatigue crack path was predicted based on experimental data from case hardened gears that had suffered from surface initiated RCF together with a finite element model of an equivalent gear geometry, see Paper A. The crack path prediction of RCF cracks was based on linear elastic fracture mechanics (LEFM) and the mode I fracture mechanism and captured experimental observations. RCF life was then estimated, see Paper B and the asperity point load mechanism was found to explain both fatigue crack initiation and propagation.

The non-proportional, plane mixed-mode loads on the RCF crack together with crack closure complicate both the predictions of crack path and fatigue life. Furthermore is RCF a complex problem due to the large number of interactively influencing parameters: load, contact geometry, dimensions of individual asperities, lubrication film, additives, contaminants, slip, rolling velocity, coefficient of friction, material properties, inclusions, micro-structure, surface treatment, etc. The complexity of the surface initiated RCF problem asks for focusing on important parameters such as the contact geometry, material properties and load.
Rolling contact fatigue

Typical applications or components suffering from RCF are rolling bearings, cams, gears or wheel-rail contact, see Fig. 1. Following the nomenclature by Tallian (1992), surface distress designates micro-scale contact fatigue damage, i.e. of a size comparable to the dimensions of asperities on the contacting surfaces. Macro-scale contact fatigue damage is commonly referred to as spalling, Tallian (1992), with spall being used to describe both the crater and the chipped off material. Other designations for RCF damage such as pitting or flaking exist in the literature. RCF damage can either initiate under the surface, see Fig. 1(a) or at the surface, see Fig. 1(b). Different initiation points and damage mechanisms yield also different damage characteristics. In this thesis focus will be on surface initiated RCF on gear flanks.

Characteristic damage on components that suffered from surface initiated RCF or spalling are fatigue cracks and small craters or spalls. The damage developed at separate positions along the contact surface, see Fig. 1(b). Surface initiated RCF craters present a characteristic v- or sea-shell shape with the apex directed against the rolling direction, see Fig. 2(a). Fig. 2(b) presents different spall profiles of separate craters measured on the gear wheel in Fig. 1(b). The different spalls present similar profiles with an entry angle in the range $23^\circ - 30^\circ$. The shallow entry angle is a typical feature of surface initiated RCF damage and various observations were reported in the literature: according to Tallian (1992) the entry angle is less than $30^\circ$. Smaller ranges were reported by Bastias et al. (1994), $20^\circ - 24^\circ$ and

(a) Sub-surface initiated RCF damage in a cam wheel.  
(b) Surface initiated RCF damage on gear flanks.

Figure 1: Machine components that suffered of RCF damage.
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(a) Characteristic v- or sea-shell shaped surface initiated spall.

(b) Measured profiles of 3 separate spalls on the same gear. Note that the axes scales differ.

Figure 2: Surface initiated rolling contact fatigue or spalling.

by Dahlberg and Alfredsson (2007), 25° – 30°. The exit angle is observed to be steeper than the entry angle. The sub-surface initiated spalls are however irregular in shape, see Fig. 1(a) and lack the shallow entry angle of the surface initiated spall: Tallian (1992) reports an entry angle larger than 45°. A more comprehensive description of spalling damage can be found in the Failure Atlas by Tallian (1992).

Surface initiated spalling was initiated just below the pitch line in the region with small negative slip and propagated in the rolling direction, see Fig. 2(a). Different stages of the RCF crack growth are illustrated in Fig. 3: after fatigue crack initiation, small inclined cracks are observed at the surface, see Fig. 3(a). These continue to propagate into the material and

(a) Short inclined surface cracks.

(b) Detachment of spall particles.

Figure 3: Different stages of surface initiated rolling contact fatigue or spalling.
may turn to a path parallel to the contact surface. Finally the fatigue crack will reach the contact surface creating a spall. Prior to final detachment of the spall particle, small particles of the undermined material may detach as shown in Fig. 3(b).

**Asperity point load mechanism**

Since the first comprehensive work on RCF by Way (1935), many researchers have studied the complex problem of spalling and proposed different mechanisms to explain the damage process. The asperity point load mechanism was first presented by Olsson (1999) and further developed by B. Alfredsson and J. Dahlberg. The current work is a contribution to further validation and study of the asperity point load mechanism.

Two contacting bodies with perfectly smooth surfaces are modelled as a cylindrical contact and would introduce at most small tensile surface stresses for a finite body. For an infinite body zero surface stress would be obtained. However when small asperities on the contacting surfaces are considered, local three-dimensional point loads are introduced, which disturb the two-dimensional cylindrical contact profile, see Fig. 4. The small asperity acts locally as stress raiser yielding large tensile surface stresses in front of the asperity. The hypothesis behind the asperity point load mechanism is that these stresses can cause fatigue initiation and crack propagation leading to RCF damage.

![Diagram of the asperity point load mechanism](image-url)

*Figure 4: The asperity point load mechanism.*
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A purely two-dimensional contact load could explain bands of damage over the contact width but not separate spalls as in Fig. 1(b). By inducing locally high tensile surface stresses, the asperity point load mechanism explains local damage. The presence of asperities on gear flanks and their influence on the surface stress was pointed out by Dahlberg and Alfredsson (2007). Dahlberg and Alfredsson (2008) then showed that these large tensile surface stresses could be responsible for fatigue crack initiation and how friction on the asperity could increase the risk for initiating fatigue damage. Besides fatigue crack initiation, the asperity point load mechanism was used to explain fatigue crack propagation, see Paper A. The numerical crack path prediction was compared to the experimental spall profiles in Fig. 2(b). Main features such as the entry angle and the propagation direction were captured. In Paper B the fatigue life was estimated and compared to the spalling life of gears that suffered from surface initiated RCF.

Some challenges with modelling RCF

A RCF crack is subjected to plane mixed-mode loads, yielding the curved crack paths in Fig. 2(b). Hence both $K_I$ and $K_{II}$ have to be computed and considered for the crack path predictions. For the spalling life prediction an equivalent fatigue life parameter is needed. Various crack path direction criteria and equivalent fatigue life parameters can be found in the literature. Another characteristic of RCF loads is non-proportionality, i.e. the principal directions rotate and the magnitude of the principal stresses or strains varies during the load cycle. Non-proportional loading of fatigue cracks has not been investigated as extensively as proportional loading. Non-proportionality of the load yields phenomena such as crack closure or additional cyclic hardening, Socie and Marquis (2000). Furthermore, the RCF load consists of high compressive minimum loads causing crack closure, which has to be taken into account for the spalling life prediction. The effect of crack closure was accounted for using an effective measure of the stress intensity factors, based on a crack closure limit $K_{I,cl}$. In summary, the RCF loads complicate the prediction of the crack path direction and the estimation of the spalling life.
Conclusions

It was concluded in Paper A that the maximum mode I crack path for the surface initiated
RCF crack was well approximated by the trajectory of the largest principal stress in the
uncracked material. With $K_{I,cl} = 0$, the crack path direction could be evaluated when $K_I$
was the maximum during the load cycle. The simulated path agreed with the spalling profile
both in the entry details and in the overall shape, which verified the point load mechanism for
RCF crack growth. Throughout the growth simulations, $K_{I,max}$ developed when the asperity
entered the contact. Furthermore, the RCF crack growth could be modelled with LEFM
although the crack length was mostly small. The cyclic plastic zone at the crack tip as well
as the micro-structure were sub micrometer size. The predictions for initiation and growth of
RCF cracks followed accepted fatigue theory. The fatigue damage process was at both ends
explained by the asperity point load mechanism and linear elastic fracture mechanics.

Crack growth experiments on DCT specimens presented in Paper B suggested negative
$K_{I,cl}$ values for $R < 0$. It was concluded from the experimental results that the material
displayed crack closure both at the crack tip and behind the tip when $R < 0$. The combined
effect suggested that $K_{I,cl} = 0$. The crack growth life simulations showed that the stresses from
the combined asperity and cylinder contact could predict the spalling life in the investigated
gear application. The simulated crack growth life clearly depended on $K_{I,cl}$, but supported
the asperity point load mechanism for surface initiated RCF.
Summary of appended papers

**Paper A:** *Rolling contact fatigue crack path prediction by the asperity point load mechanism.*

In this paper the crack path of surface initiated rolling contact fatigue was investigated numerically based on the asperity point load mechanism. Data for the simulation were 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. When the asperity contact pressure was separated from the cylinder pressure, closed-form solutions exist for the stresses in the substrate and the crack tip loads were computed. 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 predicted 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.

**Paper B:** *A fracture mechanical life prediction method for rolling contact fatigue based on the asperity point load mechanism.*

This paper had as purpose the development of a fracture mechanics based method for determining the spalling life and to verify the life prediction against the spalling life in some gear teeth. It builds further on the asperity point load model and predictions presented in Paper A. Indeed, correct crack path prediction is a prerequisite for accurate estimation of fatigue life. The computational tool for RCF life required an equivalent mixed-mode life parameter. Such are suggested in the literature and some of these were evaluated in this paper. Also, the work required material properties for crack growth at stress cycles with highly compressive minimum loads. Hence, an experimental series was performed for crack growth at \( R < 0 \) in the case hardenend gear steel. Negative crack closure limits \( K_{1,cl} \) were
suggested by the compliance but not the crack growth rate. Simulations with small negative closure limits ($K_{I,cl} = -0.1 \text{MPa}\sqrt{m}$) predicted the spalling life in the gears. It was however noted that the life predictions depended largely on the equivalent mixed-mode life parameter and $K_{I,cl}$.
References


Paper A

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Paper  B

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