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Prediction of Lubrication Regimes of Concentrated Contacts

(reprinted at the author's request because of errors which appeared in the original)

Abstract

Friction experiments are performed on lubricated concentrated contacts (LCCs) to obtain the transitions EHL-ML and ML-BL as a function of the operational conditions under which these contacts operate. A transition diagram is developed to determine the lubrication mode of an LCC as a function of the operational conditions. In this investigation the LCCs operated macroscopically in the lubricants' liquid state regime.

INTRODUCTION

In lubricated concentrated contacts, operating in regime I of the IRG transition diagram,[1] three modes of lubrication can be distinguished, i.e., elastohydrodynamic lubrication (EHL), mixed lubrication (ML) and boundary lubrication (BL). Many studies have been performed to locate the transitions from one lubrication mode to another. For LCCs, much attention has been paid to the EHL-ML transition. A film thickness to surface roughness ratio, λ, has been defined to localise this transition. In general, it is assumed that for $\lambda \geq 3$ full-film lubrication will occur, and for values of $\lambda \leq 3$, ML can be expected. Friction experiments showed that λ varies from 1 to 3 (see references 2 and 3). For LCCs, however, extensive studies on the transition ML-BL have not been published. In reference 4, it is suggested that BL prevails at λ ratios of 0.5 or less. In this study the EHL-ML and ML-BL transitions are characterised by a lubrication number. This lubrication number implicitly contains the operational variables and element properties, defining the operational conditions[5] under which a LCC is functioning.

Nomenclature

F_n	Normal force (N)
h	Film thickness (m)
H	Operational parameter, $H = \eta_i \cdot V_+ / \bar{p}$. (m)
L	Lubrication parameter, $L = \eta_i \cdot V_+ / (\bar{p} \cdot Ra_t) = H/Ra_t$.
L*	Material parameter (Moes) for elliptical contacts[9]
M*	Load parameter (Moes) for elliptical contacts[9]

$\bar{p}$ Mean Hertzian contact pressure (Pa)
Ra_t Combined CLA surface roughness, $Ra_t = (Ra_1^2+Ra_2^2)^{1/2}$ (m)
S Slip, $S = V_-/V_+.200\%$
V Velocity (m/s)
V_- Sliding velocity, $V_- = |V_1 - V_2|$ (m/s)
V_+ Sum velocity, $V_+ = V_1 + V_2$ (m/s)
W Normal force per unit of length (N/m)
η Viscosity (Pa.s)
θ Temperature (°C)
λ Film thickness to roughness ratio, $l = h/s_t$
μ Coefficient of friction
σ_t Combined RMS surface roughness, $\sigma_t = (\sigma_1^2 + \sigma_2^2)^{1/2}$ (m)
ω Angular velocity (l/s)

Subscripts

$_{1,2}$ Refers to individual surfaces.

$_i$ Refers to inlet of the contact.

Abbreviations

BL Boundary lubrication
EHL Elasto hydrodynamic lubrication.
LCC Lubricated Concentrated Contact.
ML Mixed lubrication.

LUBRICATION NUMBER

For several reasons the use of λ as characteristic number in the ML regime is somewhat doubtful. Firstly, the calculation of the film thickness is based on smooth surface theory and will not be valid in the ML regime. Furthermore, none of the film thickness formulas presented in the literature for elliptical/circular contacts, are valid for values of $M_*>200$ and $L_*<10$, the regime where the EHL-ML transition occurs. Finally, actual roughnesses at high pressures, i.e. at deformed surfaces, are not really known.

From a study of variables involved in the frictional behaviour of LCCs, a lubrication value is derived.[6] This lubrication number reads $L = \eta_i.V_+/(\bar{p}.Ra_t) = H/Ra_t$. In **Appendix 1** it is

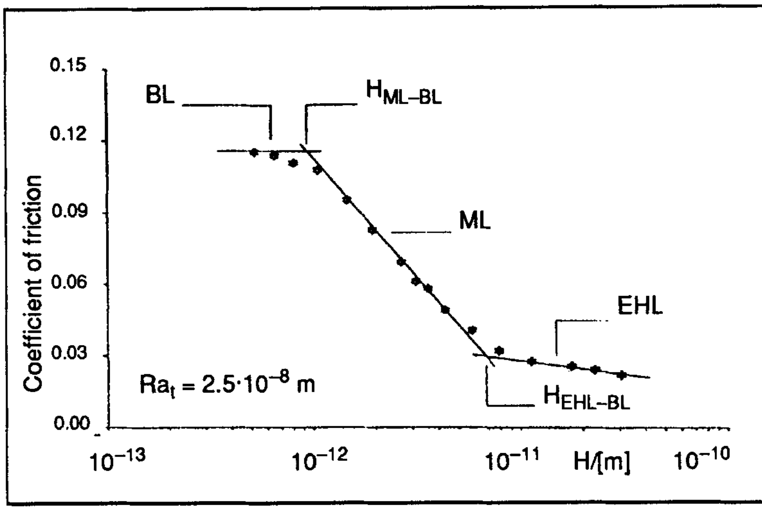


Figure 1 Coefficient of friction as a function of the operational parameter $H = \eta_i \cdot V_+ / \bar{p}$. Lubricant HVI–650, $\bar{p}$ = 0.24 GPa, η_i = 54 mPa·s

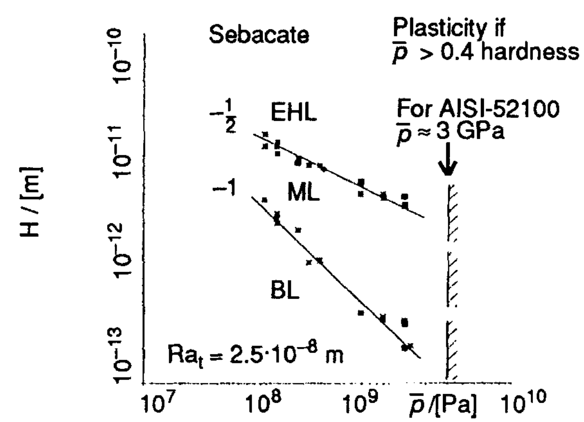
shown that there is good agreement between H and film thickness h. Besides this, it is in agreement with values used in low pressure contact situations occurring in, for instance, plain bearings. The commonly used value there is $\eta \cdot \omega / p_{proj.}$ or $\eta \cdot V / W$.[7,8] Unfortunately, in most of these studies roughness is not taken into account and not therefore incorporated in the above expressions. The lubrication value L can be applied in situations where the film thickness is not, *a priori*, known. However, to predict quantitatively the EHL-ML and ML-BL transitions, it was necessary to study the lubrication modes by Stribeck-like friction curves as a function of H or L.

TRIBOMETRY

Friction experiments were carried out on three different types of tribometer: a reciprocating pin on plate test rig, a pin-on-disc machine and a two-disc machine. The operational variables F_n, V_+ and θ could be varied between $F_n = 25 - 5000$ N, $V_+ = 10^{-3} - 10$ m/s, and $\theta = 20 - 100$°C. For a more detailed description of these tribometers refer to reference 6. The coefficient of friction values measured on these tribometers were found to be consistent to better than $\pm\, 2.10^{-3}$ under the most unfavourable conditions. The operational parameter H could be determined with a relative error of less than 4%.

Before each experiment was started, the specimens and the lubricant were heated to the desired temperature. Next,

Figure 2 EHL–ML and ML-BL transitions. For ■ see text



the specimens were run in for approximately 2 h in the ML regime near the ML-BL transition. Each measuring point for the friction curve, as shown in **Figure 1**, was obtained 2-5 min after applying the normal force.

The friction curves were obtained by changing the velocity at constant pressure and temperature. This was done to ensure that for the whole friction curve the experiment was performed under virtually the same thermal conditions. After each experiment the CLA surface roughness in the sliding direction was measured, using a cut-off length of 0.8 mm on a Talysurf 5T-120-3a or on a Taly-Formsurf.

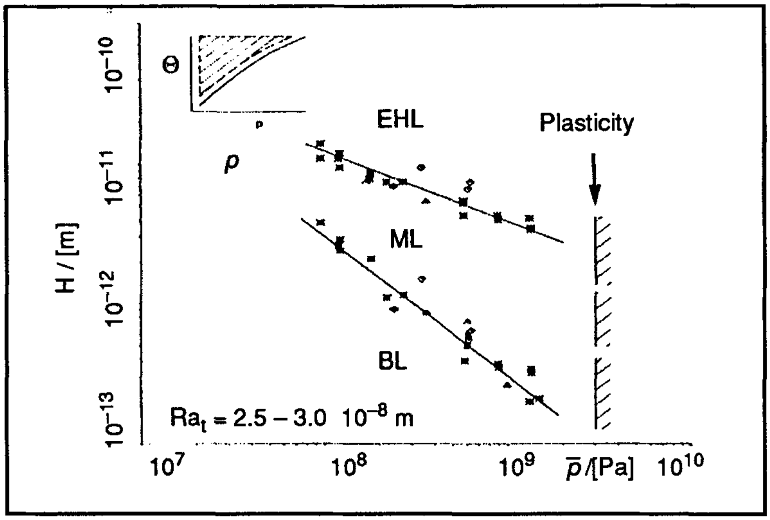
EXPERIMENTAL RESULTS

The presentation of the experimental results with respect to the EHL-ML and ML-BL transitions is divided into two parts: a. effect of operational variables under conditions of constant element properties, and b. influence of element properties on these transitions.

Operational variables

The experiments described in this section were carried out with hardened AISI-52100 specimens ($HR_c \approx 63$) with sebacate as a lubricant. Attention was focused on the influence of the opera-

Figure 3 EHL–ML and ML–BL transitions for different lubricants represented by *H* as a function of $\bar{p}$. ✱ = sebacate; △ = Santotrac-50; ⊠ = HVI – 160S; ◇ = Gadenia-30; and ✡ = HVI–650



tional conditions constant as far as possible. The friction experiments were performed at different slip values (S varied from 0% to 200%). The results of this study are summarised in **Figure 2**.

In **Figure 2**, the operational parameter $H = \eta_i \cdot V_+ / \bar{p}$ is shown as a function of the mean contact pressure $\bar{p}$. It can be concluded from this that:

- variation of the slip does not influence either of EHL-ML or ML-BL transitions leaving the sum velocity as the controlling parameter. The sliding velocity is not characteristic for these transitions.
- variation of temperature (and pressure) show that both EHL-ML and ML-BL transitions are controlled by the lubricants' viscosity in the inlet of the LCC.
- the ML-BL transition is controlled by the product $\eta_i \cdot V_+$ and is independent of the mean Hertzian contact pressure $\bar{p}$ (H is inversely proportional to $\bar{p}$). On the contrary, the EHL-ML transition is pressure dependent. The ■ data points in **Figure 2** represent experiments performed at equal values of normal force and temperature. Thus, for these experiments the relation $h = \text{const.} \cdot H^{0.7}$ is valid (see **Appendix 1**). Consequently the λ number, commonly used to characterise the EHL-ML and ML-BL transitions is pressure dependent and thus not a constant as suggested in the literature.

Element properties

Now that the effects of the operational variables for given element properties are known, the effects of lubricant and surface roughness on the EHL-ML and ML-BL transitions will be considered.

Performing friction experiments with different lubricants while operating in the lubricants' liquid-state regime (see Alsaad *et al*[9]) results in the transition diagram as presented in **Figure 3**. In this figure the operational parameter $H = \eta_i \cdot V_+ / \bar{p}$ is again shown as a function of the mean contact pressure $\bar{p}$. These measurements show that the lubricant viscosity is the only relevant element property for both the EHL-ML and ML-BL transitions. The influence of the combined CLA surface roughness on the EHL-ML and ML-BL transitions, measured at a mean contact pressure of 0.7 GPa, is shown in **Figure 4**. It can be seen from **Figure 4** that the EHL-ML transition depends more strongly on surface roughness than does the ML-BL transition. For the EHL-ML transition the relationship between H and Ra_t, also obtained at other pressures, can be characterised by $H \therefore Ra_t^{-1.5}$ and for the ML-BL transition, H is almost linearly proportional with Ra_t.

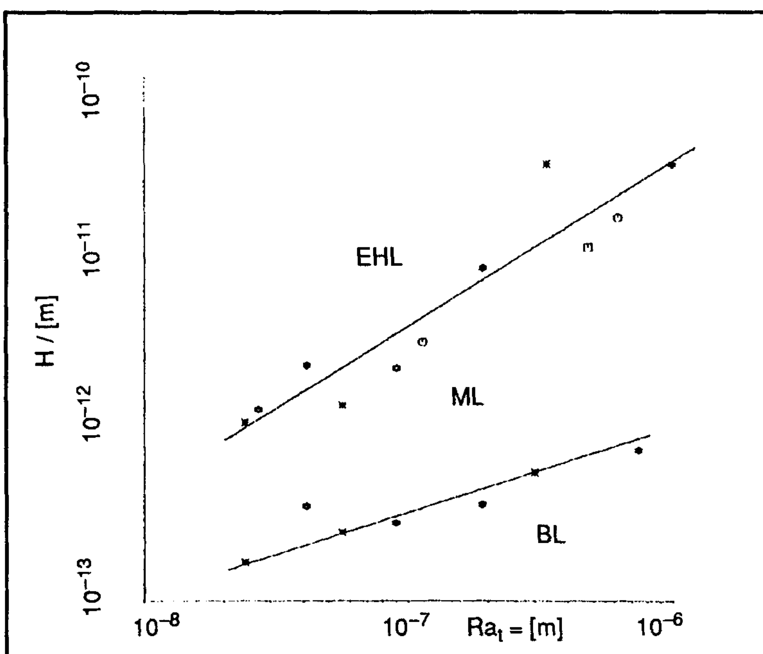
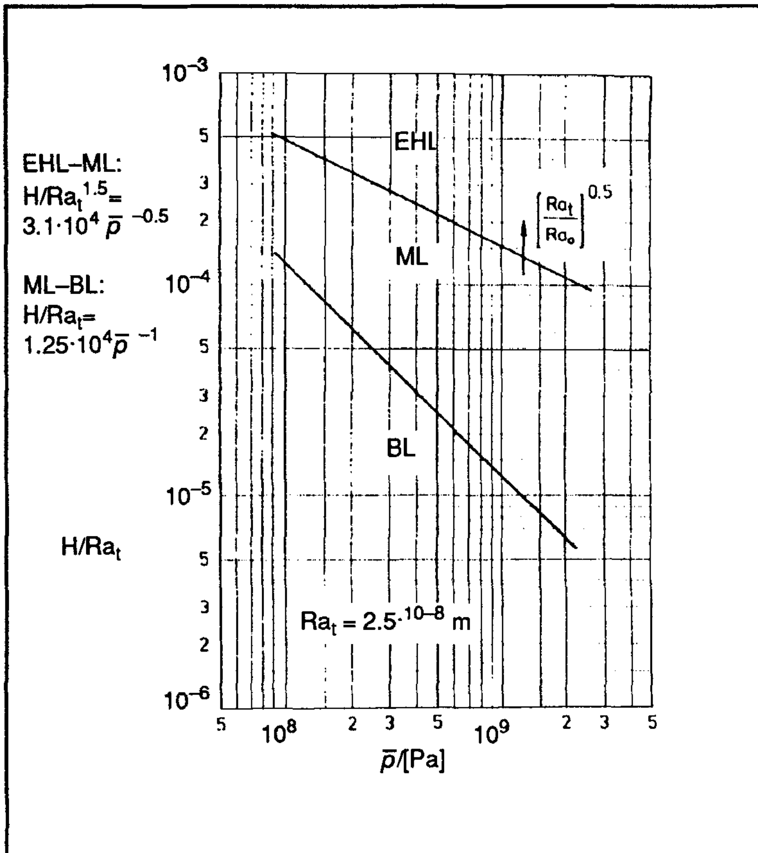


Figure 4 CLA surface roughness and EHL–ML and ML–BL transitions, obtained at a mean contact pressure of 0.7 GPa. ✱ = sebacate; ☼ = HVI-650; □ = [3]; and ⌽ = [11]

Figure 5 H /Ra$_t$ = *L* as a function of $\bar{p}$



DISCUSSION

Combining the information from **Figures 2, 3** and **4**, the EHL-ML and ML-BL transitions can now be represented as shown in **Figure 5**.

Here the lubrication number L is shown as a function of the mean contact pressure $\bar{p}$. With this figure it is possible to predict in which lubrication mode a particular LCC operates as a function of the operational variables ($V_+, \theta_i \rightarrow \eta_i$ and $F_n \rightarrow \bar{p}$) and the relevant element properties (R_*, Ra$_t$ and E_*) under liquid-state behaviour of the lubricant.

From **Figure 3** one finds for the EHL-ML and ML-BL transitions at a mean pressure of 0.60 GPa, $H_{EHL\text{-}ML} = 5 \cdot 10^{-12}$ m and $H_{ML\text{-}BL} = 5 \cdot 10^{-13}$ m resp., where $\alpha = 1.4 \cdot 10^{-8}$ Pa^{-1}, $E_* = 2.3 \cdot 10^{11}$

Pa, $F_n = 10^3$ N and $Ra_t = 2.5 \cdot 10^{-8}$ m. Substitution of these values in equation (c) of **Appendix 1** yields, for the EHL-ML transition, $h/Ra_t \approx 1$. If the 'smooth EHL' theory is applied to the ML-BL transition then $h/Ra_t \approx 0.2$ is obtained.

These h/Ra_t values are in quite good agreement with values of h/Ra_t as presented in the literatures for similar pressure. However, for a pressure region of 0.1 to 1.5 GPa, h/Ra_t for the EHL-ML transition varies with a factor of, say, 2.5 and, for the ML-BL transition h/Ra_t, varies with a factor of, say, 6.

The role of α, used in the EHL theory, becomes doubtful. The value of α for the different lubricants used in the present experiments, differs by a factor of 2 to 3 (θ varied from 20°C to 100°C). One would expect a decrease in H if α increases, which is not observed.

CONCLUSIONS

1.The λ value, commonly used to characterise the EHL-ML and ML-BL transitions is pressure dependent at these transitions, but not a constant as suggested in literature.
2.The ML-BL transition is pressure independent. Therefore a contact operating in the ML regime at constant $\eta_i \cdot V_+$ and constant element properties will not enter the BL regime by solely increasing the pressure.
3.A roughness height parameter, such as Ra_t used in this study, characterises a rough surface quite well with regard to the EHL-ML and ML-BL transitions.

Acknowledgement

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Appendix 1: Operational values *H* and film thickness *h*.

Film thickness for circular contacts, Moes and Bosma,[10] reads:

$$h = 1.585 \cdot \alpha^{0.55} \cdot \eta_1^{0.7} \cdot E_*^{-0.067} \cdot F_n^{-0.083} \cdot R_*^{0.467} \cdot V_+^{0.7} \qquad (a)$$

Mean contact pressure:

$$\bar{p} = 0.153 \cdot F_n^{0.333} \cdot R_*^{-0.667} \cdot E_*^{0.667} \qquad (b)$$

Rearranging of (a) and (b) yields:

$$h = 0.426 \cdot \alpha^{0.55} \cdot E_*^{0.40} \cdot F_n^{0.15} \cdot (\eta_i \cdot V_+ / \bar{p})^{0.70} \quad \text{or}$$

$$h = 0.426 \cdot \alpha^{0.55} \cdot E_*^{0.40} \cdot F_n^{0.15} \cdot H^{0.70} \qquad (c)$$

The values of α and E_* vary for different lubricants and metals, commonly used in LCCs, by not more than a factor of 3. Because of the low powers, equation (c) can be written as:

$$h = \text{const.} \cdot H^{0.7}$$

Table 1 Oil description

1. A synthetic hydrocarbon, di-(2-ethylhexyl), for low temperature applications.
2. A synthetic cycloaliphatic hydrocarbon plus additives especially developed for its high traction properties. Additives: antiwear (zinc dialkyldithiophosphate), oxidation inhibitor, antifoam, V.I. improver (polymethacrylate).
3. A mixed isomeric five-ring polyphenylether, developed for use in high temperature applications and high vacuum technology.
4. A high viscosity (HVI) mineral oil, predominantly paraffinic.
5. A mineral oil developed for 'gas turbine' installations under high temperature conditions. Additives: oxidation inhibitor, antifoam and metal deactivator.
6. A clean mineral oil, predominantly paraffinic, developed for light to medium loaded contacts.
7. A mineral oil predominantly paraffinic.
8. A mineral oil with additives such as antiwear, oxidation inhibitor, antifoam, etc. This oil is developed for medium speed diesel engines and highly loaded contacts

(continued on page 200)

		1		2		3		4	
	Oil:	*Sebacate*		*Santotrac**		*Santovac-5**		*HVI-650**	
Properties		η	α	η	α	η	α	η	α
	20°C	21.2	1.61	—	—	—	—	—	—
	30	14.7	1.53	45.6	3.30	—	4.01	900	3.02
η	40	10.7	1.42	28.4	2.87	266	3.50	450	2.75
(m Pa·s)	50	8.0	1.36	19.4	2.51	140	3.02	240	2.48
	60	6.2	1.29	13.1	2.28	79	2.63	140	2.29
	70	4.9	1.25	9.6	2.06	48	2.30	85	2.10
α	80	4.0	1.22	7.3	1.91	31	1.98	55	1.95
$(m^2/N)\cdot 10^8$	90	3.3	1.18	5.7	1.77	21	1.71	37	1.84
	100	2.8	1.16	4.6	1.65	15	1.49	27	1.75
	110	—	—	3.8	1.58	10	1.30	20	1.68
	120	—	—	3.1	1.50	8	1.12	15	1.64
Z		0.55		—		—		0.59	
s_0		1.04		1.21		1.45		1.28	
ρ	40°C	911		889		1184		888	
kg/m^3	100	875		855		1140		853	
Literature*				40°C		40–100°C		40°C	
$\tau_l/\bar{p}$		—		$11.3\cdot10^{-2}$		$6.8\cdot10^{-2}$		$9.0\cdot10^{-2}$	
$\tau_l/\bar{p}$	40°C	$9.4\cdot10^{-2}$		—		$8.7\cdot10^{-2}$		$9.2\cdot10^{-2}$	
	80	(≈25°C)		$10.8\cdot10^{-2}$ (63°C)		—		$8.6\cdot10^{-2}$	
Symbol		✳		Δ		○		✡	

		5	6	7	8
	Oil:	*Turbo*** *T68*	*Vitrea** *100*	*HVI**** *160S*	*Gadenia*** *30*
Properties		η	η	η	η
	20°C	183.3	297.1	—	—
η	40	58.4	87.4	90.1	91.8
(m Pa.s)	50	35.8	52.8	—	55.3
	100	7.1	9.6	9.7	10.0
Z		0.62	—	0.63	—
s_0		1.26	1.25	1.24	1.25
ρ kg/m^3	15°C	876	890	878	897
$\tau_l/\bar{p}$	40°C	—	—	8.10^{-2}	9.010^{-2}
	80	—	—	—	8.010^{-2}
Symbol		+	X	X	◊

* Evans (1983)
** Shell, 'smeermidelen voor industrie en scheepvaart'
*** Shell, report TNGR 0042.74.

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