

# TRANSITIONS IN THE LUBRICATION OF CONCENTRATED CONTACTS

PROEFSCHRIFT

ter verkrijging van  
de graad van doctor aan de Universiteit Twente,  
op gezag van de rector magnificus,  
prof. dr. ir. J.H.A. de Smit,  
volgens besluit van het College van Dekanen  
in het openbaar te verdedigen  
op vrijdag 28 oktober te 16.00 uur.

door

Dirk Jan SCHIPPER

geboren op 30 mei 1955 te Kampen

Dit proefschrift is goedgekeurd door de promotor:

Prof. ir. R. Bosma

CIP-DATA KONINKLIJKE BIBLIOTHEEK, DEN HAAG

Schipper, D.J.

Transitions in the lubrication of concentrated contacts/

D.J. Schipper. - [S.I. : s.n]. - Ill.

Thesis Enschede. - With ref. - With summary in Dutch.

ISBN 90-9002448-4

SISO 650.8 UDC 621.891 (043.3)

Subject headings: concentrated contacts/mixed lubrication/transitions.

aan mijn ouders

aan Agnieszka en David.



## CONTENTS

ABSTRACT

SAMENVATTING

### CHAPTER 1 INTRODUCTION

|                                      |     |
|--------------------------------------|-----|
| 1.1 Lubricated contacts              | 1.1 |
| 1.2 Aim of the present investigation | 1.8 |

### CHAPTER 2 MIXED LUBRICATION: A RETROSPECTIVE VIEW.

|   |      |
|---|------|
| 2.1 Introduction  | 2.1  |
| 2.2 Mixed lubrication experiments at low and high pressures | 2.2  |
| 2.2.1 Low pressures   | 2.2  |
| 2.2.2 High pressures  | 2.4  |
| 2.3 Theoretical work  | 2.7  |
| 2.4 Summary   | 2.14 |

### CHAPTER 3 LUBRICATION MODES

|  |      |
|--|------|
| 3.1 Introduction                                     | 3.1  |
| 3.2 Elasto hydrodynamic lubrication                  | 3.1  |
| 3.2.1 Introduction                                   | 3.1  |
| 3.2.2 Friction in EHL-contacts                       | 3.3  |
| 3.2.3 Rheology of the lubricant under EHL-conditions | 3.5  |
| 3.2.4 EHL, summary                                   | 3.11 |
| 3.3 Boundary lubrication                             | 3.12 |
| 3.3.1 Introduction                                   | 3.12 |
| 3.3.2 Surface film formation mechanisms              | 3.12 |
| 3.3.3 Effect of operating conditions                 | 3.14 |
| 3.3.3.1 Temperature                                  | 3.14 |
| 3.3.3.2 Normal load                                  | 3.15 |
| 3.3.3.3 Velocity                                     | 3.16 |
| 3.3.3.4 Atmosphere                                   | 3.16 |
| 3.3.4 Shear strength of the films                    | 3.17 |
| 3.3.5 Friction model                                 | 3.19 |

|                                  |   |      |
|----------------------------------|---|------|
| 3.4                              | Mixed lubrication   | 3.20 |
| 3.4.1                            | Introduction  | 3.20 |
| 3.4.2                            | Friction model  | 3.21 |
| 3.4.3                            | Dimensional analysis  | 3.25 |
| 3.4.4                            | Comparison of $\eta_1 \cdot V_+ / \bar{p}$ and film thickness h | 3.28 |
| 3.4.5                            | Summary   | 3.29 |
| CHAPTER 4 EXPERIMENTAL PROCEDURE |   | 4.1  |
| 4.1                              | Systems approach  | 4.1  |
| 4.1.1                            | Introduction  | 4.1  |
| 4.1.2                            | Structure and function  | 4.2  |
| 4.1.3                            | Input - Output variables  | 4.4  |
| 4.1.4                            | Summary   | 4.5  |
| 4.2                              | Tribometers   | 4.6  |
| 4.3                              | Specimens   | 4.10 |
| 4.4                              | Lubricants  | 4.12 |
| 4.5                              | Test procedure  | 4.13 |
| CHAPTER 5 EXPERIMENTAL RESULTS   |   | 5.1  |
| 5.1                              | Introduction  | 5.1  |
| 5.2                              | Operational variables   | 5.2  |
| 5.2.1                            | Introduction  | 5.2  |
| 5.2.2                            | Velocity  | 5.2  |
| 5.2.3                            | Temperature   | 5.14 |
| 5.2.4                            | Normal force/pressure   | 5.16 |
| 5.2.5                            | Time - Running in effects                                       | 5.19 |
| 5.2.6                            | Summary of measurements on Sebacate/AISI-52100                  | 5.26 |
| 5.3                              | Element properties in relation to mixed lubrication             | 5.27 |
| 5.3.1                            | Lubricant   | 5.27 |
| 5.3.1.1                          | Introduction  | 5.27 |
| 5.3.1.2                          | Liquid-state behaviour  | 5.28 |
| 5.3.1.3                          | Solid-state behaviour   | 5.35 |
| 5.3.1.4                          | Miscellaneous   | 5.40 |
| 5.3.1.5                          | Summary   | 5.42 |

|                                   |  |      |
|-----------------------------------|--|------|
| 5.3.2                             | Roughness  | 5.44 |
| 5.3.2.1                           | Surface characterization   | 5.44 |
| 5.3.2.2                           | Surface roughness effects on lubrication<br>and the transitions EHL-ML and ML-BL | 5.45 |
| 5.3.2.3                           | Conclusions  | 5.50 |
| 5.3.3                             | Material   | 5.51 |
| 5.4                               | Some additional observations   | 5.51 |
| CHAPTER 6 ANALYSIS AND DISCUSSION |  | 6.1  |
| 6.1                               | Review and analysis of the main conclusions                                      | 6.1  |
| 6.1.1                             | Liquid-state behaviour of the lubricant  | 6.1  |
| 6.1.2                             | Expected solid-state behaviour of the lubricant                                  | 6.6  |
| 6.1.3                             | Summary  | 6.8  |
| 6.2                               | Discussion   | 6.10 |
| CHAPTER 7 RECOMMENDATIONS         |  | 7.1  |
|                                   |  |      |
| Appendix A:                       | General nomenclature   | A.1  |
| Appendix B:                       | Lubricant properties   | B.1  |
| Appendix C:                       | Summary of the Hertzian contact formulas   | C.1  |
| Appendix D:                       | Film thickness equations   | D.1  |
| Appendix E:                       | AISI-52100 and AL 7075-T651  | E.1  |
| Appendix F:                       | Electric contact resistance measurement  | F.1  |
| Appendix G:                       | References   | G.1  |
|                                   |  |      |
| ACKNOWLEDGEMENTS                  |  |      |
| LEVENSLLOOP                       |  |      |



## ABSTRACT.

This thesis deals with the different lubrication modes present in lubricated concentrated contacts. Attention is paid to the lubrication of concentrated contacts in the mixed lubrication regime, especially the transitions from elasto-hydrodynamic lubrication (EHL) to mixed lubrication (ML) and mixed lubrication to boundary lubrication (BL). In the introduction, chapter 1, problems are discussed with respect to friction and wear in the mixed lubrication regime. In chapter 2 an outline is given of the present knowledge with regard to mixed lubrication and the above mentioned transitions gained from experimental and theoretical developments.

Chapter 3 describes friction in concentrated contacts under conditions of EHL and BL. This as a function of the operational conditions (operational variables and element properties), under which such contacts operate. A lubrication number is derived from the parameters characteristic for friction in lubricated concentrated contacts. This lubrication number consists of the operational variables (implicit) and of the relevant element properties which determine the operational conditions under which a lubricated contact is functioning. This number is also applicable for lubricated systems operating at low pressures.

In order to study friction and the transitions as a function of this lubrication number friction measurements were carried out, as described in chapter 5. The tribometers used and the most applied testprocedure are described in chapter 4. The measured friction curves, which show the different lubrication modes EHL, ML and BL, are obtained at different operational conditions. Transitions from one lubrication mode to the other are obtained from these friction curves (Stribeck-like) as a function of the derived lubrication number. An important phenomenon in friction of lubricated concentrated contacts is the solid-like behaviour of the lubricant at conditions of relatively high pressures and low temperatures. Also the existence of micro-EHL is shown.

The most important conclusions are analysed in chapter 6. A transition diagram is presented to determine the lubrication mode of a lubricated concentrated contact. In the discussion a comparison is made between the presented results and results known from literature.

Finally, some recommendations for further research are presented.

## TRANSITIES BIJ DE SMERING VAN GECONCENTREERDE CONTACTEN.

### SAMENVATTING.

Dit proefschrift handelt over de verschillende smeringsvormen aanwezig in gesmeerde geconcentreerde contacten. De aandacht gaat uit naar gemengde smering en met name de transities van elastohydrodynamische smering (EHL) naar gemengde smering (ML) en gemengde smering (ML) naar grenssmering (BL).

Als inleiding wordt in Hoofdstuk 1 het probleem gebied geschetst. De huidige kennis met betrekking tot gemengde smering en de transities is in hoofdstuk 2 uiteengezet aan de hand van experimentele en theoretische ontwikkelingen.

In Hoofdstuk 3 wordt de hedendaagse kennis besproken m.b.t. de wrijving in geconcentreerde contacten onder EHL en BL condities. Dit als functie van de operationele condities waaronder dergelijke contacten werken. Met de variabelen die karakteristiek zijn voor de wrijving in gesmeerde geconcentreerde contacten is een smeringskental afgeleid. Dit smeringskental bevat de operationele variabelen (impliciet) en relevante elementeigenschappen welke de operationele condities bepalen waaronder dergelijke contacten functioneren. Het kental is ook toepasbaar voor gesmeerde contactsituaties waarbij lage contactdrukken heersen.

Teneinde de wrijving en de transities als functie van dit smeringskental te onderzoeken zijn wrijvingsexperimenten uitgevoerd onder nagenoeg isotherme contactsituaties, beschreven in Hoofdstuk 5. De tribometers waarop deze metingen zijn uitgevoerd alsmede de meest gehanteerde testprocedure zijn beschreven in Hoofdstuk 4. De gemeten wrijvingscurves, waarin de smeringsvormen EHL, ML en BL te onderscheiden zijn, zijn gemeten onder verschillende operationele condities. De transities van de ene smeringsvorm naar de andere zijn bepaald, a.d.h.v. deze gemeten (Stribeck-achtige) wrijvingskrommen, als functie van het smeringskental. Een belangrijk fenomeen dat optreedt bij wrijving in gesmeerde geconcentreerde contacten is het vaste-stof gedrag van het smeermiddel onder relatief hoge drukken en lage temperaturen. Tevens blijkt dat micro-EHL op kan treden in de contacten die gevormd worden door de met elkaar interacterende ruwheden.

In Hoofdstuk 6 worden de belangrijkste conclusies geanalyseerd. Een transitie diagram is gepresenteerd waarmee de smeringsvorm in een gesmeerd geconcentreerd contact kan worden bepaald. In de discussie wordt een vergelijking gemaakt met bestaande kennis uit de literatuur. Tot slot worden aanbevelingen voor verder onderzoek gegeven.

CHAPTER 1 INTRODUCTION1.1 LUBRICATED CONTACTS

In many applications concentrated contacts can be found by which forces, motion, etc. are transmitted from one body to another. Examples are gears, traction drives, cam & tappet mechanisms and roller bearings. These concentrated contacts are lubricated by a lubricant to avoid wear and if required, to establish a low friction between the two approaching and relatively moving surfaces. The ideal type of lubrication occurs if these surfaces are fully separated by a lubricant film. In that situation the properties of the lubricant control the friction and wear is negligible. However, in many practical situations the pressure, generated in the lubricant, is not able to ensure a complete separation of the surfaces. The separation is not large enough to avoid contact between the asperities of the opposing surfaces. This occurs, for instance, at operating conditions of low velocities and/or high normal forces and/or high temperatures. The influence of the operating conditions on pressure generation is demonstrated by integrating twice the Reynolds equation (2.1) for the one-dimensional, incompressible and stationary situation, which reads:

$$\frac{dp}{dx} = 6 \eta V_x \frac{h - h_0}{h^3} \quad (1.1)$$

$$p = \int_{-\infty}^{+\infty} 6 \eta V_x \frac{h - h_0}{h^3} dx$$

- where: p = generated pressure.  
 x = Cartesian coordinate in the direction of motion  
 of the surfaces.  
 η = dynamic viscosity.