Evaluation of Fretting Protection Property of Lubricating Grease Applied to Thrust Ball Bearing —Comparison between ASTM D4170 Test and Impact Fretting Test—

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Fretting wear is often the case when ball-and-roller bearings oscillate under grease lubrication. Against the backdrop of fretting wear on the wheel bearings of automobiles caused by rail transportation, the ASTM D4170 fretting test method was developed to evaluate the fretting protection property of lubricating grease. The ASTM test is conducted under a fixed load, but the load condition for industrial machines usually fluctuates. Currently, there is no international standard to evaluate the fretting wear under fluctuating load. In this study, using thrust ball bearings the authors examined 14 kinds of commercially produced greases and three kinds of originally prepared greases on fretting protection evaluation under both the ASTM test and the impact fretting test. Consequently, the authors found out the inversion of the order of fretting protection superiority between the ASTM test and the impact fretting test. As for the kinematic viscosity of base oil of grease, the amount of wear of ASTM test increases with increasing the kinematic viscosity, on the other hand the wear of impact fretting test decreases with increasing the kinematic viscosity.

Keywords: fretting wear, lubricating grease, thrust ball bearing, ASTM D4170 test, impact fretting test

1. Introduction

When ball and roller bearings oscillate under grease lubrication, fretting wear tends to take place on the raceway surface of the bearing. Some means of reducing the fretting wear have been studied, for example, adjustment of bearing clearance, enlargement of groove radius of raceway¹⁾, macroscopic movement of contact point between rolling element and raceway^{2,3)}, etc. As for the lubrication, oil lubrication is much better than the grease lubrication. However grease lubrication is common by reason of less oil leakage and no need of oil supply accessory.

In the case of automotive wheel bearing, against the backdrop of fretting wear caused by rail transportation at '70s in the US, the ASTM D4170 test (Standard Test Method for Fretting Wear Protection by Lubricating Greases, abbreviate to "ASTM test" here) was developed in order to select a grease having a good fretting protection property. According to Kita et al.⁴⁾, the dominant factor on the ASTM test is an ability of the grease to supply the base oil to the contact surface. It is,

therefore, effective to protect fretting wear in which case the kinematic viscosity of base oil is much lower or the oil separation is much higher. In regard to grease thickener, since the grease which is easy to soften by shear stress tends to show low amount of wear on the ASTM test⁵⁾. So, thickeners which present poor shear stability, for example tri-urea, are sometimes used.

Generally, the fretting wear means the wear generated when tangential oscillation acts on contact surfaces. The ASTM test directs this case. But the fretting wear generates even when a fluctuating vertical load acts onto the contact surfaces⁶⁾. In industry use, bearings sometimes oscillate with fluctuating vertical or moment load, that is suffered combination load. According to de Gee et al.⁷⁾ the amount of wear under the combination load becomes double figures larger compared to it under respectively independent load. On the other hand, Sato et al.⁸⁾ have reported a beneficial effect of oiliness and phosphorus additives against fretting protection property, and this suggests another role of grease different from it for the ASTM test.

With regard to the lubricating effect of grease against

fretting wear, there are ambivalence reports. One is less fretting wear under lower kinematic viscosity of base oil⁴⁾, and the other is less fretting wear under higher viscosity of base oil⁹⁾. It is inferred that these inconsistent reports arise from different test conditions and diverse compositions of greases. In the present circumstances, there is no systematic study about the effect of test conditions, grease properties, etc. Therefore, in the case of grease selection for actual bearing suffers combination load, evaluation for actual size bearing must be desirable. But it is by no means easy to take a number of greases for testing in case where the bearing is so large. Currently, there is no adequate international standard like the ASTM fretting test method.

In the research reported here, the authors have developed a method of impact fretting test where fluctuating vertical load applies to thrust ball bearing without bearing oscillation. Additionally both the ASTM test and the impact fretting test were conducted for practical greases, and compared the effect of grease on both fretting tests. Consequently the inversion of the order of fretting protection superiority between the ASTM test and the impact fretting test was found out. In addition, the grease properties having an effect on the

respective fretting tests were made clear.

2. Experimental

2.1. Test greases

Table 1 presents the properties of 17 kinds of greases tested in ascending order of the kinematic viscosity at 40 °C. The greases except D, E and J greases are commercially available. The grease D includes an anti-wear additive in addition to grease C. The grease E includes 0.65 mass% of molybdenum disulfide (average particle diameter of 0.4 μm) as solid lubricant in addition to grease C. As for the grease J, the kinematic viscosity at 40 °C is elevated from 40.6 mm²/s of grease C to 140 mm²/s. The greases A, B, C, G, J and K do not include any extreme pressure additive, anti-wear additive and solid lubricant.

2.2. ASTM D4170 test

Table 2 lists the test condition. The temperature at the start of test was set at the room temperature (20-25 °C) and was not controlled after started. With regard to the evaluation of wear, the differences of weight before and after the test for dual bearings were measured, and the average difference was considered to the wear amount.

Table 1 List of greases tested

Grease	60 Worked penetration at 25 °C	10 ⁵ —60 Worked penetration at 25 °C	Thickener	Base oil	Kinematic viscosity, mm ² /s at 40 °C	Oil separation, mass% at 100 °C, 24 h	Additives		
							EP	AW	SL
A	304		Ca	Mineral+PAO	13		×	×	×
B	280		Li	Mineral+PAO	29.8		×	×	×
C	252		Li	Mineral	40.6	1.6	×	×	×
D	256		Li	Mineral	40.6		×	Add'l	×
E	255		Li	Mineral	40.6		×	×	MoS ₂
F	287		Li	PAO	50		×	×	Inorganic powder
G	300		Urea	Mineral	74.7		×	×	×
H	313		Urea	Mineral	97.2		×	Add'l	×
I	280		Li-complex	PAO	100		Add'l	Add'l	×
J	270		Li	Mineral	140		×	×	×
K	268		Urea	Mineral	144		×	×	×
L	270		Li	Mineral	145	0.3	×	Add'l	MoS ₂
M	280		Li	Mineral	160		Add'l	×	×
N	280	22	Li-complex	PAO	220		Add'l	Add'l	×
O	284	48	Li	Mineral	220		Add'l	Add'l	×
P	305	25	Li-complex	PAO	460		Add'l	Add'l	×
Q	300	46	Urea	PAO	460		Add'l	Add'l	×

EP: Extreme pressure additive(additives contain sulfur), AW: Anti-wear additive(additives contain phosphorous),

SL: Solid lubricant

×: Not add, Add'l: Additional

Table 2 Test conditions of ASME D4170 fretting test

Bearing	Thrust ball bearing Inside diameter: 16 mm Outside diameter: 35.69 mm Diameter of ball : 7.142 mm Number of ball: 9
Load	2450 N
Max. pressure (Authors calculated.)	1.7 GPa
Oscillation angle	0.21 rad (12 °)
Frequency	30 Hz
Amount of grease	1 ± 0.05 g
Temperature	Room temperature
Test duration	22 h (1.98 × 10 ⁶ cycle)

2.3. Impact fretting wear test

The impact fretting tester is shown in Fig. 1. Using 53408U thrust bearing (the number of balls was 10) with self-aligning washer, fluctuating vertical load was applied to the bearing by the hydraulic cylinder without bearing oscillation. The surface roughness of the bearing raceway before test was 1.1 $\mu\text{m}R_z$ and 0.20 $\mu\text{m}R_a$. Table 3 lists the test conditions. The normal load was sinusoidal wave traversed from 1.96 kN to 88.2 kN, and the oscillation frequency was 10 Hz. The maximum load of 88.2 kN is equivalent to approx. 47% of rated value for the static load. The temperature at the start of test was set at the room temperature (10-20 °C) and was not controlled after started. As for the amount of grease, firstly the grease was fully packed, and then the excessive grease protruded from the bearing was removed when the bearing was rotated by hand.

As an example of result, the photo of wear trace on the downside bearing raceway after 4 h test using grease C is shown in Fig. 2. The cross line in Fig. 2 points out the contact width (major axis, minor axis) calculated by Hertz contact theory. Lines without arrowhead indicate the contact width under 1.96 kN load, while lines with arrowhead indicate it under 88.2 kN load. There was no wear trace within somewhat larger than the contact area under 1.96 kN, and the wear was generated circularly (abbreviate to “fretting ring” here) in the intermediate area between the contact area under 1.96 kN and it under 88.2 kN⁶⁾. By the way, the grease close to contact area turned brown color when the bearing was opened after test.

Next, the appearance of wear trace when test durations varied for 2 h, 4 h and 8 h independently is presented in Fig. 3. On 2 h test, contact area became change of color to light brown and wear took place in the part of outer circumferential of contact area. On 4 h test, the wear spread whole of the fretting ring. The wear of 8 h test was equivalent to it of 4 h test, and the depth of the

Fig.1 Impact fretting wear tester

Table 3 Test conditions of impact fretting test

Bearing	Thrust ball bearing (53408U) Inside diameter: 42 mm Outside diameter: 90 mm Diameter of ball : 17.46 mm Number of ball : 10
Load	Min.1.96 kN, max.88.2 kN Sinusoidal wave
Max. pressure (Authors calculated.)	0.91 GPa—3.25 GPa
Oscillation angle	0 °
Frequency	10 Hz
Temperature	Room temperature
Test duration	4 h (1.44 × 10 ⁵ cycle)

wear trace was the same 2 μm measured by stylus method. Figure 4 shows the cross-section of wear trace after 8 h test. There is a fixing region in the middle of the wear trace, and the wear proceeds in the fretting ring. However, because the vertical load at fretting ring decreases with proceeding the wear, i.e. the fixing region supports the load, it is inferred that the wear does not make progress over 2 μm . Grease C has very poor protection quality for fretting wear because of indicating high Fe content in an actual machine. Given that the wear have proceeded all over the fretting ring during 4 h test using grease C, the wear using other various greases will be minor, and the reason why test duration was settled at 4 hours is it will be possible to evaluate a relative comparison of greases.

Fig.2 Typical wear trace after impact fretting test

Fig.3 Wear trace after 2 h, 4 h and 8 h tests using grease C

With respect to the evaluation for the fretting protection properties of greases, because the amount of wear was not more than $2\text{ }\mu\text{m}$, it was difficult to show the significant difference by the depth of wear. So the extent of wear trace was considered to be the degree of wear, and described it as five degrees of rating. Figure 5 indicates the standard rating. After preparing the standard rating, the wear trace was compared to the standard rating, and then assigned a rating. The fretting wear generates firstly at the part of outer circumferential of contact area, and then enlarges to the inner side. The degree of wear was expressed by the rating 0, 1, 2, 3 and

Fig.4 Bird's-eye view of wear trace after 8 h impact fretting test using grease C

Fig.5 Standard rating for wear trace after 4 h impact fretting test

4, in the order of increasing wear. The rating 0 means that the contact surface became change color, but no wear took place. The rating 1 means there was a little wear at the part of outer circumferential. The rating 2 means the wear at outer circumferential made progress. The rating 3 means that wear took place in the direction of minor axis, and right and left wear trace joined together. The rating 4 means the wear spread throughout the fretting ring except fixing region. The rating was directed to the lower raceway of bearing, thus marked the rating for ten balls, and then set the rating as the grease rating by taking arithmetic average. The rating may be a qualitative index for fretting wear, but since a considerable difference of the rating was obtained among the grease tested in this study, it can be represented the fretting protection property in terms of the rating.

Table 4 Results of fretting test

	ASTM D4170 test (amount of wear, mg)			Impact fretting wear test (rating)			
	1	2	av.	1	2	3	av.
A	1.3	—	1.3	4.0	—	—	4.0
B	5.4	3.2	4.3	3.9	—	—	3.9
C	8.0	8.4	8.2	3.8	4.0	—	3.9
D	12.2	15.7	14.0	2.5	—	—	2.5
E	14.2	10.6	12.4	2.5	—	—	2.5
F	4.1	—	4.1	2.3	—	—	2.3
G	1.4	2.9	2.2	3.5	—	—	3.5
H	0.7	—	0.7	4.0	—	—	4.0
I	19.8	—	19.8	1.2	2.2	1.6	1.7
J	9.1	—	9.1	1.6	1.7	—	1.7
K	10.4	—	10.4	1.7	—	—	1.7
L	13.1	14.3	13.7	1.5	2.3	1.3	1.7
M	8.7	—	8.7	0.9	1.1	—	1.0
N	29.4	—	29.4	1.3	0.8	0.8	1.0
O	6.2	—	6.2	2.5	—	—	2.5
P	30.0	—	30.0	0.9	—	—	0.9
Q	16.6	19.5	18.1	0.9	0.4	—	0.7

av.: average

3. Test results and discussions

The results of both the ASTM test and the impact fretting test are presented in Table 4. The properties such as the kinematic viscosity of base oil cover a wide range, so the number of test was set at one time in principle so as to get perspective between the properties of grease and the amount of wear. In order to check data repeatability, multiple tests were carried out for some greases. In the case of ASTM test, the data fluctuates maximum 1.8 mg from the average, and maximum 0.6 in the case of impact fretting test.

3.1. Comparison between the ASTM test and the impact fretting test

The relationship between the ASTM test and the impact fretting test is presented in Fig. 6. The data in the figure shows a tendency of negative correlation. The grease which exhibits lower amount of wear in the ASTM test tends to have higher rating, or wear larger in the impact fretting test. Namely, the inversion of the order of fretting protection superiority was found out between the ASTM test and the impact fretting test.

Taking grease C and L as examples, amount of wear for grease C is less than that for grease L on the ASTM test. Because the grease C has lower viscosity of base oil compared to the grease L, adversely it has larger oil separation as presented in Table 1, the base oil of grease C is easy to gain entry to contact area. This result is consistent with the report by Kita et al⁴⁾. On the other

Fig.6 The relation between the ASTM test and impact fretting test(black diamond: free of EP, AW and SL additives, white square: include one or more additives)

Fig.7 The relation between the kinematic viscosity of base oil and impact fretting test(black diamond: free of EP, AW and SL additives, white square: include one or more additives)

Fig.8 The relation between the kinematic viscosity of base oil and ASTM D4170 test(black diamond: free of EP, AW and SL additives, white square: include one or more additives)

hand, in impact fretting test the rating for grease C is higher than that for grease L. Hence, the order of

fretting protection superiority for ASTM test inverts with that for the impact fretting test.

The authors have applied the grease C and L to an actual bearing subject to both the bearing oscillation and the dynamic vertical load. Since uncertain oscillation and dynamic vertical load work on this bearing, it is difficult to select an adequate grease that is superior to the ASTM test or the impact fretting test. Each grease was applied to plural number of bearings, and then Fe contents in the greases were examined. The analysis for Fe content was conducted by ICP (Inductively Coupled Plasma) through sulfuric acid decomposition method. As a result, 1400-2400 ppm of Fe content for grease C and 250-810 ppm for grease L were obtained, and this order of superiority meets that of impact fretting wear test. It is often the case that selection of grease is carried out through the ASTM test, but for bearing suffers the combination load, selection of test method in consideration of load condition is very important matter.

In addition, there is no grease which shows the amount of wear below 8 mg in the ASTM test as well as the rating below 2 in the impact fretting test, in short, superior to both tests.

3.2. Effect of grease properties

3.2.1. Effect of kinematic viscosity

Figure 7 and Fig. 8 present the respective results of the ASTM test and the impact fretting test as the viscosity of base oil is set for the horizontal axis. As is seen from Fig. 7, the data shows a tendency of negative correlation. The higher the viscosity, the lower rating or less wear. Meanwhile the data of the ASTM test in Fig. 8 shows positive correlation. After all, the viscosity of base oil effects inversely on the fretting wear regarding the ASTM test and the impact fretting wear.

In order to examine the viscosity effect, grease J whose viscosity was increased from 40 mm²/s to 140 mm²/s was prepared. Although grease C and J show nearly the same wear value in ASTM test presented in Fig. 6, in the impact fretting test the grease J which has higher viscosity shows lower rating, thus less wear.

Furthermore, six greases A, B, C, G, J and K which contain no EP additive, anti-wear additive and solid lubricant are focused in order to comprehend the effect of viscosity on fretting wear. These greases are indicated as black diamond mark in Fig. 6 to Fig. 8. As is seen from Fig. 7, while grease A, B, C and G which have the viscosity of base oil below 250 mm²/s designate high wear rating, grease J and K having the viscosity over 500 mm²/s designate lower wear rating of 1.7. Under the condition of this impact fretting test, it is inferred that considerable decreasing for the wear rating could arise in the range of viscosity over about 400 mm²/s.

The reason why the inversion property in terms of the order of fretting protection superiority between the ASTM test and the impact test, the authors think as follows. Namely, because the rolling element oscillates in the ASTM test, base oil of grease always has a chance

Fig.9 The relation between the 60 worked penetration and impact fretting test(black diamond: free of EP, AW and SL additives, white square: include one or more additives)

to enter into contact area, this leads lower wear in the case of the grease which has lower viscosity or higher oil separation⁴⁾. Contrary, the rolling element always remains stationary in the impact fretting test, so exchange of base oil could not be expected. In consequence, higher viscosity grease having the ability to keep oil film becomes lower wear.

3.2.2. Effect of 60 worked penetration

Figure 9 and Fig. 10 present the relationship between 60 worked penetrations and the results of fretting test. NLGI No.2 grease is major in this report, it must be noted that the range of values for 60 worked penetration, from 252 to 313, did not vary greatly.

With respect to the correlation between the penetration and the impact fretting test as shown in Fig. 9, there is no tendency due to data spread. Meanwhile as for the relationship between the penetration and the ASTM test (Fig. 10), the data shows a tendency of negative correlation except two data surrounded with broken line, thus larger penetration becomes lower amount of wear. This is coincident with prior knowledge^{10,11)}. The two data surrounded with broken line are grease N and P. These grease show higher viscosities of base oils, 220 mm²/s and 460 mm²/s, respectively. But grease O and Q whose viscosities are equivalent to grease N and P respectively are not singular point. The reason would be related to the mixed stability, that is, subtracted 60 worked penetrations from 10⁵ worked one. Namely, grease N and P have a half of the mixed stability compared to that of grease O and Q, so the wear in the ASTM test for grease N and P could be larger because of the higher viscosity and difficult to get soft.

3.3. Effect of grease compositions

3.3.1. Effect of grease thickener

Figure 11 presents the effect of grease thickener redrawn Fig. 6. There is no obvious tendency that specific thickener excels in wear resistance. Although needs to pay attention that grease thickeners used in this

Fig.10 The relation between the 60 worked penetration and ASTM D4170 test(black diamond: free of EP, AW and SL additives, white square: include one or more additives)

Fig.11 The effect of thickeners on ASTM and impact fretting test(black diamond: Ca soap, white square: Li soap, white triangle: urea, black square: Li complex)

test are not main parameter, the effect of thickener is considered to be smaller relative to the viscosity of base oil.

By the way, the higher viscosity becomes larger amount of wear as shown in Fig. 8, but the grease G and H are singular data showing low wear. These greases have the same thickener, i.e. urea. In the case of urea, protective coating composed by urea would be formed on the contact surface^{12,13)}, it probably causes the lower wear.

3.3.2. Effect of additives

The grease D includes anti-wear additive in addition to grease C, while grease E includes 0.65 mass% of molybdenum disulfide as solid lubricant in addition to grease C. The wear rating for grease C in impact fretting test was 3.9, but the addition of anti-wear additive and solid lubricant can reduce the rating to 2.5, preventing fretting wear. On the other hand, as shown in Fig. 6, every additive leads the amount of wear in ASTM test to increase. However, given that there is not obvious difference between the grease without additives shown

as black diamond in Fig. 8 and the grease with additives shown as the white square, the effect of additive on the ASTM fretting wear would be relatively small.

3.4. Fretting protection grease

In 14 kinds of commercially available greases apart from originally prepared greases D, E and J, the greases A, G and H are known as fretting protection grease. As shown in Fig. 8, these greases certainly exhibit not more than 1.3 mg amount of wear for the ASTM test. However as shown in Fig. 7, the rating in impact fretting test are not lower than 3.5, viz. easy to wear.

In general, what is called the fretting protection grease means that it shows lower amount of wear in the ASTM test, and it would be no problem in the case of applying to automotive wheel bearing. However, since the rating shows considerably poor in the impact fretting test, the fretting protection grease could not easily apply to the bearing suffered combination load.

4. Conclusions

When ball and roller bearings oscillate under grease lubrication, fretting wear is prone to take place on the raceway surface of the bearing. In this study, using thrust ball bearing two types of tests were conducted, namely the ASTM test where the bearing oscillates under a constant load, and the impact fretting test where the vertical load fluctuates without bearing oscillation. These tests were carried out for 17 kinds of greases, mainly commercially available, then the effect of grease onto the fretting wear were investigated. The results of this study are as follows.

- (1) The impact fretting test has originally developed in such a way that fluctuating vertical load applies to a thrust ball bearing without bearing oscillation. The fretting wear generates firstly at the part of outer circumferential of the contact area, and then enlarges to inner side. The fretting protection superiority can be evaluated through the five degrees of rating for the extent of wear trace.
- (2) The inversion of the order of fretting protection superiority was found out between the ASTM test and the impact fretting test. It is quite important matter to select the fretting test method in consideration of load condition onto the bearing.
- (3) The kinematic viscosity of base oil effects inversely on the fretting wear whether the ASTM test or the impact fretting test. Higher viscosity becomes larger amount of wear in the ASTM test, meanwhile higher viscosity becomes lower rating in the impact fretting test. Focusing attention on non-additive greases, considerable decreasing effect for the wear rating could arise in the range of viscosity over about 400 mm²/s.
- (4) With respect to the effect of additives on fretting wear, anti-wear additive and solid lubricant show obvious decreasing effect on the rating in impact fretting test.

- (5) What is called the fretting protection grease which shows lower amount of wear in the ASTM test presents considerably poor protection property in impact fretting test. There is no grease in 14 kinds of commercially available greases tested here showing good protection property for both tests, more specifically not over 8 mg for the ASTM test and simultaneously not over rating 2 for the impact fretting test.

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