Effects of Load Intensity Fluctuation on Anti-Seizure

Capacity of Lubricating Oils*

(2nd Report, Anti-Seizure Capacity of Gear Base Oil

at a High Specific Sliding)

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Concerning the scoring resistance of the gear drive, the effects of the load intensity fluctuation on the anti-seizure capacity of a gear base oil were examined by two-cylinder tests at a high specific sliding considering the interference among projections. The frequency of interference among projections increases with an increase in specific sliding. Though the frequency in the heavy load intensity sector is higher than that in light one, the effects of the load intensity difference on the frequency in a higher specific sliding range are smaller than those in a lower one. The seizure tends to take place in the heavy load intensity sector where the frequency of interference among projections and the bulk temperature are high. The load intensity fluctuation does not affect the anti-seizure capacity of the gear base oil. This is because there is little difference between the lubrication states in both load intensity sectors.

Key Words : Lubrication, Load Intensity Fluctuation, Interference among Projections, Anti-Seizure Capacity, Gear Base Oil, Surface Roughness, Sliding-Rolling Contact, Two-Cylinder Test

1. Introduction

Ichimaru, et al. studied systematically the effects of the interference among projections on the seizure by two-cylinder tests and revealed under combinations of easily conformable materials that the seizure load was affected markedly by the state of interference among projections⁽¹⁾⁻⁽³⁾. It is well known that the scoring in a gear pair tends to take place when the sliding velocity is high in the region of the beginning or the end of the gear meshing where the specific sliding is large. The authors examined the effects of the specific sliding, the sliding velocity, and the surface roughness on the seizure limits of lubricating oils by two-cylinder tests under combinations of hardened materials⁽⁴⁾⁽⁵⁾. As a result, the following were made clear. In a lower specific sliding range the effects of the surface roughness on the seizure limit are small. The load carrying capacities of the EP oils with much chemical reactivities increase as the surface roughness is increased, because the EP film formation is promoted by an increased surface

roughness. On the other hand, in a higher specific sliding range, the seizure limit were less than that in a lower one. A decrease in the chemical reactivity of the EP oil causes an increase in the decreasing rate of the load carrying capacity when the surface roughness is large. The load carrying capacity decreases as the sliding velocity is increased.

The above are the results under a constant load intensity condition. For the design of the scoring load capacity of a gear pair, it is important to clarify the effects of the load fluctuation on the anti-seizure capacity of the lubricating oil, because the dynamic load takes place inevitably in the gear pair. In the previous paper⁽⁶⁾, the dynamic load in a spur gear pair was defined as a load fluctuation per unit width (the load intensity fluctuation), and two-cylinder tests were carried out under load intensity fluctuation conditions using specially designed cylinders. The results demonstrated that the frequencies of interference among projections in the heavy load intensity sectors were higher than those in the light ones, and that the sliding promoted the interference among projections. In this report, the effects of the load intensity fluctuation on the anti-seizure capacity of a gear base oil are examined at a high specific sliding.

2. Experimental Method

The two-cylinder test rig, the material, the heat treatment and the surface finishing of the test cylinders, the lubricating oil,

* Received 12 July 1984.

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and the oil supply conditions are the same as in the previous paper (6). The test cylinders were made of S45C steel which had been quenched in water and tempered, their outer surfaces had been finished by grinding in the circumferential direction, and their outer surface hardnesses after the grinding were about H_v700 . The lubricating oil used in the experiments was a #90 gear base oil and it was supplied over the contact width at a rate of 500mL/min with the temperature held at $323 \pm 1 \text{ K}$ ($50 \pm 1^\circ \text{C}$).

The experiments were carried out at

C.C.: Continuous contact tread
D.C.: Discontinuous contact tread
H.L.: Heavy load intensity sector
L.L.: Light load intensity sector

Fig.1 Dimensions of slower test cylinder to give load intensity fluctuation

three sliding velocities ($V_s=3.14, 9.42$, and 15.7 m/s) under the specific sliding $\sigma_h=+78.2\%$ of the faster test cylinder. In order to generate the load intensity fluctuations four times a rotation of the slower test cylinder, a cylinder whose contact tread width was varied intermittently as shown in Fig.1 was used on the slower side, while a cylinder with uniform contact tread width was used on the faster side. The outside diameters and the widths of both test cylinders were 60 and 20mm, respectively. Three load intensity ratios p_h/p_l of 2, 3, and 4 were selected, where p_h and p_l are the heavy and the light load intensities, respectively. In the experiments, the test cylinders were paired with similar surface roughnesses. The center line average transverse roughnesses on the outer surfaces of the test cylinders ranged from 0.03 to $0.65 \mu\text{m}$, which were obtained by changing the grinding conditions. The load was increased stepwise according to the loading procedure shown in Tabel 1 until a destructive seizure took place which made further operation impossible because of vibration and noise. The operation time for each loading

Table 1 Loading steps

Loading step	Load kN	Hertzian stress in H.L. of C.C. when $l_c=5 \text{ mm}$ MPa
1	0.25	346
2	0.50	490
3	0.75	600
4	1.00	692
5	1.50	850
6	2.00	980
7	2.50	1095

1 kN=102 kgf, 1 MPa=0.102 kgf/mm²

(a) $p_h/p_l=2$

(b) $p_h/p_l=4$

$\sigma_h=+78.2\%$, $V_s=9.42 \text{ m/s}$, $U=7.34 \text{ m/s}$, $\Sigma R_a=0.076 \mu\text{m}$ (before test)

Fig.2 Effects of load intensity fluctuation on the state of interference among projections under small surface roughness condition

step was set at 600 seconds. In order to prevent a seizure from taking place within a short time after the start of operation, a motor was switched on at no-load. The rotating speed and the load were increased to desired values within 60 seconds after the start. Friction coefficient between the test cylinders was given by subtracting the friction loss torque of bearings from the torque measured with a torsion bar connected to the axis of the faster test cylinder. The bulk temperatures on the outer surfaces of the test cylinders were measured with thermocouples at the same positions as in the previous paper (6) and were recorded on a pen recorder.

3. Experimental Results and Discussion

3.1 States of interference among projections

At first, the states of the interference among projections in a higher specific sliding range will be discussed, because the specific sliding in this report is larger than that in the previous paper (6).

Figure 2 shows the effects of the load intensity fluctuation on the state of interference among projections. The electric circuit and the data processing method are the same as in the previous paper (6). The outer surfaces of the test cylinders were as smooth as a mirror, and ΣR_a before tests was $0.076\mu\text{m}$, where ΣR_a is the sum of the center line average transverse roughnesses R_a on the outer surfaces of the faster and the slower test cylinders. The load intensity ratios in Figs. 2(a) and 2(b) are 2 and 4, respectively. U is the average of the velocities on the outer surfaces of both test cylinders, P is

the load, and H.L. means the heavy load intensity sector. In this report, the experiments to investigate the states of interference among projections were carried out in the load ranges below destructive seizure loads. Figure 3, which corresponds to Fig. 2, shows the average T_{ba} of the bulk temperatures on the outer surfaces of both cylinders on the continuous contact tread (C.C. in Fig. 1), the EHL film thickness h_o obtained by Grubin's equation (7) for T_{ba} , and the average potential difference E_{ca} between the test cylinders, which is obtained from the potential difference waves at $R_2=10^3\Omega$, where R_2 is the electrical resistance inserted in parallel to the two cylinders in Fig. 4 in the previous paper (6). H.L. and L.L. in Fig. 3 mean the values in the heavy and the light load intensity sectors (H.L. and L.L. in Fig. 1), respectively. R_{ca} is the average electrical resistance between the test cylinders. ξ_0 is the specific film thickness defined similarly to the previous paper (6) with respect to surface roughnesses before test on the outer surfaces of both test cylinders.

When the load intensity on the continuous contact tread changes to the light one from the heavy one, the edge of the discontinuous contact tread (D.C. in Fig. 1) collides tangentially with the outer surface of the faster cylinder owing to the elastic contact deformations. Therefore, to avoid this collision, the test cylinders whose contact tread widths were varied intermittently were used on the slower side. In Fig. 2, the accelerations of the slower test cylinder at $P=1.50\text{kN}\{153\text{kgf}\}$ were shown which were measured by the acceleration pickup set at the

Fig. 3 Average T_{ba} of bulk temperatures on outer surfaces of both cylinders, EHL film thickness h_o , and average potential difference E_{ca} between test cylinders on continuous contact tread (corresponding to Fig. 2)

$P_h/P_l=4$, $\sigma_h=+78.2\%$, $\Sigma R_a=0.07\mu\text{m}$ (before test), $R_2=10^3\Omega$

Fig. 4 Effects of sliding velocity on the state of interference among projections

same position as in Fig.1 in the previous paper (6). The accelerations fluctuate at the positions where the load intensities are varied. The acceleration fluctuations at $p_h/p_l=4$ are a little larger than those at $p_h/p_l=2$, because in the former the difference between the elastic contact deformation in the heavy load intensity sector and that in the light one is larger than the difference in the latter. But the effects of the acceleration fluctuation on the state of interference among projections cannot be recognized.

As demonstrated in Figs.2 and 3, also in a higher specific sliding range, even in the fully elastohydrodynamic lubrication state where ξ_0 is more than 10, the interference among projections takes place, and the frequencies are higher in the heavy load intensity sectors than those in the light ones. The frequency of interference among projections increases as the EHL film thickness decreases due to the outer surface bulk temperature rise as the result of a load increase. There is little difference between the states of interference among projections in the light load intensity sectors at $p_h/p_l=4$ and those at $p_h/p_l=2$, though the load intensities in the former are a half of those in the latter. At $P=1.00$ and 1.50 kN (102 and 153 kgf), the frequencies of interference in the former are a little higher. By comparing and examining the results in Figs.2 and 3 with those in Figs.6 to 9 in the previous paper (6), the following can be deduced about the effects of the specific sliding on the

state of interference among projections considering the conditions of the load, the outer surface bulk temperature, and the specific film thickness. As the specific sliding is increased, the frequency of interference among projections increases and the difference in the state of interference caused by the load intensity difference decreases.

Figure 4 shows the effects of the sliding velocity V , on the state of interference among projections. Figure 5, which corresponds to Fig.4, shows T_{ba} , h_0 for T_{ba} , and E_{ca} on the continuous contact tread. The effects of the load intensity fluctuation on the state of interference among projections are similar to those at $V_s=9.42\text{ m/s}$ in Fig.2. Though the bulk temperature rise increases as the sliding velocity is increased, the frequency of interference among projections tends to decrease because of the EHL film thickness increase. But in the vicinity of

Fig.5 T_{ba} , h_0 , and E_{ca} on continuous contact tread (corresponding to Fig.4)

$p_h/p_l=4$, $\sigma_h=+78.2\%$, $V_s=9.42\text{ m/s}$, $U=7.34\text{ m/s}$,
 $\epsilon R_a=0.76\text{ μm}$ (before test)

Fig.6 States of interference among projections under large surface roughness condition

Fig.7 T_{ba} , h_0 , and E_{ca} on continuous contact tread (corresponding to Fig.6)

the destructive seizure load where the outer surface bulk temperature rise is high, the effects of the sliding velocity on the frequency of interference among projections decrease and the frequencies of interference are high. In addition, as indicated in the results at $P=1.50\text{kN}\{153\text{kgf}\}$ in Fig.4, also in the faster sliding velocity range, the acceleration fluctuation of the slower test cylinder little affects the state of the interference among projections.

The above is the interference among projections under a small surface roughness condition. Figure 6 shows the states of interference among projections under a large surface roughness condition. Figure 7, which corresponds to Fig.6, shows T_{ba} , h_0 for T_{ba} , and E_{ca} on the continuous contact tread at $R_z=10^3\Omega$. ξ_0 is less than 5, and the frequencies of interference among projections are markedly high. At $P=0.25\text{kN}\{26\text{kgf}\}$ the frequencies of interference in the heavy load intensity sectors are higher than those in the light ones, while at $P=0.50\text{kN}\{51\text{kgf}\}$ the frequencies of interference are high in both intensity sectors. At $P=0.75\text{kN}\{76\text{kgf}\}$ where the outer surface bulk temperature rise is large, as indicated in Fig.6 the potential difference between the test cylinders in the heavy load intensity sectors is a little larger than that in the light ones, which is similar to the results in Fig.13 in the pre-

$$\sigma_h = +78.2\%, V_s = 9.42 \text{ m/s}, U = 14.7 \text{ m/s}$$

Fig.8 Relation of surface roughness just before destructive seizure to that before test (transverse surface roughness of slower test cylinder on continuous contact tread)

Fig.9 Relation of E_{ca} to specific film thickness ξ_0 ($R_z=10^2\Omega$)

vious paper (6). Judging from the change in color on the frictional surfaces in the heavy load intensity sectors, this is attributed to the good conformities and the rich oxidized film formations.

Figure 8, which is obtained from the experiments to investigate the effects of the load intensity fluctuation on the anti-seizure capacity of the #90 gear base oil, shows the relation of the center line average roughness on the continuous contact tread of the slower test cylinder just before destructive seizure to that before test. In Fig.8, the corresponding values are marked with a sign of *. When the motor is switched off upon the detection of a sudden increase in friction torque, the surface roughness just before a destructive seizure can be obtained because the seizure failure takes place in local areas. Figure 8 shows the results obtained according to this method. In the range of 0.03 to $0.05\mu\text{m}$ in the center line average roughness before test where the surfaces are as smooth as a mirror, the surface roughnesses just before the destructive seizures, especially in the heavy load intensity sectors, are larger than those before tests. On the other hand, in the range of more than $0.15\mu\text{m}$ in the center line average roughness before test, the surface roughness just before destructive seizure is less than that before test. Like these, the effects of interference among projections on the change in surface roughness relate to the surface roughness before test. According to the experimental results by Poon, et al. (8) and Haines (9), the frictional surfaces are in the fully EHL state when $\xi_0 > 3.7$ and the contact time ratios among projections are nearly 100%

$$\sigma_h = +78.2\%, \Sigma R_a = 0.09 \mu\text{m (before test)}$$

Fig.10 Bulk temperature on outer surface of slower cylinder

when $\xi_0 < 1$. But, as clarified in the previous paper(6) and this paper, the interference among projections takes place even when the specific film thickness ξ_0 is much more than 10. Figure 9 shows the relation of the average potential difference E_{ca} to the specific film thickness ξ_0 with respect to the surface roughness before test under a constant load intensity condition. The experiments were carried out for three contact tread widths, that is, 5, 10, and 20mm. To investigate the states of interference among projections in a lower electrical resistance range between the

test cylinders, the electrical resistance R_i inserted in parallel to the test cylinders was set at $10^2 \Omega$. When $\xi_0 \leq 10$, the relation of the state of interference among projections to the specific film thickness is similar to the usual relations, and the frequency of the interference among projections tends to decrease markedly as ξ_0 approaches 10. But, when $\xi_0 > 10$, the interference among projections takes place even at $\xi_0 = 70$ similarly to the load intensity fluctuation tests. Under sliding-rolling contact condition where the heat is generated by friction loss, the frequency of interference increases markedly as ξ_0 decreases from 50 to 10.

3.2 Effects of load intensity fluctuation on anti-seizure capacity

3.2.1 Bulk temperature on outer surface of cylinder

The bulk temperature on the outer surface of test cylinder plays an important role in the seizure occurrence. The authors have analyzed the temperature rise in a rotating cylinder due to a heat source with a constant heat quantity per unit time and unit width. The results indicated that the temperature rise on the outer surface of the cylinder could be divided into two components. One was flash temperature not affected by the heat transfer coefficient on the cylinder surface and the other was bulk temperature rise affected by it (10). Further examination demonstrated that the bulk temperature on the outer surface could be approximated by the temperature measured at the position of 3% of the outside diameter below the outer surface of the cylinder (11).

Figure 10 shows the bulk temperature on the outer surface of the slower cylinder under load intensity fluctuation condition. The temperature-measured positions were midway in the circumferential and the axial directions in each load intensity sector. In

Fig.11 Effects of load intensity fluctuation and sliding velocity on destructive seizure load P_{bs} , specific film thickness $(\xi_0)_{DS}$ and friction coefficient μ_{DS} just before destructive seizure ($\sigma_n = +78.2\%$)

the light load intensity sectors, there is little difference between the bulk temperature rise on the continuous contact tread and that in the discontinuous one. On the continuous contact tread, the outer surface bulk temperature in the heavy load intensity sector is higher than that in the light one, and the difference between these temperatures will be the wider, the higher is the range of temperatures, the greater is the load intensity ratio, and the slower is the sliding velocity.

3.2.2 Destructive seizure load, specific film thickness and friction coefficient just before destructive seizure

Figure 11 shows the effects of the load intensity fluctuation and the sliding velocity on the destructive seizure load P_{DS} , the specific film thickness $(\xi_0)_{DS}$ and the friction coefficient μ_{DS} just before destructive seizure in connection with the surface roughness. The corresponding values are marked with a sign of *. The observation by a synchroscope demonstrated that there was little difference between the friction torque in the heavy load intensity sector and that in the light one. In this experiment, the seizure took place mostly on the continuous contact tread which included the heavy load

intensity sector. The number of seizures taking place on the discontinuous contact tread to the total number of seizures was only about 6%. $(\xi_0)_{DS}$ was obtained using the EHL film thickness on the continuous contact tread and the transverse roughnesses on the outer surfaces of both cylinders before test. The EHL film thickness was calculated using the average of the outer surface bulk temperatures in the heavy load intensity sector of the faster and the slower cylinders. When $\Sigma R_a < 0.2 \mu\text{m}$, the values of $(\xi_0)_{DS}$ indicate that all the seizures took place in the fully EHL state. But the mean electrical resistance between the test cylinders just before the destructive seizure was less than 200Ω at $R_z = 10^3 \Omega$. Furthermore, the center line average roughnesses on the outer surfaces of both test cylinders just before the destructive seizure were 1.1 to 2.9 times the roughnesses before tests. As clarified before, frictional surfaces are in boundary lubrication state when $\xi_0 \leq 0.3$ (12). Therefore, from this experiment it can be concluded that all the frictional surfaces are in mixed lubrication state.

In order to compare the anti-seizure capacity of the #90 gear base oil under the load intensity fluctuation tests with that under constant ones, the seizure experiments were carried out using the test cylinders with $l_z = 5 \text{ mm}$ which was almost the same width as the continuous contact tread width in Fig. 1. The results of the constant load intensity test are marked with $\bullet$ in Fig. 11. The state of the interference among projections under constant load intensity tests were similar to those in the heavy load intensity sector on the continuous contact tread under load intensity fluctuation tests.

The results including those under constant load intensity tests demonstrate the no effects of load intensity fluctuation on P_{DS} , $(\xi_0)_{DS}$, and μ_{DS} at either sliding velocity. P_{DS} decreases as the surface roughness is increased. This tendency is promoted as the sliding velocity is increased. μ_{DS} increases

Fig. 12 Effects of surface roughness, sliding velocity, and load intensity fluctuation on outer surface bulk temperature $(T_b)_{DS}$ and maximum contact surface temperature $(T_{c \max})_{DS}$ in heavy load intensity sector on continuous contact tread ($\sigma_h = +78.2\%$)

as the surface roughness is increased. At either sliding velocity, μ_{DS} at $\Sigma R_a \approx 1.2 \mu m$ is about twice that when $\Sigma R_a < 0.2 \mu m$.

3.2.3 Bulk temperature on outer surface of cylinder and maximum contact surface temperature just before destructive seizure

Figure 12, which corresponds to Fig. 11, shows the effects of the load intensity fluctuation and the sliding velocity on the outer surface bulk temperature and the maximum contact surface temperature just before the destructive seizure in connection with the surface roughness. Both $(T_b)_{DS}$ and $(T_{cmax})_{DS}$ are the values in the heavy load intensity sector on the continuous contact tread. The equations used in the calculation of $(T_{cmax})_{DS}$ and so on are the same as used in the previous paper (11). $(T_b)_{DS}$ is the higher one of the bulk temperatures on the outer surfaces of the faster and slower test cylinders. In this experiment, the differences between the bulk temperatures of both cylinders were mostly less than 10K. On the continuous contact tread the outer surface bulk temperature in the heavy load intensity sector was higher than that in the light one. But the difference between them was less than 15K and tended to decrease as the load intensity ratio and the sliding velocity were decreased.

The results of the constant load intensity test at $l_c = 5mm$, which are marked with ●, demonstrate that at any sliding velocity the load intensity fluctuation does not affect $(T_b)_{DS}$. The authors had found on the basis of the results of the constant load intensity tests that the seizure occurrence in the mixed lubrication state had more intimate relation to the outer surface bulk temperature than to the maximum contact surface temperature⁽⁴⁾. As demonstrated in 3.2.2, all the seizures in this experiment took place in the mixed lubrication state. Thus the scatter in the temperatures shown in Fig. 12 may be considered to mean that the above mentioned conclusion from the constant load intensity tests is also applicable to the load intensity fluctuation tests.

4. Conclusions

The effects of the load intensity fluctuation on the anti-seizure capacity of a gear base oil at a high specific sliding were examined by two-cylinder tests in the load intensity ratio range of 2 to 4. A specially designed cylinder whose contact tread width was varied intermittently four times a rotation of the cylinder was used on the slower side. The results obtained are summarized as follows:

(1) The interference among projections is liable to take place as the specific sliding is increased. The frequency of the interference is high even in the fully elastohydrodynamic lubrication state where the spe-

cific film thickness is more than 10.

(2) The frequency of interference among projections in the heavy load intensity sector is higher than that in the light one. But the difference due to load intensity is less than that for the lower specific sliding.

(3) In the higher sliding velocity range where the outer surface bulk temperature rise is large, the frequency of interference among projections is high and is affected a little by the sliding velocity.

(4) The seizure took place mostly not on the discontinuous contact tread but on the continuous one which includes the heavy load intensity sector. This suggests that the probability of seizure occurrence is high in the heavy load intensity sector where the frequency of interference among projections and the bulk temperature are high.

(5) The load intensity fluctuation does not affect the anti-seizure capacity of the gear base oil, because, in the load intensity ratio range in this experiment, there is little difference between the lubrication state of frictional surfaces in the heavy load intensity sector and that in the light one.

(6) Even under load intensity fluctuation condition, the seizure occurrence in the mixed lubrication state has more intimate relation to the outer surface bulk temperature than to the maximum contact surface temperature.

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