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Study on the Scoring Resistance of Lubricating Oil in Four Ball Test*

(3rd Report, Effects of Bulk Oil Temperature and Sliding Velocity in the Test Method according to JIS)

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In this paper, effects of bulk oil temperature and sliding velocity on the scoring phenomena of non-EP mineral oils were examined by a Shell type Four Ball Machine under the conditions that new steel balls were used for each load step and the machine was operated in 60 seconds after loading. The results obtained are summarized as follows:

(1) Lubrication state of contact surface at last non-seizure load and the process of scoring at initial seizure load are affected by bulk oil temperature and in higher sliding velocity range, it is difficult to evaluate the scoring resistance of boundary lubricating film. Therefore, in the evaluation of scoring resistance of lubricating oil, attention must be paid to these points.

(2) There is a correlation between the scoring resistance of boundary lubricating film and the maximum contact surface temperature except in the region of lower sliding velocity.

1. Introduction

There are many papers which examined the relation between the scoring resistance of lubricating oil and bulk oil temperature or contact surface temperature by Four Ball Machine^{(1)~(6)}. By the way, in those papers studying the relation between the scoring resistance of lubricating oil and contact surface temperature under high-speed operation^{(1)~(4), (6)}, the effects of bulk oil temperature, sliding velocity, etc. on the lubrication state of contact surface and the process of scoring have not been considered enough. Unlike in low-speed operation such as 1 rpm, in high-speed operation, which is used generally as standard, high temperature rise on contact surface can be easily obtained by frictional heat, but, on the other hand, it is conceivable that the scoring resistance of lubricating oil is affected by oil film formation.

In this paper, using the method of shock-load test of operating time of 60 seconds which is referred to in JIS K2519, the effects of bulk oil temperature and sliding velocity on scoring resistance, coefficient of friction, lubrication state of contact surface and the process of scoring are clarified for lubricating oils without EP additives. And moreover, the relation between the scoring resistance of lubricating oil and the maximum contact surface temperature is examined.

2. Experiments

2.1 Testing machine and lubricating oil

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In the experiments a Shell type Four Ball Machine was used. Test steel ball with diameter 12.7 mm (=1/2 in.) was made of high carbon chromium bearing steel SUJ2, its surface hardness was 62 to 63 H_{RC} , retained austenite content at the surface was 13.2 to 15.6 percent, and surface roughness was 0.02 to 0.04 μR_{max} . As lubricating oils, #90 base gear oil and #200 turbine oil were used. Table 1 shows their properties. In both lubricating oils, EP additives were not contained.

2.2 Operating method and judgement of scoring

Steel balls which had been dried after being thoroughly washed with petroleum benzene were used and were lubricated in oil bath of 12 ml of oil. In this case all the surface of stationary steel ball and about 60 percent of the surface of rotating steel ball were submerged in lubricating oil. Experiments were made in the range of sliding velocities v , from 13 to 119 cm/s (from 350 to 3100 rpm in axial rotating speed) for each of the three bulk oil temperatures of 20, 50 and 80°C, and the effects of bulk oil temperature and sliding velocity on scoring resistance, coefficient of friction, lubrication state of contact surface and the process of scoring were examined. Lubricating oil was heated by a band-heater fitted around the oil pot in the state that stationary and rotating steel balls were con-

Table 1 Properties of lubricating oils

Items		#90 base gear oil	#200 turbine oil
Kinematic viscosity cSt	37.8°C	226.7	91.4
	98.9°C	18.4	9.72
Viscosity index		97.0	92.0
Specific weight 15/4°C		0.890 8	0.886 5
Flash point °C		278.0	240.0
Pour point °C		-12.5	-22.5
Sulphur %		0.58	0.1

tacted slightly with one another. And after bulk oil temperature which was measured by chromel-alumel thermocouple of diameter 0.3 mm fixed at the point surrounded by three stationary steel balls and one rotating steel ball as shown in Fig.1 reached the range of ± 1 deg. for a desired temperature, the axial load was applied by oil pressure equipment and the machine was operated for 60 seconds at constant rotating speed, and during the operation the band-heater was switched on. Steel balls and lubricating oil were changed with new ones for each load, and experiments were repeated with the axial load increased by 5 kg until a scoring occurred within 60 seconds. Coefficient of friction can be obtained by the angle of torsion of a torsion bar, but in this experiment it was calculated using the deflection of a thin cantilever plate shown in Fig.2 because at low load the angle of torsion was too small to obtain the value accurately. Wear scars of three stationary steel balls were measured by a reading microscope to the limit of 0.01 mm in the sliding direction and wear scar diameter was obtained by their arithmetical average.

Occurrence of scoring is determined by

Fig.1 Position of thermocouples for oil temperature measurements

Fig.2 Thin cantilever equipment for measurements of coefficient of friction

a sudden increase in friction torque in operation, and the maximum axial load at which a scoring does not occur in 60 seconds operation is called the last non-seizure load (LNSL) and a 5 kg higher load than that is called the initial seizure load (ISL). In these tests, experiments were made twice at LNSL and it was confirmed that a scoring did not occur.

2.3 Measurement of contact potential

In order to know the state of oil film formation in operation the contact potential was measured by using the electrical circuit shown in Fig.3. Contact potential when contact surfaces were separated by oil film (this is simply called OFF) was adjusted to 0.1 volt by a variable resistance R_1 . Even in partial metallic contact, the contact potential becomes 0 volt (this is simply called ON). In this case the total current through metallic contact surfaces was controlled to 0.1 mA by a variable resistance R_2 .

Fig.3 Electrical circuit for contact potential measurements

Fig.4 Last non-seizure load and coefficient of friction

3. Experimental results and discussion

In two experiments at *LNSL*, about five percent deviations occurred in coefficient of friction and wear scar diameter, and variation in maximum contact surface temperature was about 2 to 10 deg. But, the amount was small in each case, and there was no clear difference in the lubrication state of contact surface; therefore, after this, only initial experimental results are shown.

3.1 Last non-seizure load (*LNSL*)

Fig.4 shows *LNSL* and its coefficient of friction at 60 seconds. In both lubricating oils, in the lower sliding velocity range of $v_s \geq 69$ cm/s *LNSL* suddenly decreases with an increase in sliding velocity, but in higher sliding velocity range the effect of sliding velocity on *LNSL* becomes small. *LNSL* decreases with an increase in bulk oil temperature. In the range of $v_s \leq 46$ cm/s, coefficient of friction is not so much affected by bulk oil temperature and sliding velocity,

but in the range of $v_s \geq 69$ cm/s there is a tendency that coefficient of friction becomes smaller as bulk oil temperature becomes lower and as sliding velocity becomes higher. As shown in the next section, this is closely connected with the lubrication state of contact surface.

Fig.5 shows wear scar diameters at *LNSL*. At *LNSL* less than 35 kg, there are some cases that wear scar diameter is nearly equal to

Fig.5 Wear scar diameters at *LNSL*

Fig.6 Contact surfaces of stationary steel balls at *LNSL*

Hertzian elastic contact circle diameter, but generally wear scar diameter is somewhat larger than Hertzian elastic contact circle diameter and is not influenced by lubricating oil and bulk oil temperature.

3.2 Contact surface and contact potential

Fig.6 shows contact surfaces of stationary steel balls at *LNSL*. Fig.6 (a) shows the case of #90 base gear oil, and (b) the case of #200 turbine oil. Fig.7 shows one of the examples of the changes in coefficient of friction and contact potential with time at *LNSL* when bulk oil temperature of #90 base gear oil was 20°C. In the case of (a), contact potential is always 0 volt because of metallic contact under the conditions of lower sliding velocity and of higher axial load. And as shown in Fig.6 there are marks of scratching seen all over the contact surface. From these photographs, in these cases it is recognized that contact surfaces were under boundary lubrication. Frictional force in-

creased gradually after 3 seconds, reached a maximum at 5 seconds, decreased and became constant in 30 seconds. Coefficient of friction at 5 seconds was 0.103 and at 60 seconds it was 0.094. In comparison with those in the case of (a), in the case of (b), because of the conditions of higher sliding velocity and of lighter axial load, contact potential began to rise at about 8 seconds, reached a maximum at 43 seconds and fell again to 0 volt at 53 seconds. Frictional force rose slightly till 8 seconds after 1 second elapsed, after that it was nearly constant till 50 seconds and coefficient of friction was as small as 0.075, but in response to the contact potential falling to 0 volt the frictional force began to rise and the coefficient of friction reached 0.080 at 60 seconds. From Fig.6, it is recognized that in this case although there are dark places in the upper part of contact surface, marks of scratching are few and an oil film is formed. In the case of (c) of higher sliding velocity, by oil film formation the contact potential did not fall to 0 volt during 60 seconds operation. This is reflected on the state of contact surface. Frictional force little changed during operation, and coefficient of friction was 0.068 which was smaller than that in the case of (b).

Table 2 shows the contact state at *LNSL* corresponding to Fig.6. In the table, mark ON means that contact potential was 0 volt throughout operation, mark (ON-OFF)→ON means that during operation the contact potential fell to 0 volt, and mark (ON-OFF) means that the contact potential did not fall to 0 volt even at the end of 60 seconds test. In both lubricating oils, without regard to bulk oil temperatures, in the range of $v_s \leq 46$ cm/s, contact state is always ON and in Fig.6 marks of scratching are found almost all over the contact surface. Therefore, it is recognized that in this range the contact surface was in state of boundary lubrication. On the other hand, in the range of $v_s \geq 69$ cm/s, the contact state is influenced by bulk oil temperature and sliding velocity, and generally the lower the bulk oil temperature is and the higher the sliding velocity is, the less becomes the probability that the contact state changes from (ON-OFF) to ON. Here, in the range of $v_s \geq 69$ cm/s, the relation among the contact state, the state of contact surface in Fig.6 and the coefficient of friction in Fig.4 is examined. In #90 base gear oil, when the contact state did not become ON even after 60 seconds, marks of scratching are less on contact surface, the coefficient of friction is smaller, and from these it is recognized that the contact surfaces were in the state of good lubrication. In the case of bulk oil temperature=50°C and $v_s=69$ cm/s

(a) $v_s=13$ cm/s ($n=350$ rpm), $LNSL=125$ kg

(b) $v_s=69$ cm/s ($n=1800$ rpm), $LNSL=35$ kg

(c) $v_s=119$ cm/s ($n=3100$ rpm), $LNSL=30$ kg

Fig.7 Changes of frictional force and contact potential with time at *LNSL* (#90 base gear oil, bulk oil temperature=20°C)

Table 2 Contact state at *LNSL*

Lubricating oil		#90 base gear oil						#200 turbine oil					
Sliding velocity cm/s		13	31	46	69	92	119	13	31	46	69	92	119
Rotating speed rpm		350	800	1200	1800	2400	3100	350	800	1200	1800	2400	3100
Bulk oil temperature °C	20	ON	ON	ON	(ON-OFF) →ON† (54S)	(ON-OFF) →ON (50S)	(ON-OFF)	ON	ON	ON	(ON-OFF) →ON (51S)	(ON-OFF)	(ON-OFF)
	50	ON	ON	ON	(ON-OFF) →ON (30S)	(ON-OFF)	(ON-OFF) →ON (45S)	ON	ON	ON	(ON-OFF) →ON (12S)	(ON-OFF) →ON (42S)	(ON-OFF)
	80	ON	ON	ON	ON	ON	(ON-OFF) →ON (43S)	ON	ON	ON	ON	(ON-OFF) →ON (33S)	(ON-OFF)

† The value in parentheses denotes the time when contact state became ON.

where the time required to change the contact state from (ON-OFF) to ON was 30 seconds and was shorter than that of other case, a large wear scar is observed on the lower half of the contact surface, and because of this the coefficient of friction is larger. Unlike in #90 base gear oil, in #200 turbine oil, in higher sliding velocity range where the contact state was (ON-OFF), there were also many black strips and spots on the contact surface. This black material seems to be an insulated oxidized film, and therefore, in cooperation with oil film formation, the contact state was somewhat better than that in #90 base gear oil with higher viscosity. But, there is the same relation among the contact state, the state of contact surface and the coefficient of friction in #90 base gear oil.

3.3 Process of scoring

In section 3.2, the effects of bulk oil temperature and sliding velocity on the lubrication state of contact surface and coefficient of friction at *LNSL* were examined. In this section, it is made clear that the process of scoring at *ISL* is influenced by bulk oil temperature and sliding velocity, and it has intimate relation to the lubrication state of contact surface.

Figs.8,9 and 10 show the results of #90 base gear oil at 20°C of bulk oil temperature. Fig.8 shows the results for $v_s=13$ cm/s and *ISL*=130 kg. Photographs of contact surfaces correspond to the signs in the diagram of frictional force. Frictional force began to rise at 2 seconds and a scoring occurred at 5 seconds. Contact potential was always 0 volt throughout operation. At A there are wear scars of scratching on a fairly large portion of contact surface, and at B just before a scoring wear scars of scratching are observed almost all over the contact surface. Fig.9 shows the results for $v_s=69$ cm/s and *ISL*=40 kg. As known from Bulk oil temperature=20°C, $v_s=13$ cm/s ($n=350$ rpm), *ISL*=130 kg

and a fairly large part of contact surface is separated by oil film. Frictional force began to rise at 31 seconds when contact potential fell to 0 volt, and it is supposed that there was a transition from hydrodynamic to boundary lubrication. After 6 seconds after that, a scoring occurred. Unlike the contact surface at *LNSL* in Fig.6, as seen from photograph C almost all the contact surface before scoring was in the state of

$\mu=0.091$
A

$\mu=0.104$
B

$\mu=0.137$
C

Fig.8 Process of scoring in the case of #90 base gear oil (Part 1)

$\mu=0.079$
A

$\mu=0.081$
B

$\mu=0.094$
C

$\mu=0.113$
D

Bulk oil temperature=20°C, $v_s=69$ cm/s ($n=1800$ rpm), *ISL*=40 kg

Fig.9 Process of scoring in the case of #90 base gear oil (Part 2)

boundary lubrication and there is a mark of seizure in the lower part of the surface. Fig.10 shows the result for $v_s=119$ cm/s and $ISL=35$ kg. Frictional force began to rise at 11 seconds when contact potential became 0 volt. But even at B just before a scoring, more than half part of the contact surface was separated by oil film and coefficient of friction was as small as 0.069, and a scoring occurred with metallic sound and as the result wear scar diameter became larger than 2 mm. Fig.11 shows the result of #90 base gear oil for bulk oil temperature of 80°C , sliding velocity of 119 cm/s and ISL of 120 kg. From this figure, it is recognized that at higher sliding velocity the phenomenon of scoring was influenced by bulk oil temperature. In higher bulk oil temperature, as known from the change of frictional force, a shift to boundary lubrication began at 28 seconds and a scoring occurred after 10 seconds after that without metallic sound. Wear scar after a scoring was not so large as that at 20°C of bulk oil temperature. At C just before scoring, wear scar got out of circular shape, coefficient of friction and wear scar diameter were larger than the values at A and B. Contact potential, which was not shown in the figure, was 0 volt throughout operation and coefficient of friction was 0.08 to 0.085, which was larger than the value of 0.064 to 0.069 at 20°C of bulk oil temperature. Besides the process of scoring for sliding velocities of 13 cm/s and 69 cm/s and bulk oil temperature of 80°C was nearly the same as that at 20°C .

Here, the characteristics of scoring process with sliding velocity at ISL obtained in this experiment are summarized as follows, including the results of #200 turbine oil.

In the range of $v_s \leq 31$ cm/s, contact surface was always in boundary lubrication and a scoring occurred within 1.5 to 6 seconds. In the range of $v_s=46 \sim 69$ cm/s, a scoring occurred in the interval of 11 to 37 seconds after lasting boundary lubrication. In the range of $v_s \geq 92$ cm/s, at lower bulk oil temperature a scoring occurred suddenly

with metallic sound from the state that an oil film was formed over a large portion of contact surface and coefficient of friction was small, but at higher bulk oil temperature a scoring occurred through the same process as that at $v_s=46 \sim 69$ cm/s.

3.4 Relation between steel ball temperature and bulk oil temperature

Maximum contact surface temperature which takes account of bulk temperature rise in steel balls in operation can be given by the following equation ⁽⁷⁾.

Bulk oil temperature = 20°C , $v_s=119$ cm/s ($n=3100$ rpm), $ISL=35$ kg

Fig.10 Process of scoring in the case of #90 base gear oil (Part 3)

Bulk oil temperature = 80°C , $v_s=119$ cm/s ($n=3100$ rpm), $ISL=20$ kg

Fig.11 Process of scoring in the case of #90 base gear oil (Part 4)

$$T_{cmax} = T_{fmaxs} + T_{bs} + T_{0s} = T_{fmaxr} + T_{br} + T_{0r}$$

where, T_{fmax} is maximum flash temperature, T_b is bulk temperature rise in steel ball, T_0 is initial temperature of steel ball, and subscripts s and r refer to the values of stationary and rotating steel balls, respectively. For bulk oil temperature being nearly equal to room temperature, initial temperatures of both stationary and rotating steel balls can be assumed to be equal to bulk oil temperature. But for the reasons that the rotating steel ball is partially submerged in lubricating oil, the lubricating oil which is contained in oil pot is heated only by the oil pot heater, the rotating steel ball is fitted to the rotating shaft with a large heat capacity, etc., when the lubricating oil is heated at high temperature such as 50°C or 80°C it seems that initial temperature of rotating steel ball becomes lower than bulk oil temperature. Table 3 shows the test results of #90 base gear oil. Initial temperatures of rotating steel ball are considerably lower than bulk oil temperatures. This was also true in #200 turbine oil. Quantity of oil and heating method were the same as shown in section 2.2. Temperature of steel ball was measured at the same position as in the second report⁽⁷⁾. Besides, it became clear from the temperature measurement of rotating steel ball at the surface submerged in lubricating oil that the temperatures were only several degrees higher than the values in Table 3. Therefore, there is no trouble in approximating the initial temperature of the whole rotating steel ball, which is partially submerged in lubricating oil, by the values in Table 3. The effect of axial load on initial temperatures of steel balls is small as shown in Table 3. In Table 3, temperature of stationary steel ball is slightly higher than bulk oil temperature. This is because the oil temperature measured at the position of central thermocouple in Fig.1 where heat was easily transferred to the rotating steel ball with lower temperature was set at a desired bulk oil temperature. Besides, there was no difference between the oil temperature in neighborhood of side wall in Fig.1 and the temperature of stationary steel ball.

The above was the relation between the temperature of steel ball before operation and bulk oil temperature. But the initial temperature of rotating steel ball becomes lower than bulk oil temperature, which is higher than room temperature, bulk temperature of steel ball seems to be also increas-

Table 3 Relation between the temperatures of steel balls before operation and bulk oil temperature (#90 base gear oil, room temperature=20°C)

Bulk oil temperature °C	50			80		
	Axial load kg	0	20	100	0	20
Temperature of stationary steel ball °C	51.0	50.9	50.7	83.0	82.5	82.5
Temperature of rotating steel ball °C	28.5	29.0	29.0	40.0	41.0	42.4

ed by the improvement of heat transfer from lubricating oil under operation in addition to frictional heat. Fig.12 shows the experimental results of the temperature rise in steel ball from initial temperature for #90 base gear oil when the machine was operated under the condition that stationary and rotating steel balls were contacted slightly with one another. At 80°C of bulk oil temperature the temperature rise in the rotating steel ball was larger compared with those at 50°C and it was beyond 10 deg. at 120 seconds when the operating condition reached nearly steady state. In both bulk oil temperatures, bulk temperature rise in the rotating steel ball did not always increase with an increase in sliding velocity. Next, in #200 turbine oil with lower viscosity in comparison with #90 base gear oil, the temperature rise in the rotating steel ball was higher than that in #90 base gear oil. At 50°C of bulk oil temperature, it was 4 to 11 deg., and at 80°C it was 10 to 21 deg. The effect of sliding velocity on the temperature rise was the same as that in #90 base gear oil. Besides, in stationary steel ball, during operation the bulk temperature decreased because heat was transferred to the rotating steel ball, but in both lubricating oils the drop in bulk temperature of the steel balls was as small as within 1 deg.

3.5 Calculation method of contact surface temperature

In the second report, the equation of contact surface temperature was shown and by experiments its applicability was verified. But experiments were only made in the condition that initial temperature of steel ball was equal to room temperature. Therefore, it is necessary to confirm whether the equation is also applicable for higher bulk oil temperatures. Experiments were made at 80°C of bulk oil temperature where the difference in initial temperatures between stationary and rotating steel balls was large. Lubricating oil and experimental method were the same as used in the second report, but this time the axial load was so selected as to be nearly equal to ISL of #90 base gear oil. In calculation, in addition to the difference in initial temperature between the steel balls, the bulk temperature rise in the rotating

Fig.12 Bulk temperature rise in rotating steel ball under operation (#90 base gear oil, no axial load)

steel ball and the bulk temperature drop in the stationary steel ball with time when the axial load was not supplied were considered, too. Strictly speaking, dimensionless coefficients of relative heat transfer $\bar{h}_s$, $\bar{h}_r$ at steel ball surfaces and coefficients x_s , x_r concerning the heat transfer to ball fixtures must be determined for each bulk oil temperature, but in this paper the values in the second report were used for convenience.

Fig.13 shows one of the examples of the results. Experimental and calculated values of bulk temperatures of steel balls are in good agreement with each other. This was the same as at other sliding velocities.

Fig.13 Comparison with experimental bulk temperatures of steel balls and calculated ones (Bulk oil temperature = 80°C)

Therefore, also for bulk oil temperatures higher than room temperature, maximum contact surface temperature can be obtained by applying the equation in the second report. The values of $\bar{h}_s$, $\bar{h}_r$, x_s and x_r for lubricating oils shown in Table 1 are obtained by the following experimental equations.

For #90 base gear oil:

$$\bar{h}_s = -2 \times 10^{-5} v_s + 0.032$$

$$\bar{h}_r = 1.3 \times 10^{-4} v_s + 0.031$$

For #200 turbine oil:

$$\bar{h}_s = 2 \times 10^{-5} v_s + 0.034$$

$$\bar{h}_r = 1.8 \times 10^{-4} v_s + 0.042$$

For both lubricating oils:

$$x_s = 0.0015 v_s + 0.50$$

$$x_r = 4.8 \bar{h}_r + 0.12$$

In the above equations the unit of sliding velocity is cm/s.

By the way, the equation of maximum contact surface temperature given in the second report is for the state of boundary lubrication or metallic contact. But the equation is also applicable to the case where oil film is formed over contact surface because in other experiments the experimental values of bulk temperature rise in steel balls agreed quite well with the calculated values.

3.6 Maximum contact surface temperature

Fig.14 shows the maximum contact surface temperature at $LNSL$, $(T_{c\max})_{LNSL}$. Physical properties of steel ball used in calculation were the same as in the second report. In #90 base gear oil, without regard to bulk oil temperature, in the range of $v_s = 13 \sim 31 \text{ cm/s}$ $(T_{c\max})_{LNSL}$ suddenly increases with an increase in sliding velocity, but in the range of $v_s \geq 69 \text{ cm/s}$ the effect of sliding velocity on $(T_{c\max})_{LNSL}$ differs by bulk oil temperature. At 20°C and 50°C of bulk oil temperatures, in the range of $v_s = 46 \sim 69 \text{ cm/s}$ $(T_{c\max})_{LNSL}$ decreases at 25 deg. and beyond

Fig.14 Maximum contact surface temperature $(T_{c\max})_{LNSL}$ at $LNSL$

Table 4 Maximum contact surface temperature $(T_{cmax})_{ISL}$ at ISL just before scoring

Lubricating oil	#90 base gear oil						#200 turbine oil					
Bulk oil temperature °C	20			80			20			80		
Sliding velocity cm/s	13	69	119	13	69	119	13	69	119	13	69	119
Rotating speed rpm	350	1 800	3 100	350	1 800	3 100	350	1 800	3 100	350	1 800	3 100
ISL kg	130	40	35	80	30	20	115	35	30	70	25	15
$(T_{cmax})_{ISL}$ °C $\mu_{ISL} \uparrow$	122 0.104	181 0.094	180 0.069	124 0.098	185 0.099	188 0.085	104 0.097	169 0.098	181 0.073	126 0.109	184 0.099	182 0.089

† Coefficient of friction at ISL just before scoring.

the range $(T_{cmax})_{LNSL}$ gradually increases with an increase in sliding velocity. On the other hand, at 80°C of bulk oil temperature, in the range of $v_s=31\sim 92$ cm/s $(T_{cmax})_{LNSL}$ is nearly constant. These are closely connected with the fact that as clarified in section 3.2 the effects of bulk oil temperature and sliding velocity on lubrication state of contact surface and coefficient of friction differ beyond the boundary of $v_s=46\sim 69$ cm/s. In evaluation of scoring resistance of lubricating oil, lubrication state of contact surface must be noted. Next in #200 turbine oil, there was the same tendency as that in #90 base gear oil.

Table 4 shows the maximum contact surface temperature at ISL just before a scoring, $(T_{cmax})_{ISL}$. Here, the relation between the scoring resistance of lubricating oil in boundary lubrication and $(T_{cmax})_{ISL}$ is examined except for the case in both lubricating oils where a scoring occurred suddenly with metallic sound in the state that oil film was formed over contact surface and coefficient of friction was small. First the effect of bulk oil temperature on $(T_{cmax})_{ISL}$ is investigated. In #90 base gear oil, $(T_{cmax})_{ISL}$ at 80°C of bulk oil temperature is 2 deg. at $v_s=13$ cm/s and is 4 deg. at $v_s=69$ cm/s, respectively higher than the values at 20°C of bulk oil temperature. Meanwhile in #200 turbine oil, there is some difference in $(T_{cmax})_{ISL}$. Namely, $(T_{cmax})_{ISL}$ at 80°C of bulk oil temperature is 22 deg. at $v_s=13$ cm/s and is 15 deg. at $v_s=69$ cm/s, respectively higher than the values at 20°C of bulk oil temperature. But in comparison with 60 deg. difference in bulk oil temperature, it can be seen that in this experiment the effect of bulk oil temperature on $(T_{cmax})_{ISL}$ is small. Next, the effect of sliding velocity on $(T_{cmax})_{ISL}$ is examined in consideration of the difference in bulk oil temperature. The difference in $(T_{cmax})_{ISL}$ between the values at $v_s=13$ cm/s and the values beyond that sliding velocity is large. And in #90 base gear oil it is from 57 to 66 deg., and in #200 turbine oil it is from 43 to 80 deg. On the other hand, the difference between the values at $v_s=69$ cm/s and at $v_s=119$ cm/s is small. In #90 base gear oil it is from 3 to 7 deg., and in #200 turbine oil it is from 2 to 15 deg. From the above, it seems that in higher sliding velocity range there is a relation between the failure of boundary lubricating film and the maximum contact surface temperature. Further, in lower sliding velocity range, scoring resistance of lubricating oil can not be evaluated only by the maximum contact surface temperature and it is influenced by the mechanical

strength of boundary lubricating film.

4. Conclusions

In this paper, seizure phenomena of non-EP mineral oils were examined by shock-load test under the conditions that new steel balls were used in each load step and operating time was 60 seconds. The results obtained are summarized as follows:

(1) Lubrication state of contact surface at last non-seizure load and the process of scoring at initial seizure load are affected by bulk oil temperature and sliding velocity. Therefore, in the evaluation of scoring resistance of lubricating oil, attention must be paid to these points.

(2) At lower bulk oil temperature and in higher sliding velocity range it is difficult to evaluate the scoring resistance of boundary lubricating film because in these conditions oil film can be formed easily and a scoring does not occur after lasting boundary lubrication all over the contact surface.

(3) In calculation of the maximum contact surface temperature at higher bulk oil temperature than room temperature, initial temperature difference between stationary and rotating steel balls and moreover the changes of bulk temperatures of steel balls with time when axial load is not supplied must be considered.

(4) Thermal strength of boundary lubricating film has a relation with the maximum contact surface temperature except in the region of lower sliding velocity where scoring resistance of lubricating oil is affected by the mechanical strength of boundary lubricating film.

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