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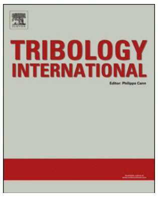

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# Bridging high pressure rheology and film-forming capacity of polymer-base oil solutions in EHL

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ABSTRACT

The development of high value-added lubricants which overcome more drastic operating conditions, are fuel-efficient and provide excellent performance for a long life remains a huge challenge for oil makers. This article sheds light on the tribological response of an EHD circular rolling–sliding contact for a base oil and three polymers mixed in solutions in order to understand the relationship between physico-chemistry and tribology. The final aim is to help formulators select the appropriate chemicals meeting engine specifications. Central and minimal film thickness measurements were run on a ball-on-disc tribometer and determined through white light optical interferometry. Experiments were compared with classical analytical predictions and with the results of a finite element numerical solver based on the generalized Reynolds' equation including the modelled rheological behavior established from high-pressure and high-stress viscosity measurements and density variations. Moreover, the role played by thermal effects and variable slide-to-roll ratio were discussed.

## 1. Introduction

Over the past few decades, many technological breakthroughs [1] have been made by both automobile and lubricant manufacturers to reduce friction and wear in engines in order to decrease pollution [2], extend the lifetime of engines and improve their performance. One of the key parameters controlling the lubrication is the film thickness which must be optimal to fulfil its role. Indeed, the fluid film must not be too thick to avoid viscous friction and not too thin to ensure a sufficient thickness to separate the moving surfaces. The prediction of the film thickness in elastohydrodynamic (EHD) contacts [3–5] can guide engine designers and oil makers in the formulation process. It is thus of main interest.

The objective of this research is to provide an accurate knowledge of the thickness of the lubricant film under severe conditions of temperature, pressure and shear stress, representative of the real conditions in an engine. Film thicknesses were measured and compared with both analytical expressions and numerical solutions which incorporate the modelled rheological behavior of three polymer-base oil solutions. Another motivation is to reach a better understanding of the tribology for a chosen pair of polymer/solvent from three specific polymers, based on the insights described in [6] into the relationship between the physico-chemistry and the interaction between these polymers and solvents. A final goal lies in the investigation of the thermal effects and of the influence of the slide-to-role ratio (SRR) on film thickness.

The present work starts with a description of the materials and the instruments used in the study. The film thickness measurements of simplified automotive lubricants, run on a ball-on-disc tribometer with a method based on the white light optical interferometry principle, are shown and compared with the classical analytical Hamrock–Dowson formulas [7]. Then, experiments are compared with a finite element numerical solver that features, in a full-system approach, the coupled resolution of the EHL equations and the physical characteristics of the fluid (compressibility and rheology). Finally, the role played by the thermal effects and the SRR are discussed.

## 2. Experimental

### 2.1. Materials

In this paper, a base oil and three polymer solutions were considered as simplified automotive lubricants. All chemicals were provided by Total and were property of Total. The base oil was a hydrocracked mineral base oil, from group III (API classification). Three polymers with different conformations, chemistries and structures were chosen: a comb poly(alkylmethacrylate) (PAMA)

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**Nomenclature**

*Latin letters*

| | |
|---|---|
| $a$ | parameter for the Carreau–Yasuda model |
| $a_v$ | thermal expansion defined for volume linear with temperature in the Tait equation ($K^{-1}$) |
| $C_1$, $C_2$, $A_1$, $A_2$, $B_1$, $B_2$ | WLF constants |
| $c_m$ | specific heat capacity (J/kg/K) |
| $E$ | Young modulus (GPa) |
| $E'$ | effective modulus of elasticity (N/m$^{-2}$) |
| $F$ | dimensionless relative thermal expansion of the free volume |
| $F_m$ | modified dimensionless relative thermal expansion of the free volume |
| $G$ | effective shear modulus (kPa) |
| $h$ | film thickness (nm) |
| $h_c$ | central film thickness (nm) |
| $h_{\min}$ | minimal film thickness (nm) |
| $k$ | thermal conductivity (W/m/K) |
| $K_0$ | isothermal bulk modulus at $p=0$ (Pa) in the Tait equation |
| $K_{00}$ | $K_0$ at zero absolute temperature (Pa) in the Tait equation |
| $K_0'$ | pressure rate of change of isothermal bulk modulus at $p=0$ in the Tait equation |
| $k$ | liquid thermal conductivity (W/m/K) |
| $M_n$ | number average molecular mass (g/mol) |
| $M_w$ | weight average molecular mass (g/mol) |
| $n$ | power law exponent |
| $PDI$ | polydispersity index |
| $p$ | pressure (Pa) |
| $p_H$ | maximum Hertzian pressure (Pa) |
| $Rq_1$, $Rq_2$ | root mean square (RMS) roughness of materials 1 and 2 respectively (nm) |
| SRR | slide-to-roll ratio |
| $T$ | temperature (°C) |
| $T_R$ | reference temperature (°C) |
| $T_g(p)$ | glass transition temperature at pressure $p$ |
| $T_g(0)$ | glass transition temperature at atmospheric pressure |
| $U_{\text{ball}}$ | ball speed (m/s) |
| $U_{\text{disc}}$ | disc speed (m/s) |
| $U_e$ | entrainment speed (m/s) |
| $\Delta U$ | sliding velocity (m/s) |
| $V_{(T,p)}$ | total volume (m$^3$) |
| $V_{(T,p=0)}$ | total volume at atmospheric pressure (m$^3$) |
| $V_R$ | total volume at the reference state (m$^3$) |
| $W$ | external normal applied load (N) |

*Greek letters*

| | |
|---|---|
| $\beta$ | temperature-viscosity coefficient (K$^{-1}$) |
| $\beta_K$ | temperature coefficient of $K_0$ (°C$^{-1}$) in the Tait equation |
| $\eta$ | dynamic viscosity (Pa s) |
| $\eta_0$ | viscosity at low shear stress (Pa s) |
| $\eta_g$ | viscosity at the glass transition (Pa s) |
| $\eta_{0(WLF)}$ | viscosity at low shear stress from the modified WLF-Yasutomi model (Pa s) |
| $\eta_2$ | viscosity on the second Newtonian plateau (Pa s) |
| $\nu_p$ | Poisson's coefficient |
| $\nu_1$, $\nu_2$ | Poisson's coefficients of solids 1 and 2 respectively |
| $\rho$ | mass density (g/cm$^3$) |
| $\rho_0$ | mass density at atmospheric pressure (g/cm$^3$) |
| $\rho(p)$ | mass density at the pressure $p$ (g/cm$^3$) |
| $\rho_R$ | mass density at the reference state (g/cm$^3$) |
| $\tau$ | shear stress (kPa) |

(with comb branches made of $C_{16}$, $C_{12}$, $C_{14}$, $C_{17}$, $C_{13}$, $C_{15}$ in the decreasing percentage of the total side chains and with the presence of short chains such as $CH_3$ or $CH_4$) which has a polar side due to the oxygen atoms in the ester group close to the backbone, a linear olefin copolymer (OCP) made of 40% in weight of ethylene and 60% in weight of propylene and a star-shaped poly (isoprene-styrene-hydrogenated) (PISH) on a styrene core. They were utilized as liquid polymers, previously diluted in another base oil (group III, API classification), chemically close to the hydrocracked mineral base oil. The final polymer concentration in the mineral base oil was 1.2% in weight, typical of automotive applications. Weight average molecular weights $M_w$ and polydispersity indexes ($PDI=M_w/M_n$, with $M_n$ is the number average molecular weight) are detailed in Table 1.

### 2.2. Ball-on-disc tribometer

The elastohydrodynamic regime was reproduced in the JEROTRIB (property of LaMCoS) test-rig. The configuration adopted for the study was a ball-on-disc contact. Although it was not representative of all the geometries found in an engine, the lubrication mechanisms were represented. The functioning principle of the rolling/sliding tribometer is described in [8]. Several improvements and modifications insured the control of supplementary parameters like the thermal boundary conditions and the absence of reactive materials regarding a possible interaction with some lubricant components in addition to the classical EHD operating parameters (normal load, independent rolling and sliding velocities). The EHD contact was created between a mirror-polished AISI 52100 steel ball whose radius is 12.7 mm and a BK7 glass disc, coated on its underside with a 20 nm semi-reflective chromium layer. The ball and the disc were carefully polished leading to a composite RMS roughness close to 3 nm and cleaned with pure acetone and heptane. The incident white light beams were perpendicular to the surface of the disc and the reflected ones were collected onto a 3CCD high resolution color camera through a microscope. The properties of the materials are reported in Table 2. The velocities of the ball and the disc were independently and precisely driven by two separate brushless motors. The contact between the two solids could be in pure rolling condition if the slide-to-roll ratio (SRR) was zero or in rolling–sliding conditions otherwise.

$$\mathrm{SRR}=\frac{\Delta U}{U_e}=2\frac{U_{ball}-U_{disc}}{U_{ball}+U_{disc}} \tag{1}$$

$$U_e=\frac{U_{ball}+U_{disc}}{2} \tag{2}$$

The bottom of the ball dipped in a reservoir containing the lubricant, ensuring fully flooded conditions in the contact. The reservoir and the two shafts were thermally isolated and heated by an external thermal control system. A platinum temperature probe monitored the lubricant temperature in the test reservoir within ±0.1 °C. The normal load was applied on the ball spindle and controlled through a stain-gauge sensor.

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