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Influence of surface topography and lubricant design in gear contacts

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Licentiate thesis
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Academic thesis, which with the approval of Kungliga Tekniska Högskolan, will be presented for public review in fulfilment of the requirements for a Licentiate of Engineering in Machine Design. The public review will be held at Kungliga Tekniska Högskolan, Brinellvägen 85, room M37, at 14.00 on October 2, 2009.

Abstract

The purpose of this thesis was to study the influence of manufacturing variations on gear performance. The manufacturing variations inherent in different manufacturing methods were studied to include the effect of real surfaces. Real surfaces have surface irregularities at least on some scale, which can significantly influence how loads are transmitted at the gear contact. To some extent, the lubricant design can help to prevent contact that could lead to tooth failures by forming a protective surface boundary layer. An experimental study was used to consider the compositions of these layers with a surface analysis method.

In Paper **A** a robust design approach was used to find out to what extent the current standard for calculation of surface durability treats manufacturing variations and the choice of lubricant. The results show that the simplest calculation method used is not enough to predict the effect of these on surface durability. Additionally, the standard quality levels are poorly incorporated in the standard calculating procedures for surface durability, and the quality of the gear tooth is restricted to include only a few parameters.

In Paper **B** a pin-on-disc machine was used to evaluate the tribofilm formation by the additives and the corresponding wear occurring in the boundary lubrication regime in environmentally adapted lubricants. Studies of the additive and base fluid interaction were carried out using glow discharge-optical emission spectroscopy. It was found that the chemically reacted surface boundary layers played an important role in terms of wear. More specifically, the oxide layer thickness had significant influence on wear. The findings also demonstrate the complexity of lubrication design formulations coupled to these layers. For example, it was found that the pre-existing surface boundary layer (before any lubricant had been added) played an important role in allowing the lubricant to react properly with the surfaces.

The aim of Paper **C** was to contribute to the knowledge of how different surface topographies, tied to manufacturing methods, influence the early life contact conditions in gears. Topographical measurements of differently manufactured tooth flanks were used as data input to a contact analysis program. The variation in surface topography inherent in the manufacturing method was found to have a strong influence on the contact area ratio.

Keywords: gear contact, surface topography, surface boundary layers

Preface

The work in this thesis was carried out between November 2006 and October 2009 at the Department of Machine Design at the Royal Institute of Technology (KTH), Stockholm, Sweden.

This project was initiated by the gear community KUGG, which forms a part of the VINNOVA-financed MERA program. This support is gratefully acknowledged.

I would first like to thank my supervisors Ulf Olofsson and Stefan Björklund for their excellent guidance and for introducing me to the thrilling world of tribology. I would also especially like to thank Sören Andersson.

I am grateful for having got to know Marika Torbacke and colleagues at Statoil Lubricants. Marika's cool and professional attitude has made her an ideal role model.

A special thanks to Sören Sjöberg for discussions in both professional and non-professional matters. I greatly appreciate our work together. Then, of course, I would like to thank my other close colleagues Anders, Björn, Jens, Jon, Petter and Rasmus for valuable discussions, help and for sparkling up the time at KTH so far.

Finally, I would like to thank my entire family for their encouragement. Especially my grandfather Johan and parents Brita and Inge, for which I'm ok just being a *teknologie dotter*, and also my brother Erik and sister Elsa for being my true mentors.

This work would never have been created without Johanna and Rikard!

Stockholm, October 2009

Ellen Bergseth

List of appended papers

This thesis consists of a summary and the following three papers:

Paper A

Ellen Bergseth, "Influence of gear surface roughness, lubricant viscosity and quality level on ISO 6336 calculation of surface durability", *Technical Report*, TRITA-MMK 2009:17, ISSN 1400-1179, ISRN/KTH/MMK/R-09/17-SE.

Paper B

Ellen Bergseth, Marika Torbacke, Ulf Olofsson, "Wear in environmentally adapted lubricant with AW technology", *Journal of Synthetic Lubrication*, Volume 25, Pages 137–158, 2008.

Paper C

Ellen Bergseth, Sören Sjöberg, Stefan Björklund, "Influence of real surface topography on the contact area ratio in differently manufactured spur gears," *Proceedings of Tribology 2008: Surface Engineering of Automotive Powertrains for Environmentally Friendly Transport*, July 8-10 2008, London.

Submitted for publication in *Journal of Engineering Tribology*

Division of work between authors

The work presented in this thesis was initiated and supervised by Professor Ulf Olofsson and Associate Professor Stefan Björklund.

Paper A

The work was performed by Bergseth.

Paper B

The experimental work was performed by Bergseth. Most of the writing was done by Bergseth and Torbacke, but Olofsson contributed. Both Torbacke and Olofsson supervised.

Paper C

The experimental work was equally divided between Bergseth and Sjöberg. Björklund performed the simulation. All authors were equally involved in both writing and editing of the text.

Contents

Appended papers

A. "Influence of gear surface roughness, lubricant viscosity and quality level on ISO 6336 calculation of surface durability"

B. "Wear in environmentally adapted lubricant with AW technology"

C. "Influence of real surface topography on the contact area ratio in differently manufactured spur gears"

1 Introduction

Gears have been and continue to be one of the most important means of mechanical power transmission. However, the demands for reduced unit weights, higher efficiency gears, and more environmentally adapted lubrication techniques — as well as striving for robustness — have forced designers and manufacturers to become aware of phenomena that were previously of less importance. This thesis relates to phenomena occurring in high precision gears used in, for example, heavy trucks (Figure 1).

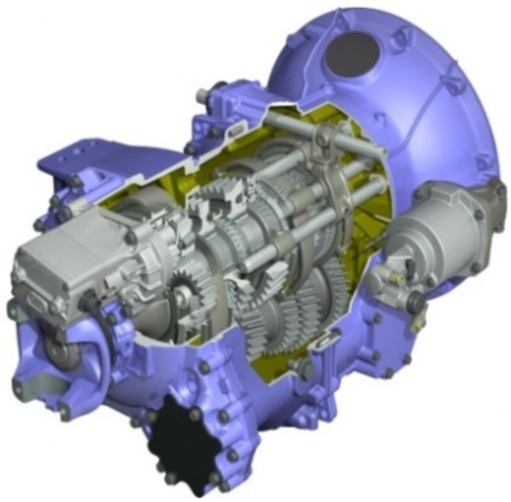

Figure 1. A heavy truck gear transmission (Scania GR875 range-change gearbox) [1].

The overall goal of this thesis was to investigate the influence of gear geometry, surface topography, and lubrication design on the gear contact load capacity. Gear geometry was studied in terms of gear standard quality levels. Surface topography was investigated by comparing the influence of different gear manufacturing methods on the contact conditions. Lubricant design was investigated in terms of the capability of environmentally adapted lubricants to form protective boundary layers on the contact surfaces. Surface topography and lubricant design were also studied in the context of the international standards procedure for calculation of contact load capacity.

When producing high precision gears, it is important to identify the effects of manufacturing variations on the gear performance. Manufacturing variations can include individual machine variations (caused by, for example, wear of tools), lack of rigidity of the workpiece, and the choice of manufacturing method. Houser [2] found that the influence of manufacturing variations on the load sharing of a tooth pair was greater than that indicated by the standard rating practice. Similar findings were reported by Li [3], who also emphasised the necessity of understanding the influence of machining variations on gear performance in order to be able to produce lightweight and compactly-sized gears. Most research on the influence of gear manufacturing variations on gear performance is related to standard gear parameters, which do not include the nature of different manufacturing methods.

Highly loaded gears often rely on a well designed lubricant (i.e. base oil and additive combination). Additives must perform their function on the surface, which thus needs to be able to react chemically with the additives in order to form a strong and low shear surface boundary layer to reduce friction and wear. Joachim and Kurz [4] used gear tests to investigate the various tooth flank manufacturing methods and lubricant combinations with regard to their effect on tooth flank service life. They illustrate the importance of the thickness of the surface boundary layer, and state that this certainly needs to be studied in detail in order to be useful for practical applications. The current international standard [5] procedure only reflects certain tendencies of how the choice of lubricant influences load carrying capacity. Höhn et al. [6] evaluated the influence of lubricants on the pitting load capacity of case-carburised gears by means of a new test method, and made some suggestions for adding an additional factor to the standard rating formulas in order to better correlate the actual lubricant performance.

The work presented in this thesis is part of a project to increase and strengthen our knowledge of gears in order to secure the future for gear manufacturing in Sweden. The Swedish gear industry has a turnover of 12 billion SEK and employs just over 5000 persons [7]. The global market exceeds 45 billion dollars, three-quarters of which is in the automotive sector [8].

This thesis is linked to a range of ongoing projects in a Swedish research project known as KUGG [9]. Bagge [10] has mentioned the importance of process planning of gear transmissions in meeting changing design requirements and being cost effective. Gerth and Werner et al. [11] have developed a test which allows the reproduction of tool wear in gear cutting. Tehler and Jonsson [12] suggest a model for simulating volume changes due to thermal expansion, which allows for accurate simulations of hardening distortions, an important source of gear quality variations. Sjöberg and Sundh [13] have investigated the influence of manganese phosphate and lubricants on the risk of scuffing, which can be related to the running-in of tooth flank surfaces.

The road map for the three papers included in this thesis is given below.

Paper **A** presents the current ISO 6336 calculation of surface durability and can be seen as a literature survey. The aim was to use a robust design approach to find out to what extent the standard treats variations in surface roughness, lubricant viscosity and gear quality level (accuracy grade). An additional aim was to use the standard without the need for experimental testing, extensive knowledge, or advanced calculation. Thus, the simplest calculation method according to the ISO standard was used.

The aim of paper **B** was to examine the tribofilm formation and the corresponding wear occurring in the boundary lubrication regime in environmentally adapted lubricants, when using synthetic ester base fluids with different AW additives. Wear was studied using a pin-on-disc machine. The worn disc surfaces were analysed by GD-OES (glow discharge-optical emission spectroscopy) to reveal the surface reactions formed by the additives.

The aim of paper **C** was to compare different gear manufacturing methods and their inherent surface topographies. The real 3-D surface topography was measured on new (unused) spur gear tooth flanks produced with four different manufacturing methods. The measured topographies were used as input to a contact analysis program (boundary element software) and the pressure distribution for two different loads was calculated at different mesh positions.

2 Gear design

Gear design has a long tradition of empirical testing and standardisation work for dimensioning procedures, beginning in the early twentieth century. This does not make gear design trivial by any means; rather the opposite.

The combination of rolling and sliding between the gear teeth, the change of size and direction of the contact load, and the constantly moving contact (Figure 2) means that gear calculations are quite complex in comparison to other machine components [14]. Additionally, demands from customers and legal regulations, such as increased efficiency and lower noise levels, call for a continuously evolving process of gear design. Besides these factors, the robustness of gears also has significant importance, as discussed by MackAldener [15].

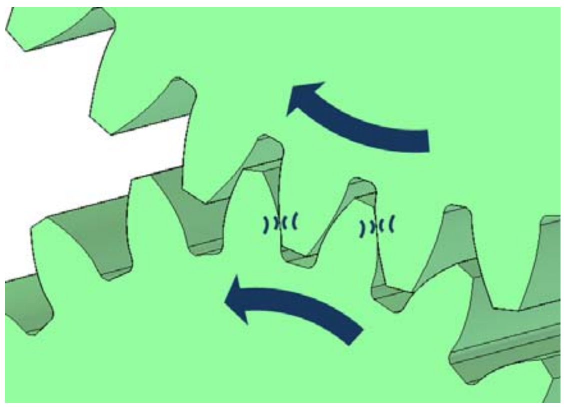

Figure 2. Gear contact – a highly loaded contact.

The gear designer specifies design properties that are directly coupled to achieve certain aspects of gear performance requirements, such as service life or noise. There are various design properties, all of which have a unique tolerance that can range from hundreds of micrometers to just a few micrometers. A brief outline of how design properties can affect gear performance is given below.

Tooth thickness, for example, is a design property which directly relates to backlash, affecting positioning and motion control. For load capacity, tooth alignment (lead) is probably one of the most critical factors, since flank edge contact increases the risk for high contact pressures at the edges and hence results in a shortened service life. The accumulated pitch (tooth-to-tooth spacing) variation is the most critical for gear ratio accuracy. For noise, profile (involute) variations are the most critical according to Smith [16], due to stiffness variation during the gear mesh.

The required gear performance can more easily be achieved by setting correct design parameters in terms of macro geometry, micro geometry, and surface topography. These will influence gear performance both independently and in combination. Macro geometry includes aspects such as module, number of teeth, and pressure angle, while micro geometry includes gear quality levels as well as tooth modifications such as lead crowning, in which the tooth centre is slightly thicker than the tooth edges (an indicative range of the additional thickness would be 10-50μm). Surface topography covers variations from the theoretical surface and is commonly divided into variations of form, waviness, and roughness, which are separated based on the surface wavelength.

The selection of micro geometry is often specified in order to achieve a robust design for a certain gear performance. The use of lead crowning, for example, can adjust for tooth alignment problems by shifting the peak load from the tooth flank edges, as illustrated in Figure 3. Bergseth and Björklund [17] compared traditional lead crowning modifications for gears with a logarithmic profile. All lead profiles were optimised with respect to low contact pressure at a specific normal load, a specified maximum misalignment in the plane of action, and a tooth flank edge contact criteria. The logarithmic profile was found to be less sensitive to small misalignments, which is of interest in terms of achieving a robust design.

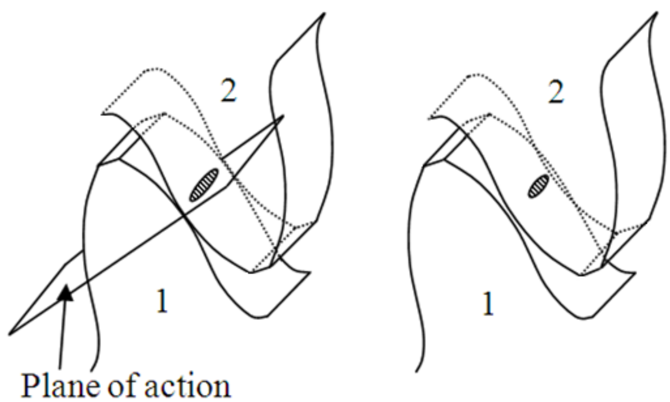

Figure 3. Schematic illustration of a gear contact with no tooth misalignments (left) and with angular misalignment (right) of gear 2 in the plane of action.

Standard rating formulas for calculation of load capacity (surface durability) are based on Hertz contact theory; they include numerous design factors, such as the dynamic load factor and the roughness factor. These factors are there to create realistic evaluations of the stress levels encountered by a gear pair. Preferably, a gear designer should look at the performance requirements of a gear and use tolerance tables to select the quality level that will meet these requirements. However, Paper **A** shows that these quality levels are poorly incorporated in the ISO 6336 [5] surface durability calculations. Furthermore, the standard is restricted to using only a few tolerance parameters. Houser [1] studied the partially equivalent American national standard (AGMA) and came up with similar findings, concluding that several factors likely to be affected by manufacturing are not quantified in terms of quality levels.

Figure 4 shows the influence of surface roughness of the flanks as a function of the mean relative peak-to-valley roughness and the allowable contact stress σ_{Hlim} value according to ISO 6336 [5]. Gears equal to standard reference test gears are used when the roughness factor is equal to 1. As seen in the diagram, the scatter (width of the hatched field) is greater than the variation due to the toughness of the flank. This indicates that there are influences which are not included in the calculation procedure. Joachim and Kurz [4] point out that the surface structure influences are not considered in the standard procedures, nor is the thickness of the lubricant film.

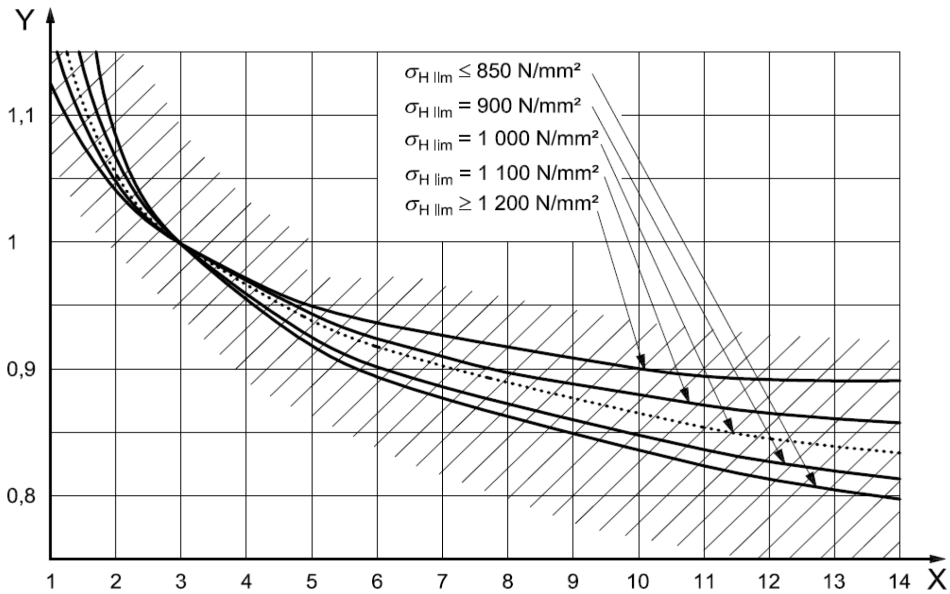

Figure 4. The x-axis shows the mean relative peak-to-valley roughness (μm) and the y-axis the roughness factor.

The gear designer has the problem of constantly weighing the effect of any proposed tolerance on gear performance and cost, and of specifying proper values. Generally, designers prefer tight tolerances, to assure product performance, while manufacturers prefer loose tolerances, to reduce costs. However, gear design and gear manufacturing go hand in hand; according to Bagge [10]. While the design properties are set during gear design in order to adjust for manufacturing variations and to achieve the desired gear performance, it falls to the manufacturers to find the source of variations, such as wear of tools, in order to be able to correct them.

3 Gear manufacturing

Gears are often manufactured in a sequence of operations. Since highly loaded gears are hardened, it is convenient to separate machining operations before and after hardening into soft and hard machining operations respectively.

The first operation is usually cutting; one common cutting process is hobbing, which is illustrated in Figure 5. Hobbing is a widely used machining process to generate involute gear profiles. It is based on rack-cutter generation where the surface is obtained as the envelope of a series of cutter surfaces formed during a continuous motion between workpiece and cutter [18]. The rack-cutter profile is a cutting edge whose straight sides and fillets machine the flanks and the gear fillet respectively. Bergseth [19] used a computer-aided design approach to study how the tool wear on a hob portrays its eigencharacteristics on the tooth flanks. However, the scale used for simulating these defects was limited by the computer and program resolution capacity. Further work is necessary to reach microscale levels.

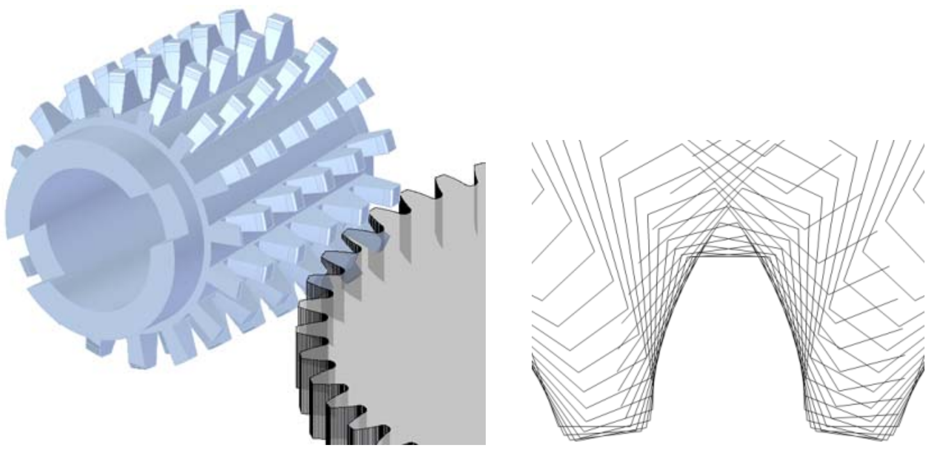

Figure 5. Illustration of a hob and gear wheel setup (left) and a close-up on gear tooth generation (right).

Hobbing is not usually used as a finishing process. To adjust for the inaccuracies inherent in the cutting process, a further soft operation known as shaving can be used. The shaving tool can be seen as a helical gear with gashes in the flanks working as cutting edges meshed with the workpiece in a crossed axis relationship. Shaving can be performed using different processes (e.g. parallel, plunge, and diagonal), with feed and sense of rotation being handled in different ways. By removing small amounts of material, shaving can enhance the overall quality of the gear tooth. Shaving can be used as a finishing operation, and so machine settings need to be chosen to make allowance for distortions after hardening. Hardening can be performed in various ways depending on, for example, the selected steel and desired machinability. In the case of case-hardened gears, the surface alone is hardened, up to a predetermined depth.

If increased quality is needed, there is a choice between two finishing operations, honing and grinding, both of which are hard machining operations. According to Dugas [20], the process of honing was developed to improve the sound characteristic of hardened gears by a) removing nicks and burrs, b) improving surface finish, and c) making minor corrections in tooth inaccuracies caused by hardening distortions. Similarly to shaving, honing is recognised by the machined gear and the honing tool meshing with their axis intersecting [4]. The honing tool made of abrasive ceramics is formed as an internal helical gear within which the machined gear is normally driven by the honing tool. The grinding tool is an abrasive coated wheel and there are essentially two techniques for grinding gears: continuous worm grinding and discontinuous profile grinding. The first is characterised by the arrangement of tool and workpiece as a worm gear and the second by each tooth gap of the machined being processed separately. Honing techniques have improved in recent years and today honing and grinding can produce almost equal quality levels. Honing has the advantage that grinding burns are avoided.

Amini et al. [21] have discussed and emphasised the similarities between the above mentioned finishing operations with respect to surface topography. They found that surface parameters due to noise activity are profile undulation properties; that is, surface lay direction, wavelength, and amplitudes. Åkerblom [22] performed experimental investigations of the influence of different gear finishing operations and gear manufacturing variations on gearbox noise and vibration. He found evidence that, for example, shaved gears do not seem to be noisier than ground gears even if their gear quality levels were larger, and that a rougher surface finish, increased lead crowning, and helix angle variations seem to increase noise. However, Åkerblom also found strong evidence that gear noise is affected by factors other than the gears themselves, for example assembly related variations.

4 Gear tribology

The contact conditions in gears are influenced by both surface topography and lubrication formation of protective surface boundary layers. Both phenomena have an impact on gear performance. The interdisciplinary science for studying these phenomena is called tribology — the science of friction, wear, and lubrication of contacting surfaces in relative motion. Friction can be seen as the resistance against sliding between two surfaces and wear can be defined as the removal of material from solid surfaces as a result of mechanical and/or chemical action. Lubrication is the most common way to reduce friction in terms of building up an easily sheared film, reduce wear and to transfer heat.

Over the years, tribology has focused towards smaller and smaller scales in the investigation of these phenomena. That is, today it is not just the presence of lubrication in a machine application that is of importance, but also the type of lubricant and where it is intended to act. This expansion goes along with the tools of surface science, such as surface analysis, which provides information about the actual surface layers (Paper **B**), and atomic force microscopy (AFM), which makes it possible to quantify 3-D surfaces with a resolution at atomic levels.

Holmberg [23] has divided tribology into different scales, since the phenomena, the characteristic set of parameters, and the relevant scientific approaches can often differ substantially between scale levels. Research at the beginning of the twentieth century focused on macrotribology or contact tribology, such as contacts between gears and wears mechanisms clearly observable by visual inspection [23]. The gear standard calculation of surface durability can be put in this scale. Microtribology or asperity tribology covers the friction, wear, and adhesion taking place at the peaks of the surface topography [24]. Here, phenomena such as fracture, elastic and plastic deformation, surface layer formation, and topography effects are of importance [23]. The overlapping scale levels covered in this thesis are macrotribology (Paper **A**) and microtribology (Paper **B** and Paper **C**).

Tribology is highly connected to energy consumption, service life, robustness, and other factors of current interest today. Although a gear transmission is a classical mature tribological system, Joachim and Kurz [4] have pointed out that there is a lack of knowledge regarding the effects of various lubricants on different tooth flank surfaces. There are several reasons why we need to know more about this; for example, one way to reduce churning losses is to use a lubricant with lower viscosity. However, a lower viscosity decreases the thickness of the lubricant film, which increases the risk of surface failure. Consequently, there is a need for more confidence in the lubricants and the nature of the surface.

4.1 Surface topography

Engineering or real surfaces are rough (uneven). Mirror-like surfaces are also rough, at least at atomic scales. A surface consists of peaks and valleys; that is, it has topography. Peaks or higher areas are referred to as asperities. The surface topography of interacting surfaces has a strong impact on the discipline of tribology, since it has an effect on the contact behaviour. Due to the surface topography, only parts of the surfaces nominally in contact are actually in contact. The real contact area (A_R) is formed by the sum of the contact spots and the nominal contact area (A_N) is formed when the surfaces are perfectly smooth (Figure 6). The contact ratio (A_R/A_N) is used in Paper **C** for comparing various combinations of gear surfaces in contact at two different loads.

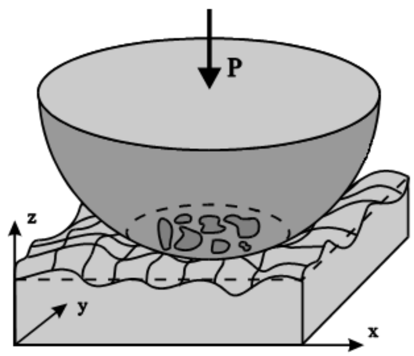

Figure 6. Schematic contact between a rough surface and a smooth sphere [25]. The nominal contact area is marked with a hatched line; contact spots form the real contact area within this.

Surface topography is traditionally measured using stylus instruments; a fine diamond stylus is drawn over a surface, and the vertical movements reveal variations from the theoretical surface. The stylus method is robust and reliable but excessively time consuming compared to, for example optical methods. The surface measurements in Paper **C** were performed with a stylus instrument, a standard measurement device known as a Form Talysurf. Different surface measurement equipment and various surface evaluating parameters that can be appropriate for gears are discussed by Xiao [26].

Gear inspection during the sequence of many operations involved in gear manufacture is crucial for facilitating adjustment of the machines to achieve the desired gear modifications and quality. The complex shape of the gear tooth has resulted in unique gear parameters and inspection techniques. The single gear tooth form are measured along the involute profile and face width (lead) detecting, for example, profile form and lead form variations. Figure 7 provides two illustrations of how tooth flanks can be inspected.

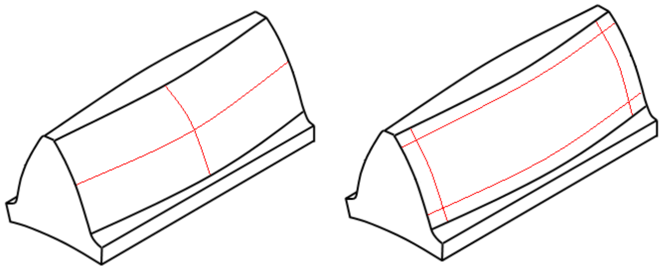

Figure 7. The stylus is drawn along the centre of the tooth profile and lead direction respectively (left). If the stylus is drawn along the gear tooth edges (right), bias or twist variations can more easily be detected.

4.2 Lubrication

Highly loaded gears often rely on lubrication to prevent gear tooth failures. In a gearbox, lubrication is usually applied by so-called splash lubrication; the gears dip into a reservoir of oil in the bottom of the gearbox and splash the oil around.

A lubricant consists of base oil and additives, and its properties depend upon various parameters such as rheological, chemical, thermodynamic, environmental, and additive response properties [27]. These properties help to ensure that a mild wear condition is obtained. Two broad wear regimes are mild and severe wear. Each of these includes several wear mechanisms. Running-in of the surfaces, which may have a positive impact on the gear performance and service life, can be seen as a mild wear or a normal wear condition. However, mild wear is also likely to act as a catalyst for surface fatigue, as discussed by Flodin [28]. A mild wear would (visually) give mirror-like surfaces, in contrast to pitting and scuffing, two classical gear wear phenomena illustrated in Figure 8. Pitting and scuffing can be referred to as severe wear, if they do not regress during the running-in stage. The standards define failure by pitting (fatigue failure) to mean a substantial number of destructive pits, where material particles break out of the surface due to exceeding the surface capacity [5]. Failure by scuffing is recognised by roughing bands in the involute profile direction. Generally, the failure mode of scuffing is based on a critical contact temperature at which the lubricant film fails and micro-welding between asperities takes place [14].

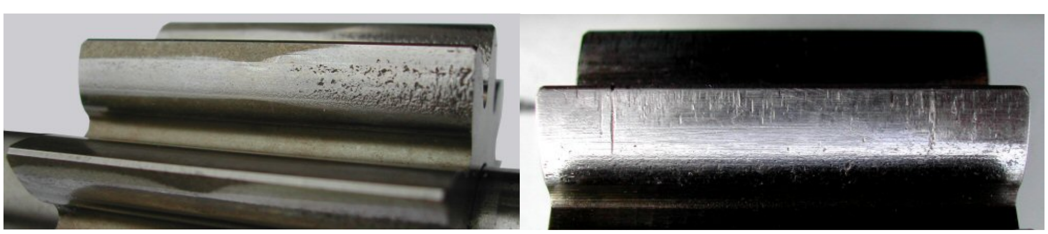

Figure 8. Pitting (left) and scuffing (right) [29].

Depending on the amount of direct contact between the surfaces, the lubrication regime is classified as boundary, mixed, or full-film. Stribeck [30] studied the general dependence between the friction force and the lubricant viscosity, sliding speed, and load; this resulted in the creation of the Stribeck curve shown in Figure 9. The Stribeck curve is often used to show the different regimes of lubrication, ranging from boundary lubrication where metal contact or contact via boundary layers occurs, to full-film lubrication where the surfaces are totally separated by the lubricant and no metal contact occurs.

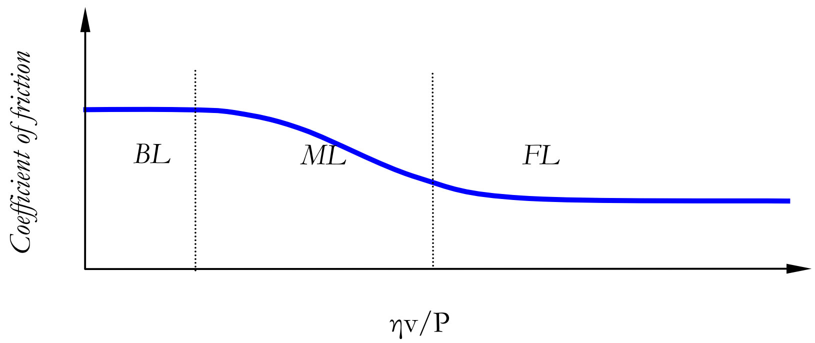

Figure 9. The coefficient of friction varies depending on lubricant viscosity (η), sliding speed (v), and load (P). BL – Boundary lubrication; ML – Mixed lubrication; FL – Full film lubrication.

Gears predominantly operate in the so-called elastohydrodynamic lubrication regime, which ranges from mixed lubrication to full-film lubrication. Elastohydrodynamic behaviour occurs in cases where contact pressures are large enough (1-3 GPa [31]) to cause the bounding surfaces to elastically deform. Castro et al. [32] believe that in the mixed lubrication regime the lubricant film separating the contacting teeth is thin, usually of the same order of magnitude as the roughness, which may cause lubricant film breakdown. When the lubricant film fails for one reason or another, boundary conditions occur. At this point, reduction of friction and wear depends on the surface boundary layer formed on the surface asperities by the additives. These chemical changes occurring within a few nanometers are key to the performance of lubricants in the boundary lubrication regime, according to McFadden et al. [33].

The surface boundary layer is typically formed by chemical reactions between additive elements such as sulphur and/or phosphate. The surface must be able to react chemically with the additives and form a strong and low shear surface layer. The reaction is activated by high temperatures. Dizdar found that pre-heating of the surfaces with common additives can cause these chemically reacted layers to be formed prior to contact [34]. Gears are sometimes coated with a manganese-phosphate-treated layer in order to achieve a better run-in. Sjöberg and Sundh [13] found that the manganese-phosphate coating has a greater advantage in terms of resistance to scuffing than a bare ground surface. However, this coating was found to be worn off at the early stage of the gear run-in.

The formation and composition of surface layers depends strongly on the chemical composition of the lubricant and also on the nature of the surface. The formation of oxide films is known to play an important role in the reduction of wear and friction in sliding metal surfaces [35]. The thickness of the oxide layer was found to play an important role with respect to wear in Paper **B**. The mechanism of formation and rupture of oxide layers and boundary layers is not completely known, and according to Rapetto [36] there is no reliable model for rough surfaces in boundary lubrication.

The market is still dominated by mineral oil based lubricants. As a result of this, most of the standards are based on tests using mineral oils. Höhn et al. [37] found that with synthetic oils, oil ageing (caused by high operational temperatures and long exposure times) had only a minor effect on gear life, in comparison to a reference mineral oil.

Today, we are faced with a broad range of environmentally adapted lubricants based on both natural and synthetic esters. The chemistry of natural and synthetic esters differs from that of mineral based oils. Hence, the additive responses in these esters in turn differ from those in mineral based oil. In order to optimise the benefits of an environmentally adapted lubricant, a better understanding of the additive and base fluid interaction is desirable. Both natural and synthetic esters can be used as a base fluid for an environmentally adapted lubricant. Synthetic esters are manufactured and tailored to a specific structure and are produced by reacting an alcohol with a fatty acid. The alcohol is usually of petrochemical origin, while the fatty acid is prepared from natural vegetable and animal oils and fats. There is a wide variety of both fatty acids and alcohols. Hence, there is a wide range of esters available.

4.3 Gear contact modelling

It is hard to find a substantial solution among the existing gear design methods suggested by Townsend [38], Litvin and Fuentes [18], and standards [5] for the estimation of surface durability. These methods may lead to overdesign and so many gear researchers develop their own models to obtain more accurate results.

The finite element method (FEM) has become the prevalent technique used for analysis and simulation of gears [39]. The method is used for studying the mechanical behaviour of gears influenced by various factors, such as the tooth profile (profile shift), the appearance of the gear fillet, rim thickness, tooth modifications, assembly errors, and so on. Li [40] developed a 3-D finite element method to calculate surface contact stress and root bending stress for a pair of spur gears with machining errors, assembly errors, and tooth modifications. Li suggests that FEM should be used for gear pairs exposed to these sorts of errors, instead of using standard rating procedures. Mao [41] applied micro geometry modification and simulated the gear contact behaviour using an advanced non-linear finite element method. This technique can simulate rolling/sliding and separation without a first estimation of the contact calculated with Hertzian theory. However, there are commercial programs available ([42], [43]) which are usable even when the design chosen does not conform with the design considered in the standard.

The above solutions assume that the contacting surfaces are smooth. This assumption is often made, since sufficient resolution in the contact area would make the size of the finite element model very large. Hertz's theory remains the basis for the analysis of most contact problems. It is based on the following assumptions: 1) the surfaces in contact are smooth, 2) the contact is elliptical, 3) the contact area between the bodies is generally small compared to the dimensions of the bodies themselves, 4) the strains are sufficiently small for linear elasticity to be valid, and 5) the contact is frictionless so that only normal pressure is transmitted. Other approaches allow a more general shape of the contact, not limited to an elliptic shape, and can be used to simulate rough surfaces in contact.

In the rough case the load will be carried by several contact spots, as illustrated in Figure 6. There are two types of approach to modelling the contacts between rough surfaces; the numerical and the statistical. Numerical approaches are used for limited contacts where the actual topography of the surfaces is known and where it is possible to calculate the real contact pressure due to the real surface topography. Björklund and Andersson [44] developed a numerical model for studying micro-slip contact phenomena where the contact patch is subjected to both normal and tangential loading. Almqvist et al. [45] developed a similar deterministic model to be used for numerical simulation of the contact of linear elastic and perfectly plastic rough surfaces. Statistical approaches, on the other hand, make use of the stochastic nature of rough surfaces and are not concerned with the exact topographies of the surfaces [25]. Greenwood and Williamson [46] made a first approach to this by assuming a convenient shape for the asperities (e.g. spherical) and using statistical parameters to describe their heights and sizes in order to compare different kinds of surface roughness.

The assumption that highly concentrated stresses in the region close to the contact zone are not greatly influenced by the shape of the bodies at a distance from the contact area plays an important role in contact mechanics, and is usually called *the half plane assumption*. This introduces the potential for error, which may be avoided by using the finite element approach. Vijyajakar [47] has addressed the problem by combining boundary element and finite element solutions; however, this method also contains an assumption about when the boundary and finite element solutions are valid, and so the potential for error is still present.

5 Methods

The work described in this thesis was both experimental and analytical. It was primarily related to highly loaded contacts, for example those seen in gear transmission for heavy trucks.

5.1 Surface Analysis

In order to obtain information about the composition of chemically reacted surface layers, the specimens used in Paper **B** were analysed with a method called glow discharge - optical emission spectroscopy (GD-OES), a technique recognised within the international standards [48].

GD-OES combines sputtering and atomic emission techniques for element depth profiling. During analysis, a low-power argon plasma is generated in the analysis chamber by the applied voltage between the anode and cathode (the sample surface forms the cathode). Material is continually removed from the sample area by ionised argon atoms at a rate of 1μm/min in steel. The constituent atoms are then exited in an electrical field so that they glow. The light, which is characteristic to the emitting element, is detected and analysed using a conventional optical emission spectrometer, and the elemental depth profile is obtained from the emission intensities as a function of sputtering time. Example of an element depth profile can be seen in Figure 10. The advantages and limitations of the method are discussed by Dizdar [34].

The additives will react with or adsorb to the surfaces. In order to characterise the work of the additives, the crossing point between oxygen and iron (D_O in Figure 10) was chosen for studying the oxide layer formations. A thick oxide surface layer can reduce the wear coefficient for boundary lubricated contacts [49]. To examine the importance of sulphur, compounds of which are active in preventing wear, the crossing point between sulphur and iron was selected (not shown). Additionally, the increase of iron (by comparing different levels of iron) was also used to gain information about the degree of the reacted surface layer.

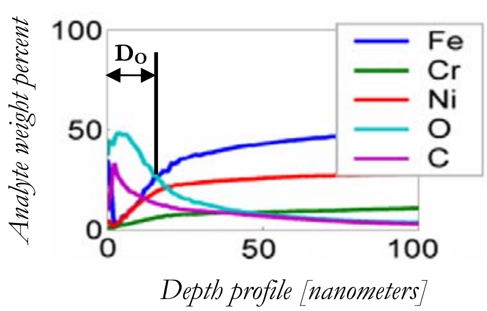

Figure 10. A quantitative depth profile diagram using GD-OES. The crossing point (D_O) *between oxygen and iron is marked.*

5.2 Pin-on-disc

The pin-on-disc machine used in Paper **B** consisted of a horizontal rotating disc and a calibrated dead-weight-loaded pin. The pin has a spherical end that is sliding against the disc. The normal load, temperature, and humidity were kept constant during each test run. The friction force was automatically measured in the pin-on-disc configuration by a load cell. A small brush was used to apply the lubricant continuously with the aid of pressurised air. Due to sliding distance, there was significantly more worn-off material on the pin than on the disc, and so the wear was coupled to the pin only.

5.3 Contact modelling

A numerical model for contact analysis was used in Paper **C**. The model makes use of a boundary element method, along with topographical measurements of differently manufactured tooth flanks as data input.

The contact computation program works by replacing the continuous pressure distribution with a discrete set of cells. The pressures and deformations are calculated for each cell. In this case, the contact computation applies to normally loaded, frictionless, elastic contacts. In an elastic contact, the deformation at one point will be influenced by the pressure and deformation at all other points. Moreover, modelling the interacting bodies as infinite half-spaces implies that the region of contact is small compared to the size of the bodies and that the slopes of the asperities are small, so that the tangential component of a normal traction can be neglected. The materials are considered homogeneous and isotropic. A brief outline of the program developed by Björklund and Andersson [44] is given below.

The contact area is divided into rectangular cells, each of these being subjected to a uniform unknown pressure $\boldsymbol{p}$. Knowing the gap $\boldsymbol{h}$ between the cells before deformation and the applied normal displacement δ_z, the solution is obtained from an equation system which written in matrix form becomes:

$$\mathbf{C}\ \boldsymbol{p} = \delta_{\mathbf{z}} - \boldsymbol{h} \qquad (1)$$

where **C** is the influence coefficient matrix. The sizes and shapes of the real contact areas are not known in advance. An initial estimate, which will contain the true contact region, is the contact area obtained if the bodies are allowed to penetrate each other without any interaction (Figure 11). When solving Equation 1, the pressures at cells outside the true contact regions become negative. These cells are removed and the equation system is solved iteratively until all pressures are positive.

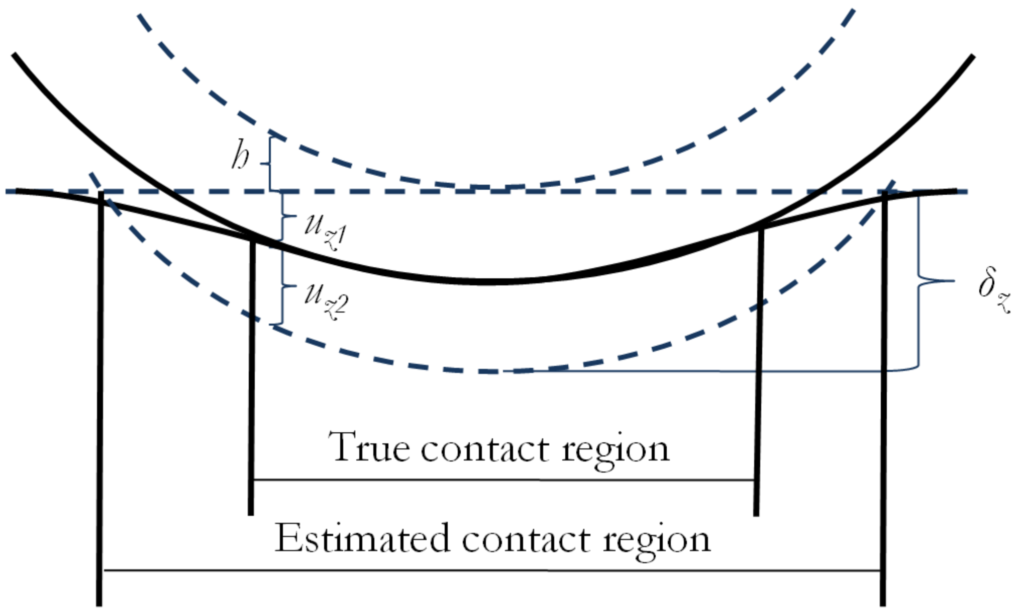

Figure 11. Schematic geometry of a contact before (hatched) and after (solid) deformation [25]. The estimated contact region is obtained if the bodies are allowed to penetrate each other without any interaction.

6 Concluding remarks on the appended papers

This thesis comprises three papers (Appendices **A**-**C**) relating to phenomena occurring in highly concentrated steel contacts in gears. Paper **A** summarises the knowledge embodied in gear standards, while Papers **B** and **C** use experimental and numerical tools of surfaces science to study contact phenomena. Although it is a challenge to scale up knowledge from microscale levels to a gear system in practical application, it is at these levels that progress can be made in increasing the gear contact load capacity.

Paper **A** can be seen as a literature survey of the current international standard gear rating procedures. The paper reports that the standard is not useful in simulating variations in gear quality levels (accuracy grades), since these are poorly incorporated in the standards and are limited to variations in pitch error, lead variations (misalignment), and profile form variation; this has also been reported by Houser [2]. The results in Paper **A** prompt the recommendation that these quality levels should mainly be used only for guidance and for communication purposes. Additionally, variations in surface roughness and lubricant design are restricted to standard reference test gears and mineral oils respectively. These gaps in information are addressed in Papers **B** and **C**.

The lubricants of tomorrow will certainly shift towards more environmentally adapted lubricants based on both natural and synthetic esters. The chemistry of natural and synthetic esters differs from that of mineral base oils, and so esters also show different additive responses. In Paper **B,** a pin-on-disc machine was used to evaluate the tribofilm formation by the additives and the corresponding wear occurring in the boundary lubrication regime in environmentally adapted lubricants. Studies of the additive and base fluid interaction were carried out using a surface analysis method (GD-OES). The results showed that the chemically reacted surface boundary layers played an important role in terms of wear. More specifically, the oxide layer thickness had a significant influence on wear; this is in agreement with the results of Olofsson and Dizdar [49]. The findings of Paper **B** also demonstrate the complexity of lubrication design formulations coupled to these layers. For example, it was found that the pre-existing surface boundary layer (before any lubricant has been added) plays an important role in allowing the lubricant to react properly with the surfaces. The results of Paper **B** indicate that the base fluid itself was highly reactive, leaving no surface available to the additives under the prevailing test conditions.

Paper **A** also reports that the standard rating procedures make very little consideration of the effects of various initial tooth flank properties inherent in the manufacturing method. In Paper **C,** surface topography was investigated by comparing the influence of different gear manufacturing methods on the contact conditions. The variation in surface topography inherent in the manufacturing method was found to be an important factor for early life contact conditions.

7 Future work

The general research question for further research based on this thesis is how to increase the contact load capacity and still be able to make robust gears; that is, gears insensitive to variations in manufacturing. As emphasised in this work, there are a number of phenomena for which little data is available in the literature, but which nevertheless have an influence on the gear contact load capacity.

A natural way to continue the work is to find out the effects of various lubricants on different tooth flank surfaces, since it was found that the pre-existing surface boundary layer (before any lubricant has been added) plays an important role in allowing the lubricant to react properly with the surfaces. Additionally, the variation in surface topography inherent in the manufacturing method has been shown to be an important factor for the contact condition in the early life of gears. The surface analysis used in this thesis may be used to investigate whether there is any correlation between different finishing methods and the choice of lubricant. Since the combined effect of these is hard to calculate, this analysis would need to be followed by appropriate transmission tests, for example pitting tests in a FZG test rig.

The coupling between standard quality levels and the gear performance needs to be studied in more detail to determine the consequence of manufacturing variation.

Experimental testing should preferably be used in combination with computer simulations, since it can enhance and contribute to the understanding of the problem. A further step here is to include the elastohydrodynamic effects and temperature calculations in the contact analysis program.

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