after passing a certain time from the start. The revolutionary speed of the roller is always in good agreement with the conventional theory in these tests.

(2) In case of a comparatively large radial clearance, the roller in the unloaded zone travels, being guided by the raceway of the outer race and retainer pocket, and continues to decrease its rotational speed until coming into the loaded zone. The value of $\log_{10} \omega/\omega_0$ will decrease proportionally to the roller position, but when the number of revolution is low a sudden deceleration occurs at the roller position of $180^\circ \sim 360^\circ$. The rotational speed of the roller in the loaded zone is always in good agreement with the conventional theory. In case of a small or negative radial clearance there is no slip at any roller position.

(3) The value of $(\omega/\omega_0)_{t=2\pi/\omega_0}$ is expressed by the empirical formula (24) and the theoretical formula (18) or (20). By comparing these formulas

the more detailed behaviour of the roller will be investigated.

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Determination of Load Carrying Capacity of Lubricating Oil by I. A. E. Type Gear-Lubricant Testing Machine*

By Mitsuru TOYOGUCHI** and Yoshiro TAKAI**

In this article, effect of E.P. additives on the load carrying capacity by I.A.E. type machine, was discussed and compared with results obtained by Timken and Soda four ball machine. Then commercial mild E.P. and E.P. type gear oils in Japan were tested by these testers.

It was found that it was possible to use I.A.E. type machine for evaluation of load carrying capacity of mild E.P. type gear oil but not for E.P. type one.

Introduction

Test equipments such as Timken, Falex, Almen, SAE Four-Ball Lubricant Tester and others of this type are widely employed for the evaluation of load-carrying capacity of gear oils. These devices are simplified to produce a motion simulating a frictional condition in practice of gear lubrication and have the advantages of easy test procedure and a little expense, but it is now widely recognized that because of the lack of correlation with field performance characteristics and among

various lubricant test equipments, evaluation of load carrying ability of gear oils should be done by a full scale test⁽¹⁾.

The present paper gives a summary of investigations into the effect of some E.P. additives and load-carrying ability of commercial E.P. and mild E.P. type gear oils.

These investigations were made in the I. A. E. type gear-lubricant testing machine^{(2)~(4)}, and the results were compared with those of the Timken tester and Soda four-ball lubricant tester⁽⁵⁾.

Test Procedure

Apparatus

The testing machine is of the power-circulating

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** Research Fellow, Research Laboratory of Mitsubishi Oil Co., Ltd., Kawasaki.

type in which two pairs of gears are of spur type with fifteen teeth for driver and sixteen teeth for driven gear, their dimensions being same as those of the I. A. E. testing machine. Appearance and ground-plan of the testing machine are shown in Fig. 1 and 2. The load used in the run was applied by an oil pressure system.

Procedure

The test condition used is as shown in Table 1.

Test Oils

The physical properties of the SAE 90 solvent refined mineral oil, commercial mild E. P. and E. P. oils used in this investigation are given in Table 2.

Test results and discussion

Effect of lubricants containing E. P. additives

A number of oils containing additives of various kinds, including proprietary ones, have been tested by the I. A. E. type gear-lubricant testing machine and also for comparison by the Timken machine and Soda four-ball tester.

The results obtained are summarized in Table

Fig. 1 I.A.E. type gear lubricant testing machine

3.

Fig. 3 shows the results of the effect of adding various concentrations, ranging from 1.5 to 3 per cent of each of three additives to an SAE 90 solvent refined mineral oil obtained on the I. A. E. type gear-lubricant testing machine.

It will be seen that response of an SAE 90 solvent refined mineral oil to varying concentration of chlorinated paraffin and dibenzyl disulfide (DBDS) is superior to that of tricresyl phosphate (TCP).

Table 1 Test condition

	This experiment	I. P. (6)
Drive gear speed	2 000 r.p.m.	2 000 r.p.m.
Test oil temperature	60°C	60°C
Test lubricant	2.5 lit.	1 I.G. (4.44 lit.)
Test oil flow	300 cc/min	1/2 pint/min (280 cc)
Nozzle dia.	0.8 mm	1/32 inch
Loading method	Oil pressure	Weight on 18 inch lower end
Initial load	10 lbs. (eq. 18 inch lever end)	10 lbs
Load increment	5 lbs. (eq. 18 inch lever end)	5 lbs
Test period	5 min	5 min
Rest period	5 min	5 min

Table 2 Properties of gear oils

	$S_p.G_r.$ 20/4°C	Viscosity c.s. @100°F @210°F		V.I.
SAE 90 Base oil	0.907 0	240.5	18.08	88
Mild E.P. A	0.909 2	239.1	17.72	86
" B	0.910 3	242.6	17.90	87
" C	0.891 9	301.2	22.60	110
E.P. A	0.917 0	231.0	17.96	92
" B	0.911 8	194.5	16.05	92
" C	0.914 8	191.9	16.07	94

Fig. 2 Plan of I.A.E. type gear lubricant testing machine

Table 3 Load carrying capacity with the I.A.E. type gear lubricant testing machine
Soda four-ball tester and Timken lubricants testing machine (Base Oil SAE 90)

Additives	Dosage %	I.A.E. Type		Timken		Soda four-ball			
		OK load lbs	Rating	OK load lbs	Rating	200 r.p.m. (continuous loading)		750 r.p.m. (shock loading)	
						OK load kg/cm ²	Rating	OK load kg/cm ²	Rating
— (Base Oil)	0	70	1.0	16	1.0	4.0	1.0	3.0	1.0
Chlorinated Paraffin	1.5	140	2.0	22	1.4	5.5	1.4	3.0	1.0
"	3.0	160	2.3	30	1.9	6.5	1.6	3.5	1.2
DBDS	1.5	145	2.1	40	2.5	4.5	1.1	3.5	1.2
"	3.0	165	2.4	45	2.8	5.0	1.3	4.0	1.3
TCP	1.5	80	1.1	16	1.0	4.5	1.1	3.0	1.0
"	3.0	115	1.6	16	1.0	6.5	1.6	3.5	1.2

Fig. 4 shows the results of the effect of adding various concentrations, ranging from 1.5 to 3 per cent of each of three additives to an SAE 90 solvent refined mineral oil obtained on the Timken machine.

It will be seen that response of an SAE 90 solvent refined mineral oil to varying concentration of dibenzyl disulfide is superior to that of chlorinated paraffin.

Dibenzyl disulfide had marked effect for improving the load-carrying ability of oil in particular for the Timken machine, but tricresyl phosphate had no influence for improving the load-carrying ability of oil with increase in the concentration within the range of this experiment.

It is not clear at present why tricresyl phosphate has no influence for improving the load-carrying ability of oil. Figs. 5 and 6 show the results of the effect of adding various concentrations, ranging from 1.5 to 3 per cent of each of three additives to an SAE 90 solvent refined mineral oil obtained on the Soda four-ball tester under the condition of 200 r.p.m. (continuous loading) and

750 r.p.m. (shock loading) respectively.

As illustrated by Fig. 5, it will be seen that response of an SAE 90 solvent refined mineral oil to varying concentration of chlorinated paraffin is superior to those of dibenzyl disulfide and tricresyl phosphate.

But the effects of chlorinated paraffin and dibenzyl disulfide with the Soda four-ball tester were in reverse compared with the I. A. E. type gear-lubricant testing machine and Timken machine.

On the other hand, a sample of oil containing

Fig. 3 Effect of EP additives with I.A.E. type gear lubricant testing machine

Fig. 4 Effect of EP additives with Timken machine

Fig. 5 Effect of EP additives with Soda four-ball lubricant tester (200 r.p.m.)

1.5 and 3.0 per cent tricresyl phosphate gave a rating of 1.1 and 1.5 respectively on the I.A.E. type gear-lubricant testing machine and Soda four-ball tester under the condition of 200 r.p.m. and it has been found that there exists correlation among them in this case.

But whether the fact is unexpected or not is the question. Fig. 6 shows the results of the effect of adding various concentrations, ranging 1.5 to 3 per cent of each of three additives to an SAE 90 solvent refined mineral oil obtained on the Soda four-ball tester under the condition of 750 r.p.m. (shock loading).

It will be seen that dibenzyl disulfide is superior to others but the effects of these three additives are not so good as might be expected.

A sample containing 1.5 per cent tricresyl phosphate and chlorinated paraffin respectively gave a rating of 1.0 which was the same as that of the base oil. It will be seen that concentrations above 3 per cent yield little improvement.

That is, these figures distinctly show the characteristics of each of the three test equipments and each of the three additives. The facts indicate that even though an oil containing E.P. additives is lower in load-carrying capacity on a laboratory test equipment than another, the performance of the oil in practice of actual gear lubrication is not always inferior to that of the other.

Load carrying capacities of commercial E. P. oils

Load-carrying capacities of commercial E.P. oils were tested by I.A.E. type machine, Timken machine and Soda four-ball tester.

The results obtained are shown in Table 4 and Figs. 7 to 10.

It will be seen that load rating of an oil containing E.P. additive has a different dependence on the testing machine and the ranking of E.P. oils with I.A.E. type gear machine does not always agree with the one with other testing

machines.

For example, SAE 90 E.P. type oil C has a load rating of above 2.8, 3.4 and 2.4 with I.A.E. type gear machine, Timken machine and Soda four-ball tester to which a continuously increasing load at a constant rate is applied at 200 r.p.m. until seizure of the test ball is indicated by a large increase in torque while it has a lower load rating of 1.5 than other SAE 90 E.P. oils with Soda four-ball tester to which a shockingly increasing load at a constant rate is applied at 750 r.p.m.

Fig. 6 Effect of EP additives with Soda four-ball lubricant tester (750 r.p.m.)

Fig. 7 Load carrying capacity of commercial gear oils with I.A.E. type gear lubricant testing machine

Table 4 Load carrying capacity with the I.A.E. type gear lubricant testing machine Soda four-ball tester and Timken lubricants testing machine (Base Oil SAE 90)

Sample	I.A.E. Type		Timken		Soda four-ball			
	OK load lbs	Rating	OK load lbs	Rating	200 r.p.m. (continuous loading)		750 r.p.m. (shock loading)	
					OK load kg/cm ²	Rating	OK load kg/cm ²	Rating
Mild E.P. A	160	2.3	35	2.2	7.5	1.9	4.5	1.5
" B	190*	2.7	35	2.2	8.0	2.0	5.0	1.7
" C	165*	2.4	25	1.6	9.0	2.3	5.0	1.7
E.P. oil A	190*	2.7	50	3.1	9.5	2.4	6.0	2.0
" B	190*	2.7	50	3.1	10.0	2.5	6.0	2.0
" C	195*	2.7	55	3.4	9.5	2.4	4.5	1.5

* Spalling occurred

until seizure of the test ball is indicated by a large increase in torque.

But although load ratings of SAE 90 E. P. type oils A and B have a different dependance on the testing machine, their rankings agree comparatively well between them.

SAE 90 mild E. P. type oil C has a lower load rating of 1.6 than other SAE 90 mild E. P. type oils with Timken machine while the effect of SAE 90 mild E. P. type oil C is good with I. A. E. type gear machine, and Soda four-ball tester.

Because of the small number of samples, no definite conclusion may be drawn, but it is considered that the Timken machine is capable of distinguishing between the effect of mild and active E. P. type oils while the I. A. E. type gear machine and Soda four-ball tester are not capable of differentiating between them within the range of this experiment.

Fig. 8 Load carrying capacity of commercial gear oils with Timken machine

But it is noteworthy that for evaluation of load-carrying ability of oils containing E.P. additives the effect and ranking of them with I. A. E. type gear machine do not always agree with those with the Timken machine as above mentioned.

I. A. E. scuffing test on SAE 90 mild E. P. type oil B and SAE 90 E. P. type oils A, B and C gave a rating of above 2.7 and there has been found to exist no marked difference between them.

Fig. 9 Load carrying capacity of commercial gear oils with Soda four-ball lubricant tester (200 r.p.m.)

Fig. 10 Load carrying capacity of commercial gear oils with Soda four-ball lubricant tester (750 r.p.m.)

Face of typical test gear

Scuffed gear face at 75 lbs (SAE 90 base oil)

Scuffed gear face at 165 lbs (mild EP A)

Spalled gear face at 195 lbs (EP oil A)

Fig. 11 Typical gear faces before and after scuffing test with I.A.E. type gear lubricant testing machine

In addition, the evidence of scuffing was not found on the gear-tooth surface at 190 lbs for mild E.P. type oil B while pitting or spalling occurred on the gear-tooth surface as shown in Fig. 11.

And also such phenomena were observed on the test of commercial SAE 90 E.P. type oils A, B and C. Although the effects of lubrication on pitting are not to be underestimated, it is considered that the pitting may be due to the fatigue of the gear-tooth material or the powerful activity of E.P. additives.

The facts indicate that it is difficult to determine the load-carrying capacity of such powerful E.P. oils by the I.A.E. type gear machine under the condition of 2 000 r. p. m. and it seems impossible to compare one with another.

But a reduction in scuffing load with increase in sliding velocity is generally observed.

Accordingly, it seems that it might be possible to determine the load-carrying capacity of such powerful E.P. oil, if the speed is increased to 4 000 or 6 000 r. p. m. as indicated in the tentative scuffing test method i. e. I. P. 166/58 T⁽⁶⁾. But it is not considered a satisfactory test equipment for conducting evaluation of the load-carrying capacity of hypoid gear lubricant.

That is, as above mentioned, the load-carrying capacity of an E.P. lubricant depends on the type of additives, test equipment and the test condition.

And even though an oil may be lower in load-carrying capacity with a laboratory test equipment than another one, the performance of the oil in actual practice of gear is not always inferior to that of another one.

Summary

1. Within the range of this experiment, chlorinated paraffin and dibenzyl disulfide are better than tricresyl phosphate with I.A.E. type gear machine and little of them is needed to obtain a substantial increase in scuffing load.

2. Within the range of this experiment, dibenzyl disulfide is better than chlorinated paraffin with I.A.E. type gear machine and Timken machine.

3. Within the range of this experiment, dibenzyl disulfide is inferior to chlorinated paraffin with Soda four-ball tester under 200 r. p. m. (continuous loading) but better than the latter under 750 r. p. m. (shock loading).

4. With Timken machine tricresyl phosphate is not effective within the range of concentrations 1.5~3.0 per cent.

5. Within the range of this experiment, commercial mild E.P. type oils have a scuffing load about 2 times higher than that of straight mineral oil and commercial E.P. type oils have a scuffing load above 2.7 times higher than that of straight mineral oil with I.A.E. type gear machine.

6. Some powerful E.P. oils cause pitting or spalling on the gear-tooth surface with I.A.E. type gear machine.

7. Ranking of E.P. oils with I.A.E. type gear machine does not always agree with those with other testing machines.

8. I.A.E. type gear machine is a satisfactory test equipment for evaluation of the load-carrying capacity of mild E.P. type oils, but not for evaluation of the load-carrying capacity of powerful E.P. lubricants such as hypoid gear lubricants.

9. Oils containing a large quantity of E.P. additive should be tested at higher speeds of 4 000 and 6 000 r. p. m. than 2 000 r. p. m.

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