Grease Lubrication Technology of Rolling Bearings

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Friction loss of rolling bearings that support rotational motion in machinery is generally smaller than that of sliding bearings. Moreover, rolling bearings lubricated with grease can contribute much more to reduction of friction loss in machines, machine size, and machine weight than those lubricated with oil due to smaller agitation resistance of lubricant and simpler sealing equipment. Development and improvement of rolling bearings and greases have been carried out to support higher performance of machinery. This paper introduces trends in greases for rolling bearings used in main industrial fields and recent examples of research and development results.

Key Words: *grease, rolling bearing, boundary lubrication, elastohydrodynamic lubrication*

1. Introduction

For global environment conservation and global warming prevention, much effort is being made regarding the development of machinery, with the aims of achieving smaller size, lighter weight and longer service life, reducing friction loss and increasing efficiency. The rolling bearing is an important elemental component which supports the rotational motion of machinery and, in general, the friction loss of rolling bearings is smaller than that of sliding bearings. Moreover, the lubrication method of rolling bearings can be broadly divided into oil lubrication and grease lubrication, however, in the case of the latter, frictional loss caused by agitation of the lubricant is less than that of oil lubrication. In addition, the sealing equipment can be simplified and the machinery can be made smaller and lighter if grease lubrication is used. However, due to needs such as making machines with even less friction loss, smaller size and lighter weight, more and more is being demanded of rolling bearing performance. In order to respond to these needs, greases for various applications are being improved and developed. This paper introduces the trends of greases for rolling bearings in the main industrial fields and recent research and development trends.

2. Characteristics of Grease for Rolling Bearings

Rolling bearings are required to work across a range of temperatures, from low to high, sometimes at a high surface pressure where plastic deformation will occur in the bearing material. Bearings are also expected to support rotational motion, and sometimes swaying motion, lightly, quietly, smoothly and for a prolonged period over the duration of the product's life. Therefore, while bearing model selection, internal design optimization and so forth is important, so too is selecting the appropriate grease. For rolling bearings to be able to perform well, the grease used must be heat resistant, have good oxidation stability, work at low temperatures, have good load carrying capacity, low torque, high speed and acoustic properties, be resistant against corrosion and so on. These characteristics are determined by combining thickener to maintain the semi-solid state of the base oil, the main acting agent in lubricant, and various additives to improve each characteristic.

Characteristics such as heat resistance, oxidization stability, load carrying capacity and so on are also necessary in grease for other applications, such as gear grease. On the other hand, good acoustic properties are only required in grease for rolling bearings. The contact portion between the rolling elements of rolling bearings and the race has a high surface pressure of several GPa, and also performs rolling motion at a high speed. If the grease in this contact portion contains solid particles, the rolling bearing will begin to vibrate, which will create abnormal noise.

Solids inside the grease include lumps of thickener, which is a component of grease, and other foreign matter. As **Fig. 1** shows[1)], thickener lumps are dispersed finely in roll mill treatment when grease is manufactured, however roll mill treatment increases the cost of grease as it is time consuming. Various efforts such as using a filter on the base material and manufacturing in clean rooms are taken to prevent foreign matter entering the grease and help improve acoustic properties.

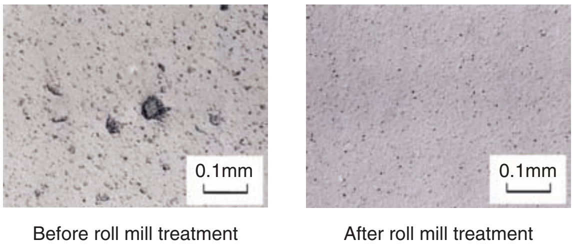

Fig. 1 Microscopic observation results of greases before and after roll mill treatment

3. Trends in Greases for Rolling Bearings in Main Industrial Fields

3. 1 Automotive

Recently there is a tendency to incorporate the rolling bearings for wheels of passenger vehicles into hub units due to advantages such as being more compact, lightweight, maintenance-free and simpler to assemble. In order to prevent false brinelling when vehicles are transported and eliminate the need for maintenance, we select JIS 1-2 penetration grade grease for hub units, urea mineral oil grease, with excellent heat resistance, adhesiveness to the friction surface, fluidity and lubrication.

Regarding the rolling bearings used in automotive electrical components and engine accessories, previously there was a problem of early flaking during usage on actual vehicles due to the microstructual change of steel in the fixed ring. This problem was largely related to the fact that operation conditions of rolling bearings have become quite severe, i.e. high speed, high temperature, high load and high vibration, because devices are smaller, lightweight and have higher performance.

This flaking is completely different to the flaking originating from within the rolling bearing noted previously, and is characterized by a white etching band, therefore it is also known as "white band flaking". The main cause of this flaking is an increase in internal stress due to sliding, high surface pressure, shock load, etc. and it was assumed that the hydrogen created when grease in the race breaks down and intrudes the steel facilitated the process of flaking. Grease to prevent white band flaking was developed based on this hypothesis. Throughout the development of this grease, studies were conducted for the alleviation of shock load caused by oil film as well as reducing friction caused by additive membrane, hydrogen creation and intrusion into the steel. As a result, a grease was developed by adding organic metal extreme-pressure additive to urea grease with a base oil of alkyl diphenyl ether (ADE) which has excellent oil film forming ability as well as large kinetic viscosity and pressure-viscosity index[2]. The properties of this developed grease and the results of an alternator endurance test are shown in

Table 1 Compositions and properties of grease for alternator bearing

		Conventional grease	Developed grease
Thickener		Diurea	Diurea
Base oil		Poly-α-olefin/ Mineral oil	Alkyl diphenyl ether
Base oil kinetic viscosity mm^2/s at 40℃		56	97
Worked penetration		244	238
Dropping point, ℃		>270	>270
Evaporation loss, % 100℃×22 h		0.15	0.19
Oxidization stability, kPa 99℃×100 h		15	10
Low temperature torque N･m, −30℃	Starting	0.274	0.322
	Rotation	0.042	0.048

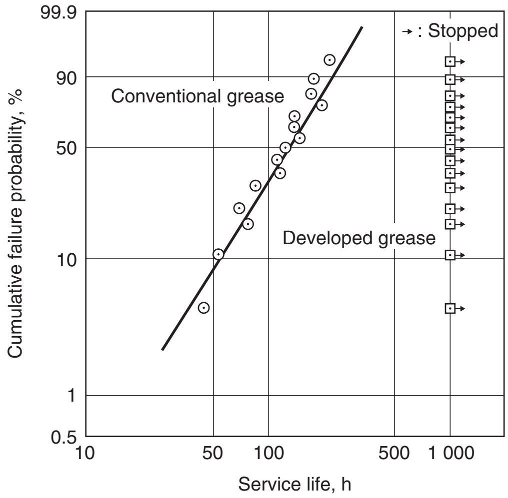

Fig. 2 Results of alternator endurance test

Table 1 and **Fig. 2** respectively. By using this developed grease, it was possible to prevent white band flaking of the fixed ring and contribute to the long service life of rolling bearings.

3. 2 Industrial Device Field

3. 2. 1 Wind Turbin

Figure 3 shows the typical structure of a wind turbine. Wind turbines are configured from a main shaft, gear box, generator and so forth, meaning many rolling bearings are used. In many cases, oil lubrication is adopted for the rolling bearings of the gear box, and grease for lubrication of all other parts.

The main shaft bearing is an important component which supports the load caused by the wind working through the rotor and transmits rotational torque to the gear box. The grease for the main shaft bearing is required to have low torque at low temperatures, have good load carrying capacity, be resistant against corrosion and have a long service life. Therefore, as indicated in **Table 2**, lithium soap grease, lithium complex soap grease and other grease types which use poly-α-olefin and mineral oil as base oils, are adopted[3].

3. 2. 2 Iron and Steel Equipment

Rolling bearings used in iron and steel equipment must be not only able to cope with high temperatures and high loads, but also perform satisfactorily in severe environments with water, dust, oxidized steel and so on.

The roll neck bearings used in roller mills are used under high loads and shock loads. Furthermore, the large amount of cooling water used in the rolls and scale intrudes the rolling bearing, leading to problems such as softening of the grease and shortening of the rolling bearing service life. Conventionally, lithium soap grease with superior water resistance and load carrying capacity or special lithium complex soap grease with high PV performance were used, however in recent years, the use of calcium sulfonate complex grease is becoming more popular as it has excellent extreme pressure performance, is anti-corrosive, has good adherability and shear stability when mixed with water[4].

The guide roll bearings used in continuous casting equipment are used in high temperature, extremely low speed and under high loads, making oil film formation difficult and meaning operation takes place at the boundary lubrication regime. Conventionally, aluminum compound soap was used as sealed grease as it had superior heat resistance, however in recent years, urea grease, which has a base oil of high viscosity, has been gaining popularity[4].

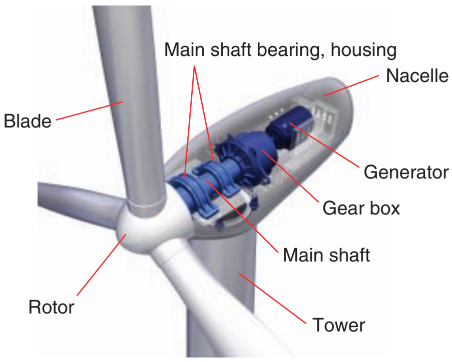

Fig. 3 Typical structure of wind turbine

3. 2. 3 Railway Carriages

Previously, axle bearings for bullet train carriages used oil bath lubrication, but the shift to grease lubrication was made in 1997 when the 500 series bullet trains commenced operation. Because sealing equipment can be simplified, axle bearings have been made smaller and lightweight, and can now support high-speed operation. There are also expectations that the axle bearings can be made maintenance-free[5]. For the packed grease, in order to increase the length of time between inspections, lithium soap grease was adopted. Lithium soap grease is made from hydro-treated mineral oil, which has excellent oxidization stability compared to common mineral oil and a high viscosity index. Grease-packed bearings using the same model grease is adopted on the carriages of the Kyushu (800 series) bullet train that commenced operation in March of 2004.

Since the introduction of the induction motor and shift to brushless, the inspection period of the traction motor, which is the power source of a railway carriage, has depended on the rolling bearing using grease lubrication and grease service life. In bullet trains, induction motors were adopted in carriages from the 300 series and, so that the rolling bearings could support high speed/high temperature operation, grease made from a combination of lithium complex soap, which has excellent heat resistance, and mineral oil was adopted. This grease is now used in the later model bullet train carriages and many traction motors. To further increase the length of time between inspections, grease made from the same lithium compound soap with a synthetic base oil is becoming commonplace.

Table 2 Compositions and properties of grease for wind turbine main spindle bearing

	Grease A	Grease B	Grease C	Grease D	Grease E
Thickener	Lithium soap	Lithium/ calcium soap	Lithium complex soap	Calcium sulfonate complex	Lithium complex soap
Base oil	Mineral oil	Mineral oil	Mineral oil/ PAO	Mineral oil/ PAO	PAO
Base oil kinetic viscosity mm^2/s at 40℃	200	400	130	80	460
Penetration grade	Grade 1	Grade 2	Grade 1	Grade 2	Grade 1/2

4. Recent Research and Development Trends

4. 1 Tribological Characteristics

4. 1. 1 Organometallic Extreme-Pressure Additives

When used under hydrodynamic lubrication conditions, sufficient lubrication can be maintained with an oil film formed from the base oil, however, the conditions of use are becoming increasingly severe, (e.g. high temperature, high load), and in order to improve lubrication when used under mixed or boundary lubrication conditions, an oiliness-improving agent and extreme-pressure additive are added. There are sulfur and phosphorous extreme-pressure additives, however it has been discovered that organometallic extreme-pressure additives best represented by organomolybdenum compound, are effective in preventing white band flaking. To verify this, an evaluation of the friction and wear characteristics of organometallic extreme-pressure additives and an analysis of the formation and structure of surface film generated by tribochemical reaction were performed.

Regarding the friction and wear characteristics of ADE-based urea grease combined with different organometallic extreme-pressure additives, it was discovered that in some cases, the effect of reducing friction was good, however the friction coefficient was sometimes great, or, wear prevention was good, however, friction reduction was small. Characteristics differed depending on the variety of extreme-pressure additive used[6]. Furthermore, a study was carried out to see the improvement in the friction and wear characteristics when two types of additives were used with the extreme-pressure additive. **Figure 4** shows the change over time of the friction coefficient, and a reduction in friction and wear was recognized when zinc additive was used, proving that the friction and wear characteristics improved when additives were used together rather than independently[7].

These friction and wear characteristics are determined by the surface film generated by tribochemical reaction, and as such, it is important to find out the chemical structure and thickness of this surface film. Therefore, the surface film was analyzed using surface analysis devices such as Auger Electron Spectroscopy (AES).

For example, **Fig. 5** shows the AES analysis results of a friction surface after a friction and wear test when antimony dithiocarbamate (SbDTC) and a zinc additive were used together. The surface film structure is thought to be formed from layers of antimony oxide and sulfide on the top and a layer of zinc sulfide underneath, suggesting that antimony oxide and sulfide were effective for friction reduction while zinc sulfide was effective for preventing wear[7].

Furthermore, a comparison was made of the surface films formed in the case of rolling contact and sliding contact[8]. **Figure 6** shows the analysis results of a surface film formed in rolling contact. The surface film formed by rolling contact is made mainly from antimony and lead oxides, which differed from the surface film formed by sliding contact, made mainly from sulfide. It is believed this is due to differing friction conditions and whether or not there is contact with oxygen.

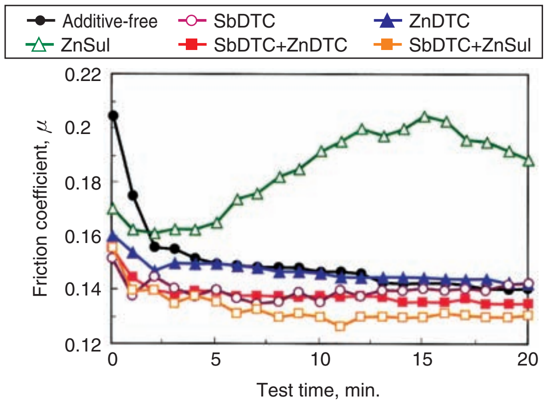

Fig. 4 Friction coefficient of greases combination SbDTC with Zn additives

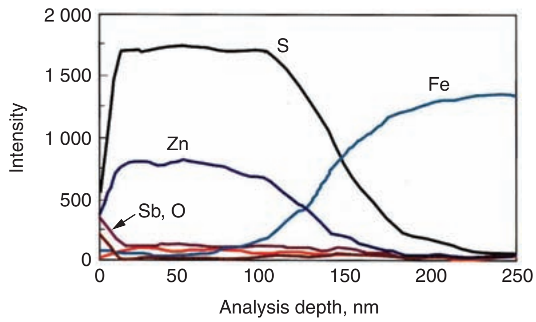

Fig. 5 AES analysis results of sliding friction surface (SbDTC + ZnSul)

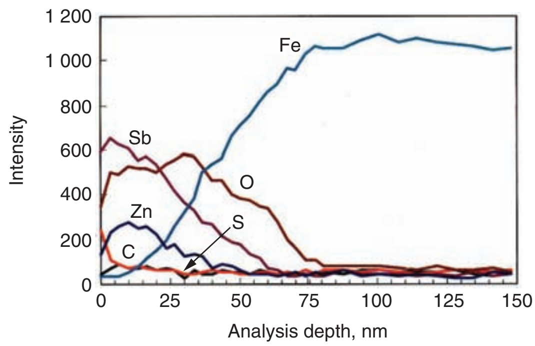

Fig. 6 AES analysis results of rolling friction surface (SbDTC + ZnSul)

4. 1. 2 Bismuthic Extreme-Pressure Additive

Due to the importance of protecting the global environment and improving human safety, a shift from lead and chloride compounds to alternative additives has already taken place in the extreme-pressure additive field. However, new stipulations and restrictions on the effects of additives towards humans and the environment may be made in the future, therefore the research and development of an even safer additive is important.

Bismuth is part of Group 15, the same family as arsenic, however compounds of bismuth are used in pharmaceuticals, cosmetics, etc. and it has relatively low toxicity compared with other heavy elements. Bismuth is also used in lead-free soldering alloy. Furthermore, there is research that claims organic bismuth compound could serve as an alternative to lead extreme-pressure additives[9] and as such the characteristics of bismuth compound as an extreme-pressure additive were researched. As **Fig. 7** shows, this research confirmed that bismuth dithiocarbamate (BiDTC) has excellent friction and wear characteristics[10].

Furthermore, an evaluation of tribological characteristics under sliding friction conditions and an analysis of the surface film formed under sliding friction conditions and rolling friction conditions were performed for a BiDTC-added grease which uses ADE as its base oil[11]. As **Fig. 8** shows, under sliding friction conditions, the BiDTC-added grease has equivalent friction and wear characteristics to the SbDTC-added grease, and, as **Fig. 9** shows, it was discovered that the surface film formed was made from bismuth and sulfide. The surface film formed by rolling friction was, as shown in **Fig. 10**, made from bismuth, oxygen and sulfur, showing that the surface films formed by sliding friction and rolling friction differed. This is thought to depend on the same factors as SbDTC, i.e. differing friction conditions and whether or not contact is made with oxygen.

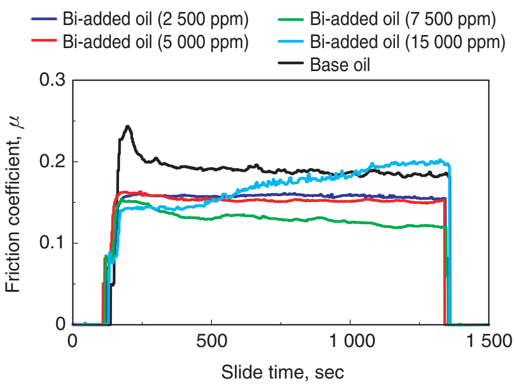

Fig. 7 Friction characteristics of ADE oil containing BiDTC

4. 2 Rheological Characteristic

Extreme-pressure additives are most effective mainly in the regimes between boundary lubrication and mixed lubrication. If used together with the improved lubrication state from the boundary to the mixed lubrication regime, and from the mixed to the hydrodynamic lubrication regime, extreme-pressure additives contribute to improvement of performance by reducing the friction and wear of rolling bearings, extending service life and so on. In grease lubrication, the lubrication state is affected significantly by the rheological characteristic of the grease

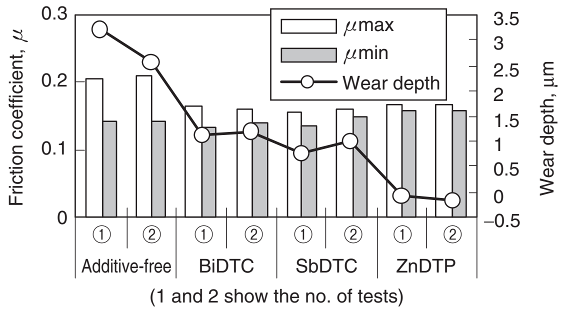

Fig. 8 Friction and wear characteristics of BiDTC-added grease

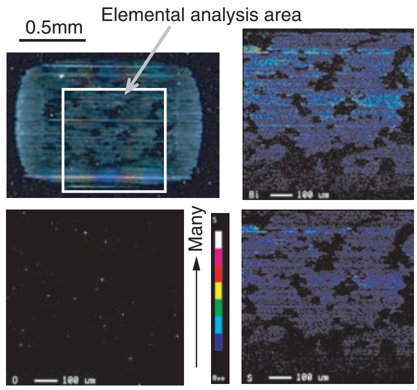

Fig. 9 Analysis results of friction surface after sliding friction test

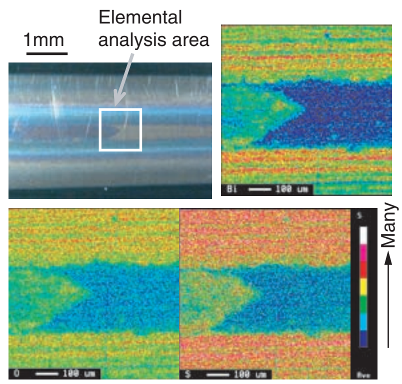

Fig. 10 Analysis results of friction surface after rolling friction test

itself as well as conditions of use such as temperature, load and rotational speed. Thus, it is important to understand the rheological characteristic of grease.

Furthermore, the need to lubricate with only a small amount of packed grease is growing from the perspective of reducing friction loss caused by the agitation resistance of grease and the need to reduce grease consumption. However, one of the concerns of using a small amount of packed grease is that the amount needed for lubrication will not be supplied to the contact portions. It is necessary to understand the rheological characteristic of grease in this lubrication-deprived state and make it appropriate in order to increase the amount of grease by contributing effectively to lubrication, hence improving the performance of rolling bearings.

Conventionally, the discussion on fluidity of grease mainly focused on worked penetration therefore first a study of the correlation between the rheological characteristic of grease in this lubrication-deprived state and worked penetration was carried out[12]. As **Fig. 11** shows, the anti-seizure characteristic under sliding contact in a deprived-lubrication state is effected by penetration. It was discovered that, it takes a long time before the grease seizes when penetration is high, and a correlation exists between grease fluidity to the friction surface and the shear viscosity and yield stress of the grease reserve at the entrance to the contact portion. Furthermore, the respective impact of thickener types and base oil kinetic viscosity on the rheological characteristic was studied and it was discovered that, even if the penetration was the same, the grease fluidity would differ depending on the thickener type[13, 14].

4. 3 Elastohydrodynamic Lubrication Film Forming Ability

The theoretical analysis and measurement of the elastohydrodynamic lubrication (EHL) film of grease have been carried out in comparison with the EHL film forming ability of base oil. To date, studies have been done on the impact of thickener type, amount, fiber structure, base oil type, grease penetration and so on[15].

Figure 12 shows the results of an evaluation of grease film forming ability using optical interferometry[16]. In this evaluation, no extra grease was supplied after grease was applied before measurement. In the case of common grease, the grease film breaks early on, as is the case for Grease A, but by adjusting thickener type, volume, worked penetration and so on, the grease film can be maintained for an extended period of time, as is the case for Grease B.

The following section introduces 2 research cases of grease film forming ability of urea grease in the low-speed regime.

In the first case, the results of measuring grease film thickness up to the extreme low-speed regime show that the grease film thickness in the low-speed regime is a different order of magnitude to the film thickness of base oil[17]. Even in the low-speed regime, horseshoe-shaped interference marks, typical for EHL film, were observed, and the increase in film thickness was assumed to be caused by hydrodynamic lubrication. Meanwhile, in the second case, while the grease film thickness did increase in the low-speed area, observation results of the sealed-in grease film[18] and FT-IR analysis results of the disk rolling contact surface[19] led to the assumption that the grease film became thicker due to the adherence and accumulation of thickener on the rolling contact surface during rotation.

The above two cases both show that urea grease has superior grease film forming ability in low-speed regimes, however, the respective mechanisms differ. In the first case, it is assumed the grease film forming ability is due to hydrodynamic lubrication, while in the latter it is assumed to be a result of boundary film formation. This is thought to be due to the difference in evaluation conditions. Moreover, these evaluations were carried out using optical interferometry and verification using actual rolling bearings is still necessary.

5. Conclusion

It is predicted that machinery will continue to be made smaller, lighter, able to operate at higher speeds and so on, making the environment in which rolling bearings are used even more severe, while at the same time increasing the demand for rolling bearings with low torque and

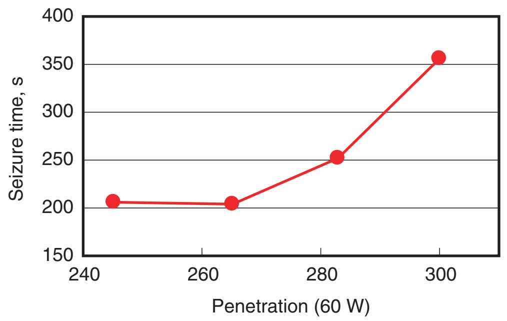

Fig. 11 Relationship between penetration and seizure time

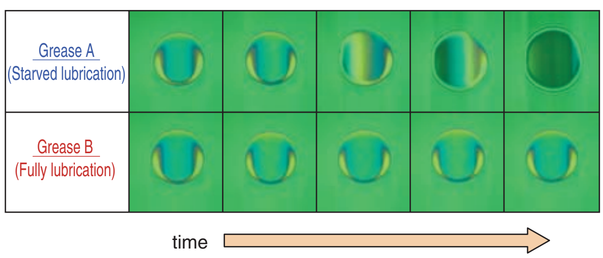

Fig. 12 Observation results of grease film

a long service life. Furthermore, efforts to reduce environmental load are also an important issue. In order to support these trends, rolling bearings must evolve. In the same way, grease, an "element" of rolling bearings, must also evolve. Grease must become high performing and highly functionable by using additives technology and rheology/oil film forming ability analysis. It is believed this will contribute to the advancement of rolling bearings.

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