Effects of Surface Roughness on the Seizure Limits of Lubricating Oils*

(1st Report, In the Case of Non-additive Gear Oil)

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In this paper, as the first step to get a key to clarification of the mechanism of scoring in gear pairs, effect of surface roughness on the seizure limit of non-additive gear oil was examined by two-cylinder tests. As the result, the following conclusions are deduced : (1) In the lower range of specific slidings and the slower range of sliding velocities where seizure occurs in boundary lubrication, the seizure limit is not affected by surface roughness or rather it increases as surface roughness increases. (2) In the higher range of specific slidings where seizure tends to occur in mixed or full elastohydrodynamic lubrication regardless of surface roughness, the seizure limit decreases as surface roughness increases. (3) In order to increase the seizure limit in the higher range of specific slidings and the faster range of sliding velocities where seizure occurs easily and to decrease the frictional power loss, finishing the surface roughness fine is an effective means.

Key Words: Gear Lubrication, Scoring, Non-EP Gear Oil, Seizure Limit, Surface Roughness, Sliding-rolling Contact

1. Introduction

Scoring in a gear pair tends to occur when sliding velocity is faster in the region of the beginning or the end of gear meshing where specific sliding is larger. Nevertheless, up to now there were no studies systematically examining the effects of specific sliding and sliding velocity on the seizure limit of lubricating oil. Then, the authors studied the effects of both factors by two-cylinder tests ^{(1),(2)}. As the result, it was made clear that the seizure load of lubricating oil, the lubrication state of frictional surfaces before seizure, and the temperature at seizure occurrence were significantly affected by specific sliding and sliding velocity.

This is a basic study to make clear the mechanism of scoring in gear pairs by clarifying both the effect and the cause of surface roughness on the seizure limit of lubricating oil. In this paper, the effect of surface roughness on the seizure limit of non-additive gear oil is clarified. The magnitude of surface roughness directly affects the interference frequency among projections. Therefore, there are many studies examining the effect of surface roughness on seizure failure such as scoring in a gear pair ⁽³⁾⁻⁽¹⁰⁾. But, there are no studies examining it on the basis of the above-mentioned result that lubrication state of frictional surfaces before seizure

occurrence is significantly affected by specific sliding and sliding velocity.

2. Experimental Method

2.1 Test rig, test cylinder, and lubricating oil

A two-cylinder test rig was used in the experiments. Shapes, dimensions, material, and heat treatment of test cylinders are the same as in the previous paper ⁽¹¹⁾. The outer surfaces of test cylinders were finished by grinding in circumferential direction in the surface roughness range of 0.04 to 0.77 μmRa . The hardnesses of their surfaces after grinding were about H_V700 .

Table 1 shows the properties of the non-additive gear oil used in the experiments.

2.2 Experimental method

As the outer surface diameters of the faster and slower test cylinders are the same, the specific slidings S_h for the faster cylinder and S_l for the slower one are given by $(N_h - N_l)/N_h$ and $(N_l - N_h)/N_l$ respectively. Where, N_h and N_l are the rotating speeds of the faster and the slower cylinders respectively. A desired specific sliding was obtained by changing the transmission ratio of a gear pair. The experiments were performed in the range of $S_h = +41.9$ to $+78.2\%$ ($S_l = -72.1$ to -358%) and in the sliding

Table 1 Properties of non-additive gear oil

Specific gravity 288/277 K	0.8897
Flash point K	541
Pour point K	260.7
Kinematic viscosity mm^2/s { 311 K	225.6
372 K	18.25
Viscosity index	97
Sulfur wt%	0.48 ⁺
+ : natural content	

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velocity range of $V_s=3.14$ to 15.7m/s respectively. In addition, to clarify how the effect of surface roughness on the seizure limit of the non-additive gear oil is affected by the contact width l_z in axial direction, two kinds of the test cylinders with $l_z=5\text{mm}$ and $l_z=20\text{mm}$ were used.

The experiments were performed by such a method that on the same test cylinders the load was increased stepwise according to the loading procedure shown in Table 2 until a destructive seizure⁽¹¹⁾ occurred. Continuous operation time for each loading step was set at 600 seconds. In the interval of 300 seconds between loading steps the frictional surfaces were observed. In order to prevent seizure from occurring within a short time after start of the operation, a motor was switched on at no-load. The rotating speed and the load were increased to desired values within 60 seconds after start.

In the experiments, the cylinders were paired with similar surface roughness before test. The lubricating oil was held at $323\pm 1\text{K}\{50\pm 1^\circ\text{C}\}$ and supplied at a rate of 500mL/min through the engaging side nozzle. Coefficient of friction between the test cylinders was obtained by subtracting the friction loss torque of bearings. The bulk temperatures of outer surfaces of cylinders were measured by thermocouples⁽¹¹⁾.

3. Experimental Results and Discussion

3.1 Changes in bulk temperature of outer surface of cylinder and coefficient of friction with an increase of load

Figures 1 and 2 show the changes in the bulk temperature of outer surface of cylinder T_b , coefficient of friction μ , and specific film thickness ξ_0 with an increase of load P at $S_h=+41.9\%$ and at $S_h=+78.2\%$ respectively for $l_z=5\text{mm}$. Except the values just before destructive seizures, the values are shown just before the end of the operation at each loading step. T_b is the higher value between the bulk temperatures of cylinders. ξ_0 was obtained by the same method as in the pervious paper⁽¹⁾ for the roughness of outer surface of cylinder in axial direction. $\overline{ER}_a$ is the sum of the center line average roughnesses R_a of the outer surfaces of both cylinders. The values of $\overline{ER}_a$ shown in the figures are the ones before tests. From now on, the value of $\overline{ER}_a$ is usually the one before test.

Figure 3 shows the sectional curves in axial direction and the metallographs in the

non-seizure regions of the frictional surfaces corresponding to Fig.1 after the destructive seizures occurred. $(\xi_0)_{DS}$ in the figure is the specific film thickness just before destructive seizure for the roughness before test. In some cases of Fig.3(a), as R_a in the non-seizure region could not be measured because the width of the non-seizure region in axial direction was small, R_a after test was not shown.

Figure 4 shows the results of line analyses for oxygen by an X-ray micro-analyzer(XMA) in the axial direction corresponding to the case of Fig.3. The state of oxidized film formation can be known in this figure.

In the following, it is shown on the basis of the results given in Figs.1 to 4 how the effects of surface roughness on T_b and μ are affected by specific sliding and sliding velocity with an increase of load.

First, the results at $S_h=+41.9\%$ shown in Figs.1, 3 and 4 are examined. As shown in Fig.1(a), though μ and hence T_b increase as surface roughness increases at $V_s=3.14\text{m/s}$, the effects of surface roughness on μ and T_b change with an increase of load. Namely, though at $\overline{ER}_a=0.14\mu\text{m}$ μ gradually increases as the load increases, at $\overline{ER}_a\geq 0.51\mu\text{m}$ the load at which μ is maximum becomes smaller as surface roughness increases and over the load for the maximum μ the value of μ gradually decreases. When $\overline{ER}_a\leq 0.80\mu\text{m}$, the effects of surface roughness on P , μ , and T_b at seizure occurrence cannot be recognized. On the other hand, at $\overline{ER}_a=1.07\mu\text{m}$ seizure does not occur even at a load of $P=14.8\text{kN}\{1510\text{kgf}\}$ which is more than the permissible load of the test rig and the temperature of $T_b=525\text{K}\{252^\circ\text{C}\}$. In this case, μ at the final loading step is 0.023 which is two-sevenths of the maximum value and is less than half of the value just before the destructive seizure.

Judging from the experimental results by Poon, et al.⁽¹²⁾ and Haines⁽¹³⁾, frictional surfaces are in full elastohydrodynamic lubrication when $\xi_0>3.7$ and contact time ratio among projections is almost 100% when $\xi_0<1$. Further, from the results of the two-cylinder tests, the authors estimated that the frictional surfaces were in boundary lubrication when the specific film thickness ξ_0 for the roughness before test was not more than 0.3⁽¹⁾. In Fig.1, the line of $\xi_0=0.3$ is indicated by a broken line. Now examine the above-mentioned behavior that μ when $\overline{ER}_a\geq 0.51\mu\text{m}$ decreased after it became maximum. μ begins to decrease after ξ_0 becomes not more than 0.3 due to an increases of P and T_b . At $\overline{ER}_a=1.07\mu\text{m}$ where μ decreases considerably, ξ_0 at the final loading step is as small as 0.05. In this case, unlike in the case of other surface roughnesses, the decrease of surface roughness is enormous and a larger amount of oxygen is detected on the frictional surfaces. Therefore, it seems that the decrease of μ is due to a decrease of surface roughness during the operation and the effect of the oxidized film to prevent seizure from occurring.

Figure 5 shows the change in surface roughness between the values before and after tests. Generally, surface roughness more decreases when the specific film thickness for the roughness before test is not more than 0.3 than when the specific film

Table 2 Loading steps

Loading step	Load kN	Hertzian stress MPa	
		$l_z=5\text{ mm}$	$l_z=20\text{ mm}$
1	0.25	346	173
2	0.50	490	245
3	0.75	600	300
4	1.00	692	346
5	1.50	850	425
6	2.00	980	490
7	3.00	1200	600
8	4.00	1384	692
9	6.00	1700	850
10	8.00	1960	980
11	10.00	2190	1095
12	12.00	2400	1200

Fig.1 Bulk temperature of outer surface of cylinder T_b , coefficient of friction μ , and specific film thickness ξ_0

Fig.2 Bulk temperature of outer surface of cylinder T_b , coefficient of friction μ , and specific film thickness ξ_0

thickness is more than 0.3.

At $V_S=9.43\text{m/s}$, as shown in Fig.1(b), seizure occurred in boundary lubrication only at the maximum surface roughness of $\Sigma R_a=1.24\mu\text{m}$. In this case, a decrease of μ with an increase of load can be recognized when $\xi_0 \leq 0.3$. The values of P and T_b are nearly equal to those at $\Sigma R_a=0.12\mu\text{m}$. On the other hand, when $\Sigma R_a \leq 0.78\mu\text{m}$ at which $(\xi_0)_{DS}$ is more than 0.3, P and T_b at seizure occurrence tend to decrease as surface roughness increases. Judging from the results shown in Figs.3 and 4, when $(\xi_0)_{DS} > 0.3$, it seems that seizure occurs in the state of an oxidized film which is effective to prevent seizure from occurring⁽¹⁴⁾ being formed only at the tips of projections.

As shown in Fig.2, at $S_h=+78.2\%$, unlike the results at $S_h=+41.9\%$, regardless of surface roughness and sliding velocity, when seizure occurred, ξ_0 exceeded unity and the frictional surfaces were in a mixed or full

elastohydrodynamic lubrication. Generally, as the surface roughness increases, μ increases, and both P and T_b at seizure occurrence decrease. The decrease of surface roughness due to running-in was minor and an oxidized film was formed only locally.

The results for $l_z=20\text{mm}$ were nearly the same as the above-mentioned results for $l_z=5\text{mm}$. The results at $S_h=+58.9\%$ came in between those at $S_h=+41.9\%$ and at $S_h=+78.2\%$.

3.2 Effect of surface roughness on seizure limit

In this section, from the viewpoints of load, coefficient of friction, and temperature, the effect of surface roughness on the seizure limit of the non-additive gear oil is examined.

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

Figure 6 shows the effects of surface

(a) $V_S=3.14\text{ m/s}$

(b) $V_S=9.43\text{ m/s}$

$S_h=+41.9\%$, $l_z=5\text{ mm}$

Fig.3 Sectional curves in axial direction and metallographs in non-seizure regions of frictional surfaces (corresponding to Fig.1)

roughness on destructive seizure load P_{DS} , coefficient of friction μ_{DS} , and specific film thickness $(\xi_0)_{DS}$ just before destructive seizure. At $S_h=+41.9\%$, the experiments at $V_s=15.7\text{m/s}$ were not performed due to an excess over the permissible value of the rotating speed of the test rig. When seizure did not occur even at the load exceeding the permissible load of $12\text{kN}\{1220\text{kgf}\}$ or at the bulk temperature of outer surface of cylinder exceeding $600\text{K}\{327^\circ\text{C}\}$, the values at the end of a final loading step were indicated with a sign of + in the figure. In the following, the effect of surface roughness on the seizure limit of the non-additive gear oil is examined for each specific sliding.

At $S_h=+41.9\%$, the effects of the contact width in axial direction on P_{DS} , μ_{DS} , and $(\xi_0)_{DS}$ cannot be recognized regardless of sliding velocity. At $V_s=3.14\text{m/s}$, when $\Sigma R_a \geq 0.4\mu\text{m}$, seizure occurred in boundary lubrication because $(\xi_0)_{DS}$ was less than 0.3. Though the effects of surface roughness on P_{DS} and μ_{DS} cannot be recognized when $\Sigma R_a \leq 0.8\mu\text{m}$, seizure does not occur until higher loads; and coefficient of friction tends to decrease as surface roughness increases when $\Sigma R_a > 0.8\mu\text{m}$. This seems as mentioned in section 3.1 to be due to the effects of the oxidized film to prevent seizure from occurring and the decrease of surface roughness during the operation. On the other hand, at $V_s=9.43\text{m/s}$, though P_{DS} decreases and μ_{DS} increases as surface roughness increases when $\Sigma R_a \leq 0.3\mu\text{m}$, they are not affected by the surface roughness when $\Sigma R_a > 0.3\mu\text{m}$. This is due to the lubrication state of frictional surfaces. When $\Sigma R_a \approx 0.1\mu\text{m}$, judging from the value of $(\xi_0)_{DS}$ not being more than unity, seizure occurred at a smaller frequency of interference among

projections. In addition, at $V_s=9.43\text{m/s}$ where $(\xi_0)_{DS}$ is not much smaller than 0.3, the above-mentioned phenomena does not occur when surface roughness becomes larger. Here, from the viewpoints of permissible transmission power of a gear pair for scoring and transmission power loss, we should pay attention to the fact that P_{DS} does not decrease and μ_{DS} becomes smaller with an increase of sliding velocity when frictional surfaces are finished as fine as less than $0.1\mu\text{m}$ in ΣR_a .

Also at $S_h=+58.9\%$, as at $S_h=+41.9\%$, marked effects of contact width in axial direction on P_{DS} , μ_{DS} , and $(\xi_0)_{DS}$ cannot be recognized regardless of sliding velocity. As surface roughness increases, P_{DS} steeply decreases and μ_{DS} increases. But, when ΣR_a exceeds a certain value, P_{DS} and μ_{DS} are not affected by the surface roughness. When $V_s \geq 9.43\text{m/s}$, almost every $(\xi_0)_{DS}$ is more than unity and μ_{DS} decreases as sliding velocity increases. When $\Sigma R_a \approx 0.1\mu\text{m}$, similarly to the results at $S_h=+41.9\%$, P_{DS} is not affected by sliding velocity and μ_{DS} decreases as sliding velocity increases.

The results at $S_h=+78.2\%$ are in the same tendency as those at $S_h=+58.9\%$.

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

The temperature at seizure occurrence is examined considering the lubrication state of frictional surfaces. In the previous paper⁽¹⁾, the surface roughness of outer surface of cylinder in axial direction before test was in the range of 0.15 to $0.34\mu\text{m} R_a$, and the decrease of surface roughness through running-in could be ignored⁽¹⁾. But, as shown in Fig.5, in this experiment the decrease of surface roughness due to running-in cannot be ignored. Therefore, in this paper, when $(\xi_0)_{DS}$ for the roughness just before seizure is not more than 0.3, it is judged that seizure has occurred in boundary lubrication. Figure 7 shows the relation between $(\xi_0)_{DS}$ for the surface roughness before test and $(\xi_0)_{DS}$ for the surface roughness after test. When the surface roughness just before a destructive seizure was unknown, the lubrication state of frictional surfaces just

Fig.4 Line analyses for oxygen by XMA in the axial direction in the non-seizure regions of frictional surfaces (corresponding to Fig.3)

Fig.5 Change in surface roughness due to running-in

before a destructive seizure was estimated by this figure.

In this experiment, destructive seizures occurring in boundary lubrication were partially recognized both at $S_h=+41.9\%$ and at $S_h=+58.9\%$. In a gear pair, scoring is more likely to occur in the higher range of

specific slidings and the faster range of sliding velocities. Considering these facts, in the following, the results are examined only when seizure occurred in mixed or full elastohydrodynamic lubrication.

Figure 8 shows the effects of surface roughness on the bulk temperature of outer surface of cylinder $(T_b)_{DS}$ and the maximum contact surface temperature $(T_{cmax})_{DS}$ just before destructive seizure. $(T_b)_{DS}$ is taken as the temperature which corresponds to the higher value between the bulk temperatures of outer surfaces of both cylinders. In about 80 % of all results, the difference in bulk temperatures of both cylinders was not more than 15K. The maximum contact surface temperature was obtained using the equation, the heat source distribution, and the physical properties of the test cylinders shown in the previous papers (1), (11).

At $S_h=+41.9\%$, though $(T_b)_{DS}$ tends to decrease just a little as surface roughness increases when $\Sigma R_a \leq 0.3 \mu m$, it is almost constant regardless of surface roughness, sliding velocity, and the contact width in axial direction when $\Sigma R_a > 0.3 \mu m$. On the other hand, though $(T_{cmax})_{DS}$ is not affected by the surface roughness, it is significantly affected by sliding velocity and the contact width in axial direction.

At $S_h=+58.9\%$, in the higher range of sliding velocities $(T_b)_{DS}$ and $(T_{cmax})_{DS}$ steeply decrease as surface roughness increases. When $\Sigma R_a \geq 0.4 \mu m$, the effects of sliding velocity and the contact width in axial direction on $(T_b)_{DS}$ are very small in comparison with the effects of those on

(a) $S_h=+41.9\%$

(b) $S_h=+58.9\%$

(c) $S_h=+78.2\%$

Fig.6 Destructive seizure load P_{DS} , coefficient of friction μ_{DS} and specific film thickness $(\xi_o)_{DS}$ just before destructive seizure

$(T_{c\max})_{DS}$. Conversely, when $\Sigma R_a \approx 0.1 \mu\text{m}$, $(T_b)_{DS}$ is affected by both factors. The value of $(T_b)_{DS}$ is higher when sliding velocity is higher and the contact width in axial direction is wider. When $\Sigma R_a \approx 0.1 \mu\text{m}$, in both cases of $V_s = 3.14 \text{ m/s}$ and $V_s = 9.43 \text{ m/s}$, though P_{DS} shown in Fig.6(b) is not affected by the contact width in axial direction, $(T_b)_{DS}$ for $l_z = 20 \text{ mm}$ are not less than 70K higher than that for $l_z = 5 \text{ mm}$. This is due to the fact that, during the operation, the coefficient of friction gradually increased and shortly it began to rise sharply and meanwhile seizure occurred after it was over two times the value before it began to rise.

At $S_h = +78.2\%$, except that $(T_b)_{DS}$ at $V_s = 15.7 \text{ m/s}$ when $\Sigma R_a \approx 0.1 \mu\text{m}$ is higher than that at another sliding velocity, unlike the case

of $(T_{c\max})_{DS}$, $(T_b)_{DS}$ is not affected by sliding velocity and the contact width in axial direction. When $V_s \leq 9.43 \text{ m/s}$, though $(T_b)_{DS}$ when $\Sigma R_a \leq 0.5 \mu\text{m}$ is almost constant regardless of surface roughness, it decreases when ΣR_a is in the range of 0.5 to $0.7 \mu\text{m}$. At $V_s = 15.7 \text{ m/s}$, though not so remarkably as at $S_h = +58.9\%$, $(T_b)_{DS}$ decreases also as surface roughness increases.

As clarified in the above, the effect of surface roughness on the seizure limit of the

Fig.7 Relation between $(\xi_0)_{DS}$ for the roughness before test and $(\xi_0)_{DS}$ for the roughness after test

(b) $S_h = +58.9\%$

(a) $S_h = +41.9\%$

(c) $S_h = +78.2\%$

Fig.8 Bulk temperature of outer surface of cylinder $(T_b)_{DS}$ and maximum contact surface temperature $(T_{c\max})_{DS}$ just before destructive seizure (when $(\xi_0)_{DS}$ for the surface roughness before test is not more than 0.3)

non-additive gear oil becomes marked as specific sliding and sliding velocity increase. In the mixed or full elastohydrodynamic lubrication, it would be reasonably said that seizure occurrence has more intimate relation to the bulk temperature of outer surface of cylinder. Because this bulk temperature is little affected by sliding velocity and the contact width in axial direction at destructive seizure occurrence in comparison with the maximum contact surface temperature.

4. Conclusions

By two-cylinder tests, from the viewpoints of load, coefficient of friction, and temperature, the effect of surface roughness on the seizure limit of non-additive gear oil was examined under various specific slidings and sliding velocities. The results obtained are summarized as follows:

(1) In the lower range of specific slidings and the slower range of sliding velocities where seizure occurs in boundary lubrication, the seizure limit is not affected by surface roughness or rather it increases as surface roughness increases due to the decrease of surface roughness during operation and the effect of oxidized film to prevent seizure from occurring.

(2) On the other hand, in the higher range of specific slidings where seizure tends to occur in mixed or full elastohydrodynamic lubrication, the seizure limit decreases as surface roughness increases. Particularly, the tendency is marked in higher sliding velocity range.

(3) In order to increase the seizure limit in the higher range of specific slidings and the faster range of sliding velocities where seizure occurs easily and to decrease the frictional power loss, finishing the surface roughness so fine that the sum of center line average roughness of contacting

bodies is not more than $0.1\mu\text{m}$ is a very effective means.

(4) Seizure occurrence in mixed or full elastohydrodynamic lubrication has more intimate relation to the bulk temperature of outer surface of cylinder in comparison with the maximum contact surface temperature.

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