Low Torque and Low Noise Technology for Ball Bearings Under Grease Lubrication

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A study was conducted to verify the effect of grease on the low torque property and low noise property which are particularly highly sought bearing performances. We focused on the viscoelasticity of grease as the dominating factor of bearing rotational torque. As a result, we clarified that the higher the viscoelasticity, the lower the torque, and that grease families with short carbon chains were superior in terms of low torque characteristic. Moreover, bearing noise increases when grease thickener becomes trapped between the raceway and rolling element causing the oil film thickness to vary, therefore low noise was better achieved if thickeners with low Young's modulus and small particle size were used as this minimizes oil film variance.

***Key Words**: grease, bearing torque, grease noise, young modulus, particle size*

1. Introduction

In recent years, demands relating to energy-saving, such as minimizing the use of fossil fuels and reducing power consumption, have been increasing. Particularly with regard to the industrial motor field, which is said to account for 55% of domestic annual electricity consumption, there is a strong requirement to improve energy efficiency. In reality, a Top Runner Program was formulated in 2011 targeting the three-phase motors used in plant pumps, fans and so on, and higher-efficiency motors have become mandatory. As such, strong demands have also arisen relating to torque loss caused by bearings used in these motors and there is much pressure from the industry to develop grease-lubricated ball bearings with low torque performance.

Many motors are already used for automotive applications, however it is predicted that, due to the promotion of electrification, the quietness of automobiles will continue to improve in the future. For this reason, there is a need to further improve the quietness of grease-lubricated ball bearings.

The impact of grease on the low torque performance of ball bearings has been studied to date and many research reports have been published. In regards to bearing torque, Watabe and company have conducted an evaluation using lithium soap grease and shown that a correlation exists between the yield stress of grease and the bearing rotational torque1). Moreover, Akutsu and company focus on the thixotropy of grease and have concluded that the tendency for grease viscosity to decrease due to shearing depends on the three-dimensional network structure of thickener2). However, hardly no reports have been made of case studies quantifying the factors affecting bearing rotational torque. As such, this research focused on viscous transition stress as a new factor affecting bearing rotational torque and, as a new concept deriving from thickener-originating loss, introduced stirring loss energy to investigate the correlation between the composition and properties of grease, bearing torque and stirring loss energy3).

Regarding bearing noise, Endo and company discuss the smoothness of the thickener film from analysis results of EHL (elasto-hydrodynamic lubrication) thickener film thickness and have concluded that grease which forms a smooth thickener film has high quietness4). Furthermore, Igarashi and company have studied the effect of base oil viscosity of grease and thickener fiber diameter on bearing noise and demonstrated that the greater the base oil viscosity and the smaller the fiber diameter, the more bearing noise is reduced5). Komiya investigated the relationship between the base oil viscosity and penetration of grease and the size of solid components and clarified that the lower the base oil viscosity and the greater the penetration, the louder bearing noise caused by thickener becomes6). In response to these theories, we believe that the mechanical property of thickener affects bearing noise, and devised a technique to measure the Young's modulus of thickener bulk using a nanoindentation. Furthermore, using samples with differing Young's modulus and particle diameter, which are affecting bearing noise, we measured the change in the EHL film

Table 1 Compositions and properties of test grease

Sample sign			T1	T2	T3	T4
Thickener	Composition (Diurea)		MDI-Octylamine	MDI-Decylamine	MDI-Dodecylamine	MDI-Octadecylamine
	Carbon chain length		8	10	12	18
	SP value, $(J/m^3)^{1/2}$		21 887	21 478	21 068	20 250
	Amount, mass%		15	15	15	18
Base oil	Composition		PAO			
	SP value, $(J/m^3)^{1/2}$		17 182			
	Kinetic viscosity, mm^2/s	40℃	30.5			
		100℃	5.82			
	Density	15℃	0.827			
Grease	Penetration	60W	251	248	246	258

MDI：Methylenediphenyl 4.4'-Diisocyanate

Table 2 Compositions and properties of test grease

Sample sign			N1	N2	N3	N4	N5
Thickener	Isocyanate		MDI				
	Amine		Aliphatic	Alicyclic	Aromatic	Aliphatic Alicyclic	Aliphatic
	Amount, mass%		15				
Base oil	Composition		PAO				
	kinetic viscosity, mm^2/s	40℃	30.5				
		100℃	5.82				
Grease	Penetration	60W	256	329	356	267	302
	Average particle size of thickener, μm		2.8	2.4	1.3	0.3	13

thickness in order to investigate the mechanism of bearing noise exacerbation.

2. Test Method

2. 1 Test grease

2. 1. 1 Low torque performance

Table 1 shows the compositions and properties of the various greases used to study low torque performance. By using the same base oil and isocyanate (MDI), and changing only the amine composition, we prepared four types of urea grease with differing molecular structures (T1, T2, T3, T4). For the base oil, we used a synthetic hydrocarbon oil (Poly-Alpha-Olefin: PAO) which is low in impurities and widely used as a base oil of grease. Unlike lubricant oil, grease contains the solid component of thickener, and we believe that this solid component is a causing factor of stirring resistance and affects the fluidity of grease. Here, in order to quantitatively evaluate the stirring resistance caused by thickener, we used an aliphatic diurea, made from reacting and synthesizing aliphatic amines of different alkyl chain length and 4.4'-diphenyl methane diisocyanate (Methylenediphenyl 4.4'-Diisocyanate: MDI) in base oil as the thickener. Also, in order to eliminate the effect of grease penetration, which is believed to affect stirring resistance, we controlled thickener amount and miniaturization processing conditions to standardize the worked penetration (JIS K2220) at 250±10.

2. 1. 2 Quietness

Table 2 shows the compositions and properties of the various greases used to study quietness. All of these greases used the same base oil and isocyanate. PAO was used as the base oil and MDI was used as the isocyanate. PAO6, which is classified as a low-viscous grease base oil for rolling bearings, was used as the base oil, due to the high demand to reduce torque loss of rolling bearings and based on the anticipation that the affect of thickener on the noise property would be prominent. The urea compound, which is a thickener, was made from reacting and synthesizing isocyanate and amine in base oil. For this investigation, we prepared the samples of N1, N2 and N3, all of which had different amine compositions. Amines used for each of the samples were of the straight-chain alkyl group for sample N1, the monocyclic alkyl group for sample N2 and the aromatic alkyl group for sample N3. Moreover, sample N4 was prepared by combining the two types of amines used in N1 and N2 and sample N5 used the same amine as N1 but had a different miniaturization processing condition and larger average thickener particle diameter.

2. 2 Test conditions

2. 2. 1 Bearing rotational torque

Figure 1 is a schematic view of the apparatus used to measure bearing rotational torque and **Table 3** provides the test conditions. For the test bearing, we used a deep-groove ball bearing (62022RU) with a non-contact seal and a crown type resin cage filled with 0.72 grams of grease. Rotational torque was found by measuring the tangential force applied to housing assembled with a test bearing in a load cell and multiplying this by half of the housing's outer diameter. Furthermore, using a bearing with 0.11 grams of base oil applied to the balls, we measured rotational torque in the case of only a small amount of base oil lubrication, and established the torque causing stirring resistance deriving from thickener as the difference between rotational torque caused by grease lubrication and rotational torque caused by a small amount of base oil lubrication, then calculated the time integral of this torque causing stirring resistance deriving from thickener then defined the obtained loss energy as stirring loss energy. We did this as we believed it would make it possible to consider not only the starting torque and rotational torque during stable operation, but also all variations in rotational torque during the test period.

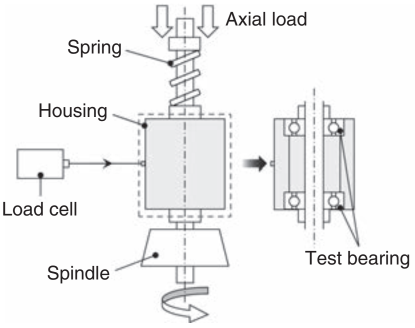


Fig. 1 Schematic view of torque test apparatus

Table 3 Rotational torque test conditions

Test bearing	6202
Axial load, N	44
Grease inclusion quantity, %	35
Oil inclusion quantity, *g*	0.11
P_{max}, GPa	0.93
Rotation speed, min^{-1}	1 800
Temperature, ℃	25 ± 2
Test time, s	1 800

2. 2. 2 Viscous transition stress

A viscoelasticity measurement apparatus was used to measure the viscous transition stress of the grease. **Figure 2** is a schematic view of the measured portion. Grease was wedged between two parallel surfaces and a measurement was made under the conditions shown in **Table 4**. We measured the storage modulus G' and loss modulus G" when strain control was applied to gradually-increasing sine wave strain. Grease was vibrated with a strain of 0.01 to 1 000% and frequency of 1 Hz. At this time, storage modulus G' is an elastic component holding the stress accumulated inside the grease and loss modulus G" is a viscous component dissipated by the applied energy, which acts as a heat source. When the applied strain is small, G"/G' is less than 1, which is a stress response close to an elastic body, and as the strain gradually increases, G" increases. As G"/G' gradually increases G"/G' becomes equal to 1, and loss modulus G" is equal to storage modulus G', the stress is known as "yield stress." However, strictly speaking, yield stress is the size of the stress when a force is applied to an object which exceeds the elastic limit, therefore the strain on the object increases rapidly and it cannot return to normal. As such, yield stress is not appropriate as an expression of grease fluidity. Therefore, we have defined the stress when complex modulus G*=G"/G'=1 as the viscous transition stress of grease rather than yield stress and tested this as the fluidity of grease. The greater this viscous transition stress of grease is, the greater the force when grease begins to flow while the bearing rotates, and it becomes more difficult for the grease inside the bearing that has been discharged once through the raceway to flow back into the raceway, which indicates excellent channeling performance.

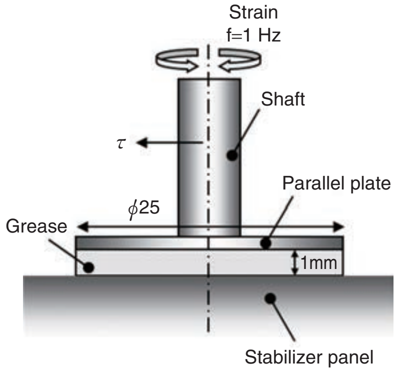


Fig. 2 Schematic view of transition stress of viscoelasticity measurement method

Table 4 Rheological property test conditions

Plate	ϕ25 Parallel plate
Clearance, mm	1
Frequency, Hz	1
Strain	7×10^{-5}～6×10^{0}
Temperature, ℃	25±2

2. 2. 3 Thickener relative surface area

The relative surface area of the thickener particles was derived from the measurement result of thickener particle size distribution. A laser diffraction type particle size distribution measuring apparatus was used to measure the thickener particle size distribution. **Table 5** shows the measurement conditions. To measure the thickener particle size distribution, we diluted 1 gram of grease for the low torque study in small amount of toluene, injected to the circulating toluene in the measuring apparatus, then irradiated it with a laser 50 000 times to measure the scattering pattern. As **Fig. 3** shows, light scatters at a small angle in relation to the laser beam in the case of large particles, but scatters at a large angle in the case of small particles. Here, the thickener particles are deemed spherical and, using the Mie theory for light scattering, the diameter for a sphere that creates the same scattering pattern as the thickener particles was derived as the valid diameter of the particles. This valid diameter was established as particle diameter to obtain particle size distribution. From the results of the particle size distribution measurement obtained here, Formula (1) was used to derive the surface area of thickener particles with particle diameter d. Here, "A" is the surface area of the thickener particle [μm^2], "d" is the particle diameter [μm], "V_a" is the overall volume of all the particles [μm^3], and "R" is the volume fraction [%] occupied by the particles with the particle diameter d.

$$A=\frac{4\pi(d/2)^2\times V_a\times R}{4\pi(d/2)^3/3} \qquad (1)$$

From the sum total of the surface area obtained for all particle diameter d, the surface area of the thickener for the unit of volume was found, then by multiplying the thickener amount TC [%], the relative surface area S of the thickener in the defined grease was found by applying Formula (2).

$$S=\sum_{d} A(d)\times TC \qquad (2)$$

The reason why the thickener particles were deemed spherical was because it was verified from results of a differential interference microscope observation that the thickener in the grease contained many agglomerated particles with a shape close to a sphere.

Table 5 Particle size test conditions

Test method	Laser diffractometry
Mesurement range, μm	0.01～3 500
Carrier fluid	Toluene
Number of measurement	50 000
Agitation speed, min^{-1}	3 000
Scattering intensity, %	15±5

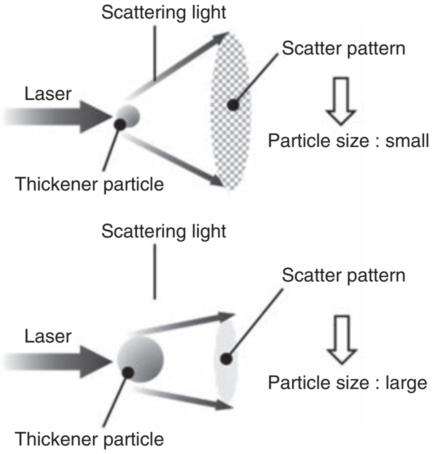


Fig. 3 Schematic image of particle size measurement

2. 2. 4 Bearing noise value

The bearing noise was tested based on the bearing vibrational acceleration. **Table 6** shows the measurement method for bearing vibrational acceleration rate (bearing noise value). 0.72 grams of test grease for the quietness study was injected into a bearing (62022RU) and sealed in by attaching a non-contact rubber seal. Next, we set the bearing in the spindle of the measuring apparatus, applied an axial load of 20 N then used a piezoelectric acceleration sensor to measure the vibrational acceleration rate in the radial direction of the bearing outer ring, which is greatest in the initial stage of rotation, when the bearing was rotated at an inner ring speed of 1 800 min^{-1}.

Table 6 Bearing noise test conditions

Items	Conditions
Bearing I.D×O.D×W, mm	62022RU 15×35×11, mm
Grease quantity, g	0.63
Axial load, N	20
Rotation speed, min^{-1}	1 800
Measurement time, s	1

2. 2. 5 Thickener Young’s modulus

1) Measurement sample adjustment method

We prepared the samples used for the measurement of the thickener Young’s modulus in accordance with the conditions shown in **Table 7** and the method shown in **Fig. 4**. After isolating the thickener from the grease, we applied the thickener to the bottom of the die, then injected phenolic resin on top of this and finally used heat compression to form a sample specimen with embedded resin. We believed that by using these adjustment conditions it would be possible to keep the effect of temperature on the thickener to a minimum and, due to the pressure also being small, keep the effect of sample fabrication to a minimum also.

Table 7 Sample preparation method

Item	Condition
Resin	Phenolic
Heating temperature, ℃	130
Pressure, MPa	1.5
Compress time, s	900

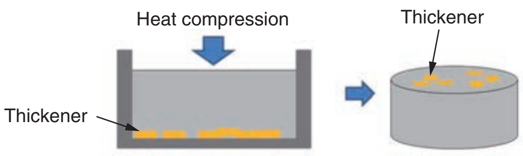


Fig. 4 Schematic image of sample preparation method

2) Thickener Young’s modulus

Table 8 shows the measurement conditions for the thickener Young’s modulus. Nanoindentation was used as the measuring apparatus. After applying an indentation load, we found the Young’s modulus from the inclination of the unloading curve when the indentation load was removed. We set the indentation load in a preliminary measurement so that the indentation depth would be one-tenth or less of the thickener’s thickness.

Table 8 Measurement conditions of Young's modulus

Item	Condition
Number of measuring location	4
Load, μN	500
Load time, s	5
Wait time, s	3

2. 2. 6 Film thickness

In this test, optical interferometry was used to measure the thickness of the grease EHL film in a point-contact state comprised of a glass disc and steel ball. **Figure 5** is a schematic image of the film thickness measuring apparatus and **Table 9** shows the condition used when measuring film thickness. The measurement itself involved using a glass disc with chrome vapor-deposited on it and a 38.1mm-diameter steel ball for bearings, pressing the ball up against the glass disc and measuring the thickness of the grease oil film under pure rolling conditions from the order of the interference fringes. For the measurement, we performed a test under a low speed condition (5mm/s), in which the film thickness becomes thinner, and observed the inflow of thickener to the contact interface. Also, with consideration to bearing rotational speed, we conducted a test under a high speed condition (100mm/s) and measured film thickness from the observation result of interference fringes.

Table 9 Measurement conditions of oil film thickness

Item	Condition
Load, N	90
Grease coating thickness, mm	1
Temperature, ℃	25
Rotation speed, mm/s	5 100
Measurement time, min	1

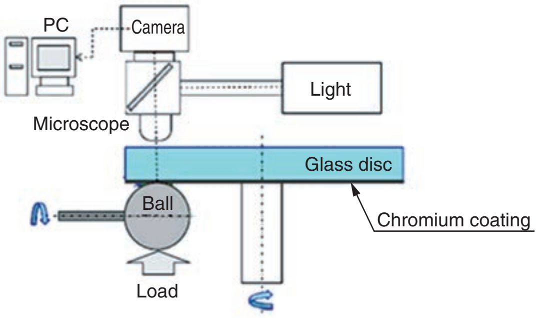
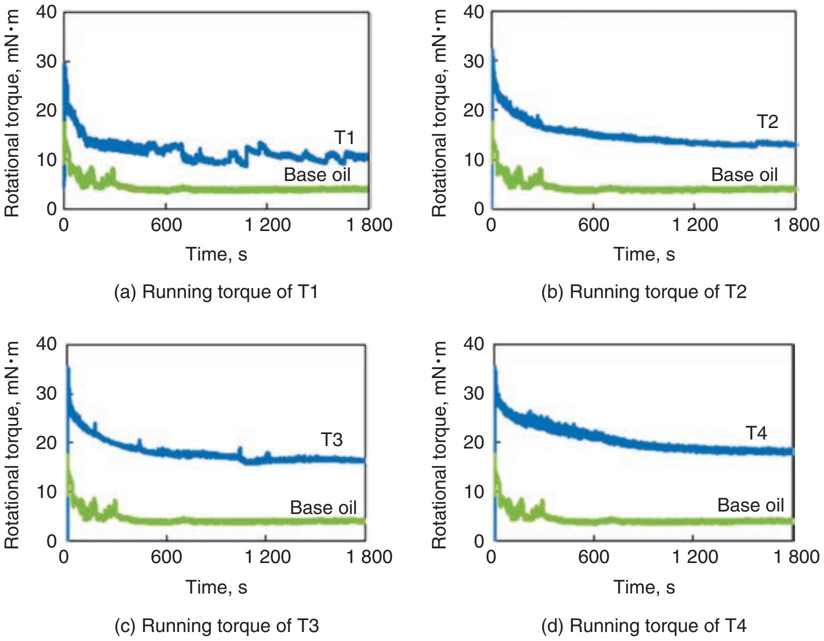


Fig. 5 Schematic image of oil film thickness measuring tester

3. Results and Observations

3. 1 Bearing rotational torque and stirring loss energy

Figure 6 shows the change over time of rotational torque by using greases or base oil which were injected into bearings. We confirmed that the rotational torque with grease lubrication was higher than the rotational torque with a small amount of base oil lubrication. Moreover, because a difference in rotational torque was recognized between the various greases for studying low



(a) Running torque of T1
(b) Running torque of T2
(c) Running torque of T3
(d) Running torque of T4

Fig. 6 Rotational torque of sample grease

torque performance, it was apparent that the terminal alkyl chain length of thickener urea does have an affect on rotational torque. As shown in **Fig. 7**, in order to test overall rotational torque variation throughout the duration of the test (e.g. initial stability of rotational torque, etc.), we found the time integral of torque caused by stirring resistance and calculated the energy lost during bearing rotation due to stirring resistance deriving from the thickener. The colored portion of the figure indicates the stirring loss energy, and the smaller this stirring loss energy is, the more difficult it becomes for grease that has been discharged from the raceway once, to re-enter, therefore indicating channeling type. It is also indicated that grease which maintains a low absolute value for rotational torque from the initial phase has superior rotational torque stability. **Figure 8** shows the stirring loss energy of the greases for studying low torque performance. In the same way as for rotational torque, T4 shows the highest stirring loss energy while T1 shows the lowest. These results clarify that the terminal alkyl chain length of thickener has an effect on stirring resistance and, as the alkyl chain length increases, both stirring loss energy and rotational torque increase. This is believed to be because the fluidity of the grease overall is changed due to the terminal alkyl chain length of thickener.

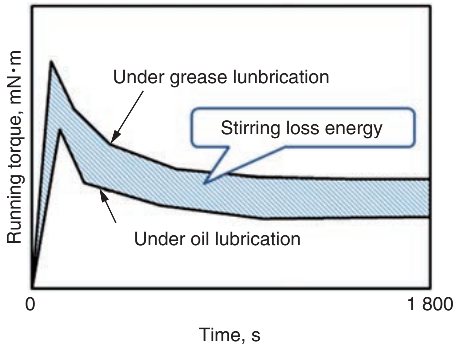


Fig. 7 Schematic of stirring resistance

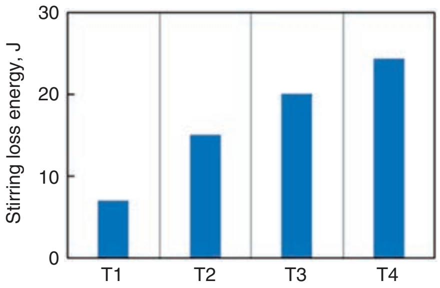


Fig. 8 Stirring loss energy of sample grease

3. 2 Stirring loss energy and viscous transition stress

Figure 9 shows the measurement results of viscous transition stress in greases for studying low torque performance. A trend of viscous transition stress increasing as the terminal alkyl chain length of thickener urea grows shorter (short chain length) is recognized, therefore it is clear there is a difference in fluidity. **Figure 10** shows the relationship between the obtained viscous transition stress and the stirring loss energy deriving from thickener, however in the greases for studying low torque performance, a trend was recognized whereby the higher the viscous transition stress becomes, the more the stirring loss energy decreases. **Figure 11** shows the results of an observation of the grease adhesion status within the bearing. For T4, which has a long terminal alkyl chain length (long chain length), a large amount of grease is adhered to the ball surface, but in comparison, only a small amount of grease is adhered to the ball surface but large on seal for T1, which has a short chain length. It is believed that for T1, which has high viscous transition stress, rotational torque was reduced as the movement of the ball did not inhibit the grease and a stable channeling status was maintained, therefore stirring resistance was suppressed. From these results, we ascertained that, regarding the flow of grease inside a bearing, the grease moves due to the centrifugal force generated in the initial phase of rotation then by the movement of the ball and cage until finally it adheres to a location, such as inside the seal, where it does not contribute to stirring resistance. Afterwards, in the case of grease with high viscous transition stress, only the small amount of grease which is not removed from the adhered portion and remains in close proximity to the ball and raceway, as well as the base oil separated from the grease adhered to the seal and cage, are supplied to the raceway face. Meanwhile, in the case of grease with low viscous transition stress, there is a large volume of residual grease, therefore stirring resistance is high. This means that, by designing grease with a thickener urea of a short terminal alkyl chain length and high viscous transition stress, it is possible to improve channeling performance. We believe that this result is consistent with the theory of grease stirring resistance becoming smaller when the ball moves.

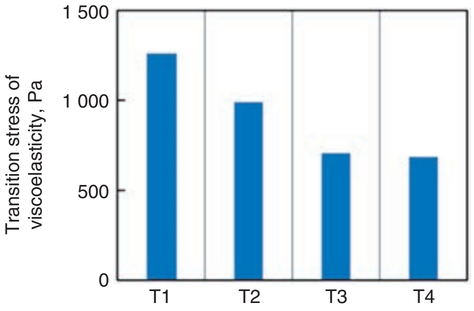


Fig. 9 Measurement result of viscous transition stress

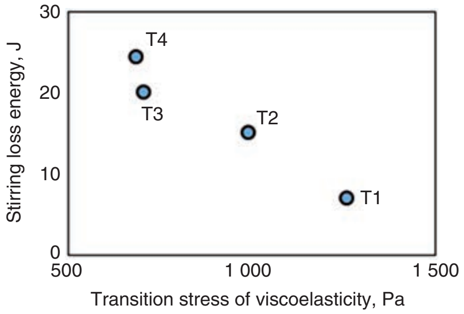


Fig. 10 Correlation between transition stress of viscoelasticity and stirring loss energy

Sample	T1		T4	
	Side of tabs	Back side	Side of tabs	Back side
Observation of the balls and retainer				
Grease amount	0.559 g		0.570 g	
Observation of the seals				
Grease amount	0.079 g		0.045 g	

Fig. 11 Observation result of test bearing

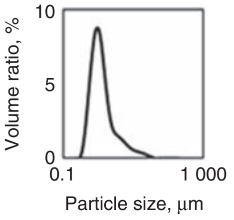
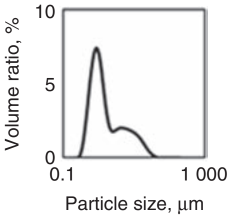
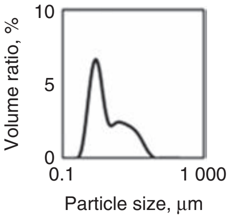
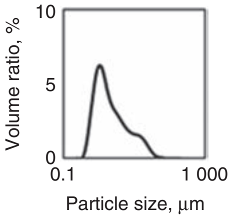
Sample	T1	T2	T3	T4
Particle size distribution				
Average grain size, μm	2.23	3.682	3.93	4.624
Relative surface area	8 953	8 154	7 632	7 472

Fig. 12 Particle size distribution and relative surface area of thickener

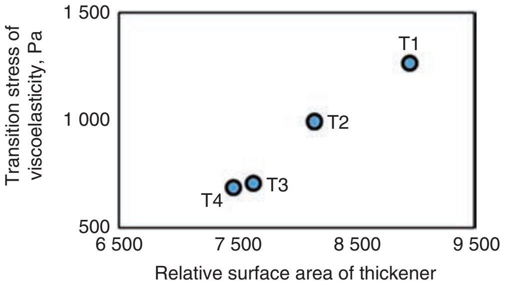


Fig. 13 Correlation between relative surface area of thickener and viscoelasticity

Table 10 Measurement result of bearing noise

Sample sign	N1	N2	N3	N4	N5
Amine	Aliphatic	Alicyclic	Aromatic	Aliphatic Alicyclic	Aliphatic
Average particle size of thickener, μm	2.8	2.4	1.3	0.3	13
Bearing noise value, G	0.029	0.157	0.243	0.021	0.186

Table 11 Measurement result of Young's modulus

Sample sign		N1	N2	N3	N4	N5
Young's modulus, MPa	n = 1	685	1 568	3 382	783	706
	n = 2	729	1 678	2 621	821	627
	n = 3	734	1 526	2 592	689	687
	n = 4	685	1 663	2 273	755	592
	Average	708	1 609	2 717	762	653

3. 3 Factors affecting viscous transition stress

As it was elucidated that viscous transition stress has a large affect on the reduction of rotational torque, we studied the factors affecting viscous transition stress. As one of the factors affecting viscous transition stress which indicates grease fluidity, we focused on the interaction between the thickener and base oil contained in grease. While there are said to be a number of physical property values that indicate this, we believed the relative surface area of the thickener particles, which expresses the interfacial area between the thickener and base oil, to have a particularly large effect. **Figure 12** shows the particle size distribution and calculated thickener relative surface area for each of the greases. It was elucidated that, in contrast to the short-chain T1, whereby surface area was large due to increased number of small thickeners with small particle diameter, long-chain T4 had a small relative surface area due to increased number of thickener with large particle diameter. Here, **Fig. 13** shows the results of studying the correlation between the obtained thickener relative surface area and viscous transition stress, however, a tendency for the viscous transition stress to increase as the thickener's relative surface area became larger, was clarified. In the case of thickener with large relative surface area and small particle diameter, the number of particles increase, therefore the distance between the thickener particles is shorter and there is greater interaction between particles. Moreover, it is believed that the fluidity of the grease is inhibited due to the small particles dispersing in the oil and taking on a pseudo-slurry state.

3. 4 Factors affecting bearing noise value

Table 10 shows the results of measuring the bearing noise value of the greases for studying quietness with different amine types and miniaturization processing conditions. The table shows both the bearing noise value after one second's worth of rotation as well as the average particle diameter of the thickener measured from the diameter of the particle size distribution, taken with a laser diffraction method. Comparing the samples of N1, N2 and N3, it was observed that the bearing noise value varied greatly depending on the amine type of the thickener, with noise value being smallest for the aliphatic diurea, second smallest for the alicyclic type and finally, largest for the aromatic type. Moreover, we confirmed that, compared to N1 and N2, the bearing noise value for sample N4, a combination of the aliphatic and alicyclic types, was lower. Meanwhile, for sample N5, which used the same aliphatic amine as N1 but had a bigger average particle diameter, it was confirmed that the bearing noise value significantly increased compared to N1.

Table 11 shows the measurement results for Young's modulus. When a comparison was made between the samples of N1, N2 and N3, with differing thickener types, it was observed that Young's modulus was the lowest in N1, which used aliphatic amine, second lowest in the alicyclic type of N2 and highest in the aromatic type of N3. Furthermore, the Young's modulus for both sample N4 and N5 had values close to that of sample N1. The resin-embedded test specimen on which this measurement was performed was prepared by applying 1.5 MPa of compression stress, however this is extremely small compared to the absolute value obtained for the Young's modulus of the thickener on this occasion, and we deemed there to be no affect.

Based on the results obtained on this occasion, we considered the factors of grease that affect bearing noise value. Of the various greases used to study quietness, the samples of N1, N2 and N3, which use thickeners of differing amine types but have an average particle diameter of around the same size (within the range of 1.3 - 2.8 µm) were used to evaluate the effect of the thickener Young's modulus on bearing noise value. The results are shown in **Fig. 14**. There is a strong correlation between bearing noise value and thickener Young's modulus and the lower the Young's modulus, the smaller the bearing noise value. We believe that, when the contact face of the rolling element and raceway is flowed into not only by the base oil of grease but also thickener, the smaller the vertical vibration amount of the rolling element when thickener is trapped the more oil film variation can be minimized and the smaller the bearing noise value becomes. If thickener Young's modulus is low, we infer that the variation amount of the thickener when it became trapped was greater, therefore it was possible to minimize the vertical vibration of the rolling element and reduce bearing noise value.

Meanwhile, when we investigated the relationship between thickener Young's modulus and bearing noise value using the samples of N4 and N5, which have differing thickener average particle diameters, the correlation seen in **Fig. 14** was not obtained. Previous research has reported that there is correlation between the thickener particle diameter and bearing noise value, whereby the smaller the particle diameter, the more the noise value reduces4), and we verified that our investigation results demonstrated the same tendency. This is because both the thickener Young's modulus and average particle diameter are the factors affecting bearing noise value.

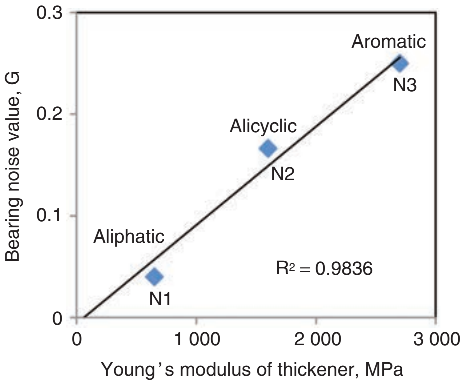


Fig. 14 Effect of Young's modulus of thickener on bearing noise

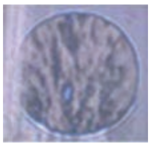
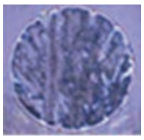
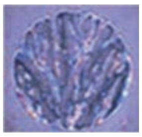
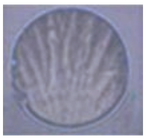
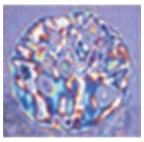
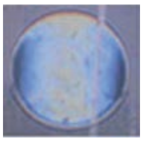
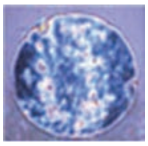
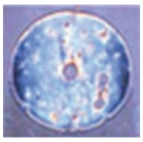
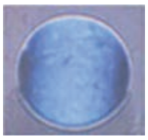
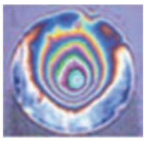
Sample sign		N1	N2	N3	N4	N5
Speed	5mm/s					
	100mm/s					
Oil film thickness, nm	Max.	690	790	800	630	850
	Min.	550	550	550	520	600
	Variation range	140	240	250	110	250

Fig. 15 Measurement result of oil film thickness

3. 5 Effect of film thickness variation on bearing noise value

Figure 15 shows the results of an observation of interference fringes under the speed conditions of 5mm/s and 100mm/s as well as the results of a film thickness measurement obtained from the order of the interference fringes under the condition of 100mm/s. Under the low speed condition of 5mm/s when film thickness becomes thinner, we were able to clearly observe variation in the oil film caused by inflow of thickener particles. Even under the high speed condition of 100mm/s, we recognized oil film variation believed to be caused by the thickener. This observation was of samples with largely-differing Young’s modulus and average particle diameter however, for all of the samples, thickener particles flowed into the contact face and we judged it was not possible to perform control so that the thickener did not become trapped in the contact face.

We found film thickness from the film thickness at the center of where the glass disc and steel ball make contact. Moreover, we performed observation in five fields of vision with consideration to the point that film thickness may vary due to thickener inflow and found the film thickness variation width by subtracting the smallest film thickness from the largest film thickness. The results of this measurement showed that the film thickness variation width was smallest for N4, the sample using a combination of the aliphatic and alicyclic amines and next smallest for N1, which used an aliphatic amine alone. We also confirmed a wide film thickness variation range for N2 and N3, which used an alicyclic and aromatic amine in isolation respectively, as well as for N5, which had a large thickener particle diameter.

We believe that the reason why the thickener Young’s modulus and average particle diameter are the factors which affect bearing noise value is because thickener flow in between the rolling element and raceway becomes trapped and causes oil film variation, which in turn causes the bearing to vibrate. Here, we investigated the relationship between the film thickness variation width, which was measured from the observation results using an optical interference method, and bearing noise value. **Figure 16** shows the results.

We recognized a strong correlation between the film thickness variation width caused by grease thickener and bearing noise value. For the N4 sample, which had low Young’s modulus and a small average particle diameter, we infer that it was possible to lower bearing noise value due to the oil film variation damping effect being great when thickener became trapped.

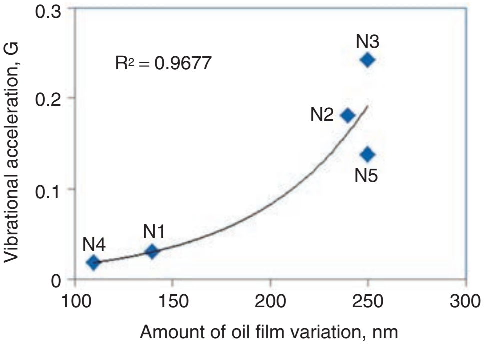


Fig. 16 Relationship between amount of oil film thickness and bearing noise

4. Conclusion

We quantified the effect of the compositions and properties of grease on rolling bearing torque. As grease properties, we introduced the concepts of viscous transition stress as a new indicator to substitute yield stress and, in regards to bearing torque, stirring resistance energy, which is the time integration of torque caused by thickener. As a result of studying the correlation between terminal alkyl chain length, stirring loss energy and viscous transition stress for aliphatic diurea grease, we elucidated that the shorter the chain length, the lower the stirring loss energy and higher the viscous transition stress. We inferred that, the shorter the chain length of aliphatic diurea grease is, the greater viscous transition stress increases due to a higher collision frequency between thickeners as a result of small particle diameter and a large number of particles.

In regards to the reduction of bearing noise value, we conducted an investigation focused on the aspects of thickener elastic modulus and oil film variation. The results showed that bearing noise value is favorably low for diurea grease with a small elastic modulus made from aliphatic amine, as well as for grease combining alicyclic and aliphatic amines for which both particle diameter and oil film variation are small.

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