EHL Oil Film Behavior of Thermo-Reversible Gel-Lubricants

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This study investigates about the characteristic of the thermo-reversible gel-lubricant (TR Gel-Lube) under elastohydrodynamic lubrication (EHL) conditions. TR Gel-Lube is the lubricant, which consists of base fluid and a gel agent. TR Gel-Lube is repeatedly able to change gel-state to liquid-state at the melting point of its gel agent. Moreover, TR Gel-Lube has good tribological properties, anti-evaporability and so on. This paper describes about investigation of the EHL oil film thickness characteristic, the oil starvation at EHL inlet region and the EHL traction characteristic. It was observed that TR Gel-Lube had low EHL traction, thick EHL film thickness and good stability of EHL oil film formation compared with conventional greases.

Keywords: EHL, thermo-reversible gel-lubricant, grease, oil film thickness, oil starvation, traction

1. Introduction

Conventional greases have been widely applied as lubricants for automobile and industrial machineries and so on¹⁾. Recently, various precision instruments have been requiring high-performances such as long-life, energy saving, downsizing and high speeding. High grade greases using synthetic base fluid and MoS₂ have been developed to apply above application. However it is well known that elongated thickeners of grease make lubricity worse in narrow clearance of precision instruments. This phenomenon is known as oil starvation.

To solve these problems, a new unique lubricant, which is called Thermo-reversible gel-lubricant (TR Gel-Lube), was developed²⁾. TR Gel-Lube is consisted of base fluid and gel-agent. The most important characteristic of TR Gel-Lube is reversible change of its physical state, as shown in Fig.1.

The present investigation was carried out to clarify merit or demerit of the TR Gel-Lube at EHL condition compared with conventional greases. It has been found that TR Gel-Lube had low EHL traction, thick EHL film thickness and good stability of EHL oil film formation compared with conventional greases. The effect can be explained by good lubricity of gel-agent.

2. High-pressure rheology at quasi-static condition

2.1. Test fluids

The base fluid P-N-0 used for this investigation is PAO (poly- α -olefin) of VG68 included 1% of TCP. The

Fig.1 Change of Physical state of TR Gel-Lube by heating and cooling.

kinematic viscosity ν , density ρ , the pressure-viscosity coefficient α and refractive index n_D of P-N-0 are shown in the Table 1. The pressure-viscosity coefficient α is obtained over the pressure range of 0 to 0.33 GPa and temperature range of 20 to 60°C by using a falling ball type high-pressure viscometer. The variation of the pressure-viscosity coefficient α with temperature is described by equation.

$$\alpha = -1.683 + 8.226 \log_{10} \nu \quad (1)$$

In case of $\nu=71.3 \text{ mm}^2/\text{s}$ at oil temperature 40°C, the experimental value of α is 13.1 GPa⁻¹ and the predicted value of α from equation (1) is 13.6 GPa⁻¹.

The two TR Gel-Lubes employed in this study were P-A-10 and P-B-10. In P-A-10, 10% gelling agent mono-amido is added to base fluid P-N-0 and in P-B-10, 10% gelling agent bis-amido is added to base fluid P-N-0. Li grease P-L-8 and urea grease P-U-12 with

Table 1 Properties of base fluid

Oil	ρ , g/mL 15°C	ν , mm ² /s		α , GPa ⁻¹ 40°C	n_D 20°C
		40°C	100°C		
P-N-0	0.842	71.8	10.6	13.1	1.466

Table 2 Properties of TR Gel-Lube and greases

	P-A-10	P-B-10	P-L-8	P-U-12
	Gel	Gel	Grease	Grease
PAO	90	90	92	88
Mono-amido	10	-	-	-
Bis-amido		10	-	-
Stearic Li	-	-	8	-
Di-urea	-	-	-	12
Consistency	271	268	279	284
M.P., °C	100	150		

same base fluid P-N-0 were used for comparison. Properties of TR Gel-Lube and greases are shown in Table 2.

2.2. Phase diagram

The phase diagram of base fluid P-N-0 is shown in Fig. 2 and the equation related to the temperature-pressure of viscoelastic solid transition temperature T_{VE} is represented in the following empirical formula³⁾:

$$T_{VE} = T_{VE0} + A_1 \ln(1 + A_2 p) \quad (2)$$

where A_1 and A_2 are parameters which depend on fluid properties. The parameters obtained are $A_1=260.9^\circ\text{C}$ and $A_2=0.549 \text{ GPa}^{-1}$. The viscoelastic transition temperature at atmospheric pressure T_{VE0} was estimated by the occurrence of photoelastic effect at lowering temperature using liquefied nitrogen gas. Determined T_{VE0} is -72°C .

The phase diagrams corresponding to transition from sol to gel for TR Gel-Lube P-A-10 and P-B-10 was made up by using diamond anvil cell (DAC). Gel transition points at several temperatures were found and plotted on

Fig.2 Phase diagram of base fluid (P-N-0) and TR Gel-Lube (P-A-10, P-B-10)

Fig. 2. Phase diagrams for Sol-state and Gel-state have drawn in the Fig. 2 as mentioned (3) for P-A-10 and (4) for P-B-10 correspondingly. The phase diagram of Gel-state follows the Equation (3), where T_G is the gel transition temperature at any pressure p , T_{G0} is the gel transition temperature at atmospheric pressure and A_1 and A_2 are constants.

$$T_G = T_{G0} + A_1 \ln(1 + A_2 p) \quad (3)$$

3. Experimental procedure

The optical interferometry technique was used to study the shape and thickness of the lubricating film in an EHL point contact. A schematic diagram of the apparatus is shown in Fig. 3. The bodies in contact are a 23.8 mm diameter steel ball (elastic modulus $E_1 = 207 \text{ GPa}$, Poisson's ratio $\nu_1 = 0.3$) and a pyrex glass optical flat disk ($E_2 = 63.7 \text{ GPa}$, $\nu_2 = 0.2$) or a sapphire optical flat disk ($E_2 = 365 \text{ GPa}$, $\nu_2 = 0.25$) of 45 mm diameter with height of 5 mm. The steel ball was loaded with 86 N via lever arm. The corresponding mean Hertzian pressure is 0.45 GPa for pyrex glass and 0.90 GPa for sapphire.

The optical flat disk is driven by motor with ring-cone type traction CVT through toothed belt. The ball is directly connected with a coupling to another driving motor with ring-cone type traction CVT. Therefore the rolling speed and slip ratio can be controlled continuously. The surface velocities of the optical flat disk and ball can be measured with a photo sensor.

The monochromatic interference fringe pattern obtained by the Halogen light through a red filter was recorded with digital high-speed camera (125 frames per second), which was attached to a microscope.

The film thickness was evaluated using the refractive index at atmospheric pressure, because of the difficulty of estimating the pressure distribution. However, it does not seem that this treatment gives a sufficient difference to influence the results of this investigation. The temperature of the lubricant of reservoir was measured by a thermocouple.

Fig.3 Experimental apparatus

4. Results and discussion

4.1. Entrapped film thickness at halting EHL

The film thickness with TR Gel-Lube, with continuous supply, under rolling condition was difficult to measure in the usual EHL observation, since TR Gel-Lube have the thick oil film thickness and the oil film thickness changes. Authors previously reported on the entrapped oil film thickness at EHL halting h_e is dependent on $\alpha\eta a$, where α is the pressure-viscosity coefficient, η is the absolute viscosity and a is the deceleration⁴⁾.

Here, the measurement technique of entrapped film thickness at halting EHL was used to study the shape and thickness of lubricating film in the EHL point contact. The experiments were carried out at a room temperature of around 23°C. The dynamic viscosity η and pressure-viscosity coefficient α of base fluid P-N-0 are $\eta = 0.136$ Pas and $\alpha = 16.5 \text{ GPa}^{-1}$ ($G = \alpha E = 1697$). The experiments were run at a load $w = 86 \text{ N}$ ($W = w/ER_x^2 = 5.90 \times 10^{-6}$), which gives a mean Hertzian pressure of 0.45 GPa and Hertzian diameter of 0.49 mm. In this study pure rolling motion was used. The pure rolling was realized by an optical flat disk driven and a freely rotating steel ball without a coupling. To obtain shut down motion, the power supply of motor with traction CVT which drives disk was cut off. The speed of the disk was ramped down linearly to halting, always moving forward in one direction.

Figure 4 shows the interferograms of entrapped oil film of the base fluid P-N-0 and the TR Gel-Lube P-B-10 when the initial rolling speed $u = 0.065 \text{ m/s}$ ($U = \eta u/ER_x = 7.3 \times 10^{-12}$) was halted by deceleration $a = 0.13 \text{ m/s}^2$. Figure 5 shows the midplane film profile of entrapped film that calculated from the intensity on interferograms, left-hand side is the EHL inlet region at initial rolling state, and right-hand side is the EHL outlet region.

The central film thickness of base fluid P-N-0 at initial rolling speed was $0.094 \text{ }\mu\text{m}$ by the experiment and $0.089 \text{ }\mu\text{m}$ from Chittenden equation⁵⁾. The central entrapped film thickness h_e of base fluid P-N-0 was $h_e = 0.016 \text{ }\mu\text{m}$. The central film thickness of TR Gel-Lube P-B-10 at initial rolling speed was difficult to measure in the cause the thick oil film thickness and the oil film thickness changes. The central entrapped film thickness h_e of TR Gel-lube P-B-10 was $h_e = 0.594 \text{ }\mu\text{m}$, which is thick film compared with the base fluid P-N-0 as shown in Fig. 4 and Fig. 5.

Figure 6 shows the relation between obtained entrapped film thickness h_e and $\alpha\eta a$ for all experiments with the initial rolling speed of $u = 0.065 \text{ m/s}$ and $u = 0.13 \text{ m/s}$ and thus decelerations, $a = 0.13 \text{ m/s}^2$ and $a = 0.26 \text{ m/s}^2$, respectively. The solid line in Fig. 6 got from the regression analysis of the relation of entrapped film thickness and $\alpha\eta a$ that obtained from thirty-six experiments for nine kind of lubricating oil previously reported⁴⁾. The experiment point of base fluid P-N-0 is close to the regression line. The good repeatability of this

Fig.4 Interferograms of entrapped oil film

(a) P-N-0 (Fig. 4 (a)) (b) P-B-10 (Fig. 4 (b))

Fig.5 Midplane film profile of entrapped film

Fig.6 Relationship between entrapped film thickness h_e and $\alpha\eta a$

experiment is recognized as this result. The entrapped film thickness h_e is the order of base fluid P-N-0 < grease (P-L-8, P-U-12) < TR Gel-Lube (P-A-10, P-B-10). Therefore, the characteristic of TR Gel-Lube is thick oil film formation compared with conventional greases.

4.2. Starvation at EHL inlet region

In general it is found that under fully flooded conditions, the grease films formed in the EHL contact are thicker than those observed when using the grease base oil. Under conditions where the grease film has been found to be thinner than the corresponding base oil this effect has usually been ascribed to starvation in the inlet region of the contact. The collapse of oil film due to starvation on the EHL inlet region causes a trouble for the grease lubrication⁶⁾. The purpose of the experiment here is to clarify the influence on starvation of the TR Gel-Lube. So, we measured the time that the full starvation i.e. parched lubrication is causing on EHL inlet region at the mean Hertzian pressure 0.45 GPa and pure rolling speed $u = 0.52 \text{ m/s}$. The applied lubricant

Fig. 7 Full starvation of Gel-Lube (P-A-10, P-B-10) and greases (P-L-8, P-U-12)

thickness was 1mm to the optical flat. The experiment was conducted twice in each lubricant. Gel-Lube and greases has the thick oil film thickness at the beginning. After about 180 s, the thickness maintained a constant value of about 90% of the base fluid P-N-0. The results of full starvation are shown in Fig. 7. Time to full starvation was indicated over 7200 s for TR Gel-Lube (P-A-10, P-B-10). The time period of TR Gel-Lube (P-A-10, P-B-10) was significantly long compared with conventional greases (P-L-8, P-U-12). TR Gel-Lube showed stable oil film formation.

4.3. EHL traction

The traction forces of all lubricant were measured under test conditions of continuous supply, central film thickness 0.2 μm in base fluid P-N-0, slide/roll ratio $\Sigma=50\%$, and mean Hertzian pressure 0.45 GPa and 0.90 GPa. The testing conditions are the same as previous report⁷⁾. Traction forces were measured by varying slip ratio in positive and negative directions, and the average value of traction coefficient at each operating condition was calculated. The results are summarized in Fig. 8.

Figure 8 shows traction coefficient μ in mean Hertzian pressure 0.45 GPa and 0.90 GPa of each sample lubricant. Experimental conditions are plotted in A point ($\blacktriangle$) and B point ($\blacklozenge$) as shown in the phase diagram of Fig. 2. $T_{VE}-T$ of A point calculated from Equation (2) is -39°C , and it exists in liquid region⁷⁾. Compared with it, B point is the viscoelastic solid transition region with $T_{VE}-T=8^\circ\text{C}$. Therefore, in case of the base fluid (P-N-0), it originates in the difference of an oil molecule packing condition that the traction coefficient raises in high contact pressure.

The traction coefficient of TR Gel-Lube (P-A-10, P-B-10) is low compared with the traction coefficient of base fluid (P-N-0), and the difference is remarkable. This is thought that the gelling agent amide adsorbs a steel ball and a flat, and it is considered that absorbed film participated in the low traction characteristic. To clarify the mechanism of tribological properties of TR Gel-Lube in detail, a great deal of work is still required.

Fig. 8 Coefficient of traction μ for each lubricants

5. Conclusions

Summarizing the results the following conclusions are drawn:

- (1) Thermo-Reversible Gel-Lubricants assumed the thick film compared with greases and base fluid under the EHL condition. Also, the traction coefficient of TR Gel-lube is low.
- (2) TR Gel-Lube has an advantageous characteristic to be less likely to fall in oil starvation, compared with greases in EHL condition.

6. References

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